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Disaster Resilience by Design:

A framework for integrated assessment and risk-based planning in Canada

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with Research Contributions by:
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CRTI CBRN Research & Technology Initiative

Canada

i. Acknowledgements

Disaster Resilience by Design: A Framework for Integrated Assessment and Risk-Based Planning in Canada is the result of a five-year research and development effort by the Earth Sciences Sector of Natural Resources Canada (ESS/NRCan). The study explores the realm of disaster risk reduction in North America, and introduces a framework for integrated assessment and scenario planning to assist local and regional governments in managing the risks associated with growth and development in areas exposed to natural hazards.

The work that forms the basis of this study has evolved through two cycles of research and development by the Earth Sciences Sector of Natural Resources Canada. The initial phase of work was carried out as part of the Reducing Risk from Natural Hazards Program (2006–2009). It examined the broader concepts and practices of disaster risk reduction, and evaluated approaches and methods that might be suitable for the assessment of natural hazard risks in Canada. The second phase of work was carried out as part of the Public Safety Geoscience Program (2009–2014). The study was focused on the development and testing of an operational framework for risk-based planning at local and regional scales using available best practice methods and tools. The analytic-deliberative framework, known as *Pathways*, is aligned with and contributes to broader efforts by the Centre for Security Science (Public Safety Canada; Defence Research and Development Canada) to establish a capability for all-hazard risk assessment in support of Canada's platform for disaster risk reduction. Overall coordination and support for this second phase of work was provided through the Risk Assessment and Capability Integration Program of Defence Research and Development Canada with support from the Chemical, Biological, Radiological/Nuclear, and Explosives Research and Technology Initiative (CRTI), and the Public Security Technical Program (PSTP) of the Centre for Security Science (Risk 09/10-0001SCP; Quantitative Risk Assessment Methods Project).

This report documents principal outputs and findings of our work so far. It contributes to a growing body of scholarly work on risk assessment and disaster risk reduction in the public domain, and is the result of an interdisciplinary effort that has involved ongoing collaboration between a dedicated team of researchers and practitioners—all of whom have willingly shared their knowledge and expertise to help address needs and operational requirements for disaster risk reduction at local and regional scales in Canada.

Murray Journeay is a research scientist with the Geological Survey of Canada (ESS/NRCan) and has served as principal investigator and author of this study. He is an executive board member for the Canadian Risk and Hazards Network (CRHNet), and has actively pioneered the development of methods and tools to support risk-based planning and sustainable land use through contributions to the Reducing Risk from Natural Hazards Program (2006–2009) and the Public Safety Geoscience Program (2009–2014).

Sonia Talwar is a researcher with the Geological Survey of Canada (ESS/NRCan) and a co-investigator on early stage development and testing of the Pathways framework (Reducing Risk from Natural Hazards Program). She has contributed to research on public science and community-based planning, and helped guide development and validation of the Pathways framework through a collaborative case study project with the District Municipality of Squamish in southwest British Columbia.

Boyan Brodaric is a researcher with the Geological Survey of Canada (ESS/NRCan), and a co-investigator on early stage development and testing of the Pathways framework (Reducing Risk from Natural Hazards Program). He currently leads research and development efforts in the fields of geoscience knowledge representation and systems interoperability for the Groundwater Program of the Earth Sciences Sector, and has provided ongoing support for the integration of spatial decision support methods and tools that are used to implement the Pathways framework.

Nicky Hastings is a geographic information systems analyst with the

Geological Survey of Canada (ESS/NRCan), and currently leads research and development activities for the CRTI Risk Assessment Methods Project in western Canada (Public Safety Geoscience Program). She helped pilot the use of FEMA's loss estimation methodology (HAZUS) in our case study project with the District Municipality of Squamish, and is actively involved in efforts to adapt the HAZUS methodology for broader use in Canada.

Collectively, we acknowledge the many contributions of research colleagues from the Earth Sciences Sector of Natural Resources Canada, the US Geological Survey (Western Region Geography), and the Institute for Resources, Environment and Sustainability (IRES) at the University of British Columbia. In particular, we would like to thank fellow members of the Risk Assessment Methods project: Marianne Ceh, Bert Struik, Malaika Ulmi, Carol Wagner, William Chow, Jorge Prieto and Maggie Wojtarowicz for their support. We also thank the US Geological Survey team of Richard Bernknopf, Anne Wein, Richard Champion, and Peter Ng (Western Geography Division); and research partners John Robinson, Stephen Sheppard, James Tansey, Jeff Carmichael, Stephanie Chang, Cynthia Girling, and Ron Kellett representing the UBC Institute of Resource and Environmental Sustainability (IRES), the Collaborative for Advanced Landscape Planning (CALP), the Design Centre for Sustianability (DCS), and the School of Community and Regional Planning (SCARP). Each has contributed in many important ways to our collective understanding of integrated assessment and its application in the field of disaster risk reduction and scenario-based planning.

Validation of working hypotheses and methodologies was undertaken through a collaborative partnership with staff and community members at the District Municipality of Squamish in southwest British Columbia, and with academic, private, and public sector partners involved in Smart Growth on the Ground and related land use projects across British Columbia. In particular, we thank municipal staff planners Cameron Chalmers, Heather Evans, Sabina Foofat, Jim Lang, and members of the Squamish Risk Assessment Working Group for their constructive feedback and support throughout the project; academic partners Shana Johnstone, Susan Milley, David Flanders, John Salter, and Cam Campbell (UBC Design Centre for Sustainability) for valuable insights on place-based planning; and Steven Kuan of the BC Building and Safety Policy Branch (Ministry of Housing and Construction Standards) for his input on disaster mitigation efforts in British Columbia. In addition, we thank Doug Bausch, Jesse Roselle, and Eric Berman of the US Federal Emergency Agency for their ongoing support in helping to adapt the HAZUS methodology for use in Canada. Implementation of the Pathways framework using integrated assessment and scenario modelling capabilities of CommunityViz® was facilitated through collaboration with Lex Ivey (TerraCognito) and the Placeways team of Doug Walker, Kelley Lewelling, and Eric Christensen.

Early draft versions of this manuscript were peer reviewed by Ian Burton, Marc Saner, and Ian Bayne, all of whom offered critical feedback and suggestions that have helped to refine the ideas and methods presented in this report. We thank Pierre Friele for reviewing results of our quantitative risk analysis of flood and debris flow hazards in Squamish, and for sharing his thoughts and perspectives on community-based risk assessment. We also thank Bob Turner (Earth Sciences Sector), and Stephanie Chang (UBC School of Community and Regional Planning) for final peer review of this manuscript.

I am grateful to Shana Johnstone, who helped guide the final stages of writing for this project. Her insights as both a technical editor and urban planner helped clarify the essence of the study and improve the overall organization and structure of the report to better assist those working on the ground to promote disaster resilience and sustainability.

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iv. Introduction

Earth system processes are subject to change without notice. They have the potential to trigger earthquakes, floods, and other natural hazards that can easily overwhelm the capabilities of communities to withstand and recover from unexpected disasters. Although hazard events may last for only a few minutes or days, they can undermine the sustainability of a region for years to come. As communities continue to grow and develop in areas exposed to natural hazard threats, so too does the potential for increasingly severe and devastating events like the ones recently witnessed in Japan, New Zealand, Chile, Haiti, Pakistan, China, and the United States. Lessons learned from these disasters underscore the need for a comprehensive risk-based approach to land use planning and emergency management at all levels of government—one that utilizes available knowledge about the risk environment to inform actions that can be taken on the ground to minimize future disaster losses and to marshal the resources that will be needed to build safe and secure communities that are resilient to the dynamic and uncertain forces of change.

Canada does not yet have a comprehensive framework for managing risks associated with growth and development in areas exposed to natural hazards. There are national policy guidelines that advocate mitigation and disaster resilience at the community level, and progress is being made to refine the knowledge and methods required to analyze natural hazard risks in terms of potential impacts and consequences. However, questions of what might constitute a tolerable threshold of risk for a specific geographic area or community, or how to decide on an appropriate course of action to manage shared risks in the public domain, remain largely unanswered. If addressed at all, these are questions generally negotiated on a case-by-case basis by planners and emergency managers who work on behalf of local and regional governments to balance a wide range of competing policy objectives.

Land use planners bring a comprehensive and forward-looking perspective to the challenges of disaster risk reduction, one that is based on a tacit understanding of how natural and human systems interact in the context of a changing landscape. They are responsible for managing the allocation and use of land in ways that reconcile individual and collective rights, and that balance competing demands for economic vitality, environmental integrity, and quality of life for existing and future generations. Emergency managers have a primary role in developing strategic and operational plans that will protect people and critical assets in the event of an unexpected disaster. They are responsible for all aspects of pre-event planning to identify and prioritize hazard threats of concern, to prepare for hazard events that are considered most likely in the context of a particular place or planning horizon, and to provide coordination for the response and short-term recovery from unexpected disaster events that may threaten the safety and security of a community or region. Unfortunately, the opportunities for collaboration across these communities of practice are few and far between, particularly in the domain of mitigation and emergency planning.

Community visioning, integrated assessment, landscape modelling, and the development of land use guidelines are the mainstay of the planning profession, and are also the keys to risk avoidance and disaster mitigation. Land use planners are well versed in policy analysis and have a legislated responsibility to manage growth and development in ways that promote safe, secure, and sustainable communities. However, they often lack a clear mandate from elected officials to manage risks associated with natural hazards. More often than not, this mandate is deferred to emergency managers with an expectation that they will develop the capability to mitigate hazard threats through investments in risk treatment measures that reduce vulnerability and the potential for loss. Though emergency managers are well versed in the methods of risk assessment, hazard mitigation, and the coordination of response and recovery operations, they are not always involved in the review of development applications or the negotiation of comprehensive land use plans. As a result, there is a tendency to focus on reactive measures that increase the capabilities of communities to withstand and respond to unexpected disaster events, but that do not necessarily address the underlying root causes or driving forces of societal risk.

While it is clear that land use planners and emergency managers each have the potential to influence decisions that will reduce disaster losses and increase the resilience of communities living with risk, there is very little guidance to assist them in working together toward a common set of goals and solutions. There is a need for an overarching framework of methods and tools that extend beyond conventional modes of rational analysis to address broader questions of risk-based planning. Salient questions include how to analyse the dimensions of vulnerability in a changing landscape; how to integrate objective measures of risk with varied and often competing societal views of who and what are vulnerable and most in need of safeguarding; and how to evaluate risk management alternatives in order to choose an appropriate course of action that will promote disaster resilience and the sustainability of communities within the limits of available knowledge and resources.

Study Mandate and Rationale

This study documents key findings and principal outputs of research and development efforts by the Earth Sciences Sector to address the challenges of disaster risk reduction in Canada. Study results are aligned with and contribute to broader efforts to establish a national framework and capability for all-hazard risk assessment and scenario-based planning in Canada. A framework that will increase the safety and security of Canadians by helping risk managers target investments in mitigation strategies that reduce potential disaster losses, and that enhance the resilience and longer-term sustainability of communities and regions.

Efforts to establish a coordinated approach to risk-based planning are facilitated at the national level through Canada's platform for disaster risk reduction; a consortium of public, private, and academic sector partners who are working together to adopt international policies and guidelines that have been adopted as part of the UN Hyogo Framework for Action (2005–2015). Efforts to establish a capability for disaster risk reduction by federal and provincial or territorial governments are coordinated through the Centre for Security Science, a joint endeavour between Public Safety Canada and Defence Research and Development Canada to address policy goals and objectives that are set out by the national Emergency Management Act (EMA: 2007).

The Earth Sciences Sector of Natural Resources Canada contributes to these broader risk reduction efforts by providing scientific knowledge and expertise required for the assessment of natural hazard risks, and by developing methods and tools that promote the uptake and use of this knowledge in support of place-based planning and policy development at all levels of government. In 2005, the Earth Sciences Sector launched an R&D program that was specifically targeted on knowledge generation and the evaluation of methods that might be suitable for the assessment of natural hazard risks in Canada (Reducing Risks from Natural Hazards Program; 2005–2009). Key findings and outputs of this project have provided the foundation for follow-up work by the Earth Sciences Sector as part of its Public Safety Geoscience Program (2009–2014). Program activities are focused on a characterization of geological and geophysical hazards in Canada (earthquakes, volcanoes, landslides, etc.), and the refinement of methods to assist planners in managing the risks associated with growth and development in areas exposed to natural hazard threats. The risk assessment component of the ESS Public Safety Geoscience Program is sponsored through a joint partnership with Defence Research and Development Canada.

Primary objectives of this study are to research best practices for the assessment of natural hazard risks at local and regional scales in Canada; to design and build a framework for integrated risk assessment and scenario-based planning that is standards-based and that can be implemented using available methods and tools; and to evaluate the efficacy of the proposed framework through case-based research with agencies that are actively involved in disaster mitigation activities on the ground. Motivating questions for this work include:

- What measures of risk are most relevant and useful for disaster mitigation at local and regional scales of governance, and how can these measures be used to support the needs and operational requirements of both land use planners and emergency managers?
- How do changing patterns of land use influence the vulnerabilities

of people and critical assets over time, and to what extent can this knowledge be used to inform on-the-ground actions that will reduce potential losses and promote disaster resilience of communities and regions?

- How do agencies responsible for land use planning and emergency management determine who and what are most vulnerable and in need of safeguarding through investments in disaster mitigation, and on what basis are these decisions made?
- What constitutes a tolerable threshold of risk for a community or region, and how are these thresholds negotiated within the limits of available knowledge and resources?
- What are the legitimate roles of analysis and deliberation in support of risk-based planning, and what are the associated responsibilities of those involved in the process?

The overarching goal of this work is to develop a process-oriented framework of methods and tools that will help build a capacity to anticipate, plan for and mitigate the risks associated with growth and development in areas exposed to natural hazard threats.

Approach and Methodology

This study explores the overall landscape of disaster risk reduction and the pathways needed to bridge existing gaps between concept and practice, and between knowledge and action. It investigates an earth systems approach to planning and decision making that extends beyond conventional modes of rational analysis to include principles of integrated assessment and scenario-based planning. The resulting framework, known as *Pathways*, conforms to international guidelines for risk assessment in the public domain, and incorporates best practice methods for the analysis and evaluation of natural hazard threats.

The analytic core of the framework is an integrated assessment model that links risk assessment outputs with policy goals and management objectives identified in the National Disaster Mitigation Strategy for Canada (2007) and Canada's National Platform for Disaster Risk Reduction. The framework is adaptable to the needs and requirements of the local planning process, and can be implemented using available best practice methods and tools for risk analysis, integrated assessment, and scenario-based modelling. As the name implies, Pathways offers a way forward through the planning process, but is not prescriptive in terms of the specific steps or the methods that may be required to address the needs of a particular community or region. Rather, it is a guide to assist planners and emergency managers in navigating the landscape between knowledge about natural hazard risks and the actions required to mitigate potential losses and to promote disaster resilience on the ground.

The Pathways framework represents a first step in establishing a comprehensive approach to risk-based planning at local and regional scales in Canada. It is designed to assist local and regional authorities to:

- Characterize the risk environment and prioritize mitigation goals and objectives
- Analyze the impacts and likely consequences of natural hazard threats on people and the things they care about
- Evaluate mitigation choices with respect to thresholds of safety, security, resource efficiency, and social equity
- Transform knowledge about the risk environment into actionable strategies that promote disaster resilience and sustainability

This study has evolved through an iterative process of adaptive design. As summarized in Figure 1, the process has involved extensive research into the practices, challenges, and theories of risk governance for the purpose of developing an operational framework that could be used to discover general patterns and to identify best practices for risk-based planning at local and regional scales. Design elements for this cycle of research and development draw heavily from guidelines for risk assessment in the public domain (Stern and Fineberg, 1996; CAN/CSA-Q850, 1997; International Strategy for Disaster Reduction, 2002; ISO 31000, 2008b) and from insights and experiences gained through interactive case-based research with local and regional governments that are actively engaged in the process of disaster mitigation planning. The design is rooted in the theoretical foundations of sustainability science and planning in the public domain (Robinson, 1982; Friedmann, 1987; Burby, 1998; Berke, 2002; Turner *et al.*, 2003; Robinson *et al.*, 2006), and has been made operational using a blend of analytic and deliberative methods from the fields of natural hazard risk analysis, integrated assessment, and scenario-based modelling (Jaeger, 1998; van Asselt and Rotmans, 1999; Pahl-Wostl *et al.*, 2000; Rotmans and Van Asselt, 2000; Bernkopf *et al.*, 2001; National Institute of Building Sciences, 2002; van der Sluijs, 2002; Cutter *et al.*, 2003; FEMA, 2004; Engels, 2005; Girling *et al.*, 2006; Sheppard, 2006; Wein *et al.*, 2007; Andrey and Jones, 2008; Bostrom *et al.*, 2008).

Although the approach and methods developed as part of this study have evolved independently, they are consistent with principles and guidelines established by the International Risk Governance Council (IRGC, Renn, 2006b; a; 2008). The IRGC framework has been tested and evaluated in the context of international case studies that focus on risks associated with genetic engineering, global environmental change, energy security, and nanotechnology (Renn and Walker, 2008). Elements of the IRGC framework have also been incorporated into risk assessment methods that are used to guide land use planning in the European Union (Greiving *et al.*, 2006b; Klein *et al.*, 2006; Margottini *et al.*, 2008). However, to the best of our knowledge, the IRGC framework has yet to be incorporated into an operational framework for risk-based planning that is suitable for use in support of community-based land use planning and emergency management in North America.

Research and development of the Pathways framework have been informed by a critique of existing risk assessment methods in the public domain (see Appendix II), and by experiences gained as part of an interactive case study partnership with the mountain community of Squamish in southwest British Columbia, Canada. Our premise is that adaptation of existing best practices and case-based research with practitioners who are actively managing natural hazard risks at the community level will lead to the discovery of general principles and solutions that can be applied in other regions across Canada.

Innovations

Preliminary results suggest that the Pathways framework offers a viable platform for hazard mitigation and disaster resilience planning at local and regional scales of governance. It extends existing standards and guidelines for risk assessment, and incorporates emerging new methods of integrated assessment and scenario modelling that help build a capability for risk-based planning in regions exposed to natural hazards. Significant innovations include:

- Development of a comprehensive planning process that integrates existing international standards for risk assessment with IRGC guidelines for risk governance, thereby establishing a bridge between existing practices of emergency management and land use planning at the community level.
- Development of an integrated assessment model comprising an internally coherent system of target indicators that are aligned with broader policy goals and objectives of Canada's platform for disaster risk reduction. The Pathways model provides overall structure to the risk assessment process, and offers an evidence-based approach to decision making that is informed by the best available science and that is governed by local community values and preferences.
- Adaptation of existing best practices to enable the analysis of target indicators for multi-hazard risk scenarios using methods of semi-quantitative appraisal and/or quantitative modelling. Analytic methods can be combined and adapted to meet the particular needs and operational requirements of the local planning process.
- Implementation of the Pathways framework through the development of a spatial decision support system that integrates standard risk assessment methods with emerging new techniques of landscape modelling and scenario planning. The integration of these analytic methods and tools provides a capability to evaluate changing conditions of vulnerability over time, and to develop mitigation strategies that promote disaster resilience in accordance with available resources and local thresholds of risk tolerance.

Intended Audience and Report Structure

Outputs of this study will be of particular interest to domain experts and practitioners involved in risk-based planning at the scale of individual communities and regions, and to those working toward the development of a broader framework for disaster risk reduction in Canada. Domain experts include those involved in fundamental and applied research on natural hazard risks, and those responsible for developing and implementing methods and tools to support the process of risk-based planning. Practitioners include land use planners who are responsible for managing risks associated with growth and development in areas exposed to natural hazards in Canada, and emergency managers working across various levels of government who share a mandate to protect the safety and security of Canadians through policies and legislative mandates set out in the national Emergency Management Act (EMA: 2007).

Each community of practice will have different interests and information needs. Those working in the applied sciences and engineering require technical information on the methods used to analyze the risk environment and to evaluate the strengths and weaknesses of mitigation alternatives. They are likely to be interested in theoretical aspects of the study and the documentation of specific analytic methods and tools that have been developed as part of the Pathways framework. Those working in the fields of planning and policy development require guidelines on how best to integrate objective measures of risk with community values and preferences in order to fully characterize the risk environment and to identify actions that can be taken to promote disaster resilience over time. They are likely to be interested in the pragmatic challenges of risk-based planning, general methods developed as part of the Pathways framework, and insights gained through case-study testing and validation.

The structure of this report mirrors that of the overall study (see Figure 1). It provides a guide to risk-based planning that will be of primary interest to researchers and practitioners working in the fields of land use planning and emergency management. Part 1 establishes overall context and focus for disaster risk reduction in the public domain, and introduces an earth systems approach to risk-based planning that is rooted in theoretical principles and best practices of risk analysis, integrated assessment, and scenario modelling (Chapter 1, 2, and 3). Part 2 introduces an integrated framework of processes, methods and tools (Pathways) that has been developed to guide risk-based planning at local and regional scales (Chapter 4). It also documents the results of an interactive case study project in which elements of the Pathways framework were tested and evaluated in support of a comprehensive risk-based planning process in southwest British Columbia, Canada (Chapter 5).

Chapter 1 begins with an overview of disaster mitigation in Canada. It describes the shifting policy mandate for disaster mitigation and documents the unintended consequences of current land use and emergency management practices that have a potential to undermine broader principles of disaster resilience and sustainability. The discussion establishes overall context for the study, and will be of interest to those who may be unfamiliar with the overall landscape of risk-based planning.

Chapter 2 explores the physical and human geography of risk in the context of a hypothetical mountain community. It describes fundamental characteristics of the risk environment (hazard threat, hazard risk, vulnerability, and resilience), and highlights the challenges of incorporating these concepts into the planning process. Issues of system complexity, judgment, and perspective are used to frame a discussion about the gaps between concept and practice, and to identify a core set of propositions for moving forward. The section brings focus to some of the practical challenges of risk-based planning, and will be of primary interest to those working in the fields of land use planning and emergency management.

Chapter 3 delves into the theoretical principles of risk-based planning, introducing an earth systems approach that builds on the strengths of rational analysis and integrated assessment. Earth systems thinking acknowledges the importance of place and the changing dynamics of vulnerability and risk over time, and is an iterative process of analysis and evaluation through which expert and local knowledge about the risk environment is used to inform decisions that promote the resilience of communities and regions. The section outlines fundamental design principles of the study and offers a critique of existing best practices that will be of primary interest to researchers working in the fields of risk assessment and method development.

Chapter 4 introduces the Pathways framework and provides full documentation of the processes, methods and tools that have been developed to support risk-based planning. It provides a general roadmap for implementation, and can be used as a general guide to assist planners and emergency managers in navigating "pathways" between knowledge and action.

Within Chapter 4, the sections outlining general tasks and activities will be of primary interest to land use planners and emergency managers who may want to design a risk-based planning process for their own community or region. Descriptions of target indicators that comprise the Pathways model will be of primary interest to researchers and policy analysts who are working to support broader goals and objectives of Canada's platform for disaster risk reduction. Technical documentation of analytic methods and tools will be of primary interest to domain experts and those who share the responsibility of developing a capability for risk-based planning at all jurisdictional levels.

The final section of this chapter provides examples of how the Pathways framework might be used in support of specific land use planning and emergency management functions at local and regional scales of operation. It offers some insights on how to bridge the gap between knowledge and actions, and will be of general interest to both researchers and practitioners.

Chapter 5 presents the results of a collaborative risk-based planning project with the District Municipality of Squamish in southwest British Columbia. The project addresses the challenges of managing risks associated with growth and development in areas exposed to multiple natural hazard threats (landslides, floods, and earthquakes), and provides a foundation for ongoing development, testing, and refinement of the Pathways framework.

The chapter begins with a characterization of the risk environment in Squamish, and an assessment of driving forces that are influencing

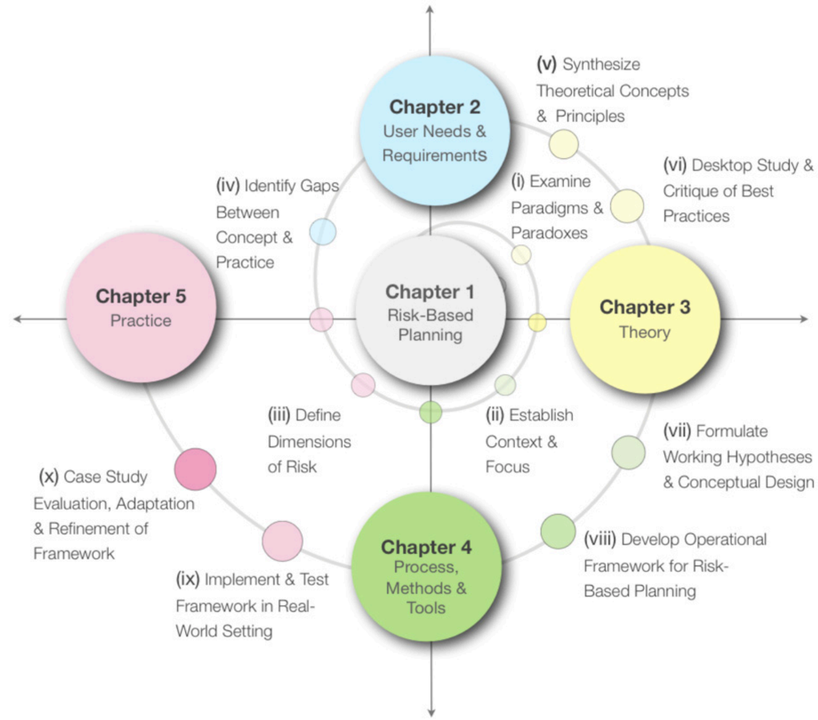


Figure 1: The overall approach, methodology, and report structure for this study are based on principles of adaptive design, an iterative process of research and development that is informed by insights and experiences gained through ongoing testing and validation in a real-world environment.

changing patterns of vulnerability on the ground. Semi-quantitative methods of risk appraisal are used to make evident principal hazard threats of concern to the community, to identify who and what are considered most vulnerable and in need of safeguarding, and to provide an assessment of existing capabilities to withstand, respond to and recover from unexpected disaster events. Methods of quantitative risk analysis are used to measure the physical impacts and anticipated socio-economic losses caused by flood, earthquake, and landslide hazards in the region. The results are combined into a portfolio of risk scenarios that provide a basis for evaluating the strengths and weaknesses of mitigation alternatives that might be considered by the community to reduce vulnerability and help strengthen capabilities for disaster resilience and overall sustainability.

The case study offers insights into the real-world challenges of risk-based planning, and provides overall validation of the processes, methods and tools that have been developed as part of the Pathways framework. Lessons learned are transferable to other communities living with natural hazard risks, and will provide a foundation for broader efforts to develop an institutional capability for disaster risk reduction in Canada.

Lastly, **Chapter 6** provides a summary of the key messages and results of the study described in earlier chapters, with a focus on the Pathways framework and its use in support of risk-based planning. This chapter offers a mechanism for quick review of the framework and its primary components. It also provides a brief discussion of the path forward to establish a comprehensive all-hazard risk assessment framework to build safe and disaster-resilient communities in Canada.

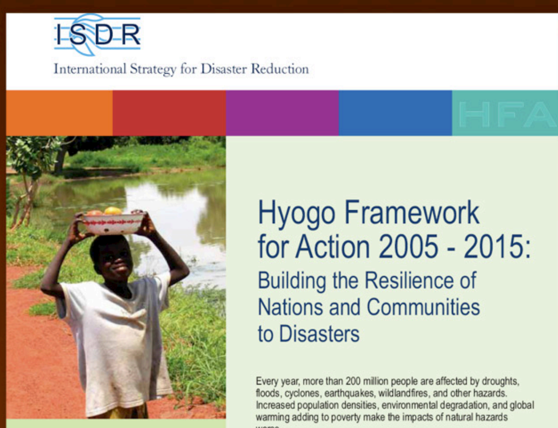
pathways

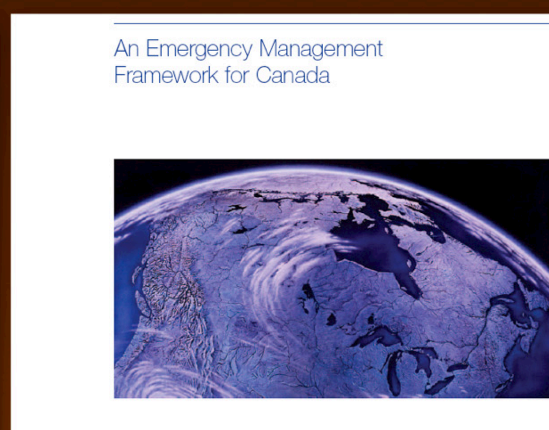
Chapter One:

Risk-Based Planning in the Public Domain

"The eighteenth century bequeathed to us a dual legacy of reason and democracy. Reason meant trust in the capacity of the mind to grasp the orderly process of nature and society, and to render them intelligible to us. Democracy meant trust in the capacity of ordinary people for self-governance. It presupposed a capacity for reasoning in all of us."

John Friedmann, 1987 – Planning in the Public Domain: From Knowledge to Action.





1. Risk-Based Planning in the Public Domain

The concept of risk is deeply embedded in all facets of culture, planning and policy development. It is the lens through which public sector and corporate enterprise view and measure the prospects of change on behalf of their constituents, whose interests they represent and to whom they are ultimately accountable.

Disaster mitigation is perhaps one of the more challenging modes of risk-based planning. The objective is to utilize available information and knowledge about hazard threats to anticipate the actions required to promote the resilience of a place and its people. Such actions must address social, economic, and environmental imperatives at multiple geographic scales and over variable time horizons (Godschalk et al., 1994; Burby, 1998; Mileti, 1999; Berke, 2002; ISDR, 2006).

In the context of emergency management, disaster mitigation anticipates short-term impacts (0-5 years) and likely consequences of hazard threats, and identifies capabilities for risk reduction through targeted investments in prevention, preparedness, response, and recovery. Mitigation activities are focused primarily on issues of public safety and socioeconomic security, and seeks to optimize the utility of risk treatment measures (effectiveness) within the limits of available resources (efficiency).

In the context of land use planning and community development, disaster mitigation has a broader and more strategic focus on the changing conditions of vulnerability and risk over time (5-30 years), and the capability of human-natural systems to withstand and adapt to these changes in ways that promote the resilience of communities and regions (International Strategy for Disaster Reduction, 2002; Organization for Economic Co-operation and Development 2003). Comprehensive land use planning extends the scope of disaster mitigation and is charged with a mandate to promote social equity, economic vitality, and environmental integrity through sustainable development. This involves a balancing of trade-offs between mitigation measures that promote short-term goals of safety and security, and longer-term goals that promote disaster resilience through a reduction in system vulnerability.

Whether short-term emergency management or long-term land use planning and community development, the practice of disaster mitigation is the domain of local and regional governments. An examination of current paradigms and paradoxes reveals the difficulty of managing societal risk when established practices have the unintended consequence of increasing levels of vulnerability rather than reduce them. The additional challenges faced by governments to understand the dynamics of a changing risk environment and to develop the capacity to engage in disaster mitigation planning activities are considerable, and further exacerbated by a lack of available resources (frameworks and tools) to help guide the way. The research community can assist by developing methods of risk assessment that will accommodate the dual needs of disaster risk management (preparedness, response, and recovery) and the governance of emerging risks associated with growth and development in hazardous terrain (foresight and pre-event planning).

This chapter examines the realm of disaster mitigation from the perspective of emergency management and comprehensive land use planning. Principal objectives are to:

- Describe the shifting policy mandate in Canada and the associated challenges of integrating disaster mitigation planning at local and regional scales of government.
- Examine the paradigms and paradoxes of conventional risk treatment measures.

1.1 A Shifting Policy Mandate

The World Conference on Disaster Risk Reduction (2005; Kobe, Japan) established the foundation for an important new international policy mandate known as the Hyogo Framework for Action (HFA 2005–2015: *Building the Resilience of Nations and Communities to Disaster* A/CONF. 206-6). The Hyogo Framework is focused on building disaster resilience at the national, regional and local scales. It has established a ten-year commitment and operational plan to promote:

- More effective integration of disaster risk considerations into comprehensive planning and sustainable development policies and programming at all levels, with a special emphasis on disaster prevention, mitigation, preparedness, and vulnerability reduction.
- Development and strengthening of institutions, mechanisms, and capacities at all levels, in particular at the community level, which can systematically contribute to building resilience to hazards.
- Systematic incorporation of risk reduction approaches into the design and implementation of emergency preparedness, response and recovery programs in the reconstruction of affected communities.

The Hyogo Framework was developed through extensive consultation with 168 participating government states, risk reduction experts, and collaborating organizations. It is endorsed by the United Nations General Assembly (Resolution 60/195), and is administered through the UN Secretariat for the International Strategy for Disaster Reduction (ISDR), which supports implementation and monitors progress of HFA objectives through partnership with participating governments. Canada is a participating member of the Hyogo Framework for Action and launched its national platform for disaster risk reduction in June 2009.

The shift in focus from response and recovery to more proactive modes of disaster mitigation and pre-event planning requires that methods of risk assessment (analysis and evaluation) be integrated into the broader context of growth management and sustainable development. The implication is that uptake and use of risk assessment methods must also shift from the domain of emergency preparedness to more forward-looking modes of spatial planning and community development.

Advancement of a national strategy for disaster risk reduction in Canada is occurring against the backdrop of focused and sustained efforts on the global stage to establish standards and guidelines for risk management (ISO 31000; AS/NZ 4360), and the governance of emerging threats associated with globalization and environmental change (Organization for Economic Co-operation and Development 2003; Renn and Klinke, 2004; Renn, 2006a). The shift in focus for disaster risk reduction activities is driven by an acknowledgement that escalating vulnerabilities associated with globalization and a changing climate will increase the potential for natural disasters that transcend geographic boundaries. The challenge is in developing capabilities for local and regional authorities to manage a changing risk environment in ways that build disaster resilience over time.

The European Union, Australia, New Zealand, and the United States have all responded to this challenge by implementing national risk-assessment frameworks that support each nation's respective mandate for disaster mitigation through the coordination of pre-event emergency planning and community-based risk reduction activities (Council of Australian Governments, 2002; FEMA, 2002; Greiving *et al.*, 2006b; Schmidt-Thomé, 2006). The Government of Canada is responding to this challenge by investing in research and development of an All-Hazards Risk Assessment Framework (Goudreau, 2009) and the establishment of guidelines to streamline emergency management planning and operations across local, regional, and national levels of government (Public Safety Canada, 2010).

1.2 A National Strategy for Disaster Risk Reduction in Canada

Elements of the Hyogo Framework for Action are captured in the National Disaster Mitigation Strategy (NDMS, 2007), which is part of the broader Emergency Management Act for Canada (EMA c.15/E-4.56; Public Safety and Emergency Preparedness Canada, 2007). NDMS is intended to serve as a policy guideline to assist federal, provincial, and territorial agencies in managing risks associated with natural and anthropogenic hazards. It has a broad mandate to "protect lives and maintain resilient and sustainable communities by fostering disaster reduction as a way of life," and reflects with the views of risk-management professionals across Canada (Hwacha, 2005; Public Safety and Emergency Preparedness Canada, 2005). Principles and policy guidelines of the National Disaster Mitigation Strategy for Canada are summarized in Figure 1-1.

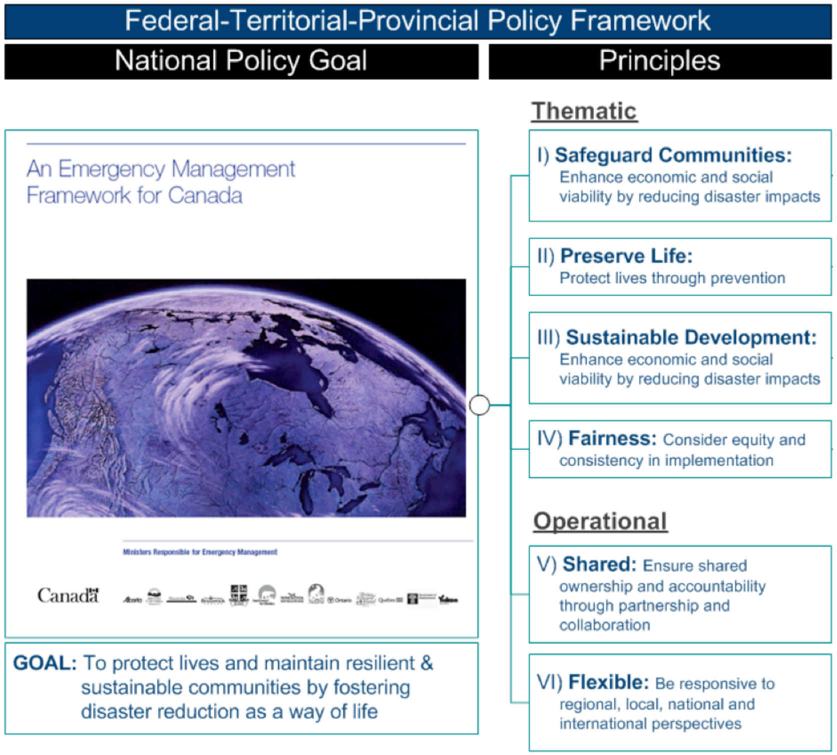


Figure 1-1: The National Disaster Mitigation Strategy for Canada ((EMA c. 15/E-4.56; Public Safety and Emergency Preparedness Canada, 2007).

The National Disaster Mitigation Strategy for Canada (NDMS, 2007) defines mitigation in a Canadian context as "the sustained and ongoing measures required to reduce or eliminate societal risks and vulnerabilities associated with and caused by natural and human-induced hazards," (Public Safety Canada, 2007).

The first four principles of the NDMS address policy goals and objectives that are meant to guide risk-based planning at all jurisdictional levels across Canada. They encourage the development of mitigation strategies that safeguard communities, preserve life, enhance socio-economic vitality, and promote fairness and equity. Additional operational principles address the need for shared ownership and accountability through collaboration across sectors and jurisdictional boundaries, and also the need for flexibility in implementation to ensure relevance and responsiveness to local, regional, national, and international perspectives.

The Auditor General of Canada extends the scope of recommended risk assessment activities to include a consideration of socioeconomic and environmental consequences that may result from existing and/or emerging threats. Recommendations include the evaluation of tolerable thresholds of risk to assist in setting priorities, developing plans, and allocating resources that effectively reduce negative impacts while realizing the benefits of growth and development (Auditor General of Canada, 2005). Policy mandates outlined by the NDMS and the Auditor General provide an overarching framework for disaster mitigation planning in Canada.

Responsibility for implementation of the NDMS and the encompassing Emergency Management Act is shared between Public Safety Canada (PSC) and Defence Research and Development Canada (DRDC). Research and policy development are coordinated through partnerships with other federal departments and provincial or territorial agencies, and through partnerships with public- or private-sector organizations and groups. Collectively, these agencies, organizations, and groups share a responsibility for implementing the National Disaster Mitigation Strategy.

1.2 1. Emergency Management

Emergency management organizations provide a front line of defence for disaster risk reduction in Canada and have the primary responsibility for implementation of the National Disaster Mitigation Strategy. They are charged with a mandate to ensure safety and security in situations where individuals and communities are overwhelmed by the unexpected consequences of hazard events. Emergency management functions are formalized by strategic command and control structures and are well understood and rehearsed across jurisdictional boundaries to ensure an effective, efficient and coherent response to hazard events. Key risk decisions for the emergency manager are focused on questions of who and what are vulnerable to the impacts of hazard threats; what are the likely consequences of these hazard events in terms of public safety and system resilience; what are the capabilities to withstand, respond to and recover from disaster events, and; how to allocate available resources to reduce vulnerability and risk through mitigation and pre-event planning.

The Emergency Management Framework for Canada is directed at a national level by the Emergency Management Act and implemented at local and regional scales through provincial-territorial legislation. The framework is based on an all-hazards approach to risk management that acknowledges municipal and regional governments as the primary authority responsible for provision of emergency management services. In situations where local capabilities are overwhelmed by impacts of a hazard event, the responsibility for emergency management is transferred to provincial-territorial governments. The Government of Canada is responsible for the provision of emergency services in areas that fall exclusively under federal jurisdiction, and supports provincial-territorial governments in responding to and recovering from hazard events through disaster relief funding and the coordination of relevant research and development activities across federal departments with a mandate for disaster risk reduction.

Until recently, emergency management practices in Canada emphasized preparedness, response, and recovery aspects of the overall disaster mitigation planning process. The revised Emergency Management Framework for Canada and accompanying Emergency Management Planning Guide encourage a shift toward more proactive modes of disaster mitigation and capability-based planning that are based on principles of prevention, protection, and resilience (Public Safety Canada, 2007; Public Safety Canada, 2010),

The shift in focus for emergency management activities explicitly acknowledges the interdependence between longer-term recovery, pre-event planning and the mitigation of *future* disasters. The intent is to promote broader integration of disaster mitigation activities in both emergency management and community-based planning. Ontario, Quebec, and British Columbia have already revised their emergency preparedness policies to reflect the shift in national policy toward pre-event planning and disaster mitigation. It is likely that other provinces and territories will do the same in the near future. Although a key element of the Hyogo Framework for Action, the question of how to integrate concepts and practices of disaster risk reduction into land use planning and community development has yet to be fully addressed in Canada.

Emergency Management Framework for Canada

The Emergency Management Framework for Canada (2007) defines emergency management functions in terms of a strategic planning cycle that includes:

- Prevention and Mitigation – to eliminate or reduce the impacts and risks of hazards through proactive measures taken before an emergency or disaster occurs, for example: land-use management, public education, and protective structures (such as flood dykes). Prevention and mitigation may be considered independently or one may include the other.
- Preparedness – to be ready to respond to a disaster and manage its consequences through measures taken prior to an event, for example: emergency response plans, mutual assistance agreements, resource inventories and training, equipment, and exercise programs.
- Response – to act during or immediately after a disaster to manage its consequences through, for example, emergency public communication, search and rescue, emergency medical assistance, and evacuation. Response activities are aimed at minimizing suffering and losses associated with disasters.
- Recovery – to repair or restore conditions to an acceptable level through measures taken after a disaster, for example: return of evacuees, trauma counseling, reconstruction, economic impact studies, and financial assistance. There is a strong relationship between long-term recovery, prevention and mitigation of future disasters.

1.2 2. Comprehensive Land Use Planning

Comprehensive land use planning has tremendous potential to mitigate the risks associated with growth and development in hazardous terrain, particularly when practiced through the lens of sustainable land use and development. Sustainable land use is based on the premise of risk avoidance through the reduction of vulnerability. This can be achieved through planning or regulatory measures that keep people and community assets out of harm's way, and through design guidelines that call for any new developments to be built only if within acceptable thresholds of risk tolerance.

Comprehensive land use planning in Canada is governed through federal, provincial, and territorial policies and legislation that address a wide array of issues such as ecosystem health, environmental degradation, critical infrastructure, and climate change. As illustrated in Figure 1-2, policies that direct land use planning are administered largely through federal, provincial, and territorial legislation. The mandate for disaster risk management is less clearly articulated.

Comprehensive land use policies and associated legislation at provincial and territorial levels have undergone a significant transformation in recent years. They are more coherent and streamlined from a governance perspective, and provide the necessary context and the operational capacity to advance policy goals that promote overall system resilience and sustainability at different geographic scales and over variable planning horizons (Condon, 2003). Many of these policies address issues of public safety and socioeconomic security, but only in general terms.

For example, provisions in the Local Government Act for British Columbia require that settlement patterns be designed in such a way as to "*minimize the risk of natural hazards*," and that private and public lands intended for development be certified as "*safe for the intended purpose*" by qualified professional scientists and/or engineers (Local Government Act, 1996; Land Title Act, 1996; Community Charter, 2003), Similar provisions are reflected in land use policies for other provinces and territories in Canada, and are incorporated in a general way into professional planning guidelines for Smart Growth and sustainable development (Arigoni *et al.*, 2002; Berke, 2002; American Planning Association, 2005a). However, there are no standards or professional

Figure 1-2: A summary of comprehensive land use and disaster risk management policies that guide growth and development at international, national, provincial/territorial, and regional/local levels of government in Canada.

guidelines in Canada that define what constitutes a tolerable threshold of safety and/or risk for human settlement, or that describe methods for how to determine these thresholds in areas exposed to natural hazard threats (Kuan, 2007; Friele et al., 2008).

So, while there are clear policy mandates at all levels of government to manage the impacts and consequences of natural hazard risk, there is very little capacity to do so at present and no clear framework for integrating disaster mitigation processes and protocols into the broader context of comprehensive land use planning and sustainable development. Significant challenges remain, even in situations where there is clarity on the risk management problem and scientific information is available to assess cause-effect relationships between natural hazard events and their potential consequences. If addressed at all, these questions are generally negotiated on a case-by-case basis by local and regional governments, and in the context of emergency management and/or land use legislation (Government of Canada, 2008) that may be ambiguous in terms of specific policy goals and management objectives.

1.3 Paradigms and Paradoxes of Disaster Mitigation

The ultimate goals of disaster mitigation are to save lives, protect property, promote socioeconomic security, and preserve the environment. These are among the most important responsibilities of government agencies at all jurisdictional levels. While the intent is clear, there are political challenges in implementing disaster risk reduction measures that draw scarce resources way from more immediate public policy issues. These challenges are compounded by a growing recognition that current practices of disaster mitigation can in some cases have the unintended consequence of increasing levels of vulnerability and promoting risky behaviour.

Understanding the relationship between vulnerability and risk is critical in developing mitigation strategies that promote disaster resilience. As noted by Sarewitz et al. (2003), the relationship between vulnerability and risk is not commutative. Strategies that explicitly aim to reduce vulnerability and increase system resilience (prevention and avoidance) will inevitably lead to reduced levels of outcome risk. However, strategies that are focused only on reducing outcome risk, such as structural mitigation, will not necessarily reduce levels of system vulnerability or ensure base levels of disaster resilience. If time frames for measuring trade-offs between policy alternatives are set too short, solutions that reduce risk will tend to be favoured over longer-term solutions that address underlying causal structures of vulnerability. By not addressing intrinsic patterns of vulnerability, levels of risk will continue to be magnified with growth and development, resulting in escalating disaster trends that outstrip effective capabilities of conventional risk reduction practices.

As part of a reassessment of natural disasters in the United States, research by Mileti (1999) and Burby (1998) cited an overreliance on conventional risk-reduction strategies (safe development practices) and a lack of coherence in policy response at all jurisdictional levels (governance) as paradoxical root causes for unprecedented losses and escalating disaster trends in North America. More recent studies have drawn attention of the paradoxical consequences of New Urbanism principles and associated Smart Growth principles for potentially increasing community vulnerability by putting more people in harm's way (Berke, 2002).

1.3 1. Safe Development

It is not surprising that hazardous places have attracted growth and development over the years. River valleys, coastal ports, and mountain passes have long provided for agriculture, industrial development, the transportation of goods, and access to opportunities for growth and commerce. The shorter-term economic benefits and political advantages of settlement in these areas have justified the practice of "safe development"—ongoing construction of increasingly elaborate systems of engineering works and emergency management practices to *protect* existing physical assets and to *promote* continued growth and development through the reduction and/or transfer of consequent risk. The paradox of safe development is that in trying to make hazardous areas safer, governments have, in fact, substantially increased the potential for catastrophic property damages and economic loss. (Burby, 1998; 2006).

Structural mitigation measures can be effective in establishing minimum thresholds of safety for routine hazard threats of concern. However, they do not necessarily provide protection from unexpected disaster events that are relevant in the context of longer-term comprehensive land use planning. As a result, they promote a false sense of security that can lead to circumstances where damages, loss potential and underlying conditions of vulnerability are actually increased as a result of ongoing mitigation investment. The situation is compounded by policies that aim to protect financial investment in existing development by transferring risk (expected losses) through insurance markets and/or disaster relief funding. While the goal is to provide financial security, these policies can inadvertently encourage risk-taking behaviour that may undermine longer-term resilience to disaster events.

1.3 1..1 The Concept

Dyke systems and related waterworks in the Netherlands are iconic examples of structural mitigation measures that have been developed to protect low-lying and densely populated settlements from the impacts of storm surge and floods. Equivalent North American examples include the system of dams, dykes, levees, pumps, channel improvements, diversions, sea walls and other structural measures developed along major river systems in the US and Canada. Other forms of structural protection include deflection berms and channel control measures to protect from the impacts of landslides; seawalls and pumping systems to protect from the impacts of storm surge; and structural hardening of building stock to withstand the impacts of hurricanes and earthquakes. Though different in terms of scale and function, all of these engineering works serve the intended policy goal of *protecting* existing community assets from the impacts of natural hazards while *promoting* further growth, development and socio-economic well-being at regional and national scales.

Structural mitigation measures vary widely in terms of design standards. For example, flood protection dykes in most parts of the European Union are constructed to withstand low-frequency/high-consequence flood events that range from once every 1,250 years to once every 10,000 years. Equivalent structures in North America are built to manage higher-frequency/lower-consequence flood events with design and safety standards that range from once every 100 years to once every 200 years.

Though intended to manage the impacts and consequences of natural hazards over defined planning horizons, structural mitigation measures are fallible and do not necessarily provide adequate levels of protection against unexpected disaster events that exceed standard design guidelines. Instead, they can have the paradoxical effect of promoting growth and amenity-driven development in areas of high hazard potential, thereby increasing vulnerability and risk. In addition to potentially promoting a false sense of security, structural mitigation measures require massive capital investments by all levels of governments that can overwhelm other risk-reduction initiatives.

Risk transfer is another strategy to promote safe development. It is intended to provide financial security to individual homeowners, businesses, and communities exposed to natural hazard risk, and who do not otherwise have a means of bearing the consequences of actual losses. Disaster relief funds provide compensation for actual losses, and offer the prospect of financial security during the recovery process. The amount of relief funding is usually negotiated on the basis of per capita costs incurred as a result of a disaster event, and is meant to be provided on the basis of need. If smaller jurisdictions cannot cover the losses themselves, residual levels of risk are borne by higher levels of government. Private insurance markets offer a mechanism through which hazard risks can be transferred from one party to another. For many, the economic benefits of locating and developing in hazardous terrains outweigh the costs of insurance premiums, particularly if liability is transferred with ownership of the principle assets and not held for long periods of time. In cases where insurance rates are set to reflect actual levels of vulnerability and risk, the costs of locating in a hazardous area may not be justified.

Though intended to provide financial security, the transfer of risk through disaster relief or insurance markets effectively subsidizes individuals, businesses, and communities by discounting future costs of potential hazard events. This can have the unintended consequence of encouraging (and in some cases rewarding) short-term risky behaviour, thereby leading to inequities between those who have the means to financially negotiate risk and those who do not.

1.3 1..2 Current Practices

Burby et al. (1998) cite results of a US government study indicating that nearly 75% of flood-related losses in the country have been caused by "catastrophic" hazard events that exceeded design limitations of engineering works built to protect community assets against high-frequency/low-consequence events. The gamble for society is that benefits gained by investing in mitigation works to promote short-term growth and development may be minor compared with the longer-term consequences of disaster events that exceed standard thresholds of safety.

Following the devastating losses sustained in hurricane-related events in 1947 and 1965, the US Congress provided federal assistance to construct a system of levees and drainage canals (the Hurricane Protection Project) with the intent of protecting New Orleans and surrounding areas slated for future urban expansion from storm surge flooding caused by category 3 hurricanes (a 1 in 200-year design event). In the decision analysis and risk evaluation for New Orleans, protection of existing development accounted for only 21% of the benefits needed to justify costs of the proposed mitigation structures (US$5–8 billion over 100 years). More than 79% of the anticipated benefits were to come from new development made possible by converting 3,884 hectares (9,600 acres) of wetland to "productive use" for expanding businesses and neighbourhoods, thereby promoting economic development of a critical inland port facility (Burby, 2006). During this same time period, Congress passed the National Flood Insurance Act (1968), which provided a national mechanism to transfer residual flood risks from homes and businesses located in areas protected by flood mitigation structures (levees, canals, etc.).

These "safe development" strategies had the intended effect of promoting growth and development of more than 76,000 new residential units in the Lake Pontchartrain area and more than 122,000 new residential units and associated infrastructure in areas surrounding New Orleans. Though New Orleans did grow and thrive as a socio-economic centre, many of the desirable low-lying areas that were developed and protected as key assets would be devastated by storm surge and flood waters that exceeded established design criteria for "safe development."

Ironically, Hurricane Katrina weakened from a Category 5 to a Category 3 storm event by the time it hit the mainland 50 km east of New Orleans on August 29, 2005. Nonetheless, it resulted in wind speeds and storm surge heights that exceeded anticipated (scientifically predicted) levels of hazard potential that had been modeled for a Category 3 hurricane event. Significant parts of New Orleans (~80%) were flooded when levees and artificial drainage canals along Lake Pontchartrain failed. Low-lying neighbourhoods were inundated by as much as 6 m of water, locally exceeding established Base Flood Elevation (BFE) construction levels (limit of safety) by up to 3 m. Impacts of this flooding included significant damage (>50% replacement cost) and/or destruction of more than 357,000 homes (FEMA, 2006), resulting in ~1,577 deaths, direct overall economic losses of ~US$125 billion, and insured losses of US$40.6 billion. Direct and indirect losses caused by Katrina made this the third deadliest hurricane event in the US, and the most expensive disaster loss ever recorded from a single event (Münchener Rückversicherungs-Gesellschaft, 2006).

Though less devastating, Canadian examples of the safe development paradox include flood protection measures in the Red River valley, Manitoba, in Saguenay valley, Québec (Haque, 2000), and a federal disaster relief policy that effectively transfers risk associated with private development in hazardous areas to the Canadian taxpayer. Major flood events in the Red River valley and Saguenay valley exceeded design capacities of established mitigation structures resulting in more than $2.2 billion in damages. Nonetheless, evidence suggests that urban growth rates and property values in these valleys are continuing to increase at equivalent or greater rates (~25%) than in adjacent areas where there is no flood hazard (Robert et al., 2003). Similar trends are reported for urbanized areas of the Upper Thames River watershed near Toronto (Nirupama and Simonovic, 2006).

Other examples of mitigation measures that may inadvertently reinforce the safe development paradox include building codes and design guidelines for seismic loading in areas that are known to have a high potential for earthquakes and related ground shaking. All would agree that building code requirements for seismic loading and design are essential, and should be incorporated as part of any hazard mitigation strategy in earthquake country. Yet, without detailed information about seismic risk or thoughtful consideration about where new buildings are located with respect to local ground shaking hazards, even stringent and well-intentioned building code regulations can lead to land use and development decisions that create a sense of safety and security in areas that are known to have a potential for intense groundshaking and associated permanent ground deformation.

Of concern is that enforcement of national seismic design guidelines only applies to new buildings and/or buildings undergoing renovation as part of a development permit approval process. Recent earthquake events in the United States have shown that buildings and engineered structures designed to meet older codes provide inadequate levels of protection and are vulnerable to severe damage or total collapse under conditions of strong or unanticipated ground motion (Foo et al., 2001). The stock of unmitigated pre-1980s buildings as well as buildings designed and constructed to older standards in earthquake prone urban centres far exceeds the number of newer buildings designed and built in accordance with more recent codes.

Major earthquakes in California, Washington, and Kobe (1994–2005) resulted in loss of life and many hundred billion dollars in economic losses. Most of these losses were caused by structural failures of older buildings that were poorly designed or constructed. Without proactive measures to screen and retrofit older buildings that are susceptible to earthquake damage, there is potential for significant collateral damage to people and adjacent buildings in centres of rapid growth and high-density urban development (Foo and Davenport, 2003).

A secondary concern is that existing standards for seismic loading and design do not take into account damages to operational and functional components of buildings (architectural elements, mechanical and electrical equipment, building contents, etc.), which are known to cause more injuries, fatalities, and economic losses than those inflicted by structural damage alone (Naumoski et al., 2002). While there are national research and development efforts underway to address these concerns, the decision to proactively screen and retrofit older buildings and to increase the seismic resilience of operational and functional components of buildings situated in earthquake prone urban centres rests with local municipal and regional jurisdictions acting on behalf of provincial and territorial government mandates. It is at this level of governance that hidden vulnerabilities and risks associated with continued growth and development in hazard prone areas are ultimately negotiated and decided.

1.3 2. New Urbanism, Smart Growth, and Sustainable Development

In theory, sustainable land use and development are based on the premise of risk avoidance through reduction of vulnerability across any and all planning issues. With sustainable development practices, disaster resilience can be achieved through planning or regulatory measures that reduce vulnerability by keeping people and community assets out of harm's way, and through design guidelines that locate new developments in areas with acceptable risk tolerance thresholds.

Principles of New Urbanism and Smart Growth continue to gain traction in the context of urban and rural interface planning. They provide an overarching framework for integrated land use planning and sustainable development, and are the basis of specific policy guidelines that are increasingly implemented by local and regional governments across North America (Arigoni et al., 2002).

However, there is a growing concern that land use planners and decision makers may encourage the implementation of legislative land use policies and design guidelines that inadvertently amplify or in some cases even create conditions of vulnerability and risk. Though known as best practices for land use planning, New Urbanism and Smart Growth have the potential to undermine the very principles of social vitality, environmental integrity, and economic security that are the foundations of truly sustainable development.

1.3 2..1 The Concept

Since 1996, the US Environmental Protection Agency and other organizations like the American Planning Association have been adopting and promoting Smart Growth as an effective strategy for mitigating impacts of ongoing growth and suburban/rural sprawl, the results of which are leading to increased fragmentation of habitat and degradation of essential environmental services (Eley *et al.*, 2003; American Planning

Association, 2005a). Smart Growth principles of density and compact development do much to mitigate the negative effects of sprawl, and they reflect best planning practices from the perspective of lessening our ecological footprint through the efficient use of existing infrastructure and land. However, such practices have typically been evaluated without considering the geographic context in which hazard events may occur.

Although the premise and concepts of New Urbanism and Smart Growth are generally sound, there are inconsistencies between regional principles of environmental sustainability and neighbourhood-level principles that can inadvertently promote compact and dense urban developments in areas that are exposed to potential impacts of natural hazards (Berke, 2002: p. 26). First, of the eighteen principles set forth for regional and neighbourhood design, fifteen are focused exclusively on elements of urban liveability and sense of place with little reference to other contextual issues of natural environment, landscape integrity, or regional-local connectivity. Second, none of the neighbourhood or block-level principles explicitly address the essential life-supporting functions of ecosystems or the physical characteristics of the enveloping landscape. Finally, from the perspective of societal risk, none of the principles explicitly address issues of vulnerability (susceptibility, capacity) or the potential for damage and associated loss from natural or anthropogenic hazards. The paradox of these planning paradigms is that neighbourhood design principles that encourage compact and dense urban form often trump overarching principles of environmental sustainability and are increasingly leading to large-scale developments that are situated in harm's way, thereby increasing vulnerability and undermining the overall resilience of the human-natural system (Berke et al., 2007).

1.3 2..2 Current Practices

Studies supported by the US National Science Foundation show that sustainable land use planning—through risk avoidance—can significantly reduce the impacts of disasters (Burby, 1998; Burby et al., 2000; Olshansky, 2001). However, without a clear link to broader design patterns that promote environmental integrity and an awareness of natural processes, there is the danger that current best practices in land use planning can expose increasing numbers of people to possible harm. A recent U.S. study found that 114 out of 318 (~36%) New Urbanist developments completed or under construction are located in low-lying areas exposed to flood hazards (Berke et al., 2007). Nearly all of these developments rely on conventional measures of structural protection, thereby reinforcing the paradox of safe development.

In managing the location and density of development, local governments have the potential to effectively reduce risk and promote longer-term resilience by addressing the underlying patterns and causal structures that promote vulnerability. This can be done through a combination of regulatory measures that restrict the location, type, and intensity of development, or through non-regulatory measures that encourage development in areas that are out of harm's way. Land use guidelines and zoning bylaws are an effective means of managing vulnerability by regulating where, how much, and what type of development should occur in any given area. Hazard potential and vulnerability assessments are often used in setting land use and zoning guidelines that are commensurate with accepted thresholds of risk tolerance. Areas that exceed these thresholds are set aside as non-negotiable for development, while areas within or under the threshold are managed through graduated zoning regulations that are consistent with levels of exposure and susceptibility.

Non-regulatory land use measures can also be used to manage unacceptable risks associated with privately owned lands in hazardous areas. Strategies include property acquisition with public funds and conversion of hazardous lands to other uses so that vulnerabilities can be more effectively managed. This is done by changing allowable land use, or through the transfer of development rights to encourage growth and increased density in areas that are within accepted thresholds of risk tolerance. Patterns and locations of development can also be influenced by strategically situating critical infrastructure, public facilities, and community amenities in areas that have inherently low levels of hazard exposure. Finally, taxation and fiscal policy can be effectively used to influence patterns of development, either through economic incentives that reward densification in non-hazardous areas, or through penalties that shift the burden of managing risk onto property owners.

The benefits of tighter integration between emergency management and comprehensive land use planning are well-documented (Burby, 1998). However, policies that actively promote community resilience in the broader context of growth management and sustainable development are slow to be adopted here in North America (Institute for Business & Home Safety, 2005). Challenges and possible barriers include a reluctance to explore alternate strategies for managing conflicts between the rights of individual property owners and those of the community at large, a lack of political will to interfere with economic efficiencies and market forces of amenity-driven development, and limited capabilities to coordinate the implementation of policy changes across jurisdictional boundaries.

1.3 3. Risk Governance

As noted by Mileti (1999), the false sense of protection and prospects of short-term gains given by structural and engineering-based mitigation and risk transfer strategies tend to overshadow thoughtful deliberation about development choices that reduce vulnerability and promote longer-term resilience. Over time, this dynamic gradually increases the potential for disaster. Such disaster events can be understood as "*the predictable (in fact, predicted) outcomes of well-intentioned but short-sighted public policy decisions made at all levels of government*" (Burby, 2006).

1.3 3..1 The Concept

A comprehensive study of natural disasters in the United States concluded that the majority of losses (~US$500 billion) caused by natural hazard events between 1975 and 1994 were borne by individual home and business owners, with only a small proportion of economic losses offset by private insurance or disaster relief funding (Mileti, 1999). Data compiled on worldwide disaster losses indicate these trends are universal and have been escalating at an alarming rate since the 1960s (Münchener Rückversicherungs-Gesellschaft, 2006). If risks and disaster losses associated with development in hazard-prone areas are borne principally at the community level by home and business owners (US $500 million/week), it follows that mitigation strategies to reduce risk and promote the safety and security of citizens ought be a high priority for municipal and regional governments. The paradox of local government is that while citizens bear the brunt of human suffering and financial loss when disasters occur, local governments give insufficient attention to threats posed by hazards when they allow intensive development of hazardous areas (Burby, 1998; 2006).

There are a number of reasons for this impasse including conflicting public policy objectives surrounding local and regional land use decisions, a lack of frameworks or incentives at higher jurisdictional levels for integrating risk reduction into the comprehensive planning process, and the absence of a supportive and operationally coherent federal policy on disaster risk reduction (Henstra and Sancton, 2002; Henstra and McBean, 2005). As a result, shorter-term political pressures to promote economically beneficial land use decisions and the protection of private development rights often trump longer-term "public good" objectives of increased public safety and socio-economic security. This is particularly the case where the benefits of investing in measures to increase disaster resilience of existing and future development extend beyond the tenure of elected officials or the time horizons used for community planning and policy development.

1.3 3..2 Current Practices

National surveys commissioned by the Institute for Business and Home Safety (IBHS) and the American Planning Association (APA) document the enormous gap that exists between the intent of risk reduction and actions taken on the ground at local and regional jurisdictional levels (IBHS, 2005). The results indicate that while most US states (49) list conventional hazard mitigation measures that should be included as part of a comprehensive plan (building codes, enforcement of building codes, physical strengthening and protection, etc.), only 18 states have passed enabling legislation that actually encourage or otherwise provide incentives for local governments to adopt these measures or to consider more proactive land use management strategies. Of these 18, only 10 states require local plans to incorporate hazard mitigation strategies as part of their comprehensive planning and policy development framework. This despite estimates by the World Bank and the US Geological Survey that estimate "US$40 billion invested in risk reduction strategies could have saved as much as US$280 billion in worldwide economic losses from disasters in the 1990s, a seven dollar return for each dollar invested" (American Planning Association, 2005b). Elsewhere, the Government of Queensland, Australia, estimates that every dollar spent on disaster mitigation saves at east three dollars spent in the response and recovery cycle. Though compelling as an economic argument for disaster risk-reduction planning, these cost-benefit estimates have had little impact on local land use and risk management policy.

Similar patterns are mirrored in Canada. A recent survey of 94 out of 448 municipal jurisdictions in Ontario reveals wide variation in risk awareness and limited uptake of risk-reduction concepts and strategies (Newton, 2003). At the time of this study, only 13 municipalities had developed or implemented a risk reduction plan to mitigate potential impacts of natural hazard threats. It is not clear from the results of this study how many of these municipalities had integrated risk-reduction strategies as part of their comprehensive planning process or policy framework (likely very few). However, 47% of those responding (44 communities) indicated they were somewhat likely or very likely to incorporate risk-reduction strategies into their comprehensive planning process at some point in the future. In spite of this gradual shift in thinking, very little substantive progress has been made in promoting and sustaining effective bottom-up networks for community-based risk management in Canada (Henstra and McBean, 2005).

pathways

Chapter Two:

The Challenges of Risk-Based Planning

"In the varied topography of professional practice there is a high, hard ground where practitioners can make effective use of research-based theory and technique, and there is a swampy lowland where situations are confusing 'messes' incapable of technical solution. The difficulty is that the problems of the high ground, however great their technical interest, are often relatively unimportant to clients or to the larger society, while in the swamp are the problems of greatest human concern,"

Schön, 1983

2. The Challenges of Risk-Based Planning

Risk assessment is an iterative process of analysis and deliberation. It is a process through which knowledge about the risk environment is transformed for the purpose of developing actionable mitigation strategies that advance policy objectives while minimizing negative impacts on people and the things they value (International Strategy for Disaster Reduction, 2002; Klinke and Renn, 2002; United Nations, 2005).

The analytical component of the risk assessment process provides a measure of the physical and probabilistic dimensions of risk. It involves a synthesis of available scientific and technical information describing the extent, magnitude, and probability of existing and emerging hazard threats for a given geographic setting and planning horizon, the physical damages and casualties that might be expected if one of these events were to occur, and the anticipated consequences of these events in terms of both direct and indirect socio-economic loss. It may also include an analysis of the costs and benefits of mitigation investments and the effectiveness of these measures in reducing vulnerability and promoting overall system resilience.

The deliberative component of the process provides a measure of the human and socio-economic dimensions of risk. It involves the identification of social values, preferences, and decision criteria that will frame the planning process, an appraisal of the risk environment and how it is likely to change with time, and the characterization of tolerable risk thresholds that will guide the evaluation of mitigation alternatives.

This chapter examines the metrics used to characterize the risk environment, and the challenges involved in transforming knowledge gained through analysis and deliberation into practical strategies that reduce risk and promote disaster resilience on the ground. The intent is to:

- Explore the breadth of issues that define risk in the context of a community or region.
- Highlight general challenges of disaster mitigation that are relevant at local and regional scales of planning.
- Identify specific gaps that exist between the concepts and practice of risk-based planning.

2.1 Balancing Perspectives of Risk

Societal risk can be understood as an expression of uncertainty about threats posed by natural or anthropogenic events, their impacts on human-natural systems, and the likely consequences of these events (negative and positive) on people and critical assets. In this context, risk is defined by a combination of objective measures that describe causal linkages between hazard events and their impacts on society, and subjective measures that characterize what is considered vulnerable and in need of safeguarding through mitigation.

2.1 1. Risk as an Objective Measure

Scientific enquiry emphasizes the generation of new knowledge for the purpose of refining or expanding insight on human-natural systems and how they work. From this perspective, risk analysis encompasses the compilation and synthesis of available scientific and technical information that describes physical and social characteristics of a hazard, including event magnitude and frequency of occurrence, expected impacts on people and the environment (injuries and damages), and the likely consequences of these events in terms of direct and indirect socio-economic losses.

Knowledge claims can be based on a variety of reasoning modes such as deduction, induction or abduction. These modes of thinking rely on observations and information that are assumed to be true. The corresponding proposition is that scientific knowledge and understanding of human-natural systems (epistemology) ought to provide the necessary foundation for informed decisions of how best to manage risk on behalf of society. This might be referred to as the predictive or "science-based" approach to risk management (Sarewitz and Pielke Jr, 2001). While scientific analysis provides an objective measure of risk, it does not necessarily address the question of who or what should be safeguarded, or how to balance the potential costs and benefits of investing in mitigation measures. The concern is that descriptive measures of risk may have little meaning if separated from the social and behavioural context in which the impacts and consequences of a hazard event are likely to be experienced (Stern and Fineberg, 1996; Sarewitz, 2000; Barnes, 2002; Renn, 2006a).

2.1 2. Risk as a Subjective Measure

From the perspective of individuals and groups in society, risk is framed and assessed in terms of subjective measures and normative judgments that express what people consider of value and worth protecting from damage or harm. This framing of risk is based on underlying ethical perspectives and beliefs of what constitutes danger and how best to manage change in an uncertain world. In this context, risk is evaluated on the basis of perceived hazard threats, the potential for negative impacts and consequences, and the capacity to respond and recover in order to achieve an outcome that minimizes negative effects while promoting overall risk management objectives.

Knowledge claims are based on world views and familiarity with a place and its social fabric. They are formulated through protocols of reasoning and analysis similar to those used in the physical/natural/social sciences. The expectation is that clear articulation of what humans consider to be of value, as determined through observation, reflection, participatory dialogue and deliberation, will provide the necessary context, rationale, and focus for policy development and collective decision making. This might be referred to as the deliberative or "value-based" model of risk management (Gregory and Slovic, 1997; McDaniels et al., 2004; Gregory et al., 2005). The challenge is in reconciling individual and collective rights with varied and often competing normative views of what might constitute a desirable outcome in terms of risks and benefits. The concern is that experience and value-based judgments of risk may be marginalized if they to do not account for unforeseen or emerging threats that reflect a scientific understanding of physical and socio-economic processes and underlying system dynamics (Barnes, 2002; Stefanovic, 2003).

2.2 The Physical and Human Geography of Risk

The risk environment of a community or region can be characterized in terms of five overlapping domains that encompass increasingly broader dimensions of the human-natural system, more complex geographic settings, and the longer planning horizons addressed in sustainable development planning (see Figure 2-1). Hazard potential describes the geographic extent and severity of physical processes that have potential to trigger a disaster event and the likelihood of these events occurring at some point in the future. Hazard risk describes the probable impacts and consequences of these events in terms of damages, injuries, and anticipated socio-economic losses. Vulnerability describes the intrinsic characteristics of people and the physical environment in terms of

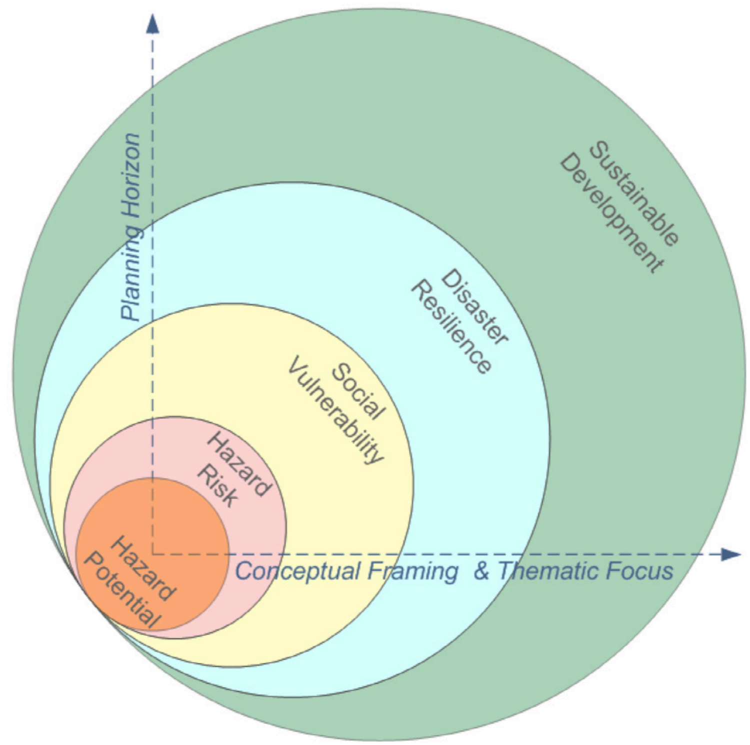


Figure 2-1: The overlapping dimensions of hazard potential, hazard risk, vulnerability, disaster resilience, and sustainable development represented as a Venn diagram. The vertical axis represents the overall scope of the risk environment. The horizontal axis represents the planning horizon in which the risk decision is framed and assessed. Modified from Birkmann (2006).

exposure and susceptibility to the potential negative impacts of a hazard event. Resilience describes the capabilities of human-natural systems to withstand, respond to and recover from the impacts of a hazard event and to adapt to changing conditions of risk over time. All of these components of the risk environment are incorporated into the broader context of sustainable development. The goal is to find a vantage point from which these different perspectives come into focus and can be fully articulated and explored through the interweaving of scientific understanding (objective measures) and judgment (subjective measures).

The following sections examine the overall geography of risk through the lens of a representative mountain community that is confronted with the challenge of managing growth and development in an area exposed to a wide range of natural hazard threats. The physical geography and patterns of human settlement are loosely based on our case study region along the Sea-to-Sky corridor in southwest British Columbia. However, the concepts, underlying principles, and related issues of managing risk in a changing landscape are universal and will be relevant to other communities both large and small.

2.2 1. *Hazard Potential*

A natural hazard is defined as any naturally occurring process or phenomena that may pose a threat in terms of public safety or socio-economic well-being (United Nations Development Program, 2006). Natural hazards that are relevant to emergency management and comprehensive land use planning in Canada include sudden-onset floods, hurricanes, storm surge, earthquakes, tsunamis, avalanches, landslides, tornadoes, and interface wildfire. Additionally, communities must also contend with anthropogenic hazards—those related to a wide range of human activities that have potential for impact to the natural and built environments and their inhabitants. Anthropogenic hazards include: physical and chemical hazards related to technology development and failure of critical infrastructure (nuclear radiation, hazardous material spills, failure of dams and levees, etc.); chemical and biological hazards related to development and associated environmental degradation (toxic wastes, environmental pollutants, genetically modified organisms, etc.); accidents or deliberate acts of violence (avalanche, fire, terrorism, sabotage, etc.). Hazard threat is an indirect measure of underlying causal factors that have potential to trigger a hazard event capable of causing damage or injury. Hazard potential is a more explicit physical description of a particular threat that is measured in terms of geographic extent, anticipated intensity and/or magnitude, and probability of occurrence over a specified period of time.

In comparison with other developed nations, the profile of natural hazard risk in Canada is considered low in terms of public safety, and

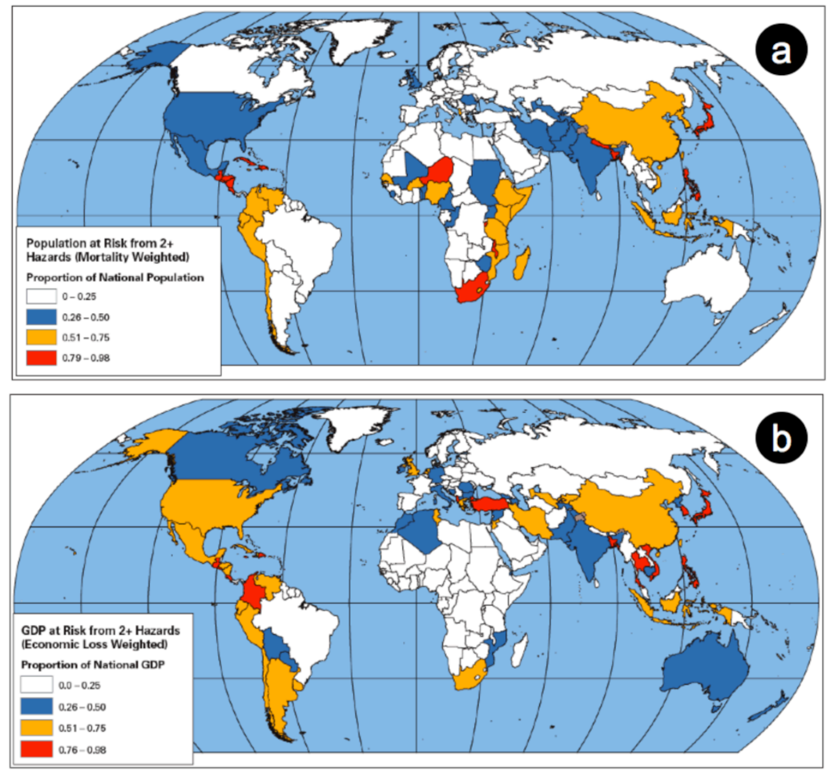


Figure 2-2: Results of Global Hotspot Analysis (Dilley et al., 2005a) summarizing, a) proportions of the national population that are exposed two or more natural hazard threats capable of causing loss of life, and b) direct economic losses that have occurred as a result of these hazard threats..

low to moderate in terms of socio-economic security (see Figure 2-2). Levels of socio-economic risk are comparable to those of Australia, New Zealand, the southern Indian subcontinent, the Mediterranean regions of Europe and northern Africa, and west-central Andean countries of South America (Dilley *et al.*, 2005a).

An underlying premise of hazard analysis is that increased scientific knowledge and geotechnical understanding (objective measures) of magnitude-frequency relationships will lead to a better understanding of potential threat that will inform decisions on how to reduce risks associated with extreme or catastrophic events. The emphasis of the hazard analysis process is on reducing scientific uncertainty about frequency-magnitude relationships, probability of occurrence, and the areas that are likely to be impacted by a hazard threat of concern.

2.2 1..1 Hazards of Place

Figure 2-3 is a schematic representation of a landscape that is susceptible to a wide variety of natural and anthropogenic hazard threats operating at different spatial scales and over variable planning horizons.

In this mountain community, uplift and erosion of mountain landscapes and the effects of a changing climate control patterns of atmospheric circulation that can trigger a wide range of hydro-meteorological hazards. These include localized extreme rainfall events and related flood hazards such as coastal storm surge, overtopping of natural river channels and inundation caused by storm water runoff, as well as broader hazard threats such as cyclones, high wind, and extreme temperatures resulting in drought and severe snow or ice conditions. These natural hazards can be significantly amplified by human activity (see Figure 2-4). Storm water drains and pumping stations are not designed to accommodate the increased volumes of surface runoff caused by changes in weather patterns and disruptions to natural infiltration. In addition, levees and other flood control measures can act as barriers to storm water runoff from upslope portions of the basin, thereby causing significant flood hazards to low-lying areas that they were meant to protect.

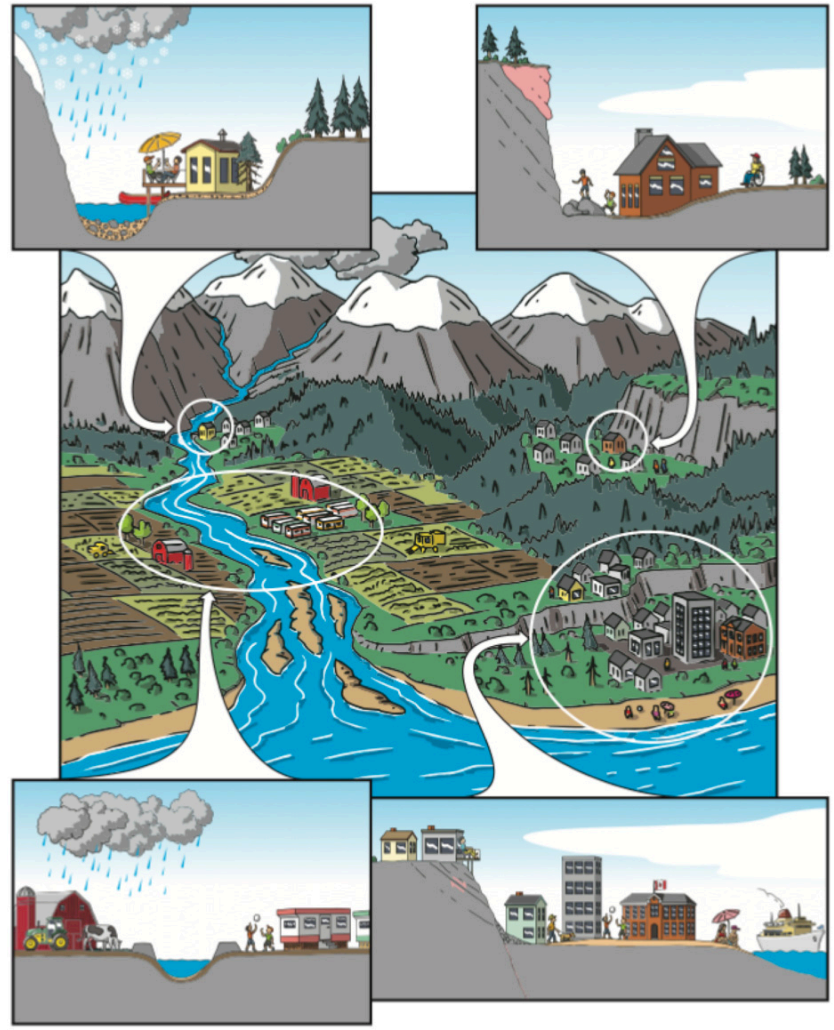


Figure 2-3: A schematic illustration of a mountain community exposed to multiple natural hazard threats.

Landslide hazards are driven by geologic processes of uplift, mass wasting, and erosion, and are caused by rapid onset or prolonged instabilities, structural failure, and downslope movement of rock or soil. While the susceptibility of landslide hazard threats in mountainous terrain is widespread (see Figure 2-5), individual landslide events are localized and occur primarily in areas of steep topography or areas underlain by unstable earth materials that are prone to loss of cohesion and structural failure under the influence of gravity. Landslide events can include any combination of mass movement (fall, topple, slide, spread, or flow) and any combination of earth materials (rock, soil, and debris). They can be triggered by seismic activity or by severe and prolonged rainfall events in which hydrostatic pressures caused by increased soil moisture lead to loss of cohesion and structural failure. In many cases, these ground deformation hazards can trigger additional hazard threats such as structural failure of critical facilities and related infrastructure (dams, levees, etc.).

Proximity of mountain communities to the active plate margin of western North America also increases their overall susceptibility to geophysical and geological hazards. These include a combination of ground shaking and permanent ground deformation hazards related to earthquake activity and the eruption of volcanic material (explosive tephra clouds, lava) caused by subduction and partial melting of the earth's

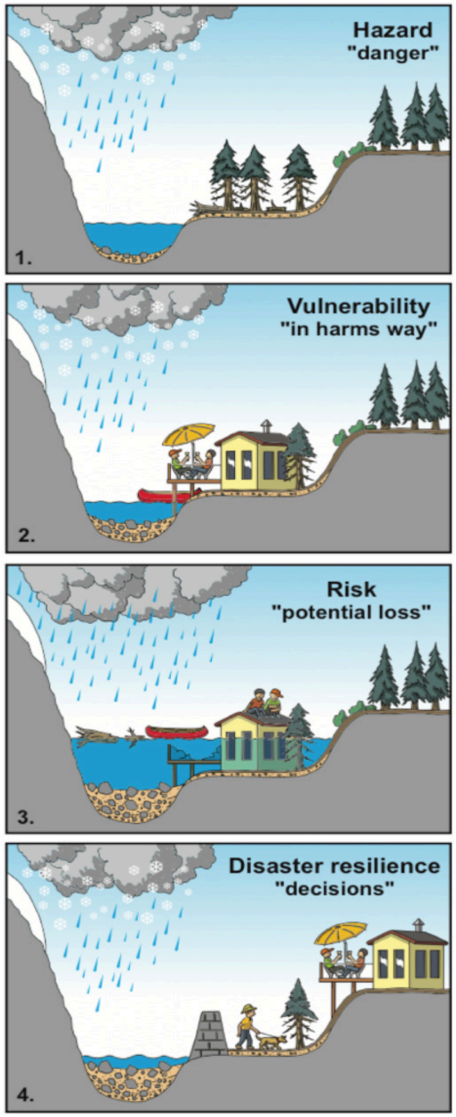


Figure 2-4: A schematic illustration summarizing the dimensions of flood risks.

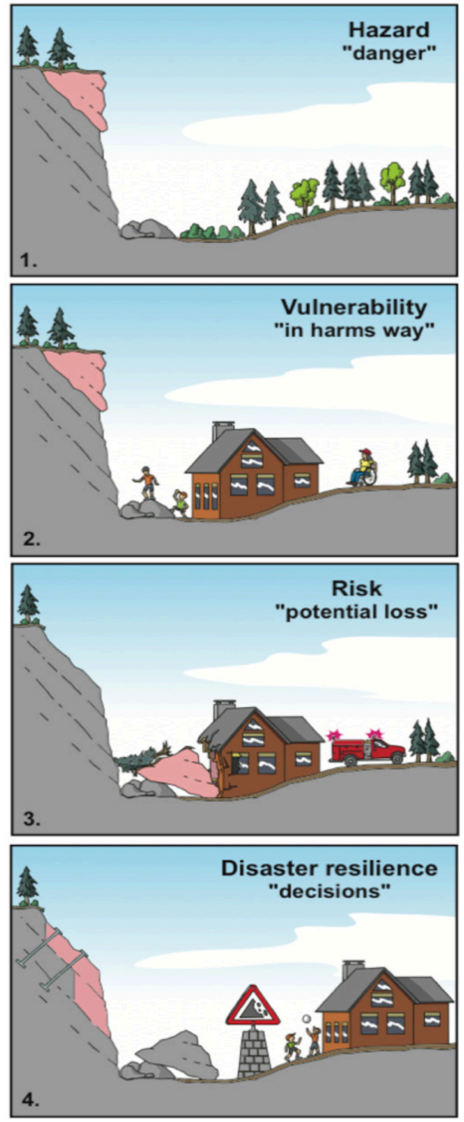


Figure 2-5: A schematic illustration summarizing the dimensions of landslide risks

crust along active plate margins. Ground shaking hazards vary spatially as a function of distance from the epicentre and can be locally amplified by physical characteristics of bedrock geology and overlying surficial materials (see Figure 2-6). Hazards related to surface rupture are localized along the trace of fault structures that accommodate slip related to regional tectonic activity. Liquefaction hazards occur in valley bottoms and in surrounding areas underlain by water-saturated sandy deposits that are prone to shaking and loss of cohesion caused by rapid changes in hydrostatic pressure.

Volcanic hazards related to the eruption of lava and explosive tephra clouds are infrequent, but have the potential to cause extensive damage. Depending on atmospheric conditions and the direction of prevailing winds, volcanic eruptions may also represent hazard threats that extend over many thousands of kilometres. Explosive blasts and effusion of lava from active volcanic centres in the northern Cascades and southwestern British Columbia are more localized, but have the capacity to impact large areas (tens of kilometres). The likelihood and extent of potential damage was made evident by the Mount St. Helens eruption of 1980 in southern Washington State. In addition to explosive volcanic blasts, the eruption also triggered additional hazard threats such as rock avalanches, landslides, and wildfire that resulted in significant collateral damage and socio-economic disruption in surrounding areas.

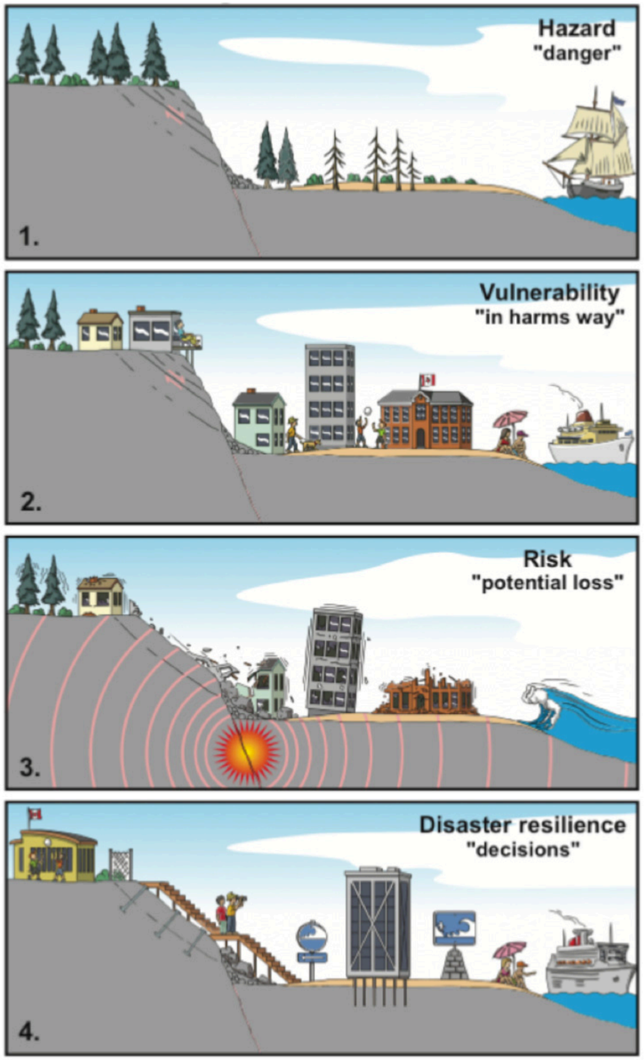


Figure 2-6: A schematic illustration summarizing the dimensions of earthquake risks.

In addition to these natural hazards, communities are also exposed to a wide range of anthropogenic hazards. These include wildfire along the interface with the built environment, hazardous spills caused by accidents along major transportation corridors, and catastrophic flood events caused by the failure of critical dam facilities used for water storage or hydroelectric power generation.

2.2 1..2 Issues and Challenges

Characterizing hazard threat in terms of extent, intensity, and probability offers a scientific basis for objectively analyzing patterns and levels of exposure for a region and provides the necessary analytic foundation for assessing dimensions of hazard-related risk, vulnerability, and disaster resilience. However, there are a number of issues and challenges that need to be considered, not the least of which are system complexity and scientific uncertainty.

Complexity refers to hazard threats that are strongly coupled and in which there are networks of cause-effect relations that interact at different geographic scales and over variable time horizons. Uncertainty is used in the classic sense to describe hazard event scenarios in which the probability of occurrence is subject to randomness in the context of a specific geographic region and time frame (aleatory), and/or in which understanding of complex system dynamics is bounded (epistemic). While issues of system complexity and uncertainty are generally acknowledged, there are limits to what can be analyzed and modelled. For this reason, it is common for scientists to reduce system complexity in order to assess hazard probabilities by framing the problem so that larger scale influences are minimized, and by making assumptions of uniformity and independence to simplify the analysis of network interactions and feedback loops.

While necessary for purposes of analysis and modelling, these assumptions may not be justified when considering hazard threats over longer planning horizons, or in geographic areas that are likely to be exposed to multiple hazard threats for a given interval of time. We know, for example, that earth system processes are not linear—they are episodic and characterized by rates that can vary with time. Secondly, even small geographic areas like the one shown schematically in Figure 2-3 are exposed to multiple hazard threats that are interconnected at any given point in time. For example, moderate-sized earthquakes have a capacity to trigger second-order liquefaction and permanent ground deformation hazards that can, in turn, cause damage to gas pipelines that induce additional fire hazards. Human activity can also create conditions that increase the probability of natural hazards. Examples include disruptions to the land surface that increase the probability of landslide activity, and storm water management practices that induce flooding.

The challenge for scientists is to ensure that outputs of a hazard assessment are communicated in ways that make evident the implications of simplifying assumptions about system complexity and uncertainty. Sensitivity analysis and Bayesian techniques are often used to address these issues but are not always transparent or fully incorporated into the process of risk modelling. The gap between our understanding of complex system behaviour and the information and knowledge that is required to describe and model these system interactions can be significant. It is not feasible or even desirable to build models that predict complex system behaviours that cannot be tested or validated. However, there is a need to ensure that scientific models used to analyze hazard potential for a given area are transparent in terms of framing, and account for uncertainties related to availability of information and knowledge (Pielke, 1999; Sarewitz et al., 2000; Pielke and Conant, 2002; Pielke and Stohlgren, 2004).

2.2 2. Hazard Risk

Hazard risk is a measure of the probable impacts and consequences of hazard events on people and critical assets. The concept of hazard risk is rooted in the physical sciences and emphasizes cause-effect relationships between hazard threats and their impacts on people and the built environment (damages, injuries, associated losses). Hazard risks can be seen as discrete phenomena caused by natural forces that are external to the socio-economic and environmental systems they impact, yet related in a linear cause-and-effect manner (ISDR, 2002; UNDP, 2006). The dimensions of hazard risk are shown schematically in Figure 2-7.

Assessment of hazard risk relies on scientific enquiry and geotechnical engineering to determine the hazard potential at any given point on the landscape, the likely impacts of a hazard event in terms of injury and physical damage, and the anticipated consequences of these impacts in terms of direct and indirect losses to a community or region. From this vantage, hazard risk emphasizes the underlying geologic, geophysical, and climate processes that can trigger a hazard event, as well as the shorter-term strategies for reducing the impacts of these hazard events through structural mitigation (protection), emergency preparedness (safety), and risk transfer (security). The focus of analysis is on identifying the likely impacts of hazard events on people and critical assets (injuries and damages), and developing mitigation strategies that have the potential to minimize the consequences of any losses (costs) that may result. Limitations of conventional hazard risk assessment include restricted capacities to account for the amplification or attenuation of hazard impacts from underlying socio-economic factors, and spatial variability in expected consequences resulting from human capacities to cope with and respond to disaster events (Turner et al., 2003).

2.2 2..1 The Built Environment

The representative mountain location shown in Figure 2-3 illustrates how concepts of hazard risk take shape on the ground. The region is characterized by a wide diversity of physical assets and related infrastructure services that are susceptible to multiple hazard threats, all with the potential for significant physical impact and economic consequences that would reach far beyond the municipal boundary. The built environment is defined by an urbanized downtown and surrounding neighbourhood nodes composed of single family detached homes, multi-family dwellings (condominiums/apartments), mobile home complexes, and a mix of commercial and industrial buildings. Essential facilities include neighbourhood schools, a regional hospital, and a dispersed network of medical care, police, fire, and emergency service facilities. Critical facilities include a dam that provides hydroelectric power along the main corridor, and a system of dykes and levees for

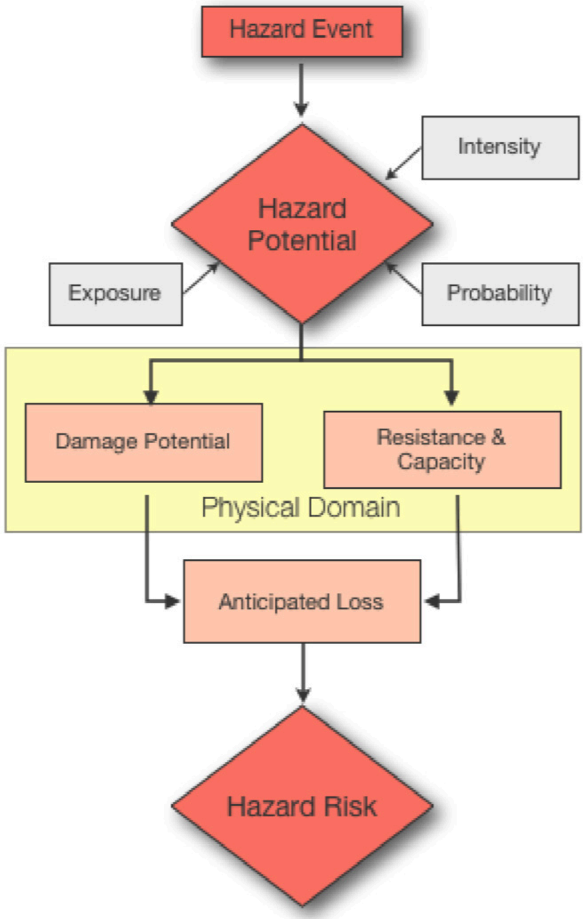


Figure 2-7: A conceptual model of hazard risk based on the premise of linear cause-effect relationships that are external to the system (ISDR, 2002; UNDP, 2006).

control of coastal inundation and river valley floods. In addition to regional highway and rail infrastructure, the site provides port facilities for the transport of people and goods by sea and air. Utility systems include municipal water, waste water, and energy networks; regional communication, power generation, and energy transmission facilities; and a natural gas pipeline.

Establishing a profile of hazard risk for such an area involves creating an inventory of assets that are considered of value and worth protecting, calculating physical damages and injuries that would be expected if a hazard event were to occur, and estimating the corresponding losses that are anticipated in terms of direct capital costs and economic hardship (loss of revenue), and indirect disruptions to services, employment, and income. Damage potential is analyzed using standard engineering models and synthetic databases that establish relationships between the intensity of a hazard event at any given location (ground shaking, water depth, etc.) and corresponding fragility of structures (buildings, bridges, roads, etc.) that are exposed to these hazard threats. Anticipated losses are assessed as a function of damage potential (physical vulnerability), asset value, and the likelihood that one or several hazard events might occur within a specified period of time. Results are reported in terms of damages to individual structures or neighbourhoods, the number and severity of injuries, the number of people displaced from their home due to damage impacts, and the overall economic costs of the hazard event.

In addition to making evident potential damages and losses, hazard risk models also provide a capability to assess the effectiveness of investing in mitigation measures that increase the resistance to physical impacts of a disaster event and the capacity to respond and recover from the consequences of these events over time. The effects of increasing structural protective measures can be assessed by creating hypothetical scenarios in which potential damages and injuries are reduced by the construction of engineering works (dykes, levees, berms, etc.) or the implementation of structural retrofits that are designed to withstand the physical impacts of specific hazard threats. The effects of increasing capacity for response and recovery to a disaster event can be assessed by modelling the effectiveness of preparedness measures such as early warning systems that alert people of impending danger, "just-in-time" mitigation measures (pumps, generators, fire-fighting equipment, etc.) that reduce localized hazard threats, and emergency services that provide shelter, basic needs, and medical assistance to those who have been impacted by a disaster event.

2.2 2..2 *Issues and Challenges*

Characterizing hazard risk in terms of impacts and likely consequences provides a basis for assessing the relative severity of hazard events and the effectiveness of mitigation alternatives. Standard methods of hazard risk assessment make provisions for system complexity by allowing flexibility in the choice of model parameters and assumptions. They account for uncertainty by analyzing cause-effect relations in terms of the probability of damage and loss. However, most hazard risk models are based on a static description of the physical environment for existing conditions only. Model outputs provide a snapshot of damage potential and anticipated injuries and losses for a particular point in time, but do not address the question of how these variables might change with growth and development, or the implications of these changes with respect to public safety, socio-economic security, and sustainable land use.

As the physical and socio-economic characteristics of a community change with time, so too do corresponding levels of hazard risk. With each new residential, commercial, or industrial development, the profile of risk changes incrementally. These changes may be small over the course of a few years, but are cumulative and can be significant in the context of a comprehensive planning cycle (5–30 years). While existing methods of risk analysis are useful in the context of emergency preparedness, they do not consider dimensions of vulnerability or risk in a futures context, nor underlying system dynamics that influence how these system variables evolve with time. Consequently, they are of limited use in managing risks associated with growth and development in the broader context of land use planning and infrastructure development. The limitation of static hazard risk models represents an important gap between the science of risk analysis and the practical requirements of planning and policy development processes.

A second issue of note is that while hazard risk models provide an objective measure of impacts and consequences, they do not directly inform progress toward or away from policy goals and associated risk management objectives. Nor do they offer any guidance on how analytic outputs of standard risk assessments ought to be interpreted in terms of thresholds of safety, vulnerability, or risk tolerance. The potential for disconnect between empirical measurement of hazard risk and societal judgement of what is considered acceptable or tolerable for a given geographic setting and planning horizon can be a significant challenge to developing a risk management plan. This limitation can be mitigated in part by broadening the definition of risk to encompass both empirical models that describe physical processes and normative models that take into account specific policy goals and management objectives through the use of indicators and performance targets.

2.2 3. *Vulnerability*

Based in the social sciences, the concept of vulnerability reveals how people and places are differentially affected by hazard threats, the socio-economic factors that allow some to resist the impacts of a hazard event and force others to succumb, and the factors that give individuals and groups the capacity to cope with and recover from the impacts and consequences of a hazard event. From this vantage, vulnerability emphasizes root causes and dynamic pressures that create unsafe conditions and expose a community or region to negative consequences of a hazard event. These causes and pressures can include intrinsic patterns of social disadvantage that may put people in harm's way or otherwise limit their ability to withstand the impacts of a hazard event, or political and economic forces that are external to the system but that have the potential to influence the ability of individuals and groups to respond and recover from the consequences of a disaster event. Depending on the point of reference taken in the assessment process, vulnerability can be assessed in terms of physical susceptibility to hazard threats and the human factors and socio-economic processes that create conditions leading to increased social susceptibility.

The UN International Strategy for Disaster Risk Reduction (UN/ISDR) defines vulnerability as the "conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of a community to the impacts of hazards," (2003). As discussed by Birkmann and others (2005, 2007), this definition of vulnerability emphasizes the measurement and analysis of factors that may influence the physical susceptibility of a community or region (fragility of buildings and engineered structures), and capacities of the

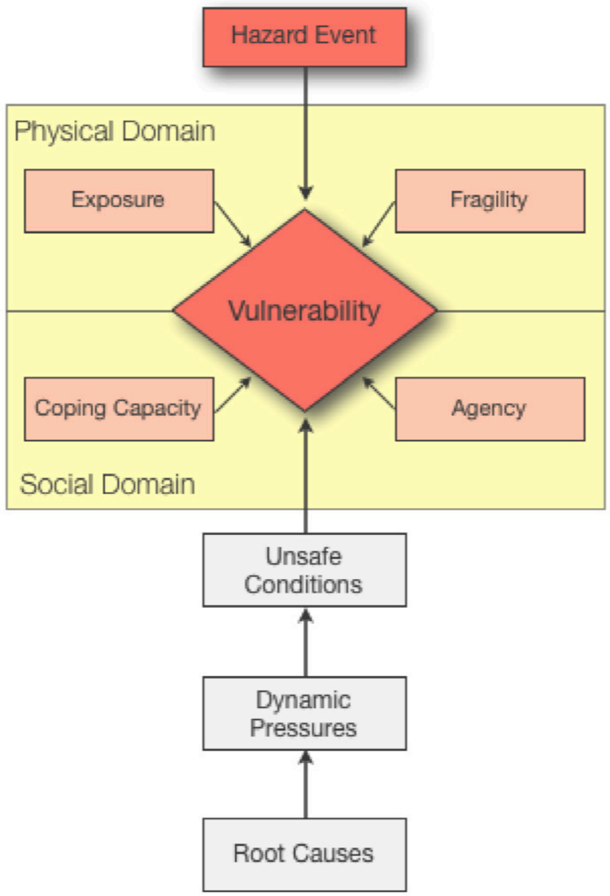


Figure 2-8: A conceptual model of vulnerability as an intrinsic property of human-natural systems that are exposed to processes capable of triggering a hazard event capable of causing damage or injury (physical susceptibility), and that are shaped by socio-economic and political forces (social susceptibility) that may negatively influence the ability of individuals and groups to respond and recover from the impacts of a disaster event over time (UNDP, 2006).

built environment to withstand and respond to the impacts of an external hazard event.

In contrast, the UN Development Program (UNDP, 2006) takes a more human-focused view and defines vulnerability to be "a human condition or process resulting from physical, social, economic and environmental factors which determine the likelihood and scale of damage from the impact of a given hazard." From this vantage, vulnerability is a condition or process that is intrinsic to the system. It is measured and analyzed through the use of spatial statistics to determine the factors or processes that may predispose a community or region to negative impacts of a hazard event and undermine their ability to meet policy goals and management objectives with respect to safety and security. The UNDP approach does not necessarily provide a direct measure of cause-effect relationships between hazard events and the socio-economic system, nor does it consider how the underlying root causes and dynamic pressures may change over time.

Regardless of the particular perspective and corresponding analytical approach, the underlying premise in assessing the vulnerability of a place and its people is that an increased knowledge and understanding of the root causes and dynamic pressures will reduce overall disaster risk. This new knowledge and understanding can lead to decisions that increase resilience, by moving people and their assets to a safer location, or by increasing people's capacities to withstand and respond to the impacts of a hazard event.

2.2 3..1 Linkages Between Place and People

Landscapes that offer potential for agriculture, resource development, or quality of life amenities (views, proximity to water, recreation, etc.) are often situated in areas that are exposed to natural hazard threats. Such landscapes offer opportunities for short-term growth and development, and can evolve quickly in response to socio-economic pressures and influences. The resulting socio-economic structures and patterns of human settlement can themselves create intrinsic patterns of vulnerability that will determine the extent to which a region can withstand, respond to and recover from the impacts of hazard threats, irrespective of the level of structural protection that may exist.

This was made evident in the aftermath of Hurricane Katrina, where the impacts and consequences of the actual hazard event were amplified several orders of magnitude by underlying patterns of social vulnerability. Those who lacked the capability to evacuate areas impacted by the hurricane and subsequent flooding were subjected to increased levels of hazard threat. Populations that were particularly vulnerable to impacts and consequences of the hazard event included the elderly those living with physical disabilities and socially disadvantaged individuals and groups who were forced to rely on emergency services for the provision of shelter and basic needs.

In general, the vulnerability of a place and its people can be understood in terms of the exposure of people and critical assets to hazard threats, the capacity of physical and human systems to withstand the impacts of a disaster event, and the agency of individuals and groups to influence or make decisions that will reduce their vulnerability (ISDR, 2002; UNDP, 2006). Exposure refers to the characteristics of physical and social susceptibility—including structural robustness of housing type, tenancy, employment and occupational diversity—that will influence the extent and degree to which individuals and groups are situated in harm's way. Neighbourhoods situated in low-lying areas on the valley floor are often exposed to significant natural hazard threats (earthquake, liquefaction, river flood and debris flow), as well as anthropogenic hazards related to dam failure, toxic material spills, and technologic accidents resulting from proximity to industrial areas and connecting transportation networks. In close proximity to agricultural and industrial lands, these settlements are some of the oldest neighbourhoods in the region. They are generally composed of a mix of residential and non-residential buildings that predate modern design guidelines and the mid-1970s' enforcement of building safety standards. These settlements also represent individuals and families who share similar employment portfolios from working in industries that are vulnerable to market fluctuations, and who are more likely to occupy rental accommodations. All of these factors contribute to higher levels of exposure and vulnerability. In contrast, neighbourhoods situated at high elevations, away from flood, liquefaction, and landslide hazards, tend to be dominated by newer home construction, be occupied by individuals and families with a more diverse employment portfolio, and be in proximity to a wide range of amenities..

Coping capacity reflects the characteristics of age and physical ability, level of education, family structure, gender, and language that may influence the extent to which individuals or groups are able to withstand and respond to a disaster event. There are notable correlations between low-lying areas susceptible to flood and liquefaction hazards and neighbourhoods with higher proportions of elderly and single parent families—conditions that are known to increase the likelihood of negative impacts in the event of a natural disaster. Hurricane Katrina took the lives of more than 1,575 people. Records show that 67% of these victims were over the age of 60. Many of the others hardest hit by the disaster were limited by physical ability or had care giving responsibilities that limited their capacity to respond to the disaster (FEMA, 2006).

Agency is the degree of influence an individual or group may have in dealing with the impacts or consequences of a hazard event. It reflects any social or economic disparities that may exist between members of a population related to differences in personal or family income, or the ability to make choices and take action based on prevailing social norms. In our case study example, there is a positive correlation between low-lying areas of the valley that are susceptible to multiple hazard threats and neighbourhoods that are characterized by lower levels of individual or family income and higher proportions of visible minorities. Similar patterns of social vulnerability were present in New Orleans prior to Hurricane Katrina. The hurricane and resulting floods struck New Orleans near the end of the month, before the cycle of paycheques had arrived. Those with discretionary income were able to leave the city and seek refuge elsewhere, while the majority of people hardest hit had no choice but to remain in the disaster area, with limited political influence and few resources to enable taking action on their own (Tierney, 2006).

2.2 3..2 Issues and Challenges

Assessment of physical and social vulnerability provides valuable insights into the underlying conditions and causal factors that will determine the extent to which different individuals and groups in a community are impacted by a disaster event, and their abilities to withstand, respond to and recover from the consequences of these events. This information provides situational awareness of disparities that may exist in a community, and is vital in developing response and recovery strategies for emergency preparedness. It also illuminates social norms and political decision-making processes that may put the most vulnerable people in harm's way and create patterns of social inequity that can significantly amplify the impacts and consequences of a disaster event for existing and future generations.

Conventional practices of risk assessment and disaster mitigation tend to emphasize objective measures of physical vulnerability (injuries, damages) and hazard risk (anticipated loss). However, they do not always take into account underlying social geography, values, belief structures, and political influences that define who and what are considered vulnerable and in need of safeguarding. Yet, these are the very issues that will determine the extent to which a community or region is able to respond to a hazard event, the severity of the disaster event, and whether it evolves into a catastrophe with longer-term consequences that limit a capacity to recover in terms of economic vitality and quality of life. In addition, patterns of social vulnerability can change dramatically, particularly in urban areas that are experiencing a rapid rate of growth (Andrey and Jones, 2008).

2.2 4. Resilience

Resilience is an expression of overall capability to live within the limits of a system in constant flux. The concept of disaster resilience is rooted in theories of complex system behaviour and the science of global environmental change (Holling, 1973). It is often defined in terms of the magnitude of shock that a system can absorb and still remain within a given state of functionality, and the degree to which the system is capable of self-organization (Carpenter et al., 2001; Folke et al., 2002; Gunderson and Holling, 2002; Holling and Gunderson, 2002; Pelling, 2003; Walker, 2005; Walker et al., 2006; McDaniels et al., 2008). Adaptability is a related concept that reflects the capacity to modify behaviour and norms of decision making to decrease levels of physical and social vulnerability over time(Walker et al., 2006).

Disasters are defined as events caused by unavoidable natural processes that impact areas of human settlement and that cause significant damage or injury (ISDR, 2002; UNDP, 2006). By extension, catastrophes are disaster events that disrupt the socio-economic stability of large regions, and that exceed the capacity for recovery over an extended period of time. Systems that are able to absorb larger physical and socio-economic shocks without changing in fundamental ways are more resilient (Folke et al., 2002). They are more diverse in terms of environmental, social, and economic attributes, and are able to reorganize themselves in response to gradual or abrupt changes in underlying system dynamics and driving forces.

Resilience models are designed to assess changing conditions of vulnerability across different spatial and temporal scales of interaction (local, regional, global). They specifically address the questions of who and what are vulnerable to the multiple environmental and human changes underway, how these changes are attenuated or amplified by different human and environmental conditions, and what can be done to reduce system vulnerability.

2.2 4..1 Resilience as a Measure of Change

Comprehensive land use planning, growth management, and sustainable development represent the larger context in which issues of community resilience are considered and negotiated. The capacity of human-natural systems to withstand, respond to and recover from the impacts of hazard events in a futures context will determine the extent to which balance between economic-environmental-human systems can be achieved and sustained over time.

Disaster resilience is defined in the context of a specific geographic area and planning horizon, and is assessed on the basis of changing physical and social conditions. Physical aspects of system resilience are measured in terms of robustness and rapidity (Bruneau et al., 2003; Chang and Chamberlin, 2004; Chang and Shinozuka, 2004; McDaniels et al., 2008). Robustness is a measure of the extent to which a system can withstand the impacts of a hazard event and remain functional. Rapidity is a measure of the time required to restore system functionality to minimum thresholds of performance. Socio-economic aspects of system resilience can be assessed in terms of social vulnerability (as discussed above) to provide a measure of overall adaptive capacity.

As illustrated in Figure 2-9, systems that are characterized by high levels of disaster resilience experience relatively small levels of disruption and are likely to recover baseline levels of performance in a relatively short period of time. In some case these systems may even experience a net improvement in overall performance due to adaptive design and reorganization during the recovery period. Systems characterized by low levels of disaster resilience experience a relatively large drop in performance following the hazard event, take a longer period of time to restore services, and may never recover to pre-event states of functionality. The capacity for any given system to withstand, respond, and recover can be assessed from a variety of perspectives including technical, organizational, social, and economic attributes that contribute to robustness and rapidity (Bruneau et al., 2003; Chang and Chamberlin, 2004).

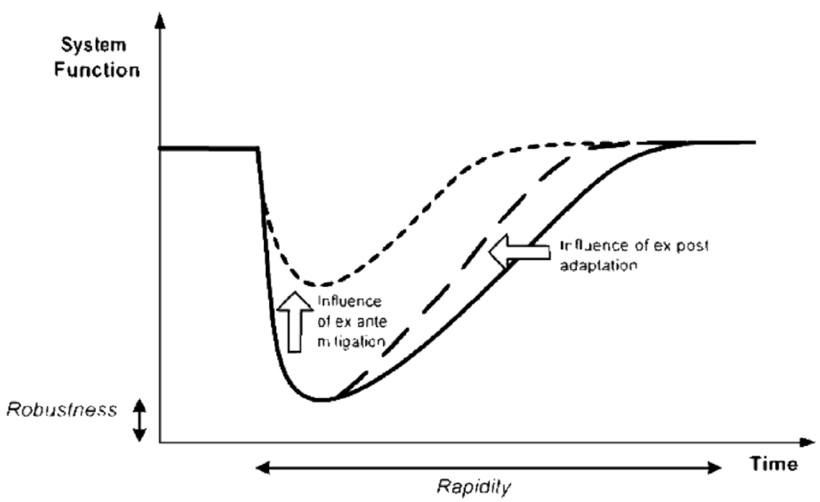


Figure 2-9: A conceptual model of disaster resilience defined in terms of the capability of a system to withstand, respond to and recover from the impacts of a hazard event over time (McDaniels et al., 2008)

2.2 4..2 Issues and Challenges

The concept of resilience encompasses the broader spatial and temporal dimensions of risk. Disaster mitigation activities that are focused on system resilience emphasizes longer-term strategies that address underlying social, economic, and environmental processes. The intent is on building internal coherence and adaptive capacity of communities and regions by reducing their vulnerability to natural hazards through a blend of mitigation strategies, and by increasing their inherent capacity for response and recovery through emergency preparedness and sustainable land use practices.

The challenges in addressing issues of disaster resilience are many. First, the assessment of disaster resilience requires a systems-based approach that accounts for changing conditions of vulnerability and risk in a futures context. This, in turn, demands a broad and diverse level of knowledge to assess complex system interactions, and access to the people and system resources that are required to undertake an integrated assessment of these systems and how they are likely to change over time. The gap between intent and available capacities to undertake a holistic study of disaster resilience can be significant for smaller municipalities that do not have the staff or resources to address these issues on an ongoing basis. At the same time, there is increasing awareness and acknowledgement that this level of assessment is essential in order to understand the dynamics of risk in a changing landscape and to anticipate emerging threats in the broader context of growth management and comprehensive land use planning.

2.3 The Gaps Between Concept and Practice

Observations and lessons learned through our examination of the physical and human geography of risk are summarized below. They serve as a basis for identifying challenges for managing risks associated with growth and development in areas exposed to natural hazard threats, and the gaps that exist between the concept and practice of disaster mitigation. Although our study is focused on disaster mitigation planning in Canada, many of the gaps identified are relevant to other geographic contexts as well.

2.3 1. *Measuring the Dimensions of Risk*

As we have seen, risk is a multi-dimensional concept that can be understood from a variety of different perspectives or dimensions. These include objective measures of hazard potential, hazard risk, vulnerability, and resilience; and subjective measures of what is considered vulnerable and in need of safeguarding. Modeling of the risk environment often requires a reduction in system complexity by narrowing the scope of enquiry, and by assuming conditions of linear and independent system behaviour. Uncertainty is acknowledged by analyzing the effects of varying model assumptions and by propagating stochastic measures of event probability through the full assessment of risk. On the basis of these simplifications, models are then constructed to represent system behaviour and to predict specific cause-effect relationships. However, the restricted analytic scope, simplifying assumptions, and limits of scientific knowledge are not always made evident in reporting model results. The consequences can be significant, particularly in situations where prediction models are used as the basis for policy analysis and decision making.

Summary Proposition: There are limits to the capacity of scientists to understand and model the complex network of interactions that characterize human and natural systems, their patterns of evolution, and the implications of uncertainty in assessing the dimensions of vulnerability and risk for any given place. Because of this, risk managers need to consider issues of system complexity and scientific uncertainty in framing risk problems for assessment, and in evaluating the implications of policy alternatives. Rather than relying on scientific models as predictive tools to provide an answer, the emphasis should be on using models to interactively explore complex system behaviour and to develop a common framework of understanding that acknowledges uncertainty and the limits of knowledge.

2.3 2. *Negotiating Thresholds of Tolerable Risk*

Rational policy analysis tends to emphasize objective measures of physical vulnerability (injuries, damages) and risk (anticipated loss). It does not always take into account human geography and the underlying dimensions of social vulnerability that can amplify the consequences of a disaster event beyond accepted thresholds of risk. Nor does it include more subjective dimensions of design or the articulation of intent based on values, belief structures, and political influences that ultimately determine who or what is considered vulnerable and in need of safeguarding.

Principles of public safety, socio-economic security, resource efficiency, and equity are the cornerstones for disaster risk management and sustainable development. However, there is a fundamental disconnect between formal definitions of these concepts and what they might actually mean in the context of a particular place and socio-economic setting. What is considered safe, secure, efficient, or equitable in the context of a small rural setting may be very different from that of a major urban centre. Assessment can provide an objective measure of risks and associated benefits through observation, informal appraisal, and scientific analysis. Assessment informs but does not answer the questions: How safe is safe enough? How much risk is an individual or group willing to tolerate in order to achieve a desired goal or set of objectives?

Summary Proposition: Societal risk is a pluralistic concept. Negotiating thresholds of safety and tolerable risk requires an understanding of who and what are at risk, and why. It follows that supporting methods of assessment ought to strive for balance between the analysis of cause-effect relationships and the evaluation of mitigation alternatives that seek to manage societal risk based on a consideration of prevailing values, goals, and beliefs.

2.3 3. *Evaluating Choices and Consequences*

Existing methods of risk assessment are based primarily on static physical models that predict cause-effect relationships for existing conditions of human settlement. While useful in support of pre-event emergency planning, these models do not consider the effects of a changing landscape or evolving conditions of vulnerability and risk. As such, they do not inform the management of systemic risks associated with ongoing growth and development. Furthermore, while vulnerability and risk models provide objective measures of impacts and consequences, they do not directly inform progress toward or away from policy goals and management objectives. As a result, they offer only limited support in evaluating the strengths and weaknesses of risk reduction alternatives in terms of vulnerability and overall state of disaster resilience.

Summary Proposition: Disaster mitigation is a forward-looking process of anticipating change; it involves the evaluation of choices and their consequences with respect to performance toward policy goals and intended outcomes. Therefore, planners and policy analysts need a structured framework for risk assessment with a capacity to analyze changing conditions of vulnerability and risk over time and to evaluate alternate decision pathways that will balance both risks and benefits.

Challenges of Risk-Based Planning in Canada

Factors contributing to a lack of community-based risk-management practices in Canada include:

- Limited understanding of natural hazard potential in the context of local landscapes and the likely impacts of these events on existing and evolving patterns of human settlement.
- A perception that existing safety measures (dykes, building codes, etc.) already offer adequate levels of protection, and that risk sharing or transference strategies (insurance, provincial/federal disaster assistance) will offset any potential direct losses.
- A fear that the public will panic if hazard threats and damage potential are made evident as part of a community planning process, thereby pitting the rights of individual property owners against the safety and security of the community overall.
- A lack of compelling and defensible cost-benefit analyses to warrant public expenditures on risk reduction measures in advance of a disaster event.
- A lack of coordination and collaboration between disaster management and community planning professions, which have been traditionally rooted in different ideologies and which are often tasked with separate functions within municipal and regional district governments (Etkin et al., 2004).

pathways

Chapter Three:

Understanding Risk and Informing Decisions

"Risk assessment and decision making are inherently forward looking processes.... The idea that predictive science can simplify the decision making process by creating a clearer picture of the future is deeply appealing in principle, but deeply problematic in practice."

Sarewitz et al., 2000.

3. Understanding Risk and Informing Decisions

Risk-based planning is the process of balancing opportunities for growth and development with the anticipated impacts and consequences of potential hazard events in ways that promote the resilience of a community or region over time. It is also a process of analysis and evaluation that brings together communities of practice that do not necessarily share the same perspective, theoretical foundation or operational mandate.

Scientific analysis expands our insight and knowledge about the world and its underlying dynamic processes through an ongoing process of questioning, hypothesizing, assessment, validation and refutation (Sarewitz, 2000). The scope of analysis can include formal scientific enquiry and/or synthesis of available local knowledge about the risk environment. In contrast, policy analysis is geared toward resolving conflicts between human wants and needs for the purpose of enabling action and achieving management goals and objectives. Evaluation of policy alternatives involves deliberation and structured decision making that is informed by science, but driven by public debate on how best to reconcile social, economic, and environmental imperatives for a given place and span of time.

Though founded on principles of rationality and democratic choice, the practice of risk-based planning usually charts a course somewhere in between analysis and evaluation. The decision pathway between science and policy is often ill defined, resulting in a process that offers little guidance to practitioners on how to transform knowledge about the risk environment into a form that supports the evaluation and judgment of policy alternatives. For the emergency management practitioner, the challenge is in prioritizing hazard threats, identifying people and community assets of concern, and developing strategies that optimize public safety and system resilience during response and recovery phases of a disaster. For the community planner, the challenge is in establishing thresholds of risk tolerance for managing growth and development in ways that balance trade-offs between public safety, socio-economic security, environmental integrity, and quality of life for existing and future generations. The emergency manager and community planner share a responsibility for disaster mitigation, but do not always have the benefit of working together toward a common set of goals or operational objectives. While there has been a shift in recent years toward more holistic approaches to risk-based planning (Klinke and Renn, 2002; Turner *et al.*, 2003; Engels, 2005; Saner, 2007), much work still needs to done to assist emergency managers and community planners in analyzing the risk environment and in evaluating policy alternatives.

The conventional approach to risk-based planning involves a process of rational assessment that is informed by the analysis and predictive modelling of cause-effect relationships, and governed by choices that seek to optimize system performance in terms of effectiveness and/or efficiency. It is often referred to as the science-based approach to decision making. In contrast, integrated assessment is a bottom-up process of adaptive planning that relies on scientific analysis and exploratory modelling to identify patterns of interaction that describe risk environments over time. The process is governed by value-based choices that balance trade-offs between system performance (effectiveness and efficiency), environmental integrity, and social justice. It is often referred to as the evidence-based approach to decision making. Rational analysis and integrated assessment are both useful in the context of disaster mitigation, but rarely incorporated into a broader framework of risk-based planning and decision making.

This chapter examines the theoretical aspects and methods of decision making for disaster risk reduction, and introduces an earth systems approach to risk-based planning that builds on the strengths of rational analysis and integrated assessment. Earth systems thinking acknowledges the importance of place and the changing dynamics of vulnerability and risk over time, and is a mode of reasoning that addresses issues of complexity and scientific uncertainty in the assessment of policy choices and their consequences. It is an iterative process of analysis and evaluation through which expert and local knowledge about the risk environment is used to inform decisions that promote the resilience of communities and regions over time.

Principal objectives of this chapter are to:

- Explore the realm of risk-based decision making and modes of interaction between science and policy that are relevant in the context of emergency management and community planning.
- Examine the process of structured decision making through the lens of rational analysis and integrated assessment.
- Introduce the concept of earth systems thinking as an overarching conceptual framework for assessing risks in complex systems where there is a need to balance trade-offs between the effectiveness and equity of mitigation decisions.
- Critique existing best practices of risk assessment for their suitability for use in Canada, and identify strategies for developing an integrated system of processes, methods and tools for emergency managers and land use planners promoting disaster resilience in their communities.

3.1 The Realm of Decision Making

Risk assessment is the process of integrating scientific analysis and evaluation of policy alternatives in order to inform decisions that seek to balance trade-offs between human health and safety, opportunities for socio-economic growth and development, environmental integrity, and quality of life for existing and future generations. Effective and accountable decision making requires a common understanding of risk in the context of a particular place and planning process, and the transformation of this knowledge into actionable mitigation strategies that are framed by social values and goals, informed by scientific understanding, and tempered by the need to make practical choices between diverse and often competing policy imperatives.

From the perspective of public policy analysis and governance, risk is generally framed in terms of choices and consequences. In this context, risk is an emergent property of a decision-making process that seeks to balance scientific knowledge and understanding with social norms and judgments. Risk-based planning is the process whereby knowledge about the risk environment is analyzed and evaluated for the purpose of determining the most appropriate course of action for moving forward. It is informed by available scientific information and knowledge about human-natural systems (hazard, vulnerability, loss potential) and governed through judgments of what constitutes acceptable or tolerable thresholds of potential loss by those impacted by hazard events. (Bouder et al., 2007). This is often referred to as the integrative or "risk-based" approach to planning (Pahl-Wostl et al., 2000; Rotmans and Van Asselt, 2000; Sarewitz and Pielke Jr, 2001; van der Sluijs, 2002; Engels, 2005).

3.1 1. A Map of the Science-Policy Interface

Figure 3-1 is a schematic map of the conceptual landscape within which risk decisions are assessed and negotiated as part of the planning and policy development process (modified from Renn, 2006a; and Saner, 2007). Situated within this conceptual landscape are the domains of society, science, and policy. Each is characterized by different perspectives and understandings of risk, and different expectations of how these world views ought to be negotiated as part of a decision-making process. The concept of risk lies at the intersection of these realms. It is determined through analysis, and is negotiated through deliberation and considered input from all those involved in the process. Facts about the world and how it works are derived from observation, measurement, and structured processes of reasoning. Social values and belief structures are discovered through deliberation, and are negotiated as part of the planning and decision making process.

The vertical axis reflects the balance of tensions between subjective views of risk at one end and objective measures of risk at the other. Subjective risk is defined by normative judgments based on values and beliefs of who and what are considered most vulnerable and in need of safeguarding, and also by policy preferences that express intent with respect to a desired set of outcomes for an organization or community. Objective risk is defined by descriptive measures of hazard threats (facts) and by interpretations (models) of their likely impacts and consequences. The integration of subjective and objective risk represents the realm of knowledge generation through which ethical perspectives

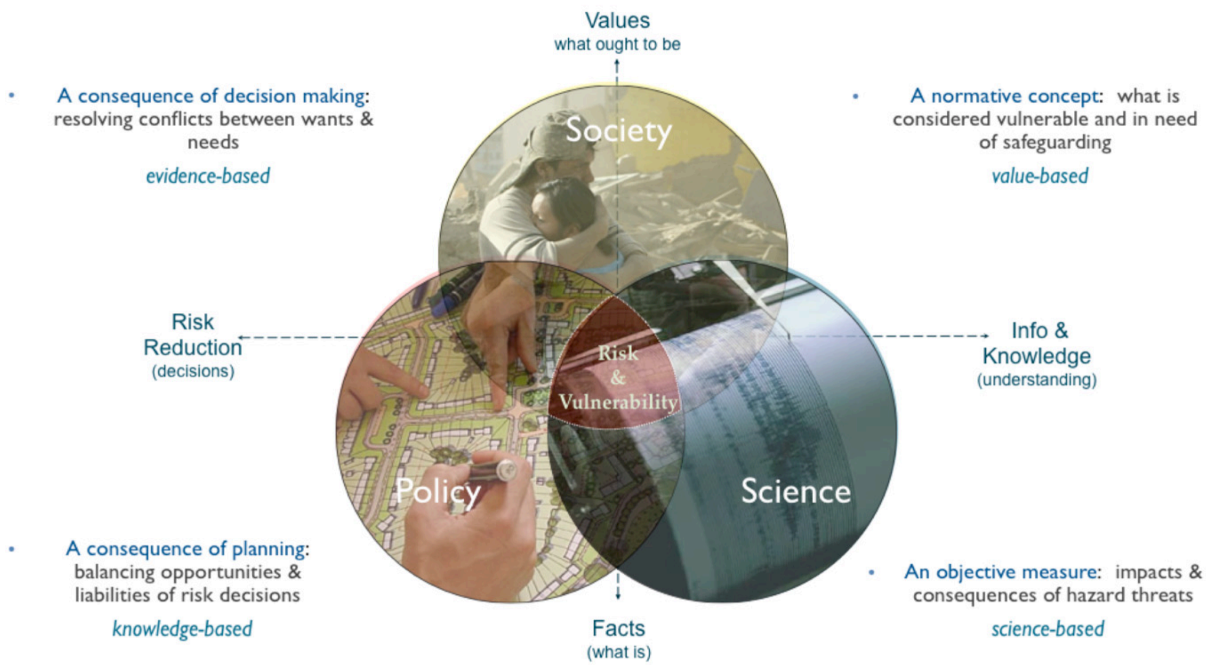


Figure 3-1: A conceptual map of the decision-making realm as it relates to risk-based planning and governance. Adapted from the work of Renn (2006) and Saner (2007).

and descriptive information about the risk environment are transformed to a common frame of understanding for the purpose of evaluating policy choices and their consequences.

The horizontal axis reflects the balance of tensions between knowledge about the risk environment at one end, and the actions required to manage risks associated with growth and development at the other. This is the realm of democratic debate and decision making through which expert and domain-based knowledge about risk is used to evaluate and implement strategies that promote disaster resilience within the limits of time and available resources. While the intent of the decision-making process is to mitigate potential negative impacts on people and critical assets for a desired outcome, the decision pathway between knowledge and action is often obscured by the complexity of interactions between natural and human systems, scientific uncertainty, and the ambiguity of potential outcomes (Klinke and Renn, 2002; Renn, 2006a).

3.1 2. Navigating the Decision Pathway

In the realm of decision making, the pathway from knowledge to action is one that can be navigated by dead reckoning an existing course of action, or by piloting a course toward a desirable set of outcomes. In navigational terms, dead reckoning is the process of estimating one's position based solely on speed, direction of travel, and the time elapsed since the last known fixed position on land, sea, or air. Predicting a future position is deduced from an analysis of how a current position will change over a specified period of time based on these same physical measures of direction and rate of change. In the realm of science-policy integration, this is equivalent to the paradigm of predictive modelling and rational planning. A conceptual model of this familiar paradigm for decision making is summarized below in a figure adapted from Sarewitz

(2000).

In contrast, piloting is the process of navigation based on visible and known landmarks that can include distant points on the horizon, stars, or other celestial bodies. Past, present and future positions along an intended course are interpreted with respect to distance and orientation from a known point of reference and any changing environmental conditions that will influence the rate and actual course of travel. This mode of navigation involves an iterative and ongoing process of reasoning that is informed by awareness and understanding of a particular place (context), and an ongoing assessment of progress with respect to a clearly defined destination (goals and targets). In the realm of science-policy integration, this is equivalent to the paradigm of integrated assessment and scenario-based planning. From this perspective, science is used as a compass to facilitate exploration, discovery, and the transformation of knowledge to inform and help guide progress toward a desired set of policy outcomes.

Rational analysis represents a tactical approach to risk assessment that focuses the decision-making process on a "willingness to pay" for mitigation alternatives that optimize utility. It provides perhaps the most effective means of analyzing dimensions of vulnerability and risk, and of transforming scientific and technical knowledge into a form of expert understanding that can be used to assess alternate means of achieving a desired outcome with respect to management objectives that are based on principles of utility (effectiveness and/or efficiency).

Integrated assessment represents a strategic approach to risk assessment that focuses the decision-making process on a "willingness to accept" trade-offs between diverse and often competing policy goals and objectives. It is a method of assessment that combines tacit and empirical knowledge about vulnerability and risk to inform decisions that balance trade-offs between utility and equity. It involves a full cycle of knowledge discovery, social learning, and the generation of risk scenarios (hypotheses) that convey both expert and local understanding of hazard threats and plausible outcomes to disaster mitigation alternatives. These scenarios, or working hypotheses, represent viable and presumably desirable points on the horizon to guide the remaining stages of policy analysis, decision making, and on-the-ground implementation of risk treatment measures.

Although distinct in terms of approach and methods, rational planning and integrated assessment both have a role in the evolving field of risk-based planning and disaster mitigation. In different ways, they represent structured forms of decision making that encompass the analysis of complex systems and the evaluation of policy alternatives for the purpose of assisting decision makers in selecting a future course of action that moves a community toward a desired set of policy goals while minimizing potential negative impacts and consequences.

3.2 Rational Planning: A Science-Based Approach

This mode of planning is based on a model of rational choice (Simon, 1955; Davidoff and Reiner, 1962) and is generally understood to be an analytical process of decision making that is focused on determining an appropriate future course of action based on the utility of alternate means and the likelihood of achieving the intended outcome. It is a means of structuring the risk management process around principles of rational behaviour whereby a set of policy alternatives are put forward for consideration, consequences are scientifically assessed and analyzed, and a course of action is selected based on ranking policy alternatives in terms of overall performance.

3.2 1. The Process

As illustrated in Figure 3-2, the rational planning process of decision making is linear and progressive (Keeney, 1982; Yoe and Orth, 1996; Malczewski, 1999; Peterman and Anderson, 1999; Costa, 2001; Belton and Stewart, 2002; Yoe, 2002). Scientific enquiry and analysis provide the necessary information, knowledge, and predictive models of risk and uncertainty to inform the evaluation of policy alternatives. Analytical outputs are transferred to risk management practitioners across well-defined professional or sectoral boundaries at specific points of interaction, each characterized by conventional modes of communication that tend to be unidirectional in nature. Similar modes of communication exist at the boundaries between restricted and unrestricted (public) knowledge and are used to account for and

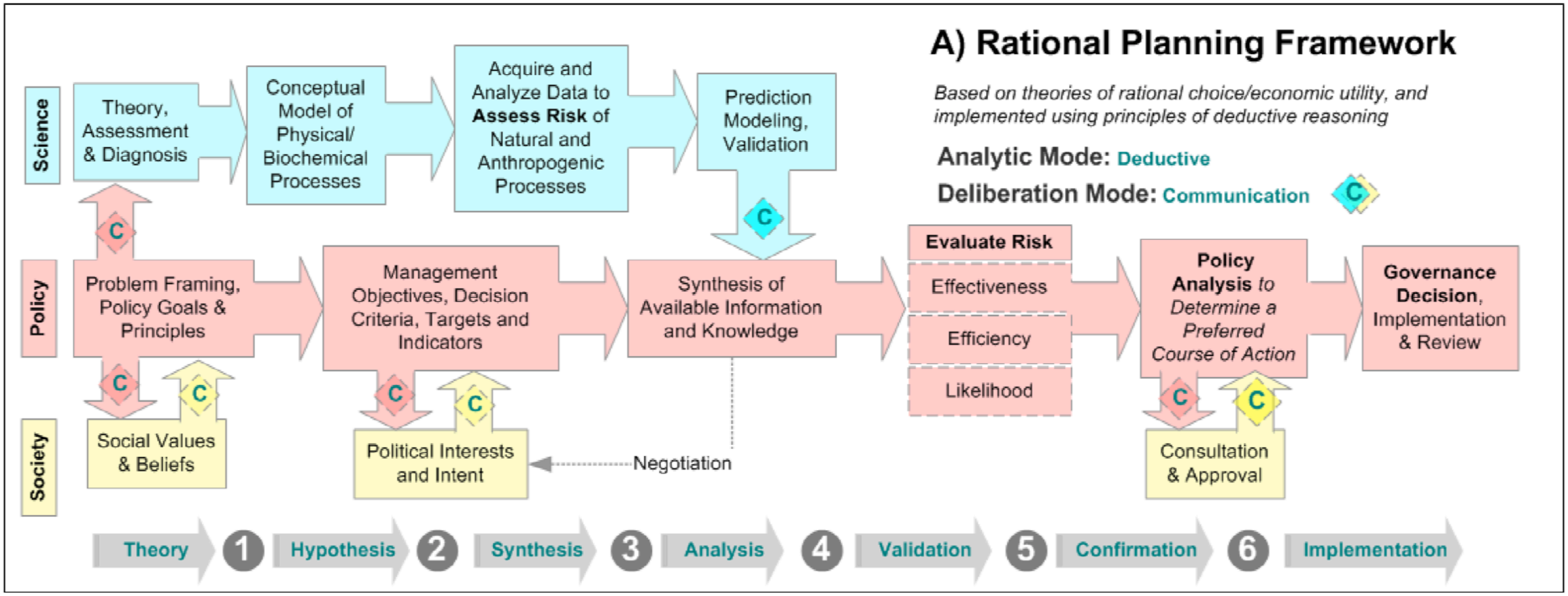


Figure 3-2: A graphic representation of the rational planning paradigm

integrate social values, beliefs, and political interests into the decision-making process.

3.2 2. Methods and Metrics

In considering the utility of a future course of action, effectiveness is analyzed on the basis of whether the consequences of a choice lead toward or away from stated policy, goals, and management objectives. It is evaluated on the basis of decision criteria determined at the outset of the planning cycle, and measured using comparative risk assessment methods—a hierarchical system of indicators that track the performance (outputs) of multiple and often competing objectives (outcomes). Efficiency is analyzed by comparing the costs of investing resources (social and economic capital) in a policy alternative with the anticipated benefits of pursuing that particular course of action. It is evaluated on an anticipated return on investment. The likelihood of a hazard event occurring is assessed using statistical analysis and/or Monte Carlo simulation modelling; both provide a means of tracking and accounting for uncertainties as part of the decision-making process (Peterman and Anderson, 1999; Warren-Hicks, 1999).

Final decisions of a rational planning process are based on outputs of a comparative risk assessment and/or cost-benefit analysis in which measures of effectiveness and efficiency are used as the principle criteria for assessing the overall performance of policy alternatives. The method assumes that only a limited number of rational choices exist for achieving a specified set of goals.

3.2 3. Strengths and Weaknesses

The strength of the rational planning model is a structured process of top-down reasoning that transforms scientific and technical knowledge into a form of expert understanding that can be used to assess policy alternatives. The expectation is that such a process will provide clarity and lead to objective decisions on societal issues that involve high levels of complexity and uncertainty. Because the underlying methods are based on facts about the world that can be observed, measured, and validated with scientific theory or experiment, there is also an expectation that policy choices will be objective and will lead to the best possible decision in terms of effectiveness and efficiency. However, the vast body of evidence suggests that this is rarely the case (Sarewitz, 2000; Frodeman, 2003).

Limitations of the rational planning model are well known in practice and have been cited widely in the literature (Jaeger, 1998; Rotmans, 1998b; van Asselt and Rotmans, 1999; Pahl-Wostl *et al.*, 2000; Rotmans and Van Asselt, 2000; Rotmans, 2005). The concern is that that science-based policy choices give the impression of informed decision making, but in fact do not always reflect a complete understanding of system complexity, empirical uncertainty, or political ambiguity. The method assumes that adequate information and knowledge is available to analyze cause-effect relationships and to evaluate policy alternatives equally in terms of effectiveness, efficiency, and likelihood of occurrence. From a scientific/technical perspective, the model also assumes that interactions between natural and human systems are linear and predictable, and thus controllable.

While the assumption of linear cause-effect relationships between a hazard event and its impacts on people and the built environment may be a necessary simplification in order to make predictions about likely consequences, there is a danger that model outputs may overshadow or even prevent a consideration of non-linear system dynamics (Pielke, 1999; Sarewitz *et al.*, 2000; Pielke and Conant, 2002). The unanticipated consequences of these complex system behaviours can in some cases be several orders of magnitude larger than single cause-effect chains that are the focus of the modelling activity. It may be difficult, impractical, or even impossible to develop a model that takes into account all relevant factors that may influence cause-effect relationships in human-natural systems. However, there is a need to make these uncertainties evident and to formally incorporate them into policy analysis and the decision-making process.

Though methods of rational planning have been modified over the years, the process is still often undermined by rigid operational boundaries, the linear and parallel tracking of assessment activities across the science-policy interface, and modes of deliberation that are often limited to the transfer of information between scientists, planners, and those responsible for the decision-making process (Jaeger, 1998). The rational planning model does not easily accommodate societal values and goals into the decision-making process, and offers a limited capacity for judgments about what may constitute a tolerable threshold of risk for a given community or region.

3.3 Integrated Assessment: An Evidence-Based Approach

Unlike rational planning, integrated assessment blends analytic and deliberative methods to assist planners in developing evidence-based policy recommendations that are actionable, informed by the best available science, and governed by value-based judgments that reflect the principles, goals and objectives of those impacted by the decision-making process. It treats empirical uncertainty and normative ambiguity as attributes of the decision-making process, and acknowledges the limited capacities of individuals and groups to fully comprehend and process information about system complexities (bounded rationality). The method allows for ongoing synthesis, interpretation and evaluation of policy alternatives as new information and knowledge becomes available through analysis, and as changing societal priorities become evident through deliberation.

3.3 1. The Process

As illustrated in Figure 3-3, integrated assessment is a process of enquiry and planning that encompasses the generation of scientific and context-based knowledge through exploration, discovery, synthesis and learning. Transformation of this knowledge is facilitated through scenario-based modelling and multi-criteria decision analysis. Although many of the process elements are similar to those used in rational planning, there are some important differences.

First, the synthesis of available information occurs at the outset of the integrated assessment process. It encompasses objective measures that describe the natural system, and subjective measures that reflect underlying values, goals and belief structures of the community or

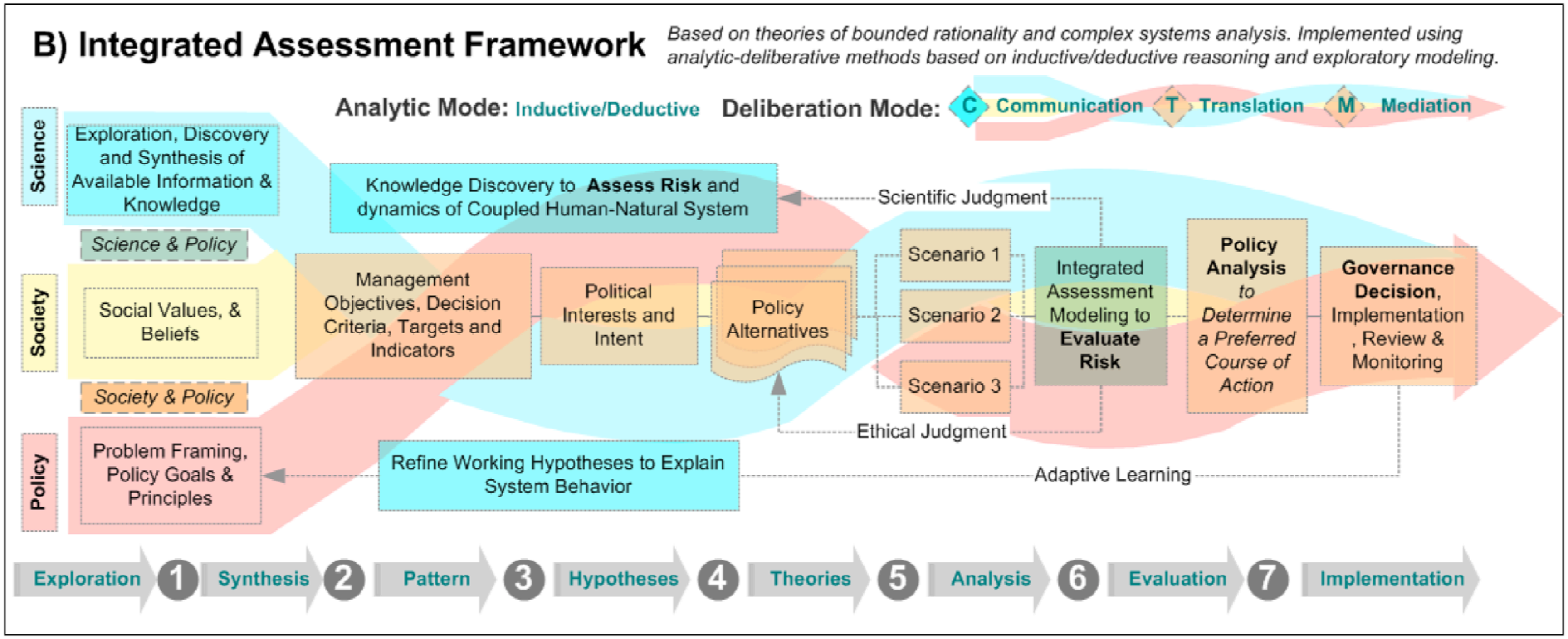


Figure 3-3: Schematic overview of the integrated assessment /evidence-based planning framework

region. From a scientific perspective, this information is used to develop conceptual and analytical models (working hypotheses) that describe the human-natural system and that explain underlying processes and dynamics that are likely to drive system change through time. Depending on the needs and requirements of the planning process, this can include semi-quantitative risk appraisal and/or quantitative risk modelling of the impacts and likely consequences of hazard threats. From a policy perspective, this information is used to diagnose the risk environment, to inform policy goals and principles, and to articulate specific decision criteria and target indicators that will guide the risk assessment process.

Second, knowledge gained through synthesis and analysis (appraisal and/or modelling) is transformed into a common framework of understanding through an ongoing process of deliberation that goes well beyond conventional modes of communication. In addition to the exchange of relevant information and knowledge about risk, deliberation seeks to broaden and deepen the planning process through dialogue, debate, and adaptive learning that incorporates the perspectives of natural and social scientists, public officials, and those interested or affected by the decision-making process.

As such, integrated assessment is a blend of analysis and design. In contrast to pure research, integrated assessment does not use scientific enquiry to advance knowledge of the world for its own sake, but rather to compile, synthesize, and interpret existing bodies of knowledge, and to evolve a common understanding in support of a decision-making process (CIESIN, 1994). The design element of integrated assessment involves the articulation of desirable future states through deliberation of alternate and often competing visions, interests, and ethical perspectives.

The importance of integrating deliberative dialogue into the risk assessment process was underscored in a formative study by the US National Research Council in 1996 entitled *Understanding Risk: Informing Decisions in a Democratic Society* (Stern and Fineberg, 1996), and has since been cited in numerous studies on participatory risk-based planning (Burby, 1998; Burby *et al.*, 1999; Checkland and Scholes, 1999; Comfort *et al.*, 1999; Renn, 2001; European Science Foundation, 2002; Yoe, 2002; Carmichael *et al.*, 2005; Gregory *et al.*, 2005; Kerkhof, 2006). A general conclusion of these studies is that success of the risk management process will depend on the integrity of deliberative methods that are used to promote a sense of trustfulness and to enhance the coherence of interaction between scientists and planners.

Collaboration between scientists and planners is essential in working toward a common understanding of risk, and in articulating viable mitigation alternatives that balance available knowledge with ethical judgments about what constitutes a tolerable threshold of risk for a given geography and planning process. The need for a balanced analytic-deliberative approach is reflected in current national and international standards for risk management (CAN/CSA-Q850, 1997; Australia/New Zealand Standards, 2006; ISO 31000, 2008b), and in associated guidelines for risk governance (International Strategy for Disaster Reduction, 2002; Organization for Economic Co-operation and Development 2003; United Nations, 2005; Renn, 2006a; Bouder *et al.*, 2007; International Risk Governance Council, 2008)

3.3 2. Methods and Metrics

As the name implies, integrated assessment combines knowledge from a range of disciplines and sources to analyze multiple physical and socio-economic dimensions of risk, and to evaluate the strengths and weaknesses of mitigation alternatives. It considers both the objective measures of risk and the subjective measures of what is considered vulnerable and in need of safeguarding. In addition to addressing principles of effectiveness, efficiency, and likelihood of occurrence, integrated assessment extends the scope of conventional rational analysis to include principles of social equity and environmental integrity. It also shifts the focus of assessment from an optimization of selected performance criteria (multi-attribute utility theory) to a negotiation of risk tolerance thresholds that balance a range of distinct and often competing policy objectives (multi-attribute value theory).

Integrated assessment and rational planning both utilize scientific modelling and methods of multi-criteria decision analysis to help structure and guide the decision-making process. Multi-criteria decision analysis (MCDA) extends the capabilities of comparative risk assessment and cost-benefit analysis by allowing a broader selection of decision criteria that more completely reflect available knowledge about complex human-natural systems, and that make evident underlying value-based judgments that are likely to influence the decision-making process. MCDA methods are rooted in choice theory and systems-based thinking, and used widely in the fields of human and ecological risk assessment (McDaniels and Thomas, 1999; Costa, 2001; Omann, 2004; Linkov et al., 2006a). Instead of focusing on a set of criteria that can be evaluated in absolute terms of market value, MCDA strives for balance across a broader set of considerations that can be evaluated in relative

Methods of Multi-Criteria Decision Analysis

Multi Attribute Utility theory (MAUT) emphasizes choices that are based on metrics of effectiveness and/or efficiency. Policy alternatives in this mode of decision making are assessed primarily in terms of measures that promote public safety and/or socio-economic security (Keeney, 1982; Keeney and Raiffa, 1993; Lahdelma and Salminen, 2001; Linkov *et al.*, 2004; Kiker *et al.*, 2005; Linkov *et al.*, 2006b).

Multi Attribute Value theory (MAVT) emphasizes value preferences and associated goal statements that reflect social values and preferences. Policy alternatives in this mode of decision making are assessed in terms of trade-offs between safety and security, environmental integrity and social equity (Costa, 2001; Goodwin and Wright, 2001; Belton and Stewart, 2002; Durbach and Stewart, 2003a; Hostmann *et al.*, 2005).

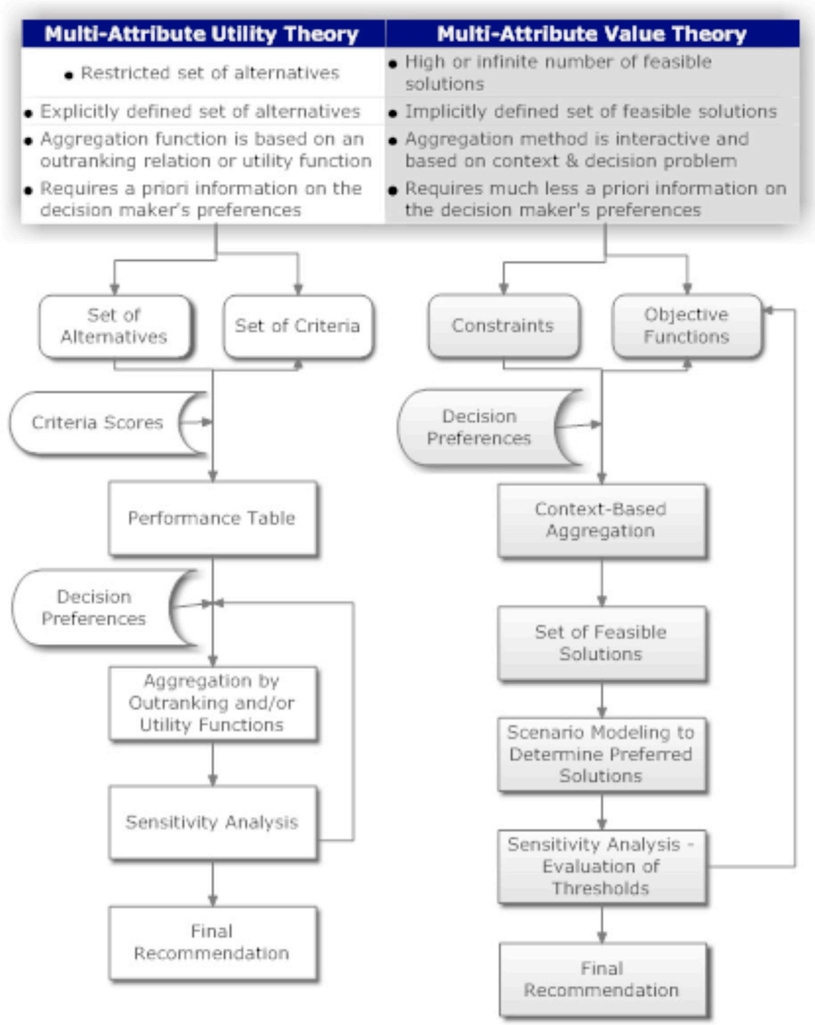


Figure 3-4: General analytical framework used in assessing policy alternatives based on models of: a) Multi-Attribute Utility Theory–MAUT; and b) Multi-Attribute Value Theory -MAVT. The accompanying table compares these two modes of decision making (Modified from: Chakhar and Martel, 2003).

terms of utility and/or value-based goals (Yoe, 2002; Linkov et al., 2004; Ely, 2005; Kiker et al., 2005).

As illustrated in Figure 3-5, decision criteria are arranged hierarchically into matrices that are calibrated and ranked on the basis of expert and/or local input, then evaluated using a variety of optimization and outranking techniques. Results of the analysis are reported as relative scores. Such multi-criteria comparisons are helpful in making evident any underlying normative principles that may drive outcomes of the decision-making process through either resonance or dissonance. Multiple and conflicting values that emerge from the deliberative process can be incorporated into the decision analysis by adjusting mitigation strategies, or by weighting criteria to reflect different ethical perspectives. This allows for the generation of multiple working hypotheses (scenarios) that reflect the integration of descriptive knowledge about the dimensions of vulnerability and risk in a community or region, and normative judgments on how best to manage risk associated with ongoing growth and development.

As part of the integrated assessment process, knowledge about the risk environment is made accessible through scenario models that facilitate the spatial analysis of risk and the evaluation of policy choices for a given landscape over a range of time horizons. Scenario modelling represents a narrative-based approach to exploring causal relationships that drive conditions of vulnerability and risk. The outputs of a scenario model are presented in the form of maps, indicator charts, and landscape visualizations. Risk scenarios represent plausible states of nature that account for real-world uncertainty by explicitly incorporating assumptions about system behaviour as model variables. Understanding gained through the use of scenario models provides a basis for evaluating a range of potential mitigation alternatives, and for deciding on a preferred course of action that is evidence-based and that reflects the values and beliefs of those impacted by the decision (van der Sluijs, 2002).

Risk scenarios emphasize the evaluation of mitigation alternatives with respect to a desired set of outcomes, rather than a predetermined set of performance targets (Goodwin and Wright, 2001; Belton and Stewart, 2002; Durbach and Stewart, 2003a; Montibeller *et al.*, 2006). Forecast scenarios project historical and baseline trends into the future using causality and prediction models to establish rational linkages

	damages avoided	injuries avoided	financial investment	losses avoided	level of exposure	agency & coping capacity
Choice A	.54	.28	.43	.25	.43	.37
Choice B	.61	.43	.61	.28	.46	.28
Choice C	.73	.58	.38	.33	.21	.45

Figure 3-5: Example of a decision hierarchy and accompanying decision matrix used to evaluate the strengths and weaknesses of policy choices based on performance measures that assess dimensions of effectiveness, efficiency, and equity (Modified from: Kiker et al., 2005; Linkov et al., 2006b).

between choice and consequence. They are typically used in situations where planning horizons are short (<5 years) and system dynamics are well understood in terms of both complexity and uncertainty. Backcast scenarios account for real-world uncertainties of future system behaviour by first articulating a desirable set of policy outcomes, then working backwards through analysis and available knowledge of system dynamics to evaluate the feasibility of proposed strategies to explore decision pathways that are capable of achieving proposed outcomes (Robinson 2004; Robinson and Tinker 1997; Robinson 1996).

3.3 3. Strengths and Weaknesses

The integration of analytical and deliberative methods provides a structured approach to characterizing physical, human and socioeconomic dimensions of the risk environment. (Turner *et al.*, 2003; Swart *et al.*, 2004; Carmichael *et al.*, 2005; Walker, 2005; Montibeller *et al.*, 2006; Rotmans, 2006; Wilson *et al.*, 2006). It also facilitates the evaluation of actionable decision alternatives that are informed by the best available knowledge and that reflect the values and goals of those who are likely to be impacted by the decision-making process. However, there are limitations to the approach and methods that warrant careful consideration.

As with the rational planning model, integrated assessment requires a large body of information with which to characterize and model the changing dimensions of vulnerability and risk. Depending on the needs and operational requirements of the planning process, the assessment of performance measures (indicators) may involve the use of mathematical algorithms and modelling applications that require a level of expert knowledge and technical expertise that may not be available. It is possible to use semi-quantitative methods of integrated assessment and scenario modeling that utilize narrative-based ranking schema to analyze hazard threats and to prioritize mitigation alternatives. However, without a standards-based approach to the analysis and evaluation of individual decision criteria (health and safety, socio-economic security, etc.), there is a danger that integrated risk assessments may yield results that are inconsistent and not comparable from one region to another.

Furthermore, the development of scenario models for analysis and evaluation can lead to an overwhelming combination of planning choices and consequences. Without a clear focus on a desired set of intended outcomes, the decision-making process can be easily undermined. Evaluating the combination of strategies and scenarios that balance performance across a range of policy objectives over variable planning horizons can quickly lead to cognitive overload.

While these are valid concerns, the benefits of integrated assessment and evidence-based planning far exceed the liabilities cited above. The field of disaster risk management is gradually shifting toward more integrative modes of analysis, evaluation, and participatory planning (Stern and Fineberg, 1996; Renn, 2001; Klinke and Renn, 2002; Pielke and Conant, 2002; Kreps *et al.*, 2006; Renn, 2006a). Increasingly, risk assessment is framed and situated in the broader context of disaster resilience and sustainable land use planning (Burby, 1998; Mileti, 1999; Burby et al., 2000; Berke, 2002), both of which require an understanding of the changing dynamics of vulnerability and risk over time and the implications of these changes with respect to social, economic, and environmental dimensions of a particular community or region.

3.4 An Earth Systems Perspective on Risk-Based Planning

Earth systems thinking is a perspective and mode of reasoning that is rooted in the field-based sciences of geology and ecology. It is based on an iterative process of discovery and interpretation that builds on the strengths of rational planning and integrated assessment by combining analytic and deliberative methods in ways that account for system complexity, the limits of scientific knowledge (uncertainty), and the inherent ambiguity of policy choices that must balance subjective and objective measures of risk. Distinguishing characteristics of this "geo-logic" perspective and way of thinking include: the importance of place in framing complex societal issues that involve spatial interactions between natural processes and patterns of human settlement; a consideration of time as a measure of continual change between past, present, and future states of an evolving landscape; a mode of enquiry that relies on abductive reasoning to reconcile system complexity and scientific uncertainty, and; a philosophical perspective that acknowledges the need to balance opportunities for growth and development with the adaptive capabilities of the natural system (Sarewitz, 2000; Frodeman, 2003).

From this perspective, it is argued that "science ought not be viewed as an authoritative voice, but rather as a source of insight that can help us understand the inevitable constraints of our knowledge and foresight, and therefore point us toward policy approaches that favour adaptation and resilience over control and rigidity," (Sarewitz, 2000, p93) Decision making from this perspective involves three primary activities. The first is to alert society to potential challenges and problems that lie ahead (diagnosis). The second activity is to define and assist in structuring complex problems to facilitate the exploration and negotiation of desirable policy alternatives through analysis and deliberation (decision support). Lastly, decision making uses scientific knowledge and understanding to help guide action prior to and after political consensus is attained (assessment).

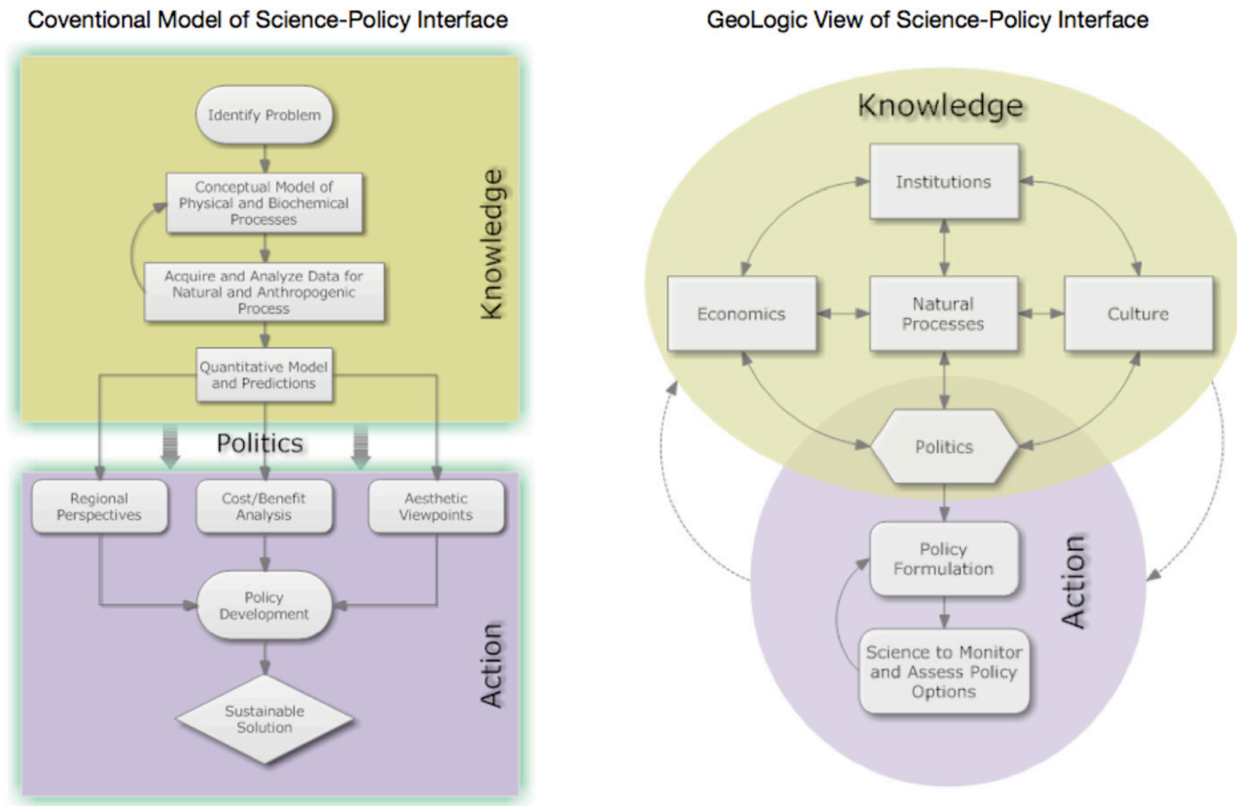


Figure 3-6: A comparison of conventional and "geo-logical" views of decision making and science-policy integration. The conventional view is based on a model of rational analysis that is linear and sequential and in which the boundary between science and policy is distinct. The "geo-logic" view is based on an iterative model of enquiry and knowledge generation that blends objective measures of nature with subjective values, goals and beliefs to inform and guide the decision-making process. Adapted from Figure 7.2 of Sarewitz (2000).

3.4 1. The Importance of Place

First and foremost, an earth systems approach is place-based. Place provides both the context and focus for scientific enquiry with the expectation that complex system processes will be manifest at different geographic scales and observed at varying levels of resolution. Processes that operate at global scales may not be evident at regional or local scales. The reverse is also true whereby the absence of a phenomena or process at a local scale is not necessarily taken as evidence that this process or phenomenon is nonexistent at regional or global scales.

This is a relevant perspective in terms of how problems are framed for purposes of risk assessment and policy analysis. The issue of climate change provides a particularly clear example of this principle. For communities situated in northern latitudes of Canada, the impacts of a changing climate are clearly evident and have tangible consequences in terms of environmental integrity, local economic vitality, and quality of life. However, for the majority of communities situated in more southerly latitudes, the impacts of climate change are not visible and have only indirect environmental and socio-economic consequences.

Furthermore, the physical characteristics of a place will vary as a function of geographic location and may not be generic enough to represent accurately with a single model of cause-effect relationships between natural and human systems. In most instances, the attributes of a landscape that are relevant in terms of vulnerability or risk may only become evident through the experience of living in a place long enough to know what to expect in terms of the likely impacts and consequences. For example, most loss estimation models are based on damage functions that relate the intensity of a particular hazard threat to the probability of damage for a specific building type or structure. While these models reference a large sampling of empirical and experimental observations, they do not necessarily take into account the influence of geographic setting and cultural norms of human settlement. As the process of planning and characteristics of the built environment vary from region to region, so too will the relationships between hazard intensity and damage potential. By not accounting for variations in the norms and physical characteristics of a particular place, there is potential for static models to either underestimate or overestimate the likely consequences of a hazard threat.

In addition to physical variability, the socio-economic characteristics of a landscape will also vary from place to place as a function of historical patterns of human settlement and resulting cultural norms. These variations, although subtle, can have a significant influence on the way in which hazard threats of comparable intensity manifest over the landscape and are framed for the purposes of risk assessment and planning. Individuals and communities that have the experience of living through the impacts of hazard events are more likely to be aware of potential threats and to take proactive measures that reduce their vulnerability to these events in the future.

The behavioural norms and modes of decision making that evolve from these experiences will influence negotiations over what constitutes a tolerable threshold of risk and the decisions on how to balance the need for mitigation with other policy imperatives. Since the characteristics of an individual landscape or community cannot be known in advance, it is critical to ensure that the approach and methods of risk assessment are flexible, capable of synthesizing both expert and tacit forms of knowledge about a particular place, and adaptable to the needs and operational requirements of a specific planning process.

3.4 2. Time as a Measure of Change

A second key characteristic of an earth systems approach is that complex systems are understood to be in a constant state of flux. Therefore, the characteristics and dynamics of these systems need to be assessed along a time continuum that encompasses conditions of the past, present, and future. Time is considered a measure of ongoing, irreversible change rather than a physical measure of variation or duration of a process. This represents a form of narrative logic, whereby interactions between individual components occur within a larger narrative or system that changes and evolves with the flow of time (Overton, 1994; Frodeman, 1995). In the case of geology, system changes can encompass millions of years. In the case of regional and global ecosystems, change can encompass several generations. In either case, there is an understanding that elements of the system can exhibit directional patterns of non-linear behaviour that interact and evolve as a function of space and time.

In some cases, existing spatial and temporal patterns of change are used to make inferences about past events, then tested and validated with historical data. In other cases, models are used to anticipate a likely sequence of events that might unfold in a futures context. Consider the familiar pattern of subsidence, inundation, and deposition of sandy sediments observed in coastal areas following an earthquake-tsunami event. The relationship between cause and effect is reasonably well known, and can be used to draw inferences about the origin of similar tsunami-related deposits in the geologic record that can be several thousand or million years old. Similarly, the number and periodicity of these deposits can be used to draw inferences about magnitude-frequency relationships between global earthquake-tsunami events and the probability that similar events might occur in the same geographic area at some point in the future. The ability to make sense of change across broad time horizons offers a unique and relevant perspective when considering the evolution of vulnerability and risk in complex human-natural systems. The same form of narrative logic underpins scenario-based models that are used to analyze complex interactions between human and natural systems over time.

3.4 3. Reconciling Complexity and Uncertainty

The third characteristic of an earth systems approach is its ability to reconcile complexity and uncertainty. As discussed in previous sections, issues of complexity and uncertainty in disaster risk management can be addressed in two very different ways. The conventional approach of rational analysis is rooted in the experimental sciences and involves a process of reducing the system into its component parts so that specific cause-effect relationships can be isolated, observed, and measured, thereby reducing complexity. The objective is to frame the problem so that uncertainty can be constrained and measured in a systematic way through predictive models that are substantiated by existing theories and scientific understanding. Though scientific methods will vary, models are most often based on some form of deductive reasoning, which is a mode of knowledge generation that attempts to validate or refine existing theories through a structured process of testing hypotheses against empirical observation and measurement. The rational planning approach is well-suited to structured problems of risk management that require answers to specific tactical questions about whether a hazard threat is likely to exceed accepted or regulatory thresholds of risk, and the strengths and weaknesses of mitigation alternatives. In contrast, integrated assessment and earth systems thinking involve a recursive spiral of enquiry that relies on a process of exploration, discovery, and interpretation to fill gaps in knowledge (a form of abductive reasoning), and a process of synthesis and analysis to derive general solutions to explain phenomena and system dynamics (Gahegan and Brodaric, 2002).

The construction of multiple working hypotheses represents a process of inductive reasoning that characterizes earth systems thinking, whereby spatial-temporal patterns and underlying system dynamics are inferred from specific observations and measures (Chamberlin, 1897). At this stage of the enquiry process, it is assumed that all hypotheses (narratives/scenarios) are viable and offer equally plausible explanations of observed features or phenomena for a specified place and time horizon. Integration occurs simultaneously and across various scales of observation for the purpose of constructing more general explanations of complex system behaviour and underlying cause-effect relationships. The resulting theories and models are then tested and validated using standard modes of deductive reasoning. Knowledge and understanding of the broader system are derived incrementally through an iterative process of interpretation, integration, and analysis (Gahegan and Brodaric, 2002). While an earth systems or geo-logic approach incorporates classic methods of deductive reasoning, it provides a more robust framework for studying complex system behaviour by acknowledging that there are limits to knowledge, and that change can only be understood in the broader continuum of space and time. In this way, it is aligned with and extends existing methods of integrated assessment (Jaeger, 1998; Rotmans and Van Asselt, 2000; van der Sluijs, 2002) and adaptive risk governance (Gregory *et al.*, 2006; Linkov *et al.*, 2006c; Renn, 2006a).

3.4 4. A Land Ethic for Decision Making

Another important characteristic of an earth systems approach is the recognition that natural systems are limited in their capability to accommodate and adapt to changes that are driven by the outcomes of human choice. The integrity of natural systems must therefore be recognized as a fundamental component shaping human choices, not shaped by them. Place-based planning is the process through which policy analysts integrate knowledge about human-natural systems to inform judgments of what might constitute a desirable future for a particular community or region. As such, it involves a process of decision making that must balance market rationality with social justice and environmental integrity (Friedmann, 1987).

Market rationality is based on the theory of economic utility. It is generally but not universally understood to grant precedence to

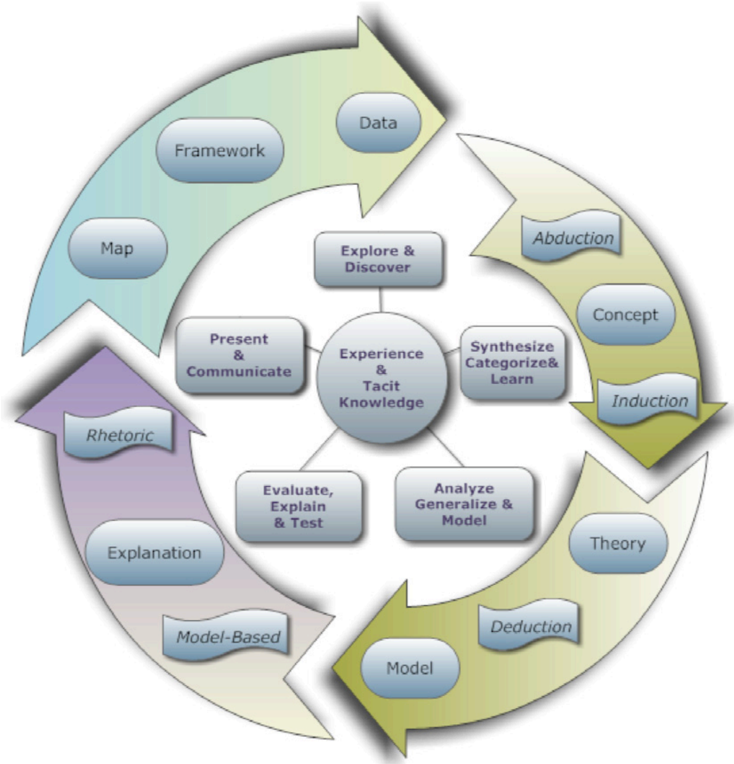


Figure 3-7: A generalized framework for scientific enquiry and knowledge generation based on an earth systems approach (from Gahegan and Brodaric, 2002). The framework integrates several different modes of reasoning into a recursive cycle of exploration, synthesis, analysis, evaluation and presentation.

individual rights over those of society. The proposition is that policy options (the means) ought to be negotiated on the basis of choices that optimize progress toward risk management objectives that reflect the goals of individuals and/or corporate entities. Utility is understood to be the basis of rational choice; effectiveness and efficiency are the preferred metrics for measuring progress toward or away from desired outcomes. In this mode of planning, the boundaries between science, policy, and society are distinct and do not necessarily overlap. They are loosely coupled through formal channels of communication whereby information, knowledge, and perspectives are transferred between the various actors at distinct stages in the planning process. The decision-making process emphasizes measures that balance system performance (utility) with a "willingness to pay." The influence of market forces on the decision-making process is often referred to as the "invisible hand of the market."

Social justice and environmental integrity are argued from the opposite viewpoint. They are based on principles of democratic choice (values and objectives) whereby socio-economic structures and shared interests of the commons are generally considered to take precedence over those of individuals or corporate entities. Decision based on these principles are based on the premise that "reason ought to be exercised on behalf of the group, so that collective interests might be properly formulated and pursued through appropriate actions," (Friedmann, 1987). Implicit in this doctrine is the notion that judgments of effectiveness and efficiency (utility) ought to be balanced with ethical judgments of fairness and intergenerational equity (Jaeger, 1998). In this arrangement, the boundaries between science, policy, and society are often overlapping. The decision-making process seeks to balance tensions between a willingness to pay and a willingness to accept.

In his classic work, *The Sand County Almanac*, Aldo Leopold introduced a set of principles intended to help guide the reconciliation of market rationality with principles of social justice and environmental integrity (Leopold, 1948). Leopold based his ideas on the premise of individuals cooperating with each other for the mutual benefit of all (the community ethic). On the basis of this principle, he advanced the proposition that interactions between individuals be enlarged to encompass non-human elements of the natural system, which he referred to collectively as "the land." He argued that economic well-being of the individual or corporate citizen could not be separated from the well-being of the overall environment. He concluded that "a land ethic, then, reflects the existence of an ecological conscience, and this in turn reflects a conviction of individual responsibility for the health of the land."

Ian McHarg's contributions in the field of landscape design affirmed core principles of the land ethic, and introduced a new suite of methods for spatially representing and visualizing multi-dimensional aspects of human-natural systems to support both land use and site planning (McHarg, 1992). His ideas and methods were validated through a series of large-scale spatial planning and community development projects in the United States, and are credited with laying the foundations for landscape design, place-based planning, and techniques of spatial representation and analysis. These theoretical and methodological contributions are also the foundation of modern Geographic Information Science (GIS) and associated technical systems that have evolved over the years to manage place-based information and knowledge.

The contributions of Leopold and McHarg are credited with setting the stage for the modern disciplines of resource conservation and sustainability science. Encapsulated as humans living in harmony with nature, current concepts of sustainable development have been formulated and advanced internationally through the 1987 World Commission on Environment and Development (Bruntland Report 1987), the 1992 Earth Summit in Rio de Janeiro, and the 2002 World Summit on Sustainable Development. One of the most widely cited definitions of sustainable development is the ability to meet the needs of the present without compromising the ability of future generations to meet their needs (World Commission on Environment and Development, 1987). Current guidelines and standards for disaster risk management also advocate a balance between market rationality, social justice and environmental integrity (CAN/CSA-Q850, 1997; AS/NZ 4360, 2004; CAN/CSA-Z1600, 2008; International Risk Governance Council, 2008; ISO 31000, 2008a).

Earth systems thinking embodies these underlying principles of resilience and sustainability. The approach has been successfully applied in the fields of ecological risk assessment and global environmental change—both of which involve the assessment of complex and uncertain future interactions between human and natural systems. However, an earth systems approach has yet to be adopted as an overarching framework for planning and decision making in the field of disaster risk reduction. This is a curious trend given the severity of recent disaster events in North America and Europe and the clear recognition of failure in terms of planning and policy development in the public domain (Light, 2005; Burby, 2006; Costanza et al., 2006; FEMA, 2006; U.S. 109th Congress, 2006). Numerous studies have identified this gap and have pointed to the need for methods and tools that provide a capability to negotiate thresholds of risk tolerance for a given geography and planning horizon, and to explore choices and consequences of risk management decisions through a blend of scenario modelling and decision analysis (Rotmans, 1998b; McDaniels and Thomas, 1999; Rotmans and Van Asselt, 2000; Renn, 2001; Folke *et al.*, 2002; Gregory, 2002; Gregory and Satterfield, 2002; Organization for Economic Co-operation and Development 2003; McDaniels and Gregory, 2004; Renn and Klinke, 2004; Rotmans, 2005; Renn, 2006a).

3.5 A Critique of Risk Assessment Methods

As part of this study, we have examined existing methods of risk assessment and their potential for use in support of disaster mitigation planning in Canada. In addition to background literature reviews, the study encompassed a critique of more than 20 risk assessment frameworks that are currently in use and that have been reported in the literature. Risk assessment frameworks were assessed in terms of their relevance to national disaster mitigation policies (NDMS), robustness of analytic and deliberative methods, and compliance with international standards and guidelines for risk management. In addition, the study assessed the strengths and weaknesses of these frameworks with respect to their capability to support integrated assessment and disaster mitigation planning in a Canadian context. Full results of this analysis are summarized below in Figure 3-8. See Appendix 2 for a synopsis of each risk assessment framework used in the analysis.

3.5 1. Analytical Frameworks

Analytic frameworks are used widely in support of legislated planning processes that require objective measures of vulnerability or risk to support decisions about conformance with regulatory standards, the expenditure of public resources for mitigation, and the transfer of liability for residual risk through insurance markets. The frameworks reviewed for this study were designed primarily for specialized modes of rational planning that utilize predictive cause-effect models to evaluate the

		1a hazard-risk, vulnerability, resilience	1b spatial extent & temporal horizon	2a hazard potential, damages, losses	2b hazard threats, level of concern	3a quantitative analysis & modelling	3b design, appraisal & evaluation
1	CAT	4.0	4.5	5.0	1.0	5.0	3.3
2	NDH	3.3	1.5	4.0	1.0	5.0	1.7
3	DRI	2.0	1.0	3.0	1.0	4.0	1.0
4	PDRA	2.3	2.5	3.0	4.0	0.0	2.7
5	EPSON	3.3	4.0	4.0	4.0	3.0	3.0
6	ARMONIA	3.7	4.0	4.0	3.0	3.0	4.0
7	GA	4.7	3.0	5.0	2.0	5.0	0.7
8	AGS	2.3	2.0	5.0	2.0	5.0	1.7
9	EMA	3.7	4.0	4.0	4.0	4.0	3.0
10	GNS	3.3	4.0	3.0	3.0	4.0	3.0
11	USRi	2.3	2.5	4.0	1.0	3.0	1.3
12	IDEA	3.0	3.0	4.0	1.0	4.0	1.3
13	ECLAC	2.7	3.0	2.0	1.0	4.0	0.0
14	GTZ	2.3	2.5	3.0	3.0	0.0	2.0
15	HAZUS-MH	4.0	4.5	5.0	3.0	5.0	3.7
16	LUPM	2.0	3.5	5.0	4.0	4.0	2.0
17	RVAT	2.3	3.5	2.0	3.0	0.0	2.0
18	SoVI	2.7	4.0	4.0	2.0	4.0	1.0
19	HIRV	3.3	2.5	4.0	4.0	1.0	3.3
20	CRM	3.7	5.0	5.0	3.0	5.0	2.0
21	EmerGeo	3.7	3.0	5.0	4.0	4.0	1.3

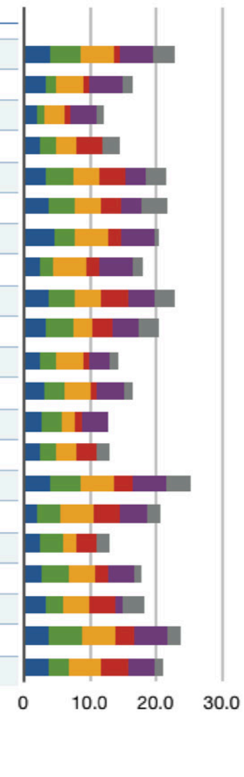


Figure 3-8: A critique of risk assessment frameworks evaluated in terms of their capability to support integrated assessment and risk-based planning in Canada.

effectiveness and efficiency of policy alternatives. The methods and tools focus attention primarily on the underlying natural processes that can trigger hazard events and the patterns of human settlement that may influence intrinsic patterns of vulnerability for a community or region. The emphasis is on estimating the impacts and likely consequences of physical threats in terms of hazard risk, vulnerability, and system resilience.

Analytic frameworks for disaster risk reduction are based on catastrophe models developed by the insurance/re-insurance industry to assist governments and corporate enterprise in managing financial risks associated with asset portfolios that are exposed to a variety of natural and anthropogenic hazards (CAT in Figure 3-8). Examples include RMS (Risk Management Solutions), EQECAT (ABS Consulting), and the AIR model. All of these frameworks have undergone rigorous peer review by the scientific and engineering communities, and are based on probabilistic models that have been calibrated by empirical observations and an extensive global database of historic disaster events. They represent the industry standard for quantitative assessment of hazard potential, expected damages, injuries, anticipated socio-economic losses, and return-on-mitigation investment.

In recent years, these proprietary frameworks have been modified to support national-level mitigation policies for risk management and disaster mitigation planning in the public domain. Examples include quantitative risk assessment methods developed by the Geoscience Australia Risk and Impact Analysis Program (GA), the Geoscience New Zealand Hazards and Society Program (GNS), the Urban Seismic Risk Index (USRi), and the European Union Applied Risk Mapping of Natural Hazards for Impact Assessment Program (ARMONIA). Perhaps the best known and most accessible of these public domain frameworks is HAZUS—a damage and loss estimation framework developed and maintained by the US Federal Emergency Management Agency (FEMA, 2004; Bostrom *et al.*, 2008). HAZUS is designed to assist local and regional agencies in developing risk management strategies that promote national-level disaster mitigation policies for floods, earthquakes, and hurricanes. As illustrated in Figure 3-9, the framework consists of three analytical components that model likely impacts and consequences for user-defined hazard threat scenarios.

The hazard potential component provides a capacity to model spatial variations in hazard intensity (water depth, ground shaking, wind velocity, etc.) for event scenarios in which the likelihood of occurrence can be specified by probabilistic or deterministic methods. Outputs of the hazard potential assessment are used to estimate physical impacts to the built environment (building structures, critical infrastructure and lifeline systems) using damage functions that are calibrated on the basis of empirical observation and geotechnical models. Resulting probabilities of damage provide a basis for modelling induced physical damages (fire, hazardous material facilities, debris), emergency shelter requirements, and anticipated socio-economic consequences including casualties, direct economic losses and resulting indirect impacts on income and employment.

Modified versions of the HAZUS methodology have been developed for use in other countries. Examples include EmerGeo, an application developed to support pre-event emergency planning in Canada, and the Riskscapes framework for risk-based planning in New Zealand. Third-party applications have also been developed to extend the analytical capabilities of HAZUS. These include the Land Use Portfolio Model (LUPM)—an application developed by the US Geological Survey to assist local and regional agencies in analyzing the financial risks and benefits of alternate mitigation strategies (Bernkopf *et al.*, 2001), and a new class of Community Resilience Models (CRM) that assess the capabilities of lifeline systems to respond and recover from the impacts of hazard threats (Bruneau *et al.*, 2003; Chang and Chamberlin, 2004; McDaniels *et al.*, 2008).

In addition to analytical frameworks that model impacts and consequences of hazard threats that are external to the system, there is another important class of quantitative risk assessment methods that are based on the UNDP "Pressure-Release" model of social vulnerability. These frameworks focus on the underlying causal structures of vulnerability and utilize multi-variable statistical techniques to identify intrinsic patterns of physical exposure or social disadvantage that may predispose a community or region to the negative impacts of a hazard

Figure 3-9: HAZUS model schema for hazard risk analysis

threat. One of the better-known examples in North America is the Hazards of Place Framework and the associated Social Vulnerability Index (SoVI; Cutter, 2001; Cutter *et al.*, 2003). Other examples include the European Spatial Planning Observation Network (EPSON) and the Applied Multi-Risk Mapping of Natural Hazards for Impact Assessment (ARMONIA) frameworks, both of which utilize a blend of quantitative methods to characterize patterns of vulnerability and risk in support of disaster mitigation planning at various scales across the European Union (Greiving *et al.*, 2006b; Klein *et al.*, 2006; Schmidt-Thomé, 2006; Margottini *et al.*, 2008).

The Sustainability Science framework (SUST) is one of the few analytical systems that explicitly situates the assessment of risk and vulnerability in the broader context of sustainability (Turner *et al.*, 2003). As illustrated in Figure 3-10, the framework accounts for both linear cause-effect relationships that are external to the system, and human-environmental factors that influence the resilience and adaptive capacity of the system over time.

The SUST framework uses conventional methods of hazard risk modelling to make evident the causal linkages explicit between underlying processes that trigger hazard events and their associated impacts and consequences. The analysis of vulnerability is anchored in the broader context of resilience planning and sustainability, using methods of integrated assessment to make evident the complexity and interconnectedness of human and natural systems. Finally, the SUST framework utilizes scenario-based models to explore complex system dynamics for the purpose of identifying existing and emerging patterns of societal risk.

Although distinct in terms of specific methods of analysis, all of the analytic frameworks critiqued in this study share the common goal of generating descriptive knowledge about complex risk environments for the purpose of reducing system uncertainty and informing the decision-making process. The emphasis is on producing an analytic outcome that is replicable and that reflects the best available knowledge about natural processes and their impacts on human systems. However, while such analytic frameworks may provide objective measures of risk, they do not necessarily address the question of what constitutes a tolerable threshold of safety or security, who or what ought to be safeguarded and at what cost, or how to manage risks that benefit some members of society while disadvantaging others.

3.5 2. Deliberative Frameworks

Deliberative frameworks are used widely in support of community-based planning processes in which there is insufficient knowledge or expertise to undertake a quantitative risk analysis, or in which the decision-making process is driven by value-based judgments of what constitutes a tolerable threshold of risk for a given community or region. Deliberative frameworks focus on articulating goals and management objectives, assessing hazard threats and likely consequences based on available information and knowledge, and evaluating trade-offs between policy choices and mitigation alternatives.

The Participatory Disaster Risk Assessment framework (PDRA) is one of several risk-based frameworks that have evolved over the last few decades. It was developed and has been used extensively by the International Federation of Red Cross and Red Crescent Societies and partners to "promote resilience at a community level by proactively implementing risk reduction measures that minimize potential for loss of

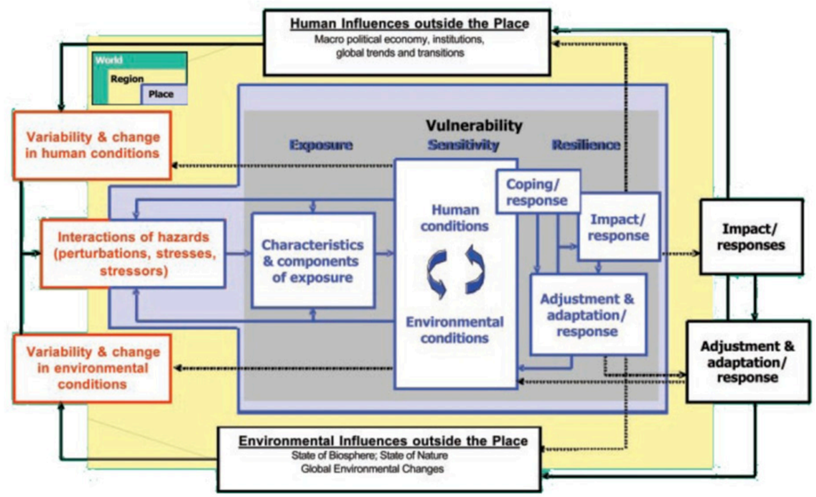


Figure 3-10: Schematic model of the Sustainability Science (SUST) framework for analyzing dimensions of hazard risk, vulnerability and system resilience.

life and disruption, while improving local, regional and international capacities for response and recovery to natural disasters," (International Federal of Red Cross and Red Crescent Societies, 1999, 2005, 2006a, b). Other examples include community-based planning frameworks developed by Emergency Management Australia (EMA, 2002), the Risk and Vulnerability Assessment Tool (RVAT) developed by the US National Oceanic and Atmospheric Administration (Flax *et al.*, 2002), and the Hazard Impact Risk and Vulnerability (HIRV) method developed for use in support of emergency management in a variety of planning contexts across Canada (Ferrier, 2001; Kuban and MacKenzie-Carey, 2001; BC Provincial Emergency Program, 2003; Ferrier and Haque, 2003; Pearce, 2003).

Common to most of these deliberative frameworks are design-based methods for establishing policy goals that promote the health and safety of vulnerable populations. The frameworks vary in terms of methods for generating knowledge about hazard threats and measuring capabilities for response and recovery. Some are based on semi-quantitative methods of risk appraisal, while others emphasize qualitative approaches to scenario planning. All are focused on generating knowledge about the risk environment to inform deliberations about how best to reduce vulnerabilities and increase overall disaster resilience. Knowledge is generated and structured through workshops and focus-group sessions using a broad range of participatory planning techniques including surveys, community-based mapping, and problem-tree analysis. While there is no formal analysis or evaluation of mitigation alternatives, results of the assessment process are used to guide risk management decisions in the broader context of community-based planning.

Capabilities-based planning (CBP) represents a complementary approach to more conventional modes of threat-based risk management. It acknowledges the complexity and uncertainty of modern risk environments by shifting the focus of assessment from specific hazard threats and vulnerabilities to the capabilities of human-natural systems to withstand, respond to and recover from a wide range of potential threats (Klein *et al.*, 2003; Caudle, 2005; Davis, 2005b; Kahan *et al.*, 2009). The objective of capabilities-based planning is to identify desirable future states of readiness that can be achieved through mitigation measures that promote overall disaster resilience within the limits of available resources. The US Department of Homeland Security and Defence Research and Development Canada have adopted capabilities-based planning as the preferred mode of all-hazard risk assessment for both strategic military operations and pre-event emergency planning.

The capabilities-based approach also lies at the heart of adaptation planning frameworks that have evolved in recent years to manage the impacts of a changing climate (Intergovernmental Panel on Climate Change, 2001; Folke *et al.*, 2002; Brooks, 2003; IISD, 2003; Lemmen and Warren, 2004; Pielke and Stohlgren, 2004; United Nations Development Program, 2004; Noble *et al.*, 2005; Brooks *et al.*, 2006; Linkov *et al.*, 2006c). Like capability-based planning, adaptation planning is a forward-looking process of planning and decision making that acknowledges the need to situate disaster mitigation in the broader context of sustainable land use planning and community development.

3.5 3. *Moving Beyond Partial Solutions*

Risk-based planning anticipates the actions required to promote the resilience of a community or region in ways that address social, economic, and environmental imperatives at multiple geographic scales and over variable time horizons (Godschalk et al., 1994; Burby, 1998; Mileti, 1999; Berke, 2002; ISDR, 2006). It involves the reconciliation of facts and values through analysis, and the transformation of knowledge into actionable mitigation strategies through a process of evaluation and deliberation.

For those working in the field of emergency management, risk-based planning and decision making are focused on a prioritization of actions required to ensure public safety, socio-economic security, and a capability to respond and recover to known or emerging hazard threats within the limits of available resources. For those working in the field of comprehensive land use planning, disaster mitigation involves the additional challenge of assessing how the dynamics of vulnerability and risk are likely to change in the future, and an evaluation of the actions required to promote longer-range policy goals of community resilience and sustainable development (Mileti and Gailus, 2005).

Each of the risk assessment frameworks reviewed in this study represents a best practice with respect to the context and purpose for which it was designed. However, they offer only partial solutions in terms of the needs and operational requirements for disaster mitigation planning in Canada. Most are focused on either the analytic or deliberative elements of the assessment process. Few, if any, of these existing best practices offer the capability to blend analysis and evaluation into an overall framework for integrated risk assessment. Core principles and guidelines for such a framework were outlined more than a decade ago in the US National Academy of Science study of risk assessment in the public domain (Stern and Fineberg, 1996), and are reflected in current national and international standards for risk governance (CAN/CSA-Q850, 1997; Australia/New Zealand Standards, 2006; International Risk Governance Council, 2008; ISO 31000, 2008b).

Developing a framework for risk-based planning in Canada could proceed in one of several ways. One approach is to import and adapt an existing method (limitations notwithstanding) that is considered "most suitable" for the intended purpose. Another approach is to invest in long-term research and development of new methods and tools that respond to specific needs and operational requirements of Canadian practitioners. A third approach involves the integration of existing best practice methods using a process of adaptive design.

The first of these options is perhaps the most straightforward. Results of background desktop studies might assist in the identification and selection of best practice methods and tools. The caution here is that imported methods designed for use in a different policy context and with different operational requirements in mind may not perform as expected. It is well documented that imported solutions can and often do fail if the full spectrum of issues required for successful implementation is not addressed up front, regardless of the promise they may hold (Gibbons *et al.*, 2000). These can include policy relevance, the adaptability of methods to specific operational requirements, and the availability of information or expertise needed to implement the method as intended.

Another approach might be to invest in a conventional cycle of research and development that responds directly to user needs and legislative or operational requirements here in Canada. The process generally begins with a formal scoping study (needs assessment), and progresses through the formulation and development of prototype methods and tools that are refined and updated through demonstration projects and associated longitudinal studies. While this approach has merit, there is an obvious danger of investing in the development of methods and tools that may already exist in other forms.

The third approach, and the one adopted for this study, is based on the principles of adaptive design and development. It too is framed by relevant policy goals and management objectives, and begins with a formal scoping study to determine requirements for risk assessment. However, it does so from the bottom up—through targeted case studies that provide an opportunity to research, test, and adapt existing methods on the ground, and in the context of actual planning and policy-development processes that make evident existing legislative and institutional needs and challenges.

Part II of this study introduces a framework for integrated assessment and risk-based planning that responds to the needs and operational requirements of emergency managers and land use planners working at local and regional scales in Canada. The framework builds on the theoretical foundations of rational planning and integrated assessment, and adopts an earth systems approach that is place-based and that acknowledges the need to integrate scientific analysis and the evaluation of policy alternatives as part of the decision-making process. The framework has evolved through an iterative process of design-based research and development that has been informed by a series of targeted case studies in southwest British Columbia. Results of this work are aligned with broader efforts to develop a national all-hazards risk assessment framework for Canada and support overall goals and objectives of both the national disaster risk reduction platform for Canada and the UN Hyogo Framework for Action.

Characteristics of a Risk-Based Planning Framework

The development of a risk-based planning framework for Canada requires the capability to blend analysis and evaluation in an integrated approach to risk assessment. Specifically, such a framework requires:

Analytic methods and tools to assess:

- Damage potential and likely consequences of natural hazard threats.
- Underlying causal structures and driving forces of vulnerability in human-natural systems.
- The capability of these systems to mitigate and/or adapt to changing conditions of vulnerability and risk over time.
- Deliberative methods and tools to assist in:
- Articulating the goals and intended outcomes of the planning process.
- Characterizing thresholds of tolerable risk that will be used to evaluate the strengths and weaknesses of mitigation alternatives.

Selecting an appropriate course of action that will balance the utility of mitigation investments with principles of social justice and environmental integrity.

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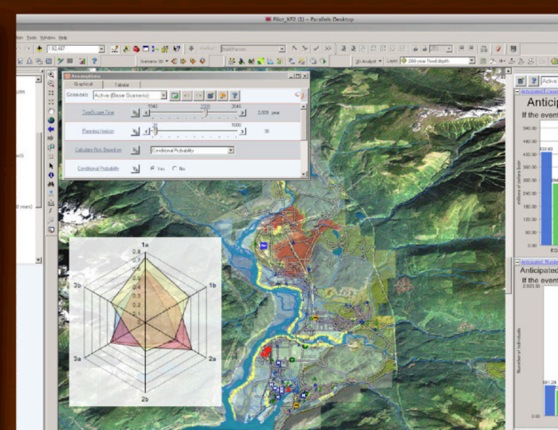
Chapter Four:

The Pathways Framework

"Given the pace and scale of the changes unfolding in the 21st century, it is becoming essential to step up efforts to complement conventional techniques of risk assessment based predominantly on past observations with forward-looking approaches that give greater weight to likely future developments. As recent advances in the assessment of risks related to climate change, earthquakes and nuclear power plants show, a range of methods are becoming available that help to strengthen the future focus, be they simulations, probabilistic calculations, straightforward projections or scenarios,"

(OECD, 2003).



4. The Pathways Framework

Practitioners need a common framework for risk-based planning—a framework that extends beyond conventional modes of rational analysis to encompass broader principles of integrated assessment and earth systems thinking (Stern and Fineberg, 1996; Burby, 1998; Mileti, 1999; Organization for Economic Co-operation and Development 2003; Greiving *et al.*, 2006a; Renn, 2006a; Pine, 2009). This is a relatively straightforward proposition in concept, but one that is both challenging and demanding in practice. Challenging in terms of finding the right balance between theory and the operational needs of risk management professionals, and demanding in terms of designing a framework that conforms with international standards and guidelines for risk assessment, that is aligned with national policy goals for disaster mitigation, and that can be implemented using available best practice methods and tools.

Objective measures of risk provide an understanding of the impacts and likely consequences of a hazard threat, but may have little meaning if separated from the social and behavioural context in which mitigation alternatives are considered and decisions are made (Stern and Fineberg, 1996; Sarewitz, 2000; Barnes, 2002; Renn, 2006a). Subjective measures of risk reflect value-based judgments of who and what are considered most vulnerable and why. However, value-based judgments of risk can be marginalized if they do not account for unforeseen or emerging hazard threats that can only be anticipated through expert understanding of system processes (Barnes, 2002; Stefanovic, 2003). Effective and accountable decision making thus requires both a common understanding of the risk environment and a clear expression of what constitutes a tolerable threshold of risk for any given community or region. From this perspective, risk is not simply a measure of system conditions, but rather the outcome of a comprehensive planning process through which mitigation alternatives are evaluated and decisions are made based on available knowledge and societal preferences.

This chapter describes an integrated system of people, processes, methods and tools for risk-based planning that we refer to collectively as the "Pathways" framework. As the name implies, the framework offers a way forward through the planning process, but is not prescriptive in terms of the specific steps or the methods and tools that may be required to address the needs of a particular community or region. Rather, it is a guide to assist planners and emergency managers in navigating the pathways between knowledge about the risk environment and decisions that may be required on the ground to mitigate potential negative impacts and promote community resilience.

Research and development of the Pathways framework have evolved over the past five years through an iterative process of design, testing, and validation that continues to strive for balance between the theory and practice of risk-based planning. The workflow component of the framework encompasses a suite of design-based methods that are used to assist members of the planning team in establishing overall context and focus for the planning process, and in negotiating tolerable thresholds of risk through ongoing deliberative dialogue. The analytic component of the framework encompasses a model for integrated assessment that provides a capability to measure changing conditions of risk over time and to evaluate mitigation alternatives using a combination of qualitative and quantitative methods. The model comprises a system of target criteria and indicators that utilize available knowledge about the risk environment to inform strategies that promote principles of disaster resilience. Target criteria are aligned with guiding principles established as part of the National Disaster Mitigation Strategy for Canada (Emergency Management Act for Canada, EMA: 2007) and the international Hyogo Framework for Action (United Nations, 2005). Pathways combines these deliberative and analytic functions into a structured framework for planning and decision making that builds on and conforms to national and international standards for risk management and emerging guidelines for risk governance in the public domain (Stern and Fineberg, 1996; CAN/CSA-Q850, 1997; IRGC, 2008; ISO 31000, 2008b).

The Pathways framework supports a process of place-based planning that brings together an interdisciplinary team of emergency managers, land use planners, scientists, engineers, policy analysts and members of the community—each contributing to a common understanding of the risk environment and the actions required to promote disaster resilience on the ground. The process is implemented using available best practice methods and tools for risk assessment and scenario-based planning. The deliberative component of the framework is facilitated through a set of structured workshops that incorporate design-based methods of participatory dialogue, community mapping, and expert solicitation to assist in visioning, problem formulation, risk appraisal, scenario planning, and the evaluation of mitigation alternatives. Analytic methods include HAZUS for damage and loss estimation, the USGS Land Use Portfolio Model (LUPM) for assessing financial risks, a modified version of the Social Vulnerability Index (SoVI) for assessing patterns of social disadvantage, and CommunityViz® for scenario-based modelling and multi-criteria analysis.

The blend of deliberative and analytic capabilities builds on the strengths of integrated assessment and rational analysis, offering an internally coherent framework for risk-based planning that incorporates broader principles of earth systems thinking. Pathways is intended for use in support of existing land use planning and emergency management functions at local and regional scales of operation, and contributes to broader efforts in the public sector to develop a national all-hazards risk assessment framework for Canada (Goudreau, 2009).

Goals for this chapter are to:

- Introduce the overall design and architecture of the Pathways framework.
- Describe the Pathways process for risk-based planning.
- Describe the Pathways model for integrated assessment—a system of target criteria and indicators that are used to develop a common understanding of the risk environment and to inform decisions about mitigation alternatives.
- Document best practice methods and tools that are used to implement the Pathways framework, and to assess the dimensions of vulnerability and risk, including innovations that are specific to this framework.
- Provide examples of how the Pathways framework might be used in support of land use planning and emergency management at local and regional scales of operation.

4.1 Overall Design and Architecture

The Pathways framework encompasses an integrated system of people, processes, methods and tools that function together in support of risk-based planning at the scale of a community or region. The framework is based on established guidelines for risk assessment and decision making in the public domain (Stern and Fineberg, 1996; Jaeger, 1998; Pahl-Wostl *et al.*, 2000; Pielke and Conant, 2002; van der Sluijs, 2002; Renn, 2006a; Rotmans, 2006). It also draws from an extensive body of literature on integrated assessment, scenario-based modelling, and decision analysis (Yoe and Orth, 1996; Corner *et al.*, 2001; Costa, 2001; Belton and Stewart, 2002; Yoe, 2002; Carmichael *et al.*, 2004; Swart *et al.*, 2004; Kiker *et al.*, 2005; Linkov *et al.*, 2006a; Robinson *et al.*, 2006; Sheppard, 2006; Wilson *et al.*, 2006). The framework has evolved in stages through a process of design-based research that has been informed by insights and experiences gained through a series of collaborative case studies on risk management and sustainable land use planning in southwest British Columbia (Design Centre for Sustainability, 2005; Journeay and Talwar, 2005; Girling *et al.*, 2006; Wein *et al.*, 2007).

Testing and validation of the framework was carried out in collaboration with the District Municipality of Squamish and the US Geological Survey (Journeay *et al.*, 2007a; Journeay *et al.*, 2007b; Talwar *et al.*, 2007; Wein *et al.*, 2007). The study was undertaken in support of a revision to the District's Official Community Plan (District Municipality of Squamish, 2007b). Results were used by District planning staff to inform policies on disaster mitigation and sustainable land use planning in the community, and by the Pathways development team to help guide ongoing refinements of methods and tools.

The cycle of research and development described in this chapter reflects lessons learned about the needs and operational requirements for risk-based planning in the context of a medium-sized community situated on the interface between a major urban centre and surrounding rural hinterland regions of southwest British Columbia. Our premise is that case-based research with practitioners who are actively managing risks associated with growth and development in areas exposed to natural hazards will lead to a better understanding of the needs and operational requirements for risk-based planning at local and regional scales, and to the discovery of general principles and solutions that can be applied in a broader context across Canada.

4.1 1. The Faces of Risk-Based Planning

At the heart of the Pathways framework are the people involved in a local or regional planning process. They include land use planners and emergency managers who are responsible for managing societal risks, members of the community who provide input on social values and policy preferences, domain experts who provide objective information and knowledge about the risk environment, and decision makers who are ultimately responsible for choosing a course of action that advances a range of policy objectives while mitigating potential negative impacts on people and the things they value.

Table 4-1 is a summary of use case profiles that have been created to help assess the needs and operational requirements for risk-based planning at a local or regional scale in Canada. Each of the profiles is defined by a combination of personas and use case descriptions that reflect insights and lessons learned through consultation with a broad cross-section of case study partners and project collaborators. The profiles represent hypothetical but plausible accounts of core planning functions, evaluation criteria and operational requirements that are likely to be of concern to those involved in a risk-based planning process.

4.1 1..1 Land Use Planners

Land use planners have a primary role in researching and developing public policy strategies to manage the allocation and use of land in ways that reconcile individual and collective rights and that balance competing

demands for economic vitality, social justice, quality of life, and environmental integrity. They are responsible for designing and facilitating the planning process in order to identify and develop policy recommendations that reflect the intent, values, and preferences of the community, and that are informed by relevant scientific and technical knowledge about human-natural systems and their interactions over time.

In the context of existing legislative frameworks such as land use bylaws and zoning ordinances (1–5 years), planners are often called on to assess whether proposed developments or land use activities are "safe for the use intended" and consistent with policies and regulations at multiple jurisdictional levels. Though responsible for informing day-to-day operational land use decisions, planners must also maintain a clear focus on the longer-term vision or intent of the community (5–30 years) — a vision that is developed through consultation, analysis, and the evaluation of policy alternatives. This involves a strategic assessment of current and anticipated future trends to direct the allocation of land in ways that will accommodate the varied needs and wants of a community while balancing thresholds for risk tolerance within the limits of available resources.

Primary needs and operational requirements for a land use planner are focused on issues of representation, judgments about scientific uncertainty, and perceptions about risk and political accountability. Planners need guidelines that help facilitate risk-based planning at local or regional scales using available best practice methods and tools. They also need access to relevant domain experts to assist in the risk assessment process and the interpretation of results. Finally, they need mechanisms to prioritize risk management options based on thresholds of risk tolerance that reflect community values and preferences and available knowledge about the risk environment.

4.1 1..2 Emergency Managers

Emergency managers have a primary role in developing strategic and operational plans that will protect people and critical assets in the event of an unexpected disaster. They are responsible for all aspects of pre-

The Faces of Risk-Based Planning

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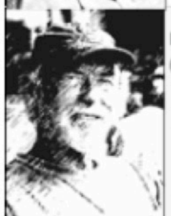
Profile	Planning Functions	Risk Decisions	Evaluation Criteria	Requirements
	**Land Use Planner** *(site/community; 1-30 yrs.)* - values, goals & preferences - development services - land use planning - policy analysis - zoning & bylaw compliance	▸ Who/what are vulnerable to hazards and in need of safeguarding ? ▸ Is the proposed structure/activity considered safe for the use intended and what is the basis for this judgment ? ▸ What are the likely impacts & consequences in the event of a disaster and who bears the consequence of the planning process? ▸ How to accommodate growth demands with available land base ? ▸ What constitutes a tolerable threshold of risk for the community ? ▸ Are there sufficient resources & capabilities to mitigate the threat ? ▸ How to balance trade-offs between competing policy demands ?	✓ Community Profile ✓ Hazard Exposure ✓ Public Safety ✓ Socioeconomic Security ✓ Social Equity	• Guidelines on how to carry out a community-level risk assessment using available best practice methods & tools • Access to relevant domain experts to assist in the risk assessment process and the interpretation of results. • Process of community engagement to identify who/what are considered vulnerable and in need of safeguarding, to prioritize principles that will guide the planning process, and to articulate specific goals and objectives that promote resilience. • A mechanism to prioritize risk management options
	**Emergency Manager** *(site/community; 0-5 yrs.)* - pre-event planning - preparedness - response - recovery	▸ Which hazards pose the greatest threat to the community ? ▸ Who/what are vulnerable to hazards and in need of safeguarding ? ▸ What are the likely impacts & consequences in the event of a disaster and who bears the consequence of the planning process? ▸ What are the capabilities to withstand, respond & recover ? ▸ What can be done in advance to reduce vulnerabilities and increase the resilience of people and community assets, and at what cost ? ▸ Are there sufficient resources & capabilities to mitigate the threat ? ▸ How to increase awareness and understanding of risk environment ?	✓ Hazard Exposure ✓ Public Safety ✓ Social Equity ✓ System Resilience	• Guidelines on how to carry out a community-level risk assessment using available best practice methods & tools • Maps showing the extent, magnitude and likelihood of specific hazard threats for a given location/area • A current inventory of vulnerable populations, community assets & critical infrastructure • A current assessment of capabilities to withstand, respond & recover from credible hazard threats • Situational awareness of risk environment to support response & recovery operations.
	**Community Member** *(home/business; 1-30 yrs.)* -values, goals & preferences -civic engagement -represents the interests of homeowners and businesses in the community.	▸ Which hazards pose the greatest threat to the community ? ▸ What are the likely impacts & consequences, and is it safe? ▸ Who/what are vulnerable to hazards and in need of safeguarding ? ▸ What are the capabilities to withstand, respond & recover ? ▸ What can be done in advance to reduce vulnerabilities and increase the resilience of people and community assets, and at what cost ? ▸ Who bears the consequences in the event of a disaster ? ▸ Are the risks and benefits equally distributed across the community ?	✓ Community Profile ✓ Hazard Exposure ✓ Public Safety ✓ Socioeconomic Security ✓ Social Equity	• Maps showing expected hazard severity for a given location/area • Information on potential impacts and consequences to assess the exposure and vulnerability of people and assets • Information to assist in mitigation of family/business assets and emergency preparedness.
	**Domain Expert/Risk Analyst** *(community/region; 1-100 yrs.)* - diagnose system conditions - measurement & observation - analyze cause-effect relations - scenario modelling - evaluation of uncertainty	▸ What are the driving forces and physical processes that trigger hazard events for a given area ? ▸ What is the extent, magnitude and likelihood of occurrence for these hazard events over variable time horizons ? ▸ What are the system conditions that determine intrinsic levels of vulnerability for people, physical structures and the environment ? ▸ Who/what are vulnerable to hazard threats ? ▸ What are the likely impacts & consequences should the event occur? ▸ How are future conditions of vulnerability and risk likely to evolve ?	✓ Hazard Potential ✓ Public Safety ✓ Socioeconomic Security ✓ System Resilience ✓ Social Equity ✓ Return on Investment	• Capability to characterize the risk environment in terms of system conditions, driving forces, vulnerabilities and social norms. • Capability to assess hazard threat(s) in terms of extent, magnitude and frequency of occurrence. • Capability to assess physical & social vulnerabilities over time • Capability to assess probable impacts and anticipated socioeconomic losses caused by hazard threat(s) • Capability to assess impacts of mitigation alternatives • Capability for cost-benefit analysis of mitigation alternatives • Capability to monitor changing conditions of vulnerability & risk.
	**Decision Maker** *(community/region; 0-50 yrs.)* - problem framing - authorization of process - allocation of resources - evaluation of policy alternatives - final judgment	▸ Which hazards pose the greatest threat to the community ? ▸ Who/what are vulnerable to hazards and in need of safeguarding ? ▸ How to balance the rights of individuals with those of the collective ? ▸ What is the most appropriate course of action that optimizes opportunities for growth and development while minimizing potential negative impacts on people and the things they value ? ▸ What are the costs & benefits of proposed mitigation options and how feasible are they given available resources ? ▸ Who bears the consequence of the decision making process ?	✓ Community Profile ✓ Hazard Exposure ✓ Public Safety ✓ Socioeconomic Security ✓ System Resilience ✓ Social Equity ✓ Return on Investment	• Guidelines on how to carry out a community-level risk assessment using available best practice methods & tools • Access to relevant domain experts to assist in the risk assessment process and the interpretation of results. • A mechanism to prioritize and rank risk management options using available knowledge and public input. • A mechanism to solicit public input to ensure the decision making process is transparent, equitable and reflects the needs and wants of the community

Table 4-1: A summary of use case profiles developed to guide overall design and evaluation of the Pathways framework. Profiles are defined in terms of planning functions, key risk decisions, evaluation criteria and operational requirements that have been identified through consultation with case study partners and project collaborators.

event planning to identify and prioritize hazard threats of concern, to prepare for hazard events that are considered most likely in the context of a particular place or planning horizon, and to provide coordination for the response to and recovery from the impacts and consequences of these events. Their primary focus is to determine who and what are

exposed to hazard threats in the immediate and short term (0–5 years); what are the likely impacts and consequences of a disaster event on people and critical assets; what are the capabilities to withstand, respond to and recover from disaster events; and how to increase awareness and understanding of the risk environment to encourage behaviours that minimize vulnerability and risk over time.

As with land use planners, emergency managers are focused primarily on judgments about scientific uncertainty, perceptions of risk, and political accountability. In support of both strategic and operational components of their mandate, they need access to relevant, timely and authoritative information about credible hazard risks for a given area (maps, tables, and reports), and require the ability to forecast likely impacts and consequences to assess mitigation requirements and to ensure critical thresholds of preparedness on an ongoing basis. They also need up-to-date and accurate inventories of vulnerable populations and critical assets of concern to enhance situational awareness during response and recovery operations.

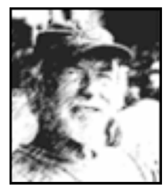
4.1 1..3 Community Members

Members of the community who are likely to be involved in a local risk-based planning process include residents and business owners and the networks of organized groups that represent the collective interests of these individuals at neighbourhood and regional levels. Their participation in the planning process is motivated by a desire to have input on land use and community planning decisions that will influence economic vitality, quality of life, or environmental integrity for existing and future conditions.

Community members represent a wide variety of social values and preferences that collectively influence perceptions of risk in a community, the identification of who and what are considered most vulnerable and in need of safeguarding, and expressions of intent that will guide the development of policy goals and objectives. Time frames of interest will vary with the planning process. They range from relatively short periods of time (1–5 years) that focus on site-specific issues with a potential for immediate impact, to longer periods of time (5–30 years) that address broader issues of socio-economic security, environmental integrity, and the distribution of risk in a community or region. Issues of concern include exposure and susceptibility to natural hazard threats; the impacts and consequences of a disaster event on individuals, families, and businesses in the community; and the capability to withstand, respond to and recover from unexpected disaster events.

Primary needs and operational requirements for a community member involved in a risk-based planning process are related to awareness, understanding, and agency. They include access to public domain information about the extent and severity of known hazard threats for a given area or region; a venue for considered dialogue and debate on values and preferences that will influence public policy on issues of safety, security, and equity: and a commitment from local authorities that community input will be considered in establishing thresholds of risk tolerance and in choosing a course of action for moving forward.

4.1 1..4 Domain Experts



Domain experts are called upon to provide insights on the causes and driving forces of natural hazard processes, and to diagnose the likely impacts and consequences of these events on society and the environment. They can include individuals from public, private, and academic sectors with a theoretical background and expertise in the physical sciences, engineering, the social sciences, or humanities. Unlike planners and members of the general public, domain experts are focused primarily on the generation of knowledge for the purpose of refining or expanding an understanding of human-natural systems and how they work. They have a primary role in identifying existing and emerging societal risk, and in assessing the implications of these risks to inform planning and policy development (analysis and evaluation).

In the context of the physical sciences and engineering, time horizons of interest will vary depending on the nature of the hazard threat. They can range from near real-time monitoring of natural or anthropogenic processes (severe weather, floods, hurricanes, etc.) that have a potential to trigger hazard events over relatively short time intervals (0–50 years) to theoretical or computational modelling of larger-scale processes (earthquakes, landslides, global climate change, etc.) that have a potential to trigger hazard events over geologic time frames of decades and centuries (100–10,000 years). In the context of the social sciences and humanities, the focus is on historical trends and existing conditions that may shed light on intrinsic patterns of vulnerability, and the adaptive capabilities of individuals to withstand, respond to and recover from disaster events.

As the creators of new information and knowledge about the risk environment, domain experts are primarily concerned about issues of complexity and uncertainty. They require an internally consistent set of protocols to measure and describe system conditions and driving forces of risk in the environment, and a corresponding set of methods and tools that can be used to analyze hazard potential, the impacts and consequences of credible hazard events, and to evaluate both single and multi-hazard event risk scenarios over time horizons of interest to the planning process. In addition, they need methods and tools to assist in communicating the results of their assessments in ways that make evident scientific uncertainties and underlying assumptions about system behaviour.

4.1 1..5 Decision Makers

Final judgment on the most appropriate course of action rests with those who are either appointed or elected to manage societal risks on behalf of the communities and constituents they represent, and to whom they are ultimately accountable. Decision makers can include regulators who must sift through available information and knowledge to determine whether a proposed course of action meets established guidelines for safety and security; municipal councillors and regional directors who must choose a path forward that balances policy objectives with available knowledge and financial resources; and representatives of the court who must render judgments in cases where decisions can not otherwise be negotiated.

Decision makers are tasked with an obligation to resolve conflicts between human wants and needs for the purpose of enabling action and the achievement of management goals and objectives. However, they share the concerns of planners, domain experts, and members of the general public over issues of inclusiveness, representation, judgments of scientific uncertainty, and political accountability. Like planners, they rely on formal guidelines to establish a policy framework that will support a structured decision-making process that is effective, transparent, fair, and that reflects the needs and wants of the community. Decision makers need access to domain experts to verify knowledge claims about scientific uncertainty, and need mechanisms to help prioritize and rank risk management options that reflect available knowledge about the risk environment and public input about what is considered most vulnerable and in need of safeguarding.

4.1 2. Conformance with Established Standards and Guidelines for Risk Assessment

The process of risk-based planning is a collaborative and interdisciplinary effort that involves a balancing of facts, values and preferences. Facts about the risk environment and how it works are derived from observation, measurement, and analysis Social values and preferences are discovered through deliberation; they reflect the vision and intent of a community, and embody the principles and goals that will guide the decision-making process. In most cases, however, there are limits to available knowledge about the risk environment, and competing views on how best to manage future growth and development. Both have implications with respect to how risk decisions are framed and analyzed, and how changing patterns of vulnerability and risk are managed on behalf of society. The Pathways framework is founded on underlying principles of integrated assessment and place-based planning outlined in Chapter III. It builds on and is aligned with national and international standards for risk assessment and emerging guidelines for risk governance in the public domain.

Standard protocols for disaster risk management (CAN/CSA-Q850; AS/NZ 4360; ISO 31000) situate the process of risk assessment in the broader context of a rational planning cycle that involves ongoing communication and consultation with relevant stakeholders and decision makers (see Figure 4-1a). By definition, risk assessment is a planning

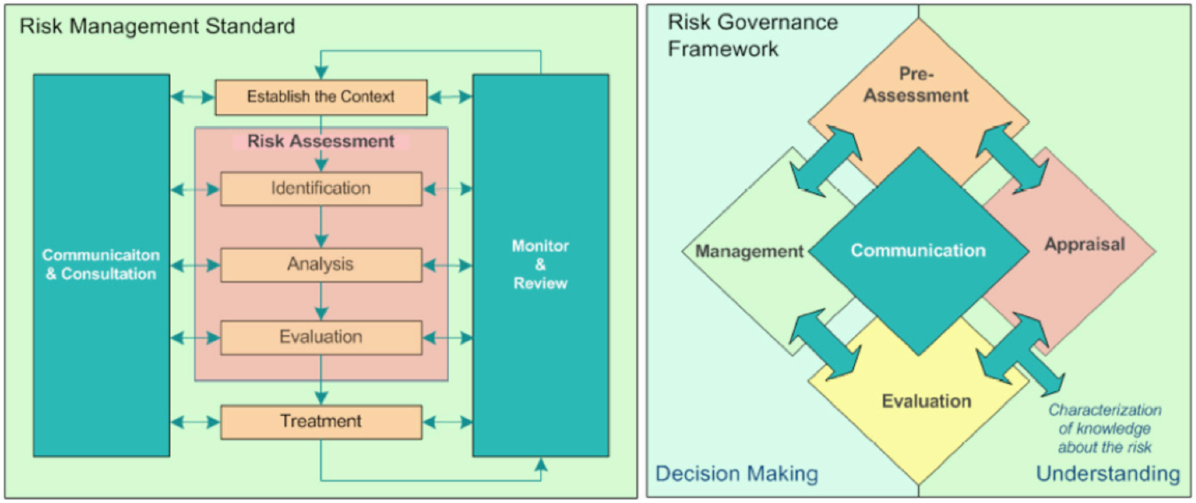


Figure 4-1: A comparison of (a) international standards for risk management (CAN/CSA-Q850; AS/NZ 4360; ISO 31000), and (b) recommended guidelines for risk governance (Renn, 2006a; International Risk Governance Council, 2008; Renn and Walker, 2008).

process that encompasses the identification, analysis, and evaluation of risks posed by existing or emerging hazard threats. It is based on available knowledge, empirical observation, or analytic modelling of cause-effect relationships. The scope and focus of the risk assessment process is determined by geographic or legislative context and by specific policy goals and management objectives that are determined at the outset of the process. Outputs are used to evaluate the consequences of policy alternatives and to select mitigation alternatives that optimize principles of effectiveness and efficiency. Effectiveness of the risk management process is generally measured in terms of physical protection, public safety, and economic security. Efficiency is generally measured in terms of costs, benefits, and the expected financial return on mitigation investments. Knowledge gained through the risk management process is used to guide the implementation of mitigation measures and to monitor changing dynamics of risk over time. Although represented as a linear process of rational planning in the ISO standard (Figure 4-1a), risk assessment is generally understood by practitioners to be an iterative cycle of analysis and evaluation that evolves as human-natural systems change and as new hazard threats become evident.

The International Risk Governance Council takes a more holistic view of risk assessment and disaster mitigation (IRGC, 2008). It defines risk governance to be a strategic planning process that encompasses "the broader institutional framework of analysis and deliberation through which dimensions of vulnerability and risk are assessed, authority is exercised, and actions are taken on the ground to promote disaster resilience," (Renn, 2006a; IRGC, 2008). The IRGC framework extends ISO operational standards for risk management by integrating science and value-based measures of risk, and by including principles of equity and resilience in the evaluation of mitigation alternatives. It also incorporates well-established guidelines for integrated assessment and participatory planning that include methods of scenario modelling and structured decision analysis (European Science Foundation, 2002; Antunes *et al.*, 2006). As illustrated in Figure 4-1b, the IRGC framework makes a distinction between knowledge and understanding about risk on the one hand, and judgments about what may constitute a tolerable threshold of risk for a given community or region on the other. Tolerable risks are those that can be reduced as low as reasonably practicable with available resources to achieve organizational objectives (Bouder et al., 2007).

4.1 2..1 Conceptual Framing

The Pathways framework incorporates ISO operational standards for risk assessment, and extends the scope of IRGC strategic planning and governance guidelines for risk-based planning in several important ways. First, it situates risk assessment in the broader context of a comprehensive planning process that involves a consideration of both land use and emergency management functions. Land use planning seeks to balance a range of policy objectives that directly influence the location, form and function of human settlements and their vulnerability to a range of natural and anthropogenic hazards. Emergency management, on the other hand, seeks to optimize the safety and security of human settlements through pre-event planning and the development of operational systems that increase the capabilities of people, places, and community assets to withstand, respond to and recover from the impacts of a disaster event. The Pathways framework combines these two functions into an integrated system that bridges the gap between conventional land use planning and emergency management.

Second, the Pathways framework adopts an earth systems approach to risk assessment by situating the analysis and evaluation of risk in the context of a changing landscape in which vulnerability is influenced both by established patterns of settlement and by legislative and regulatory policies that direct future patterns of growth and development. This has the effect of shifting the focus of risk assessment from a static analysis of impacts and consequences to an exploration of the driving forces and interactions between natural and human systems that will determine evolving conditions of vulnerability and resilience over time.

Third, it extends the scope of conventional risk communication to include the exchange of empirical and normative information through discussion and dialogue, the co-generation of knowledge through debate and social learning, and the evaluation of policy choices through deliberation and collaborative scenario-based modelling (Jaeger, 1998; Rotmans, 1998a; van Asselt and Rotmans, 1999; Pahl-Wostl *et al.*, 2000; Rotmans and Van Asselt, 2000; van Asselt and Rotmans, 2002; van der Sluijs, 2002; Turner *et al.*, 2003).

Finally, the framework incorporates formal protocols of decision making that address issues of fairness, transparency, and accountability (Ostrom, 1991; Ostrom *et al.*, 1994). As summarized in Table 4-2, these are standard policy guidelines that are used widely in the regulation of human and ecological risks to ensure transparency and public accountability (Bouder *et al.*, 2007; Fairman, 2007).

4.1 2..2 An Overview of the Pathways Process

A process map of the Pathways framework is illustrated in Figure 4-2. The map quadrants encompass the overall landscape of science-policy integration described in Chapter III (see Figure 3-1). They also reflect

Rule Type	Explication	Range of Key Types	Characteristic Trends
Boundary	Who is counted as a player?	Technocratic/participative	More participative
Scope	What is managed and what can be decided?	Broad/narrow	Extension of scope
Position	What is the hierarchy of the players?	Single organization/ multi-organization	More multi-organizations
Information	Who is entitled to know what from whom?	Open/closed	More open
Authority and procedure	Under what conditions must decision be made?	Formal/informal	More formal
Preference merging	How are individual preferences aggregated into collective decisions?	Consensus (integration)/ conflict (aggregation)	More conflict

Source: Royal Society (1992), p149

Table 4-2: Protocols for risk-based planning and decision making in the public domain (Ostrom, 1991; Ostrom et al., 1994; Fairman, 2007).

the four principal stages of comprehensive planning outlined in the ISO standard for risk management and the IRGC guideline for risk governance. The first two quadrants on the right-hand side of the diagram represent the domain of knowledge generation through which value-based judgements and scientific theory are combined to develop a common understanding of the risk environment. The two quadrants at the bottom of the diagram represent the domains of analysis and evaluation through which this understanding is transformed into actionable mitigation strategies that advance policy goals and objectives while minimizing negative impacts on people and critical assets. The two quadrants on the left hand side of the diagram represent the domain of judgment and decision making through which mitigation choices are made and acted on to balance trade-offs between policies that enhance disaster resilience and those that address broader issues of sustainable development. Finally, the two quadrants at the top of the diagram represent the domain of adaptive management through which

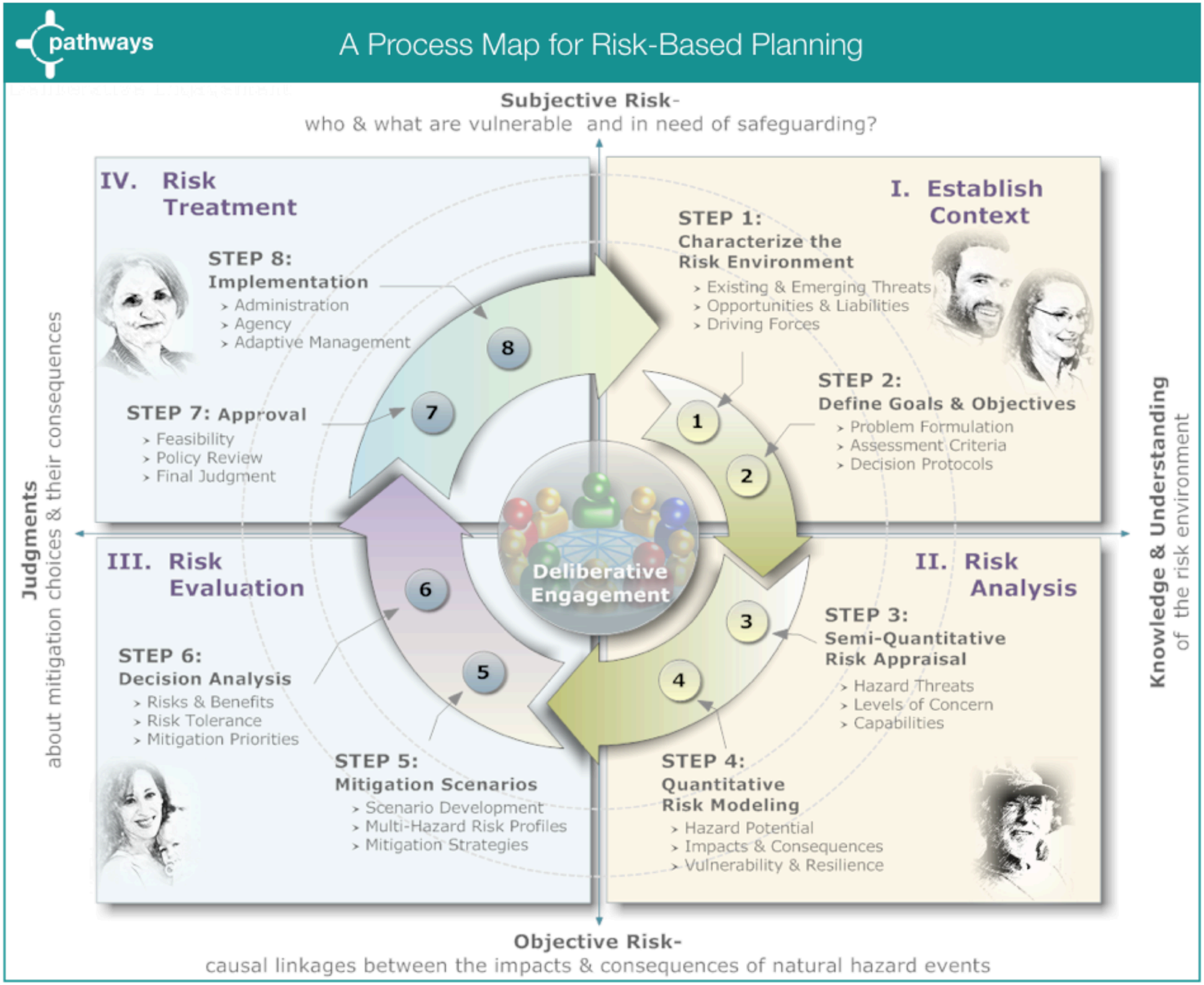


Figure 4-2: An overview map of the Pathways process for risk-based planning. The process conforms to standard protocols for risk management and incorporates recommended guidelines for risk governance (see Figure 4-1).

mitigation measures are implemented and monitored to assess changing conditions of vulnerability and societal risk over time. The process is recursive and draws on principles of adaptive management to inform each cycle of planning and decision making.

The Pathways process is navigated by first establishing the overall context and focus in terms of system conditions and goals or objectives, then progressing in a clockwise direction through analysis of the risk environment, the evaluation of mitigation alternatives, and the implementation of associated risk treatment measures. Each stage comprises a sequence of steps that provide overall guidance to the planning process. Individual steps are defined by a series of tasks and activities that can be adapted to address the needs and operational requirements of a particular place or planning process. In some instances, this may involve minor revisions to allow integration with existing land use planning and emergency management functions. In other instances, it may require modification or adaptation of the framework to accommodate available knowledge and resources, or to address a wider spectrum of natural and anthropogenic hazards that are relevant to a particular community or region (landslides, interface fire, tsunami, etc.).

4.1 3. Alignment with Canada's Platform for Disaster Risk Reduction

An important contribution of the Pathways framework is the development of a model for integrated risk assessment that utilizes a hybrid system of target criteria and indicators. This model helps transform knowledge about the risk environment into actionable mitigation strategies that promote the resilience of communities and regions to natural hazard threats. As illustrated in Figure 4-3, the model is aligned with and contributes to Canada's National Platform for Disaster Risk Reduction, and provides a capability to incorporate structured methods of risk assessment and disaster mitigation planning into ongoing land use and emergency management operations at local and regional scales.

4.1 3..1 Science-Policy Integration

Canada's National Platform for Disaster Risk Reduction is an informal governance structure that brings together an assembly of public, private, and academic stakeholders with a shared interest in developing principles, policies, and guidelines that promote the safety and security of Canadians, and that build the resilience of individual communities and regions to existing and emerging societal threats. Hazard threats of concern include the impacts and consequences of rapid onset disasters triggered by natural processes such as earthquakes, floods, and landslides, as well as evolving conditions of vulnerability and risk brought on by political instability and the impacts of a changing climate.

Guiding principles and policies of the platform are laid out in the National Disaster Mitigation Strategy (NDMS) and the Emergency Management Act for Canada, of which it is a part. The strategy is focused on the goal of protecting lives and maintaining resilient and sustainable communities by fostering disaster risk reduction as a way of life. The corresponding principles and policy guidelines are to preserve life, safeguard communities, ensure fairness, and promote disaster resilience through sustainable development.

Broader strategic goals of the national platform include the integration of disaster risk reduction into evolving policies for climate change and sustainable development; the strengthening of institutions, mechanisms and capacities that increase resilience to hazard threats; and the incorporation of risk reduction approaches into the implementation of emergency preparedness, response and recovery programs. A key element of this national strategy involves the development of "a coordinated system of disaster risk indicators at national and sub-national scales that will enable decision makers to assess the impact of disasters on social, economic, and environmental conditions, and to disseminate the results to planners, policy makers, and populations at risk," (United Nations, 2005; Birkmann, 2006).

Efforts to develop a national all-hazards risk assessment framework are coordinated through the Public Security Technical Program (PSTP)—a research and development program administered by Defence Research and Development Canada (DRDC) and Public Safety Canada as part of the Centre for Security Sciences (CSS). The mission of CSS is to collaborate with private, public, and academic sector partners to develop policies and deliver science and technology solutions that advance national capabilities to plan, prepare for, respond to and recover from high-consequence disaster events. CSS has adopted a scenario-based approach to risk assessment that utilizes a structured system of models and tools to characterize the risk environment, to assess the capabilities for response and recovery, and to evaluate the strengths and weaknesses of mitigation strategies that promote disaster resilience (Goudreau, 2009; Hales and Race, 2010). The Pathways model for integrated risk assessment is aligned with and contributes to these broader efforts by establishing a system of target criteria and indicators that can be used for scenario-based planning at local and regional scales.

4.1 3..2 An Overview of the Pathways Model

Target criteria and system indicators that define the Pathways model were selected on the basis of policy relevance, alignment with broader principles of the National Disaster Mitigation Strategy (NDMS), and their capacity to characterize the risk environment with respect to existing and future levels of vulnerability and risk. The model conforms to guidelines established in the literature for structured decision making and scenario-based modelling (Jaeger, 1998; Rotmans and Van Asselt, 2000; Durbach and Stewart, 2003a; Turner *et al*., 2003; Swart *et al*., 2004; Verburg *et al*., 2004; Alcamo *et al*., 2006; Montibeller *et al*., 2006). It also builds on the 10 core "Bellagio Principles of Integrated Assessment" (Hardi and Zdan, 1997; Phillips, 2003).

As illustrated in Figure 4-3, the Pathways model is structured around a set of six high-level assessment criteria that offer insight into overall characteristics of the risk environment. These include descriptive criteria that provide situational awareness for people and critical assets in the community (community profile), and five additional target criteria that are used to guide the overall assessment process. Target criteria are defined by a system of indicators that measure dimensions of hazard potential, public safety, socio-economic security, system functionality, and social equity).

Community profile indicators describe and track changing patterns of human settlement and physical characteristics of the built environment. They provide a snapshot of population and demographic variables that define the human and socio-economic dimensions of the community. They also provide an accounting of key physical assets in the built environment including general building stock and contents (residential and commercial/industrial), essential facilities (hospitals, police, fire, schools, etc.), critical high-potential loss facilities (dams, levees, etc.), transportation networks (highway, rail, air, and water), and major utility systems (water, energy, communications, etc.).

Hazard exposure indicators measure the severity of anticipated hazard event scenarios for a given community or region in terms of areas impacted, intensity (ground shaking, water depths, wind speeds, etc.), and likelihood of occurrence over a specified time frame (probability). They also provide a measure of hazard magnitude in terms of physical

The 10 Bellagio Principles

	Principles	Intent
1	Guiding Vision and Goals	develop a clear vision of sustainable development and the goals to define that vision
2	Holistic Perspective	consider the well-being of social, ecological and economic subsystems in monetary and non-monetary terms
3	Essential Elements	consider equity and disparity issues, ecological conditions, economic development and other non-market activities contributing to human and social well-being
4	Adequate Scope	adopt a time horizon long enough to capture both human and ecological time scales; and that builds on historic conditions and current trends to anticipate future conditions.
5	Practical Focus	generate am explicit set of categories and an organizing framework to link vision and goals to indicators and assessment criteria
6	Openness	make methods and data available to all; make explicit all judgments and assumptions in data and interpretations.
7	Effective Communication	ensure a design that is relevant and addresses the needs of its users; draw from indicators and other tools to engage decision makers
8	Broad Participation	provide avenues for inclusive representation and participation
9	Ongoing Assessment	ensure a capacity for repeated measurement; adjust goals and framework as new insights are gained
10	Institutional Capacity	clearly assign responsibilities and support the capacity for assessment at local scales.

Table 4-3: The 10 "Bellagio Principles of Integrated Assessment." Developed by an interdisciplinary group of researchers and practitioners at a meeting in Bellagio, Italy to guide the development of indicator systems that bridge gaps between the science and policy of sustainable development. Adapted from (Hardi and Zdan, 1997; Phillips, 2003).

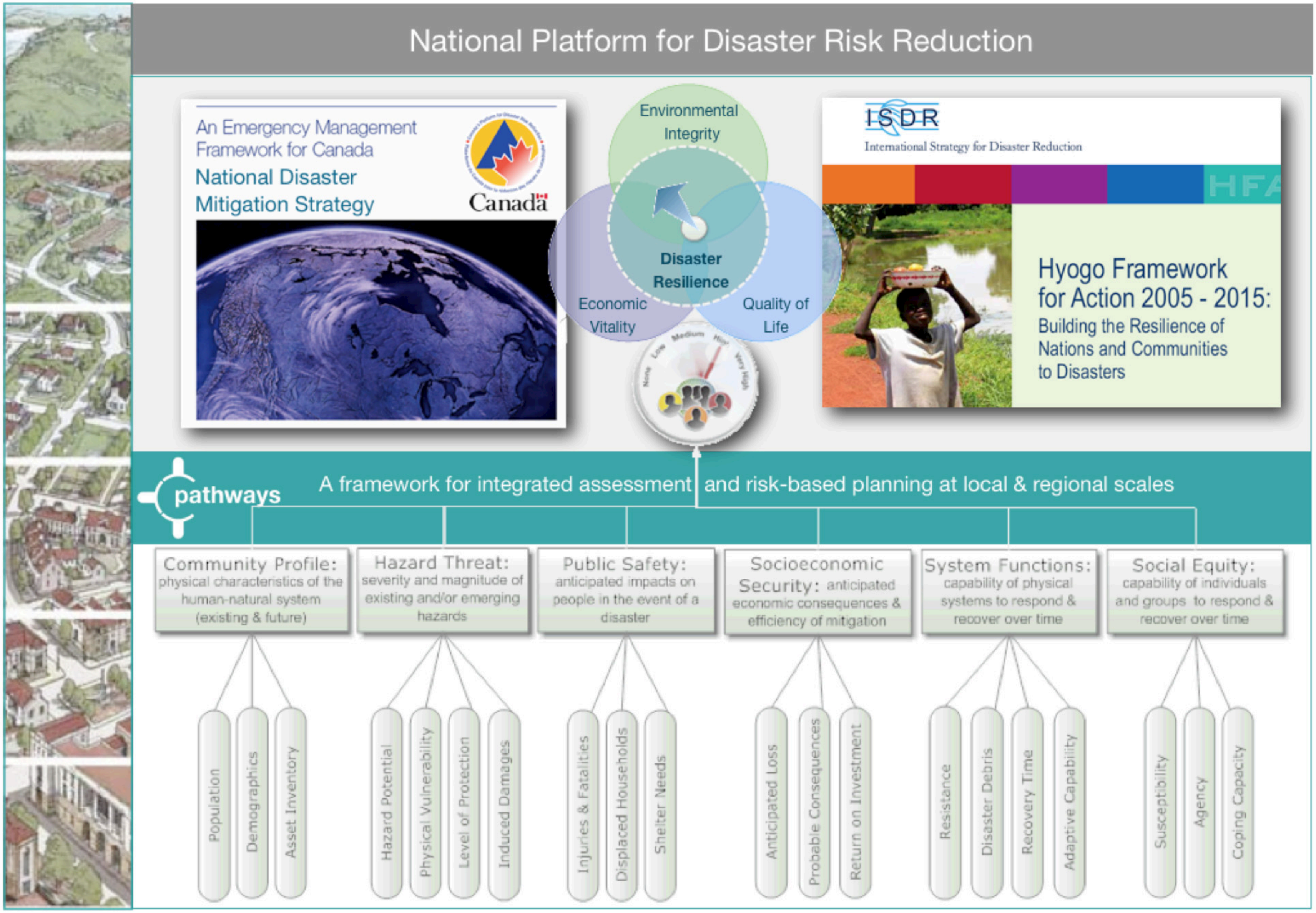


Figure 4-3: The integration of top-down policy goals and objectives of the National Disaster Mitigation Strategy for Canada (EMA c.15/E-4.56; Public Safety and Emergency Preparedness Canada, 2007) with bottom-up target criteria and indicators comprising the Pathways model for integrated risk assessment.

vulnerability and the efficacy of existing mitigation measures in a given community or region.

Public safety indicators are focused on the human impacts should an unexpected disaster event occur. They track the spatial distribution, number, and severity of injuries that are likely to require medical care or hospitalization, and the number of expected fatalities. They also provide an assessment of the numbers of households that would be displaced in the event of a disaster, and the numbers of people who are likely to seek emergency shelter based on need and social norms.

Indicators of socio-economic security provide insights on the anticipated direct and indirect losses that are likely to result from a disaster event (capital stock and income-related losses), the risks posed by these losses over time frames of interest to the planning process (probable consequences), and expected financial returns on investments made to mitigate the impacts of disaster events over time (resource efficiency).

System functionality indicators describe and track the capabilities of critical infrastructure and related lifeline services to withstand, respond to and recover from the impacts of a disaster event over time. They account for induced damages that are likely to be triggered by a disaster event, the resulting amount of debris generated that will need to be removed and managed, the time required to restore these services in the days, months and years following a disaster event, and overall adaptive capabilities.

Finally, indicators of social equity provide insights on the human dimensions of risk. They measure and track underlying system conditions that are likely to influence changing patterns of vulnerability in a community or region, and determine who is likely to bear the consequences of an unexpected disaster event and the capabilities of individuals and groups to respond to and recover from the impacts of these events over time.

Alignment of the Pathways model with top-down principles and goals of the National Disaster Mitigation Strategy provides a capability to evaluate the strengths and weaknesses of mitigation strategies aimed at promoting disaster resilience, and to compare the dimensions of vulnerability and risk in a systematic way at local and regional scales across Canada. Flexibility in the choice of target criteria and indicators at the community level ensures that implementation of the framework is a bottom-up process that reflects essential characteristics of the risk environment for a given area and the specific needs and operational requirements of the local planning process.

4.1 4. Integration of Best Practice Methods and Tools

Spatial decision-support systems are designed for addressing place-based problems that cannot be solved sequentially or in a unique way. Unlike expert systems that are geared toward optimizing decisions based on rational analysis, spatial decision-support systems are based on methods of integrated assessment and scenario modelling, both of which shift the focus of planning from static predictions about cause-effect relationships to a more interactive exploration of policy choices and their likely consequences (Carver, 1991; Jankowski, 1995; Malczewski, 1999; Jankowski and Nyerges, 2001a; Jankowski and Nyerges, 2001b; Druzdzel and Flynn, 2002). Decision-support systems are closely related to Public Participation Geographic Information Systems (PPGIS) in that they enable deliberation in a collaborative planning process using maps and analytical models to simulate system behaviour and to solve complex problems of choice among a set of alternatives (Carver, 2001; Balram and Dragicevic, 2006). The Pathways framework is implemented using a combination of these analytic and deliberative methods.

4.1 4..1 Adapting Available Best Practices

As illustrated in Figure 4-4, analytic and deliberative elements of the Pathways framework are incorporated into an operational spatial decision-support system using an integrated suite of commercial and freely available methods and tools. The initial context setting stage of the planning process requires an ability to compile and synthesize information about natural, physical, and human dimensions of the risk environment, and is facilitated using industry standard Geographic Information Systems (ArcGIS™), and specialized data management applications developed by the US Federal Emergency Management

Figure 4-4: A schematic representation of the Pathways framework, implemented as a spatial decision-support system using available best practice methods and tools.

Agency (FEMA) and Statistics Canada (CDMS and Beyond 20/20™).

During the analysis phase of the process, expert solicitation and numeric models are used to measure the impacts and consequences of existing and emerging hazard threats, and to explore the dynamics of underlying system processes that drive changing conditions of vulnerability and risk over time. A Delphi-based method is used to support semi-quantitative appraisal of the risk environment based on available domain expertise. Quantitative risk modelling is facilitated using an adapted version of HAZUS—a public domain catastrophic loss estimation methodology developed by the US Federal Emergency Management Agency (FEMA) to support risk mitigation and planning of earthquake, flood, and extreme hurricane wind hazards. Although focused on natural hazards, the Pathways framework is designed so that additional analytic models can be incorporated into the system to assess other hazard threats that may be relevant to the planning process (fire, hazardous spills, etc.). Outputs of these models are used to evaluate indicators of hazard potential, physical vulnerability, system resilience, and anticipated loss. Financial risk and expected returns on mitigation investments can be modelled using a variety of benefit-cost models including the USGS Land Use Portfolio Model (LUPM) and FEMA's Benefit-Cost Tool (BCA). Spatial patterns of social vulnerability are modeled using SoVI—a well-known assessment framework that is implemented using available geo-statistical and multivariate modelling tools.

4.1 4..2 Methodological Innovations

Most planning support systems are focused on either the analytic or deliberative elements of the assessment process. An important innovation of the Pathways framework is the coupling of design-based methods with model-based methods; the former capture social values and intent with respect to a desired future state of disaster resilience, and the latter provide a capability to analyze and explore the risk environment and to evaluate the likely consequences of policy choices over time. The integration of deliberative and analytical dimensions of the planning process is facilitated through the use of risk scenarios that are developed using CommunityViz®—an interactive modelling and scenario planning tool developed by the Orton Family Foundation to assist communities in assessing and visualizing the consequences of land use decisions.

Like other decision-support tools in its class, CommunityViz® provides a capability to assess changing conditions of human settlement over time using analytic models and landscape visualization techniques that simulate complex interactions between human and natural systems. Unlike other integrated assessment and scenario-planning applications, CommunityViz® provides an open and interactive modelling environment that incorporates design-based elements of the planning process (target criteria) with user-defined model parameters (indicators and assumptions) that can be used to visualize, explore, and assess claims about system behaviour and the likely consequences of policy choices. In the context of the Pathways framework, CommunityViz® is used to combine hazard-specific risk analyzes from HAZUS and other modelling tools into a portfolio of interactive multi-hazard risk scenarios. These scenarios provide a basis for evaluating mitigation alternatives using target criteria and indicators that reflect available scientific knowledge about the risk environment and social values or preferences with respect to risk tolerance.

As with other components of the Pathways framework, the system of tools that are used to support the process of risk-based planning conform to national guidelines for data and model interoperability, and can be adapted to reflect the needs and operational requirements of individual communities and organizations. In the context of rural and remote communities, implementation of the Pathways framework and assessment of target criteria may be focused on semi-quantitative methods of risk appraisal that leverage available knowledge about the risk environment in support of ongoing land use and emergency management functions. In the context of larger urban centres and infrastructure corridors, implementation of the framework may be undertaken in support of comprehensive planning processes that encompass both semi-quantitative methods of risk appraisal and the use of quantitative methods of risk analysis that require more specialized domain expertise and additional operational resources.

4.2 The Pathways Process

The Pathways process is a four-stage comprehensive planning cycle that builds on key elements of the ISO standard for risk assessment and the IRGC guideline for risk governance. As illustrated in Figure 4-2, each stage of the framework is comprised of a sequence of smaller steps that provide guidance to practitioners through a set of suggested tasks and related activities that can be modified to reflect the needs and requirements of the local planning process. Each step is informed by insights gained and knowledge shared through a sequence of participatory planning and deliberative engagement workshops that provide overall support to the Pathways process.

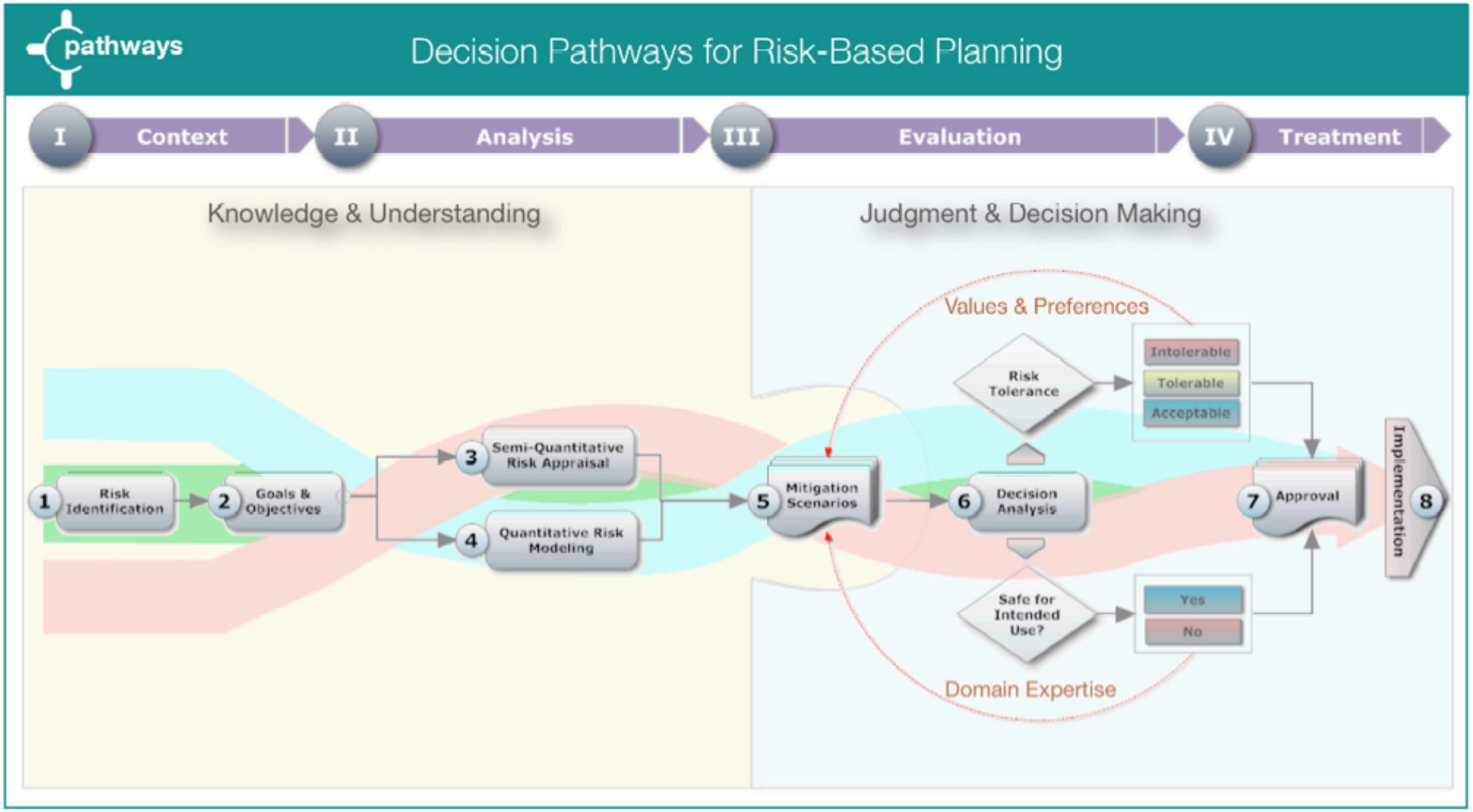


Figure 4-5: The risk-based planning process portrayed as a decision pathway that traverses through each quadrant of the standard risk management cycle. The decision pathway represents an operational workflow that will reflect the needs and operational requirements of a particular place and planning process.

The planning process for a particular community or region can be represented as a "decision pathway" that traverses through each of the four planning stages. The pathway is progressive and recursive, encompassing dimensions of vulnerability and risk that become increasingly complex, uncertain, and ambiguous with broadening problem scope and planning horizon. In general, the pathway leads from stages of the planning process that contribute to the generation of knowledge about the risk environment (context and analysis) to planning stages that focus on judgments about mitigation alternatives and the actions required to promote disaster resilience on the ground (evaluation and treatment).

The specific trajectory of the planning process will vary as a function of place and legislative context. Planning processes that are limited in scope and bounded by regulatory guidelines will follow decision pathways that spiral in a clockwise direction near the axis of the process map in Figure 4-2. With increasing complexity and ambiguity, the decision pathway will encompass broader elements of the planning process that reflect higher levels of system complexity, scientific uncertainty, and political ambiguity. When stretched out like a ribbon, the decision pathway can be represented as an operational workflow that situates people, processes, and methods in the context of a comprehensive planning process (see Figure 4-5). The context-setting stage of the planning process begins with a general characterization of the risk environment and the definition of specific goals and objectives that will make evident the scope and intended outcomes of the planning process. The analytic stage is focused on the generation of new information and knowledge about the risk environment through a combination of semi-quantitative risk appraisal (subjective measures) and quantitative risk modelling (objective measures). Analytic results are then compiled into spatially explicit scenario models that are used to develop a more comprehensive understanding of the risk environment in terms of driving forces and cause-effect relationships.

Scenario models provide a capability to evaluate baseline conditions of risk for a given community or region and to help make evident spatial interactions between natural and human processes that influence changing patterns of vulnerability in a futures context. They also provide a common framework of understanding to explore and develop mitigation strategies that are evaluated in terms of target criteria and indicators that measure compliance with respect to thresholds of risk tolerance that are prescribed by legislative or regulatory standards (public health and safety) or defined locally on the basis of community values and preferences.

Formulation and testing of mitigation scenarios is an iterative process of analysis and evaluation that relies on effective collaboration and ongoing dialogue between scientists, planners, and community members to ensure that resulting policy recommendations are evidence-based and aligned with community values and preferences. Compliance with legislative or regulatory standards for public safety is generally based on the scientific or technical judgment of a qualified professional who is tasked with the responsibility of assessing anticipated impacts, consequences, and recommendations for moving forward. Alignment with locally defined thresholds of risk tolerance is generally based on the ethical judgments of planners, community members, and decision makers who must balance trade-offs between policy objectives to achieve an outcome that addresses both individual rights and the needs of the collective.

Mitigation strategies that do not comply with minimum thresholds of safety or risk tolerance are either rejected or modified with ongoing modelling and evaluation. Mitigation strategies that meet acceptable or tolerable thresholds of risk are advanced for consideration as part of a broader disaster resilience plan. The overall process of risk-based planning involves an iterative and ongoing process of learning, monitoring, and adaptive management whereby new knowledge and insights are used to increase awareness and understanding of the risk environment and the steps needed to increase disaster resilience.

4.2 1. Navigating a "Pathway" of Disaster Resilience

While the Pathways framework provides overall guidance in terms of general roles, responsibilities and procedures for risk-based planning, it is not prescriptive with respect to the analytic-deliberative process, the composition of the planning team, or the specific decision path that ought to be followed to assess the risks and formulate a disaster resilience plan. Each of these particular dimensions of the planning process will be determined by characteristics of the risk environment and by issues that are relevant to the planning process for each particular community or region. These can include overall scope in terms of geographic area and planning horizon, the level of exposure to existing and emerging hazard threats, the level of analysis required to analyze and evaluate policy alternatives, and the availability of resources and expertise (Klinke and Renn, 2002; Renn, 2006a).

4.2 1..1 Participatory Planning and Deliberative Engagement

Participatory planning is the process through which decision pathways are identified and navigated. It is a structured and collaborative process of dialogue and negotiation that involves the exchange of information and perspectives amongst domain experts, planners, elected officials, and those who may be impacted by the decision-making process. Deliberative engagement is a related but more specific form of participatory planning that utilizes a combination of critical thought, reflection, and reasoned argumentation to inform the decision-making process. It is focused on a structured assessment of knowledge claims, social values and ethical perspectives, and is facilitated through a blend of discussion, formal surveys and polls, and the use of interactive mapping and visualization techniques. Collectively, these design-based methods are used to solicit input and to promote a common understanding of the risk environment.

Deliberation can take the form of small group dialogues, planning workshops, design charrettes, and town hall forums—each involving an iterative process of exploration, discovery, and social learning. The goal is a deeper understanding of complex system behaviour and an increased capacity to make decisions in the face of scientific uncertainty or ethical ambiguity. Figure 4-6 summarizes design guidelines for a series of workshops to support participatory planning and deliberative engagement elements of the Pathways process. As with other elements of the Pathways framework, particular details of the workshops can be adapted to meet the needs and operational requirements of the local planning process.

Participatory planning and deliberative engagement are both founded on the democratic maxim that those affected by the outcomes of a policy choice should have the opportunity to participate directly in the process of planning and decision making. By engaging experts and affected parties in a meaningful dialogue about mitigation alternatives, there is an expectation that risk decisions will be informed by the best available scientific information and knowledge. By incorporating principles of deliberative dialogue and community engagement, there is an expectation that competing interests will be fully considered, and that policy choices will take full account of financial risks to public resources and the vulnerabilities of those individuals and groups who will ultimately bear the consequences of the decision-making process.

Risk decisions that are well-constrained by existing scientific information or regulated through legislation (e.g. safety thresholds for earthquakes and flooding) are most often facilitated by a relatively small group of planners and qualified professionals with representative input from the community. Risk decisions for which there is significant scientific uncertainty or where there are varied and competing viewpoints or mandates may require a broader level of community engagement to ensure that tolerability thresholds and mitigation choices represent the interests of those who may be impacted by the decision-making process (Renn, 2006a). Figure 4-7 summarizes guidelines developed by the International Risk Governance Council that relate levels of community engagement to dominant characteristics of the risk environment and the decision-making process.

4.2 1..2 The Planning Team

At the centre of any planning process is team of professionals, community members, domain experts, and decision makers, each contributing in different ways to a common understanding of hazard threats, vulnerabilities, and the actions required to promote disaster resilience on the ground. As summarized in Table 4-1, the interweaving of social values, technical knowledge and political agency across a diverse and interdisciplinary community of practice provides a capability for comprehensive risk-based planning that far exceeds the sum of its parts.

Land use planners and emergency managers represent the central nervous system of the planning process. They provide overall structure, facilitation, and coordination for each of the principal planning stages (context, analysis, evaluation, and mitigation), and share the primary role of evaluating policy alternatives and recommending a preferred course of action that is evidence-based, aligned with local values and goals, and that conforms to legislative or regulatory requirements. They are both producers and consumers of information used in the risk assessment process, and are responsible for bridging the gap between knowledge and action.

Residents and business owners represent the heart and soul of the planning process. They provide insights on who and what are considered most vulnerable and in need of safeguarding (subjective risk), and actively participate in the identification of values and preferences that are used to negotiate thresholds of risk tolerance and to evaluate proposed mitigation alternatives. They are both producers and consumers of information used in the risk assessment process, and share the responsibility for bridging the gap between intent and action.

pathways — Design Guideline for Participatory Planning Workshops

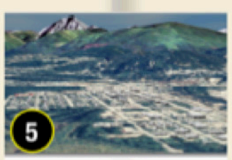
Workshop Priorities		Description
	**Workshop 1:** Establish Context	**Objective**: Define context & focus for risk assessment, and explore social values and preferences that may influence perceptions of risk and mitigation alternatives. **Description:** Part I is an introduction to the project and description of overall process/methodology. Part II is a survey of perceived risks in the community to determine reference levels for subsequent phases of assessment. Part III is a prioritization of goals and assessment criteria that will be used to guide the risk assessment process **Methods & Tools:** Deliberative dialog, surveys & DELPHI-based methods to solicit input and analyze results
	**Workshop 2:** Risk Identification	**Objective:** Validate and characterize available information and knowledge on hazard threats and identify elements at risk in the community or region. **Description:** Part I includes an overview,discussion and validation of available knowledge about hazard threats; and the identification of additional hazard threats of concern. Part II is an appraisal of potential impacts & consequences of identified hazard threats to establish baseline levels of risk tolerance. Part III includes the identification and mapping of community assets (people, places, things) that are considered 'at risk.' **Methods & Tools:** Deliberative dialog, collaborative GIS and DELPHI-based methods to solicit input and analyze results
	**Workshop 3:** Risk Appraisal	**Objective:** Establish levels of concern about potential impacts and consequences of natural hazard threats and assess overall capacities for response and recovery. **Description:** Part I of the workshop is a structured priority-setting exercise to determine those community assets that are considered of highest value and in need of safeguarding. Part II of the workshop is a structured qualitative assessment of resilience in terms of technical, operational, social and economic capacities for response and recovery. Part III focuses on the identification and prioritization of potential mitigation alternatives **Methods & Tools:** Deliberative dialog, DELPHI-based methods to solicit input and analyze results
	**Workshop 4:** Risk Modelling & Scenario Planning	**Objective:** Review outputs of risk analysis and scenario models to establish thresholds of tolerability and to compare strengths and weaknesses of mitigation alternatives **Description:** Part I is a review and validation of outputs from the risk analysis. Part II explores the implications of these risk scenarios in the context of performance measures and targets established in Workshop 1. Part III is involves a prioritization of mitigation alternatives that will be considered for policy analysis. **Methods & Tools:** Deliberative dialog, scenario-based modelling and DELPHI-based methods to solicit input and analyze results
	**Workshop 5:** Decision Analysis	**Objective:** to negotiate and characterize thresholds of risk tolerance, and a preferred course of action for managing risks associated with growth and development in hazardous terrain. **Description:** Part I of the workshop presents outputs of the cost-benefit analysis for proposed mitigation scenario(s), and elicits feedback on performance targets to characterize thresholds of acceptable, tolerable and intolerable risk for the community. Outputs of this process are used in Part II to determine a preferred future state of risk tolerance for priority assets, and to choose an appropriate course of action for achieving these objectives. **Methods & Tools:** Deliberative dialog, scenario-based modelling and DELPHI-based methods to solicit input and analyze results

Figure 4-6: Workshop design guideline to support participatory planning and deliberative engagement elements of the Pathways framework. The guideline provides high-level descriptions for a sequence of five workshops that are designed to facilitate the exchange of information and knowledge, to solicit input on values, goals and objectives, and to provide direction for the risk assessment and mitigation planning process.

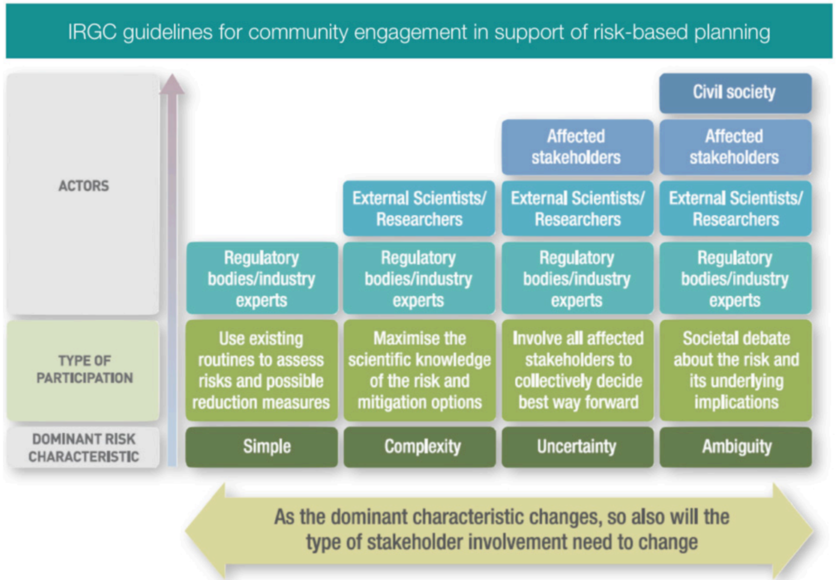


Figure 4-7: IRGC guidelines for deliberative engagement that relate level and type of community engagement to the complexity, uncertainty and/or ambiguity of the risk problem (International Risk Governance Council, 2008).

Domain experts in the physical and social sciences represent the eyes and ears of the planning process. They provide insights on the driving forces and system conditions that determine intrinsic levels of hazard potential and vulnerability for a given area (objective risk), and make evident through analysis and modelling what can be expected in terms of impacts and likely consequences should a hazard event occur at some point in the future. They are producers of information and knowledge used in the risk assessment process, and are responsible for bridging the gap between theory and practice.

Decision makers represent both the conscience and legs of the planning process. They are elected or appointed to represent the interests of their constituents and are tasked with the responsibility of resolving conflicts between diverse and often competing policy goals in order to take actions that will advance management objectives while minimizing negative impacts on people and the things they value. Decision makers have a primary role in framing the overall process of risk governance, giving direction to staff involved in the planning process, making final judgments on policy recommendations, and allocating investment in risk treatment measures that can be implemented with available resources. As such, they are ultimately responsible for bridging the gap between intent and action.

4.2 1..3 Decision Pathways

For well-defined risk problems in which there is general agreement on cause-effect relationships and corresponding risk treatment measures, the decision pathway is established through routine diagnosis and problem formulation using performance targets that are either recommended by best practices or established through regulatory standards. These are situations in which system complexity and scientific uncertainty are low, planning horizons are relatively short (0–5 years), and there is little ambiguity in terms of policy goals and management objectives. Relevant examples might include the review of design guidelines or development applications to determine if proposed structures and land use activities are within accepted thresholds of risk tolerance and considered safe for the use intended. In these cases, the overall context, problem scope, and decision protocols are likely to be established through provincial or territorial legislation and local zoning ordinances.

Depending on available resources and expertise, the risk analysis process may involve semi-quantitative appraisal or quantitative modelling of impacts and likely consequences by a qualified professional. The focus of the risk analysis is on constraining uncertainty and clarifying cause-effect relationships through observation, measurement, and modelling. The evaluation of mitigation alternatives is focused on risk treatment measures that reduce vulnerability and societal risk in order to comply with recommended or prescribed thresholds of safety and security. Those involved in the process would likely include land use planners, geotechnical engineers, and members of the community who may be impacted by outcomes of the final decision.

The scope of the planning process increases for risk problems that involve a consideration of existing and emerging hazard threats with a potential to impact neighbourhoods and shared community assets. These are situations characterized by greater system complexity, higher levels of scientific uncertainty and political ambiguity, often involving a consideration of multiple hazard threats over variable planning horizons (5–30 years), and the evaluation of mitigation strategies that involve choices between diverse and often competing policy goals. Relevant examples might include the review of a comprehensive development proposal or revisions to strategic land use policies that give direction for future growth and development of a community or region.

In these cases, establishing context for the decision-making process will involve a thorough characterization of the risk environment and a formal definition of planning goals and objectives. Analytical methods may include a mix of semi-quantitative risk appraisal and scenario-based quantitative risk modelling. In addition to information and knowledge exchange, communication protocols may include dialogue and debate to reach agreement on cause-effect relationships, to identify system vulnerabilities, and to determine appropriate risk treatment alternatives for further analysis and evaluation. Evaluation of mitigation alternatives may involve a consideration of both science and value-based judgments, often encompassing a blend of strategies including risk reduction through structural mitigation, risk avoidance through land use, and risk transfer through financial insurance markets.

For risk environments involving high levels of system complexity, uncertainty, and ambiguity, the focus shifts from an assessment of specific cause-effect relationships to the exploration of actions that are required to promote disaster resilience by increasing adaptive capabilities to withstand, respond to and recover from a portfolio of potential hazard events. In these situations, the decision pathway is extended to include the assessment of existing and emerging hazard threats and the vulnerability of human settlements in a changing landscape. Risk portfolios considered in the assessment process can include a combination of high-probability/low-consequence hazards that are triggered by processes that are reasonably well understood and can be predicted (floods, severe weather events, etc.); and low-probability/high-consequence hazards that are triggered by larger-scale processes that are more complex and less predictable (landslides, earthquakes, global climate change, etc.). With increasing scientific uncertainty, modes of deliberation shift toward knowledge generation, social learning, and negotiation. Corresponding modes of assessment involve an analysis of changing patterns of vulnerability and risk over time, and the evaluation of mitigation strategies that seek a balance between risk reduction, risk avoidance, and the transfer of outstanding liability through insurance and disaster relief.

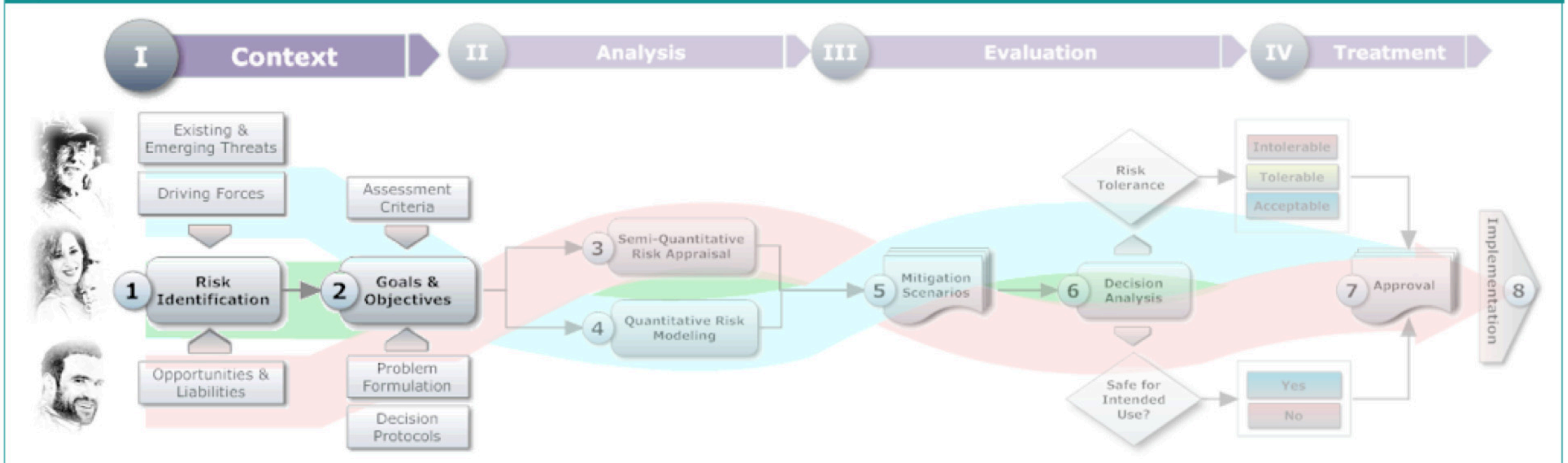
The Pathways process is defined in terms of a cycle of eight planning steps that are summarized in Table 4-4. Each step is defined and described in terms of a recommended set of tasks and activities, the people who may be required to provide input or expertise, and the corresponding methods and tools that may be needed to navigate individual steps in the process.

4.2 2. Stage I: Establish Context

Establishing overall context and focus for the planning process involves the identification of existing and emerging societal risks for a study region of interest, a diagnosis of system conditions and driving forces that are likely to influence the risk environment, the assessment of opportunities and liabilities for moving forward with a proposed set of policy goals and objectives, and the definition of assessment criteria and decision protocols that will be used to guide the planning and policy development process.

Land use planners and emergency managers have a lead role in this initial stage of the process. They are responsible for characterizing the overall risk problem; identifying hazard threats of concern; establishing the guiding principles, policy goals, and intended outcomes that will frame the planning process; and defining general rules of engagement in terms of analytic-deliberative methods and decision protocols. It is vital that those making final decisions be engaged in this initial stage to assist in problem framing and to provide assurance that outcomes of the planning process will be considered and acted on in a timely manner. Members of the community have an equally important role in making evident social values and preferences that will influence overall perceptions of risk and the formulation of policy goals and objectives. Domain experts are responsible for providing insights on general

Risk-Based Planning Process - Stage I: Establish Context



Step 1: Risk Identification

Task	Process, People & Tools	Activities
Existing & Emerging Threats	**Process**: Synthesize available information and knowledge on existing patterns of human settlement for the planning area and potential hazard threats that are of concern for the planning interval. **People**: planners, scientists **Methods & Tools**: Exploratory design workshop & deliberative dialog	☑ Establish the geographic area of interest and the time horizon for the planning process ☑ Describe existing patterns of human settlement for the planning area in terms of population and demographic profile ☑ Describe the form and function of the built environment for existing conditions of human settlement ☑ Identify existing and emerging hazard threats of concern for the planning area ☑ Assess the current state of understanding about the risk environment including both expert and domain-based knowledge.
Driving Forces	**Process**: Asses factors external to the system that may influence existing and future patterns of vulnerability and risk **People**: planners, scientists **Methods & Tools**: Risk identification workshop & deliberative dialog	☑ Assess the cause-effect relationships between credible hazard threats and associated impacts to the human-natural system ☑ Identify those factors external to the system that are likely to influence patterns of vulnerability and risk for the planning area. ☑ Assess how these patterns of vulnerability and risk are likely to change with time over the specified planning horizon.
Opportunities & Liabilities	**Process**: Explore opportunities and potential risks associated with a proposed course of action **People**: planners, policy analysts, decision makers, community members **Methods & Tools**: Risk identification workshop & deliberative dialog	☑ Identify the potential opportunities & benefits of pursuing a proposed course of action along with any legislative and/or regulatory requirements ☑ Identify who and what may be exposed to potential negative impacts and/or consequences of credible hazard threats ☑ Identify the perceived risks of pursuing a proposed course of action ☑ Determine which of these risks are likely to be considered unacceptable and in need of further mitigation ☑ Determine if identified risks can be mitigated with existing

Step 2: Goals & Objectives

Task	Process, People & Tools	Activities
Problem Formulation	**Process**: Identify specific issues of concern that will be the focus of the risk assessment process **People**: planners, policy analysts, decision makers, scientists, risk analysts & community members **Methods & Tools**: Exploratory design workshop & deliberative dialog	☑ Determine the overall scope of the risk problem, review requirements for compliance with legislative and/or regulatory guidelines, and identify who is responsible for risk decisions. ☑ Determine the hazard-threat scenarios that will be used for assessing vulnerability and risk for the community or region ☑ Determine populations and community assets that are considered vulnerable and in need of safeguarding through mitigation ☑ Identify the types of mitigation measures that will be considered as part of the risk assessment process
Assessment Criteria	**Process**: Identify principles and specific goals/management objectives that will guide the planning process **People**: planners, policy analysts, decision makers, risk analysts & community members **Methods & Tools**: Exploratory design workshop utilizing DELPHI methods to solicit input and analyze results	☑ Identify community values & goals and communicate high-level principles that will guide the risk assessment process (e.g. public safety, socioeconomic security, mitigation efficiency, etc.). ☑ Articulate the specific target criteria that will be used to make evident what needs to be achieved in order to reach a desired outcome. ☑ Select the indicators that will be used to measure progress toward and/or away from policy objectives (targets) and the efficacy of proposed mitigation measures. ☑ Identify the methods that will be used to aggregate outputs of the risk assessment and how this information will be used in support of the decision making process ☑ Identify and communicate the intended outcomes of the risk assessment and mitigation planning process.
Decision Protocols	**Process**: Establish the protocols that will guide the decision making process **People**: planners, policy analysts, decision makers **Methods & Tools**: Exploratory design workshop & deliberative dialog	☑ Establish the conditions under which risk management decision will be made ☑ Identify who will participate in the risk assessment process, and establish their respective roles and responsibilities ☑ Establish the rules by which information and knowledge is shared throughout the risk assessment process, and who is entitled to know what and from whom ☑ Identify the level of assessment and methods that will be used to analyze the dimensions of vulnerability and risk (semi-quantitative & quantitative) ☑ Identify the methods that will be used to: (i) prioritize multi-hazard risks, (ii) negotiate thresholds of tolerable risk and, (iii) evaluate mitigation alternatives ☑ Determine the modes of communication that will be used to solicit input, explore policy alternatives and share project outputs with those who may be impacted by the decision making process

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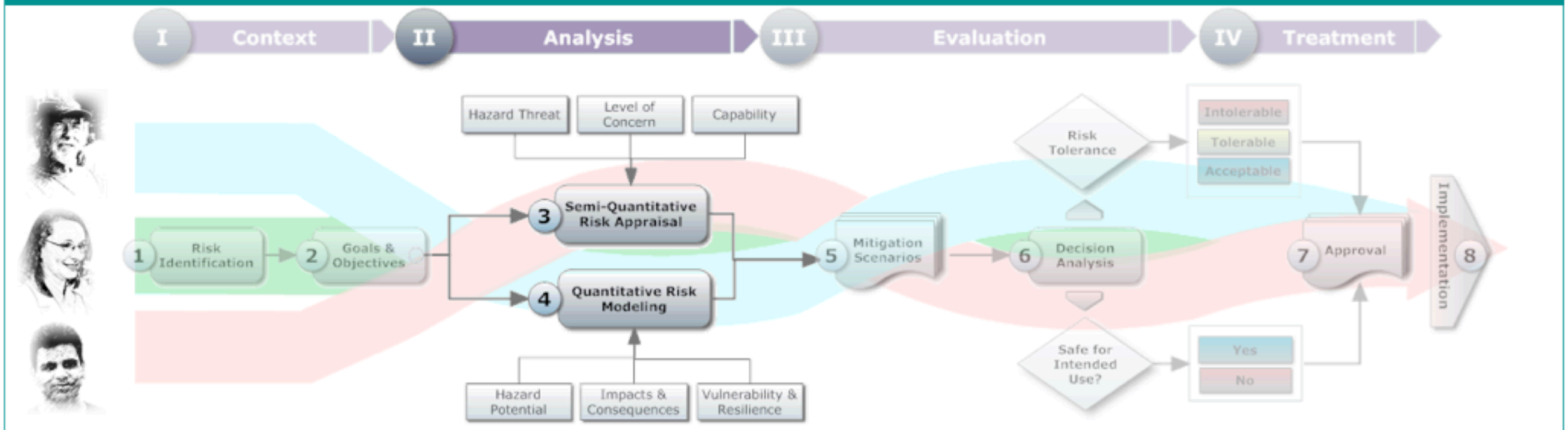
Risk-Based Planning Process - Stage II: Risk Analysis



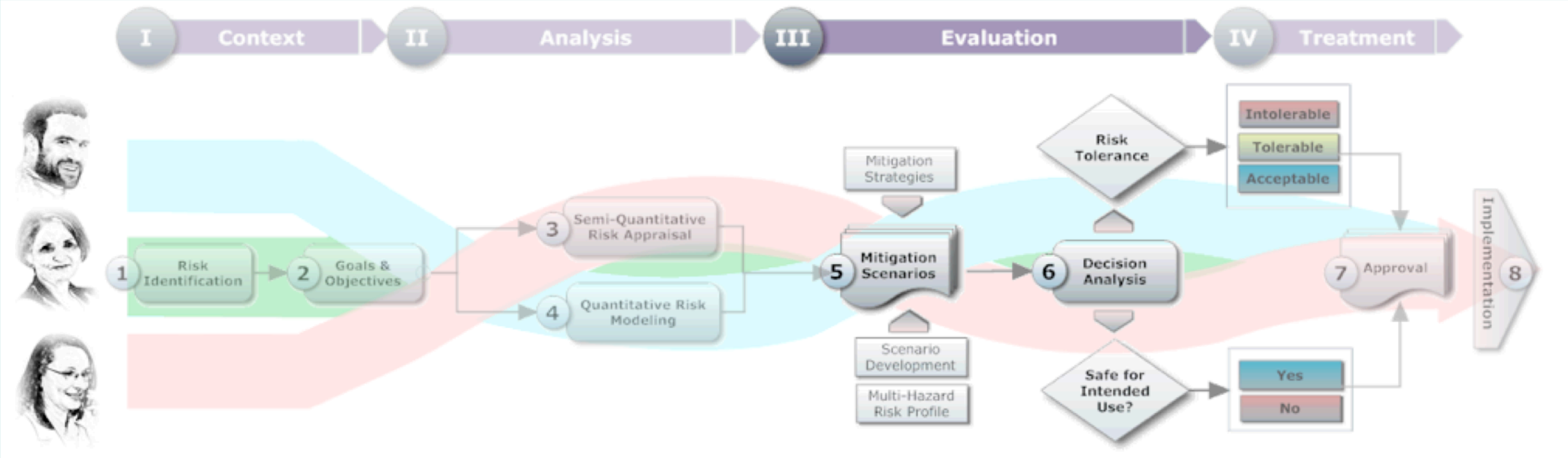
Step 3: Semi-Quantitative Risk Appraisal

Task	Process, People & Tools	Activities
Hazard Threats	**Process**: Assess the magnitude-frequency relationships for selected hazard event scenarios on the basis of available information and knowledge. **People**: planners, scientists, geotechnical engineers, community members **Methods & Tools**: Risk appraisal workshop utilizing collaborative GIS and DELPHI methods to rank hazard threats	☑ Assess the severity of selected hazard event scenarios by ranking potential impacts in terms of physical damages to the built environment, injuries & fatalities, anticipated socioeconomic losses, environmental impacts, disruption of government services and public outcry ☑ Assess the likelihood that hazard events of a specified magnitude will occur in the planning area by ranking the probability of occurrence using historical records of past events and/or scientific understanding of natural processes and cause-effect relationships ☑ Compare individual and group responses and repeat assessment until there is no significant change in the variance or the mean rank value of perceived risk Generate a multi-hazard risk profile by plotting magnitude-frequency relationships of selected hazard threats using normalized outputs of threat assessment
Levels of Concern	**Process** Assess levels of concern for vulnerable populations and community assets in the planning area **People**: planners, scientists, geotechnical engineers, community members **Methods & Tools**: CDMS & Risk appraisal workshop utilizing collaborative GIS and DELPHI methods to rank levels of concern	☑ Compile an inventory of community assets for the planning area using available geospatial information to map and describe physical characteristics of the natural/ built environment and patterns of human settlement (population & demographics) ☑ Assess the current state of vulnerability for people and community assets by ranking hazard exposure and levels of concern about likely impacts and consequences ☑ Compare individual and group responses and repeat assessment until there is no significant change in the variance or the mean rank value of perceived risk ☑ Characterize thresholds of risk tolerance by identifying those areas in which people and community assets are considered vulnerable and in need of safeguarding through additional mitigation and emergency preparedness measures
Capability	**Process**: Assess overall resilience of the community or region in terms of capabilities for mitigation, response & recovery **People**: planners, scientists, geotechnical engineers, community members **Methods & Tools**: Risk appraisal workshop utilizing DELPHI methods to rank capabilities	☑ Assess the extent to which a community or region is likely to withstand, respond to and recover from the impacts of multi-hazard threats over time by ranking the effectiveness of existing technical, organizational social and economic capabilities ☑ Compare individual and group responses and repeat assessment until there is no significant change in the variance or the mean rank value of perceived risk ☑ Explore strategies to address weaknesses of existing mitigation measures and identify specific mitigation alternatives that can be further analyzed using quantitative methods of risk modeling

Step 4: Quantitative Risk Modelling

Task	Process, People & Tools	Activities
Hazard Potential	**Process** Assess the severity and magnitude of selected hazard threat scenarios for the designated geographic area and time horizon. **People**: scientists, geotechnical engineers, risk analysts **Methods & Tools**: HAZUS-MH	☑ Assess the likelihood of known and/or emerging hazard threats occurring in the study area using deterministic and/or probabilistic methods to calculate Average Annual Probability (AAP) and the Probability of Eceedance (POE) for planning horizons of interest ☑ Assess the geogrpaphic area(s) likely to be impacted by selected hazard scenarios using deterministic and/or probabilistic methods to model cause-effect relationships of underlying natural processes and historic records of past events ☑ Assess the corresponding intensities of hazard event scenarios for a given area and probability of occurrence
Impacts & Consequences	**Process** Assess the root causes and underlying system dynamics that create unsafe conditions and/ or pre-dispose a community or region to negative consequences of multi-hazard threats **People**: scientists, planners, emergency managers, risk analysts **Methods & Tools**: SoVI, Principle Component Analysis	☑ Physical Vulnerability: determine the expected levels and probabilities of physical damage to elements of the natural and built environment, the severity and likelihood of injuries and fatalities, and secondary impacts including the loss of habitation and shelter requirements ☑ Anticipated Losses: determine the direct economic losses resulting from physical damages and associated reductions in income and employment, and the indirect consequences of these losses to people and regional economies for planning horizons of interest. ☑ Mitigation Costs & Benefits: evaluate the potential losses avoided by investing in mitigation measures and the expected rate of return on investment over planning horizons of interest
Vulnerability & Resilience	**Process** Assess the changing patterns of vulnerability and risk to determine system dynamics, anticipated reductions in functionality and response/recovery profiles over time **People**: scientists, planners, emergency managers, policy analysts, risk analysts **Methods & Tools**: HAZUS-MH; CRM; Scenario360™	☑ Assess correlations between historical trends and changing patterns of vulnerability over time to establish baselines and diagnose driving forces ☑ Assess the intrinsic social vulnerability of individuals and groups, including who is likely to bear the consequences of a disaster event, their ability to withstand the physical impacts, and their capabilities to respond and recover over time ☑ Assess the extent to which socioeconomic systems are expected to withstand the impacts of a disaster event, the amount of time required to restore baseline functionality, and capabilities for adaptation over time.

Risk-Based Planning Process - Stage III: Risk Evaluation



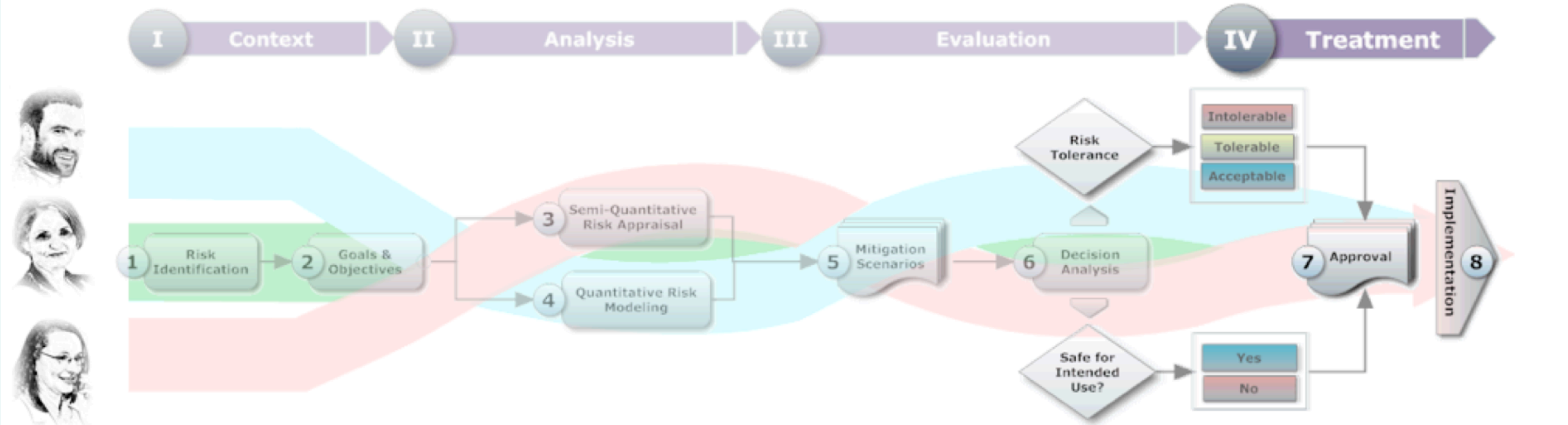
Step 5: Mitigation Scenarios

Task	Process, People & Tools	Activities
Scenario Development	**Process**: Model and analyze changing patterns of vulnerability and risk through time to inform the development of mitigation strategies **People**: risk analysts, scientists **Methods & Tools**: Risk evaluation workshop (4), group DELPHI & Scenario360™ modelling	☑ Assess incremental and step-wise evolution of the system over specified intervals of time based on frequency-magnitude relationships and anticipated landscape changes for single and/or multi-hazard events ☑ Assess model uncertainties (sensitivity analysis) for the purpose of evaluating causal linkages and driving forces that may explain observed system dynamics and scenario outcomes ☑ Assess the influence of value preferences on model outcomes by examining incremental and step-wise variations in performance indicators and the implications of these variations with respect to target criteria (goals & objectives).
Multi-Hazard Risk Profile	**Process**: Compile and synthesis outputs of quantitative risk analysis to generate multi-hazard risk profiles for the community or region **People**: risk analysts, scientists, geotechnical engineers **Methods & Tools**: HAZUS-MH, Scenario360™	☑ Determine annual probabilities of exceeding thresholds of damage/ loss for the selected portfolio of threat scenarios to assess implications of high-frequency/low consequence events (AAL: Average Annual Loss) ☑ Determine the cumulative probabilities of exceeding thresholds of damage/loss for the selected portfolio of threat scenarios to assess implications of low-frequency/high consequence events (PML: Probable Maximum Loss) ☑ Assess AAL and PML risk profiles with respect to scientific uncertainties and the implications of evolving risk conditions over time
Mitigation Strategies	**Process**: Identification and assessment of mitigation measures to be considered for policy analysis **People**: planners, policy analysts, risk analysts, scientists, community members & decision makers **Methods & Tools**: Risk evaluation workshop (4), group DELPHI & Scenario360™ modelling	☑ Assess the suitability of existing and projected patterns of human settlement with respect to the performance of selected target indicators ☑ Identify risk treatment measures and design mitigation scenarios that will be considered in policy analysis - including strategies for risk avoidance, risk reduction and risk transfer ☑ Model incremental and step-wise changes to the system associated with proposed mitigation strategies through the development of alternate risk scenarios that make evident projected trends (forecast analysis) and/or desired future states of disaster resilience (backcast analysis) ☑ Explore and evaluate causal linkages and driving forces that may explain observed system dynamics and scenario outcomes

Step 6: Decision Analysis

Task	Process, People & Tools	Activities
Risks & Benefits	**Process**: Assess the costs & benefits of proposed risk treatment measures to optimize the efficiency of financial investments in disaster mitigation **People**: risk analysts, planners, policy analysts **Methods & Tools**: LUPM, HAZUS-MH & Scenario360™	☑ Select community asset portfolios and associated risk treatment alternatives that will be used to assess the efficiency of proposed mitigation scenarios ☑ Model damage probabilities and anticipated economic losses with mitigation measures in place. ☑ Model the expected rate of return on investment for each of the selected mitigation scenarios, and evaluate the efficiency of proposed risk treatment measures. ☑ Determine the proportion of anticipated losses that can be managed with local resources using ALARP principles and develop strategies for managing residual losses through risk transfer
Risk Tolerance	**Process**: Assess performance indicators with respect to target criteria to determine thresholds of risk tolerance and whether proposed mitigation strategies are moving toward or away from the intended outcomes of policy goals and objectives. **People**: risk analysts, planners, policy analysts, community members **Methods & Tools**: Scenario360™	☑ Select the portfolio of hazard threats and corresponding risk profiles that will be used to evaluate and prioritize mitigation alternatives. ☑ Analyze performance indicators for each of the hazard event scenarios in the portfolio and aggregate results for selected target criteria that have been selected to guide the decision making process. ☑ Compare performance measures across the risk portfolio to identify mitigation measures that may be needed to balance trade offs between target criteria, and repeat the risk-benefit analysis step to assess the implications in terms of mitigation investments. ☑ Establish thresholds of risk tolerance by adjusting targets to optimize performance of priority goals or to balance trade-offs between public policy objectives
Mitigation Priorities	**Process**: Compare strengths and weaknesses of mitigation alternatives with respect to target indicators **People**: planners, policy analysts, risk analysts, community members & decision makers **Methods & Tools**: deliberative workshop (5), group DELPHI & Scenario360™ modelling	☑ Prioritize mitigation alternatives based on model outputs and judgments of what constitutes a tolerable threshold of risk for the community or region. ☑ Review outputs of the risk assessment process and prepare policy brief with recommendations for disaster mitigation ☑ Solicit feedback on draft proposal from those who are likely to be impacted by the decision making process ☑ Develop draft plan for disaster mitigation and communicate results for critical review and feedback

Risk-Based Planning Process - Stage IV: Mitigaiton



Step 7: Approval of Mitigation Strategy

Task	Process, People & Tools	Activities
Feasibility	Process: Assess the capabilities to implement disaster mitigation alternatives in terms of technical, operational, social and economic feasibility People: planners, policy analysts Methods & Tools: impact assessment	Assess the technical capabilities to implement proposed risk reduction measures through structural mitigation Assess operational capabilities to implement proposed risk avoidance and response/recovery measures through comprehensive planning and emergency preparedness Assess the capabilities to invest in proposed mitigation strategies based on available financial resources and expected return on investment Assess the social implications of implementing proposed mitigation strategies in terms of equity, fairness and the balance between individual and collective rights
Policy Review	Process: Develop disaster mitigation plan outlining core issues identified through the risk assessment process, a recommended course of action and supporting rationale People: planners, policy analysts Methods & Tools: Comprehensive plan, development regulations, zoning & land use ordinances, emergency management plan, building standards, best management practices	Summarize core issues and the decision criteria used to assess risks in the planning area Identify the recommended course of action and document supporting rationale in terms of management goals and target indicators Identify and discuss the expected benefits to be gained through mitigation and any residual risks to the organization/community Provide an accounting of alternate mitigation choices that were considered and their consequences with respect to decision criteria and negotiated thresholds of risk tolerance Identify fiscal impacts and potential legal implications of proposed mitigation plan Identify individuals/groups responsible for approving the plan and those responsible for implementing the plan Identify strategies for managing residual risks through collaborative partnerships and/or risk transfer mechanisms
Final Judgment	Process: Render judgment on proposed disaster mitigation plan and grant authority for implementation of risk treatment measures People: decision makers, planners, policy analysts, community members Methods & Tools: advisory board, deliberative dialogue, public hearing	Review of proposed disaster mitigation plan & results of feasibility assessment Consultation with other government agencies to determine authority and to ensure alignment with legislative guidelines and regulatory mandates Consultation with individuals and groups in the community who may be impacted by outcomes of the decision making process Final approval of proposed disaster mitigation plan

Step 8: Implementation & Monitoring

Task	Process, People & Tools	Activities
Administration	Process: Establish protocols to oversee implementation, monitoring and review of the mitigation plan People: Chief Administrative Officer, agency staff Methods & Tools: Adaptation of existing systems for project management and coordination	Adopt disaster mitigation plan and grant authority for implementation of risk treatment measures Amendment and/or revision of existing risk management policies, regulations and guidelines that govern comprehensive land use and emergency preparedness in the planning area Develop work plan, establish roles & responsibilities and available resources for implementation Identify and apply for external funding to assist in implementing mitigation measures Establish protocols for reporting on project milestones, deliverables and budget status Ongoing coordination and evaluation of activities across agency departments and with project partners to ensure effectiveness and efficiency of mitigation program
Agency	Process: Execute approved risk treatment measures of mitigation plan People: Chief Administrative Officer, agency staff Methods & Tools: Adaptation of existing systems for project management and coordination	Construction of protective measures to reduce the physical impacts of credible hazard threats Implementation of risk avoidance and land use planning measures to reduce the exposure of people and community assets to credible hazard threats Implementation of early warning and emergency preparedness measures to increase the capabilities to respond and recover from potential disaster events Implementation of fiscal strategies to manage residual risks through insurance markets
Adaptive Management	Process: Assess changing conditions of vulnerability and risk and evaluate performance of mitigation measures with respect to goals and target indicators People: Planners, policy analysts Methods & Tools: Adaptation of existing systems for project management and coordination	Assess trends and monitor changes to natural system that may trigger natural hazard events Assess trends and monitor changing conditions of land use and human settlement that may alter patterns of vulnerability for the planning area Evaluate and report ongoing performance of mitigation measures with respect to policy goals and target indicators Identify and characterize emerging threats that have a potential to impact planning area Analyze lessons learned and adapt/revise disaster mitigation plan

Table 4-4: Recommended guidelines for navigating the various analytic and deliberative steps that constitute the Pathways process for risk-based planning. Each step is described in terms of a recommended set of tasks and activities, the people who may be required to provide input and/or expertise, and the corresponding methods and tools that may be needed.

characteristics of the risk environment and identifying potential impacts and consequences for hazard threats of concern.

As illustrated in Figure 4-6, initial steps of the process are facilitated through a sequence of design workshops that bring together members of the planning team for the purpose of sharing relevant information and knowledge about the risk environment, identifying issues of concern and anticipated outcomes, and providing direction for subsequent phases of the risk assessment process. Depending on characteristics of the risk environment and the issues of concern in the community, workshop design and structure can range from informal working group sessions to formal town hall or interactive online forums.

4.2 2..1 Step 1: Risk Identification

Risk identification involves a preliminary assessment of existing and emerging hazard threats for the region, which involves observation and the measurement of existing system conditions and a diagnosis of how conditions of vulnerability are likely to change with time over the planning horizon (see Table 4-4). The process begins with a definition of the geographic area and time scope that will be used to frame the planning process.

Study areas can range in scale from individual neighbourhoods that are susceptible to the impacts of site-specific hazard threats (landslides, liquefaction, etc.) to entire communities or regions that are susceptible to the impacts of single or multiple hazard threats operating at larger geographic scales (earthquakes, floods, etc.). With increasing spatial scale and scope of hazard threat, there is a corresponding increase in the level of system complexity and the range of planning issues that need to be considered.

The time horizon selected for the planning process is determined by characteristics of the risk environment and whether public policy objectives are focused on shorter-term operational objectives or longer-term strategic outcomes. Shorter-term planning horizons (0-5 years) are appropriate for the assessment of high-probability/low-consequence risks that can be managed locally through land use zoning and emergency management operations. Longer-term planning horizons (5-30 years) are required to manage more complex risk portfolios involving low-probability/high-consequence risks or changing conditions of vulnerability that are likely to be influenced by future growth and development.

Regardless of the area or time horizon selected, the focus is on identifying the physical and human dimensions of risk, and determining the extent to which political and socio-economic forces are likely to influence patterns of settlement and changing levels of vulnerability in the foreseeable future. Insights gained in this step establish a point of reference for the planning process, and will determine how the risk problem is framed and expected outcomes of the decision making process.

4.2 2..2 Step 2: Define Goals and Objectives

Based on a compilation of available information and knowledge about the risk environment, the next step in the process is to articulate the guiding principles and planning goals, and to select the corresponding assessment criteria that will frame and guide the planning process (see Table 4-5).

Community values and preferences will define the vision and overall intent of the planning process. They determine how the risk problem is likely to be framed with respect to issues of concern in the community, and the selection of target criteria that will be used to evaluate thresholds of risk tolerance and the efficacy of mitigation alternatives (Stefanovic, 2003). The definition of target criteria involves the identification of operational or strategic objectives and the selection of corresponding indicators that will be used to analyze the risk environment and to track progress with respect to desired outcomes.

The focus for this step is on clarifying who and what are considered most vulnerable and in need of safeguarding, and the measures that are needed on the ground to reduce risk and enhance community resilience. With respect to human health and safety, these questions are often addressed by provincial and federal jurisdictions that prescribe minimum thresholds of tolerability through legislation or regulatory standards. Determining thresholds of risk tolerance with respect to social equity, environmental integrity, and economic vitality is more challenging and is usually negotiated on a case-by-case basis in the context of emergency management operations or comprehensive land use planning processes.

4.2 3. Stage II: Risk Analysis

Risk analysis provides insight and knowledge about the impacts and consequences of hazard threats based on direct observation and experience of past events, or indirect measurement and modelling of potential cause-effect relationships. Semi-quantitative risk appraisal utilizes input from community members or domain experts to generate knowledge about perceived hazard threats, levels of concern, and adaptive capacity. Quantitative risk analysis utilizes synthetic information based on theory and experiment to generate knowledge about hazard potential, probabilities of damages, anticipated socio-economic losses, system vulnerability and resilience. Both methods offer the means of objectively measuring the dimensions of vulnerability and risk that will inform the evaluation of mitigation alternatives. The level of analysis will vary as a function of complexity, uncertainty, and ambiguity of the risk problem, and requirements of the planning process.

As with other stages of the process, effective risk analysis is dependent on clear communication between members of the planning team to ensure there is a common understanding of context and focus, and agreement on the needs and requirements of the decision-making process. This part of the process can be facilitated through peer review workshops or online forums that provide an opportunity for validation and comment.

4.2 3..1 Step 3: Semi-Quantitative Risk Appraisal

Risk appraisal acknowledges the uncertainties and complexities of a changing threat environment by shifting the focus from cause-effect relationships to a broader consideration of the actions required to reduce vulnerability and increase community resilience over time. The appraisal process establishes a common understanding of hazard threat for a given geography and planning horizon through the integration of local and expert knowledge. It also makes evident the general levels of concern in terms of who and what are considered most vulnerable and in need of safeguarding, perceptions of what constitutes a tolerable threshold of risk, and mitigation strategies that may be worth exploring based on available knowledge, expertise, and resources.

The risk appraisal process is facilitated through the use of Delphi-based survey methods that leverage available information and knowledge to rank the severity of perceived hazard threats, levels of concern, and the capabilities for response and recovery for existing and desired future states of mitigation. The Delphi method is a systematic and forward-looking approach to assessment that is based on the input and collective judgment of local and domain experts (Dalkey and Helmer, 1963; Dalkey and Rand Corporation, 1969; Helmer *et al.*, 1983). Individual and group responses are solicited and ranked on a common ordinal scale, then aggregated into a series of indicators that reflect available knowledge and understanding of hazard risk, vulnerability, and community resilience. Indicators can be used independently to evaluate mitigation alternatives or in conjunction with quantitative methods of risk analysis to compare perceived and measured levels of vulnerability and risk for a community or region.

4.2 3..2 Step 4: Quantitative Risk Modelling

Quantitative risk analysis utilizes scientific enquiry (theory and experimentation) and the modelling of cause-effect relationships within and between human-natural systems to provide a measure of hazard potential, anticipated damages and losses, the efficacy of proposed mitigation strategies, and broader patterns of vulnerability that will influence levels of community resilience. It is facilitated through expert-driven methods of deterministic analysis that describe the parameters and interactions between natural and social systems, and on probabilistic methods of analysis that explain and predict complex system dynamics based on a statistical understanding of how these systems have behaved or are likely to behave over time.

The analysis of hazard risk focuses on the physical and probabilistic dimensions of natural hazards including: frequency-magnitude relationships (hazard potential), anticipated impacts of specific hazard events on the physical environment (physical vulnerability), the direct and indirect consequences of single or multi-hazard threat scenarios (anticipated losses), and the costs and benefits of investing in mitigation measures to reduce levels of risk over planning horizons of interest (financial risk). The analysis of social vulnerability addresses underlying characteristics of the landscape and socio-economic fabric that may predispose a region to negative impacts of a disaster event. These can include the physical susceptibility to hazard threats (susceptibility), the capacity of individuals and groups to take actions that will reduce their vulnerability (agency), and their ability to manage the impacts and consequences of a disaster event (coping capacity). Finally, the analysis of resilience addresses the capabilities of human-natural systems to withstand, respond to, recover from and adapt to changing patterns of vulnerability and risk over time. Resilience can be assessed at the scale of critical infrastructure systems and related lifeline services (system functionality) or at the scale of entire communities and regions (disaster resilience).

4.2 4. Stage III: Risk Evaluation

Risk evaluation is the process of reconciling knowledge claims about the risk environment with value-based judgments about mitigation alternatives. Judgments about empirical uncertainty involve synthesizing relevant analytic measures in order to explore the sensitivities of model assumptions with respect to anticipated system behaviour. Judgments about societal values and preferences involve an assessment of costs and benefits and the overall performance of mitigation alternatives with respect to policy targets and negotiated thresholds of risk tolerance.

An important aspect of this process is the need for ongoing dialogue between planners, domain experts, community members, and decision makers. Planners need timely access to results of the risk analysis process to validate outputs, to formulate mitigation strategies, and to provide direction on how best to communicate outputs of the analysis to inform the decision-making process. Community members need an opportunity to review results of the risk analysis to assess potential impacts and consequences with respect to vulnerable populations and critical assets of concern, and to provide input on thresholds of risk tolerance. Finally, decision makers need a synopsis of key findings and information that will help them assess the level of uncertainty associated with the risk analysis and the evaluation of mitigation alternatives. This level of interaction requires an ongoing process of dialogue and that can be facilitated through a combination of face-to-face working sessions or planning charrettes.

4.2 4..1 Step 5: Risk Scenarios

Risk evaluation begins with the development of scenarios that describe available knowledge about the risk environment, how it is likely to change through time, and the choices that may be required to reduce anticipated vulnerabilities in order to achieve a desired future state of resilience. Depending on the planning horizon and the scope of the risk problem, scenarios can be used to explain and explore system behaviour over time. They can be focused on individual hazard threats for specific areas of concern, or expanded in scope to include a portfolio of potential hazard threats that collectively define the risk profile for a community or region.

Explanatory scenarios are geared toward describing human-natural systems in terms of physical attributes and predicting how these systems are likely to change based on an understanding of underlying processes and numerical models that extrapolate cause-effect relationships into the future (forecast modelling). They are appropriate for use in situations where the state of the system can be specified and measured, and where the dynamics governing change are understood and known to be persistent over relatively short periods of time (Pielke and Conant, 2002; Swart *et al.*, 2004; Carmichael *et al.*, 2005).

Exploratory scenarios are based on the same underlying methods of modelling cause-effect relationships in the risk environment, but explicitly account for uncertainties about causal linkages by varying assumptions about system behaviour to simulate plausible outcomes or to examine the feasibility and implications of desirable future conditions (backcast modeling; Robinson, 1982; Pahl-Wostl *et al.*, 2000; Carmichael *et al.*, 2004; Swart *et al.*, 2004; Quist and Vergragt, 2006; Wilson *et al.*, 2006). Exploratory scenarios represent working hypotheses of how complex systems are likely to evolve in a futures context based on available knowledge, social values, and preferences. In the absence of quantitative risk models, narrative-based scenarios derived from outcomes of the risk appraisal process can be used to explore and assess the likely consequences of mitigation choices.

4.2 4..2 Step 6: Decision Analysis

Decision analysis is perhaps the most demanding stage of the entire risk assessment process. It involves a comparative analysis of risks and vulnerabilities for the full portfolio of hazard threats that are of concern to the community, and the final deliberation of mitigation alternatives with respect to policy goals (principles), management objectives (targets), and thresholds of risk tolerance (indicators). Analysis of the risk environment includes a consideration of disaster resilience with respect to both recurring low-impact hazard events and less frequent but potentially devastating events. Final deliberations about proposed mitigation alternatives must balance measures of effectiveness and efficiency (losses avoided) with measures of fairness, equity, and other policy objectives that may be considered in the broader context of growth management and sustainable development for a particular community or region.

Acceptable risks are those in which the potential for negative consequences exists, but is below target thresholds established for a comprehensive suite of policy goals and management objectives. In identifying a risk as acceptable, it is assumed that any negative consequences can be mitigated through routine investment in risk treatment options and that any residual risks will be counter-balanced by potential gains associated with a particular policy goal or management objective. Tolerable risks are those in which a potential for negative consequences for a given risk scenario exists, but can be reduced as low as reasonably practicable (ALARP) with available resources to achieve organizational objectives and realize potential gains (UK Health and Safety Commission, 2001). Intolerable risks are those in which a potential for negative consequences for a given risk scenario exceeds perceived benefits and thresholds of tolerability, and cannot be effectively or efficiently reduced with available mitigation resources.

4.2 5. Stage IV: Risk Treatment

Both the ISO 31000 standard and IRGC guideline include modelling, prioritization, and formulation of mitigation alternatives in the risk treatment stage. As defined in the Pathways process, risk treatment is limited to final deliberation, approval, and implementation of mitigation strategies that have been formulated and tested through an iterative process of analysis and evaluation. It marks the transition between knowledge generated through the risk assessment phase of the process to final action on the ground and the implementation of mitigation measures.

The Pathways framework does not explicitly address functions of risk treatment or implementation, as these will be determined by policy mandates and the specific legislative or institutional context in which the risk assessment is undertaken. However, it does offer a framework of target criteria and performance measures that can be used to support decision making and to monitor progress toward or away from policy goals and objectives during the final approval and implementation phases of the risk management process.

4.2 5..1 Step 7: Approval

The approval of risk treatment measures encompasses a formal process of decision making that will be dictated by existing legislative mandates for emergency management and comprehensive land use planning that are implemented at local and regional levels of government. It includes the assessment of institutional capabilities required to implement proposed mitigation measures in terms of technical, operational, social, and economic feasibility; the development of a disaster mitigation plan that outlines a recommended course of action with supporting rationale; and final judgment and the granting of authority to implement mitigation measures by agencies responsible for disaster mitigation in Canada.

4.2 5..2 Step 8: Implementation

The final stage of implementation involves the establishment of administrative protocols to oversee the execution of approved risk treatment measures and the monitoring and review of performance indicators to track progress with respect to management objectives (target criteria) and policy goals (principles). Information and knowledge gained through this process is used to adjust mitigation strategies to changing conditions of vulnerability through an ongoing process of adaptation and risk-based planning.

4.3 The Pathways Model

The Pathways framework introduces a model for integrated assessment and scenario planning that is defined by an internally coherent system of indicators and target criteria. Indicators reflect available information and knowledge about the risk environment and can be assessed using a combination of semi-quantitative and quantitative methods. Target criteria express intent with respect to a desired set of outcomes and help to establish thresholds of risk tolerance that will guide the planning and decision-making process.

The Pathways model is designed to assist planners in transforming available knowledge about risk into actionable mitigation strategies that are evidence-based and that reflect judgments of risk tolerance for a given community or region. The model is aligned with principles and policy goals of the National Disaster Mitigation Strategy and contributes to broader efforts to develop an all-hazard risk assessment framework for Canada. The model conforms to guidelines established in the literature for integrated assessment and evidence-based planning (Jaeger, 1998; Rotmans and Van Asselt, 2000; Durbach and Stewart, 2003a; Turner *et al.*, 2003; Swart *et al.*, 2004; Verburg *et al.*, 2004; Alcamo *et al.*, 2006; Montibeller *et al.*, 2006), and can be implemented using available best practices for risk assessment and scenario modelling.

As discussed in Chapter 3, risk-based planning is a multi-faceted process of analysis and deliberation that can introduce significant operational and cognitive challenges for those who must sift through the maze of facts and values in order to chart a navigable path towards resilience. Operational challenges include the management of large amounts of information used in characterizing the risk environment, and in measuring human, physical, and social dimensions of risk through semi-quantitative or quantitative analysis. Cognitive challenges include the analysis of risks that are complex or uncertain, and the evaluation of mitigation alternatives that require a balancing of trade-offs between diverse and often competing policy objectives.

As outlined in Chapter 2, there are limits to scientific knowledge for constraining uncertainties about complex system behaviour, and there will be competing interests and ethical perspectives on how best to chart a path forward. Addressing these challenges requires a shift from conventional modes of rational analysis to more integrative modes of assessment and scenario-based planning. At the national level, Public Safety Canada and Defence Research and Development Canada are working toward the development of a scenario-based framework for all-hazard risk assessment and capability-based planning that will enable decision makers to integrate available information and knowledge about the risk environment in order to identify policies that have a potential to promote public safety, increase economic security, and optimize mitigation investments at federal and provincial or territorial levels of government (Goudreau, 2009; Hales and Race, 2010)

The Pathways model contributes to these broader efforts by establishing a capability to analyze and evaluate risks associated with natural hazard threats at local and regional scales using established best practice methods of integrated assessment and scenario modelling. As illustrated in Figure 4-8, the model comprises an integrated suite of analytic and deliberative methods that transform information describing the human-natural system into a system of indicators that represent what is known about the risk environment. Associated target criteria utilize this knowledge to assess performance and to track progress with respect into policy goals and objectives.

Depending on the needs and operational requirements of the planning process, the assessment of target criteria and associated performance indicators may utilize methods of semi-quantitative or quantitative analysis. Semi-quantitative analysis can be undertaken on the basis of available knowledge and expertise using Delphi-based methods of risk appraisal. Quantitative risk analysis may require access to additional scientific knowledge or technical expertise to facilitate the use of specialized modelling applications that have been incorporated into the Pathways framework. These include public domain and commercial database and geographic information systems (GIS), FEMA's damage and

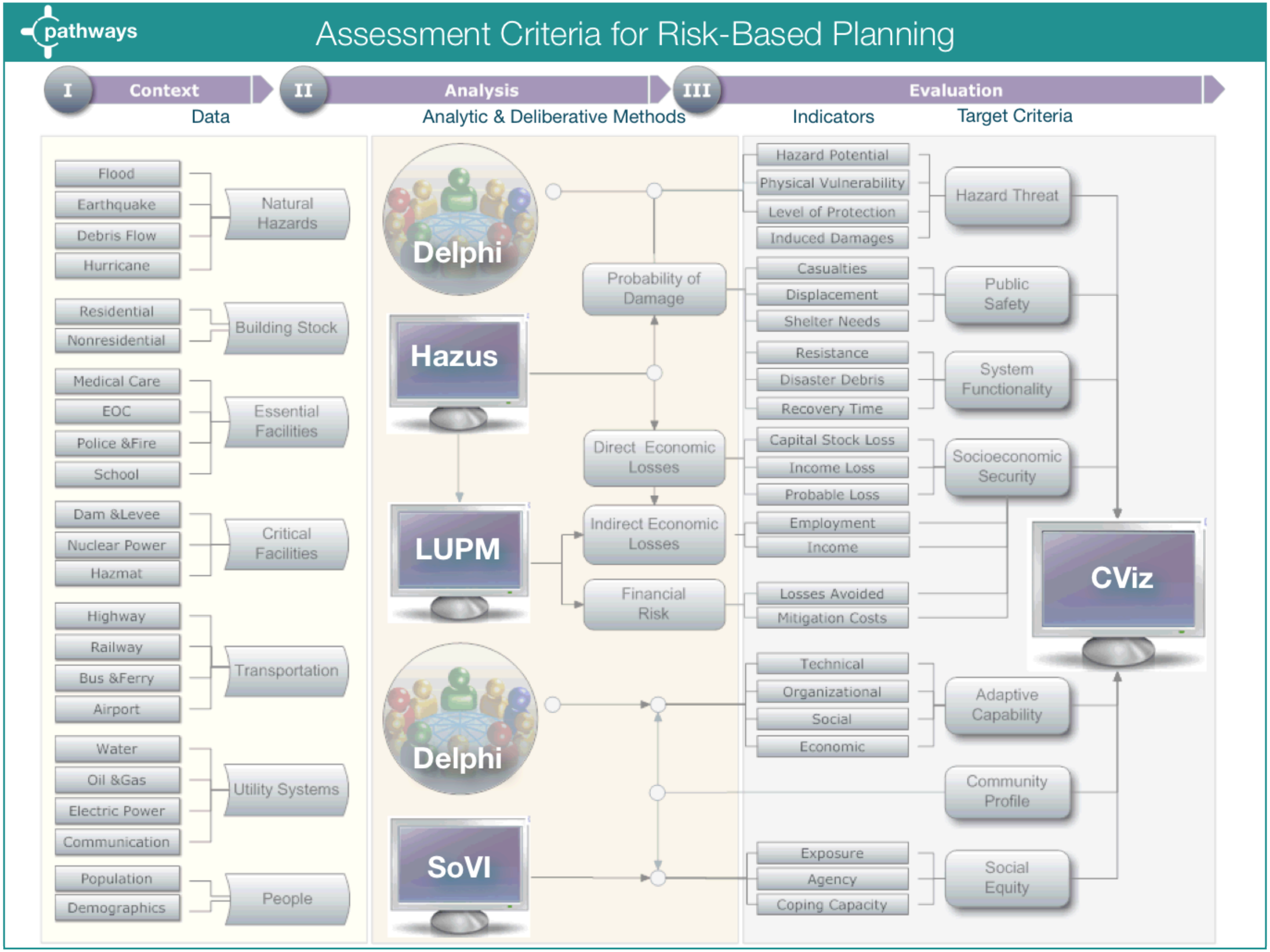


Figure 4-8: The Pathways model for integrated risk assessment showing the transformation of information used to characterize the risk environment into performance indicators and target criteria that provide structure to the overall process of planning and decision making.

loss estimation methodology (HAZUS), benefit-cost models (BCA) for analyzing financial risk, geo-statistical models for analyzing dimensions of social vulnerability (SoVI), and integrated landscape modelling applications (CommunityViz) that are used for multi-criteria analysis and scenario modelling.

4.3 1. An Overview of Target Criteria and Indicators

The Pathways model comprises a systyem of indicators that track both system conditions and policy targets. System indicators provide a means of assessing the human and physical dimensions of vulnerability. In the Pathways model, these include a set of indicators that describe patterns of human settlement and characteristics of the built environment in terms of population, demographics, and critical assets (Community Profile). Target criteria express intent and make explicit what needs to be achieved in order to reach a desired outcome without specifying how to make it happen. They provide a means of assessing progress with respect to a desired set of outcomes. Target criteria are used to measure: the intensity, likelihood and magnitude of natural processes that have a potential to cause physical damage (hazard threat); social impacts in terms of injury, loss of habitation and shelter needs (public safety); anticipated future economic losses and the financial risks of investing in disaster mitigation (socio-economic security); the capabilities of critical infrastructure and related lifeline services to withstand and recover from the impacts of a disaster event (system functionality); and intrinsic social vulnerabilities that will influence the capabilities of individuals and groups to respond to and recover from disaster events (social equity).

Target criteria reflect the outcomes of past or future policy choices and are used to establish goals and objectives for a desired future state of disaster resilience. To be effective in support of real-world decision making, targets must indicate a preference for whether the objective is to minimize, maximize, or optimize a desired outcome (directionality); have a capacity for full and meaningful assessment using the smallest number of measures (concise); encompass all aspects of the particular issue that are needed to make a choice (complete), and clearly define whether reported values represent quantitative or qualitative measures (Yoe, 2002).

When formulated with a desired future state in mind, target criteria and associated indicators offer members of the planning team a forward-looking perspective for analyzing available information and knowledge about the risk environment, for characterizing thresholds of tolerability based on community values, and for evaluating the efficacy of mitigation alternatives through the lens of local preferences and established policy guidelines. When incorporated into the full cycle of risk-based planning, target criteria offer decision makers a structured, transparent, and evidence-based framework for evaluating mitigation alternatives and choosing a path forward that advances overall policy objectives while minimizing any potential negative impacts on people and critical assets.

Table 4-5 is a summary of the six high-level risk assessment criteria and associated indicators that define the Pathways model. Each is described below in terms of overall scope and relevance to the planning process, sources of information used in measuring each of the indicators, and the supporting methods and tools that are used in the Pathways framework to facilitate the assessment process.

4.3 2. Community Profile

Community profile indicators provide a snapshot of existing system conditions for a particular town, municipality or region. They describe patterns of human settlement and physical characteristics of the built environment, and are used to increase situational awareness in support of strategic land use planning and emergency management operations. Patterns of human settlement are described in terms of population densities and demographic characteristics that define a community or region. The built environment is described in terms of the form and function of buildings and critical infrastructure, and the distribution of critical assets in the community. Collectively, these indicators are used to identify individuals and groups that may be vulnerable; building stock, critical infrastructure and related lifeline services that may be impacted by a hazard event; and additional features that are considered significant in terms of their socio-economic, cultural, or environmental value.

4.3 2..1 Population

Information about the densities, types, and locations of settlements across Canada is gathered on a regular basis though the national census. Spatial and temporal patterns of settlement are described by the numbers of people that are expected to be in a particular place (residence, place of work, etc.) at a specified time of day or night.

The two population groups most affected by disaster events include children (<5 years) and the elderly (>65 years). Both cohorts are generally more prone to minor and major life-threatening injury, and less able to respond in a timely and safe manner to disaster events due to diminished or compromised levels of health or fitness. The particular needs of these populations may increase load and demand for critical health care and social services during an emergency event and in the days and months following a disaster. However, tacit knowledge, judgment, and life experience of community elders may contribute significantly to response and recovery efforts by strengthening social fabric and assisting in the decision-making process.

Gender is a factor that can influence patterns of vulnerability in a community. Women may be less able to withstand and respond to the physical impacts of an unexpected hazard event due to care-giving responsibilities for the very young, the elderly, and the more vulnerable members of society. They may also have a more difficult time during recovery than men, often due to sector-specific employment, lower wages, and increased family-care duties. At the same time, women are more likely to be involved in community-building activities that collectively increase resilience and the capacities to respond to and recover from disaster events over time.

4.3 2..2 Demographics

Demographic characteristics are used in assessing vulnerable populations and patterns of social disadvantage that may be determined by family structure, income, education, ethnicity, language, mobility, employment, and housing type and occupation.

Large families and single-parent households often have limited finances to outsource care for dependents, and thus must juggle work responsibilities with care for family members. These factors may influence their capacity for response and recovery from disaster events. Those living alone in a community and without connection to a network of friends or family may also be vulnerable, but for different reasons; they may lack the ability to evacuate a dangerous situation on their own and are more likely to rely on others for assistance during an emergency.

Access to personal or family wealth enables communities to absorb and recover from losses more quickly in the aftermath of a disaster event. As made evident by circumstances of the Hurricane Katrina disaster, people with the available financial means were able to arrange for relocation and the provision of health care and basic services. Those with more limited resources and who relied on municipal, state, and federal agencies to provide monthly pension, disability, or unemployment insurance payments did not have the means to evacuate on their own. They were dependent on emergency operation services that failed to anticipate the demand for medical care and short-term shelter, thereby increasing social impacts on the most vulnerable members of the community.

Available housing stock has the capacity to increase or decrease vulnerability. People that rent typically do so because they are either predisposed to migrate due to circumstances of employment or do not have the financial resources for home ownership. Renters often lack access to information about financial aid during recovery, and in the most extreme cases they can lack sufficient shelter options when lodging becomes unsuitable or too costly.

Education can be linked to socio-economic status and has the capacity to limit awareness and understanding of the impacts and potential consequences of natural hazards. Higher educational levels generally correspond with increased capacities to access and interpret hazard-related information, greater lifetime earnings, and potential for political agency. Lower educational levels may constrain access to information and services, the ability to respond to warning and evacuation procedures, and may limit access to financial resources for recovery.

The extent to which people migrate within the country or emigrate from other countries over the course of their lifetimes can play a

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Assessment Criteria for Risk-Based Planning

Model Parameters

- Natural Hazards: Flood, Earthquake, Debris Flow, Hurricane
- Building Stock: Residential, Nonresidential
- Essential Facilities: Medical Care, EOC, Police &Fire, School
- Critical Facilities: Dam &Levee, Nuclear Power, Hazmat
- Transportation: Highway, Railway, Bus &Ferry, Airport
- Utility Systems: Water, Oil &Gas, Electric Power, Communication
- People: Population, Demographics

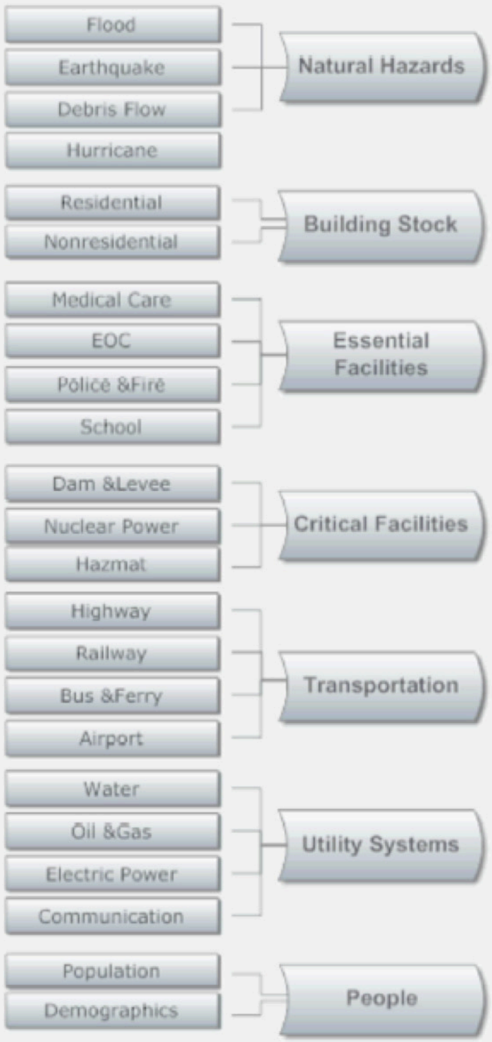
Community Profile

Descriptive Criteria: Physical characteristics of the built environment and patterns of human settlement described in terms of population and demographic variables derived from the National Census (Statistics Canada Community Profile Database)

Indicator	Description	Source	Relevance	Methods & Tools	*Qualitative Appraisal*	*Quantitative Analysis*
Population	Total population, the average number of people per dwelling and overall density on the landscape	Statistics Canada: Community Profile Data	planners, community members, domain experts	Beyond 20/20; CDMS& CommunityViz (Scenario360)	☐	☑
Demographics	Socioeconomic profile of the population described in terms of age, gender, ethnicity, household income and housing tenancy.	Statistics Canada: Community Profile Data	planners, community members, domain experts	Beyond 20/20; CDMS& CommunityViz (Scenario360)	☐	☑
Asset Inventory	Numbers and dollar exposure of buildings, essential facilities, critical facilities, and engineered structures that comprise transportation & utility system infrastructure	Statistics Canada; regional assessment authorities; local planning data	planners, community members, domain experts	Beyond 20/20; CDMS& CommunityViz (Scenario360)	☐	☑

Assessment Criteria for Risk-Based Planning

Model Parameters



Hazard Threat

Descriptive Criteria: Characteristics of the natural and built environment that will determine physical vulnerabilities and capabilities to withstand the impacts of hazard processes that have a potential to cause damage

Indicator	Description	Source	Relevance	Methods & Tools	*Qualitative Appraisal*	*Quantitative Analysis*
Hazard Potential	Expected severity of a specified hazard event, assessed in terms of area impacted, intensity and likelihood of occurrence	scientific research organizations	emergency managers, planners, community members, domain experts	DELPHI appraisal; HAZUS & CommunityViz (Scenario360)	✓	✓
Physical Vulnerability	Probability of reaching or exceeding a specified threshold of physical damage to buildings and/ or engineered structures	engineering damage functions relating hazard intensity to damage state	emergency managers, planners, domain experts	DELPHI appraisal; HAZUS & CommunityViz (Scenario360)	✓	✓
Level of Protection	Susceptibility of critical assets to the impacts and consequences of a hazard event; measured as the ratio of anticipated loss to dollar exposure of asset.	information derived from loss estimation models and asset inventory	emergency managers, planners, community members, domain experts, decision makers	DELPHI appraisal; HAZUS & CommunityViz (Scenario360)	✓	✓
Induced Damages	Number of ignitions and percent of area burned as a result of damages caused by ground shaking and/or permanent ground deformation.	empirical models that relate fire ignitions and % area burned to damage state	emergency manager, domain expert, decision maker	HAZUS & CommunityViz (Scenario360)		✓

Assessment Criteria for Risk-Based Planning

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Model Parameters

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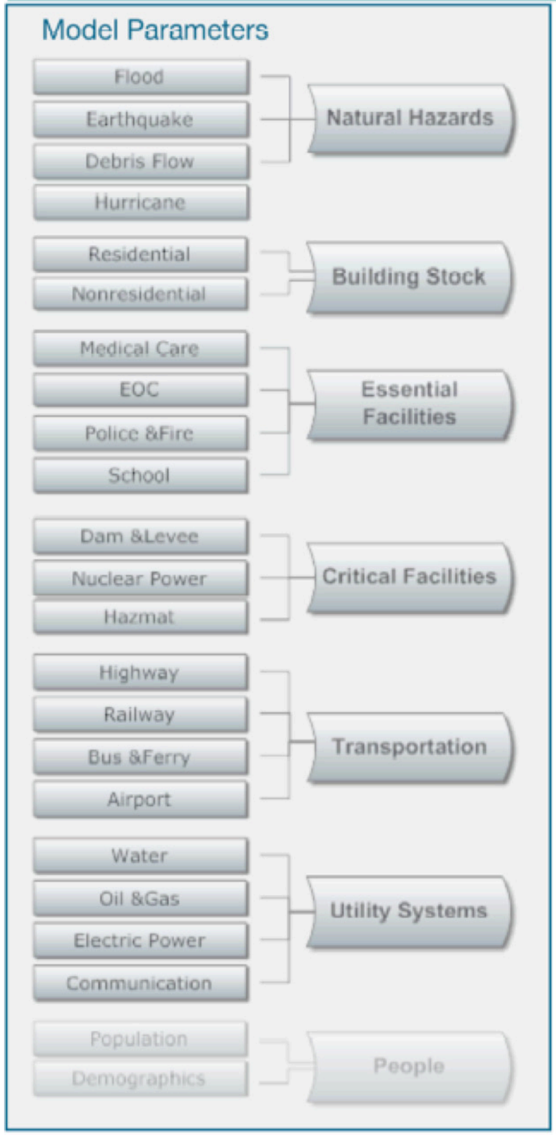
- Transportation: Highway, Railway, Bus &Ferry, Airport
- Utility Systems: Water, Oil &Gas, Electric Power, Communication
- People: Population, Demographics

Public Safety

Target Criteria: Maximize the safety of individuals and groups through mitigation efforts that reduce intrinsic physical vulnerabilities of a community or region, and the potential for casualties, social disruption and/or loss of critical lifeline services.

Indicator	Description	Source	Relevance	Methods & Tools	*Qualitative Appraisal*	*Quantitative Analysis*
Injuries & Fatalities	Extent and severity of injuries sustained by individuals as a result of direct and indirect impacts of a hazard event and the expected number of fatalities	empirical models relating hazard intensity to probable injury states	emergency managers, community members, domain experts, decision makers	DELPHI appraisal; HAZUS & CommunityViz (Scenario360)	☑	☑
Loss of Habitation	Number of households displaced as a result of physical damages that exceed minimum safety thresholds	empirical models relating hazard intensity to probable damage state	emergency managers, community members, domain experts, decision makers	HAZUS & CommunityViz (Scenario360)	☐	☑
Shelter Needs	Number of individuals who are likely to seek short-term emergency shelter following a disaster event	empirical models relating demographics of displaced households to shelter needs	emergency managers, community members, domain experts, decision makers	HAZUS & CommunityViz (Scenario360)	☐	☑

Assessment Criteria for Risk-Based Planning



Socioeconomic Security

Target Criteria: Maximize community wealth and the integrity of social, economic and environmental assets through investments in mitigation measures that protect what is considered of value and that yield a positive rate of return over time horizons of interest.

Indicator	Description	Source	Relevance	Methods & Tools	*Qualitative Appraisal*	*Quantitative Analysis*
Anticipated Loss	Capital stock and income-related losses resulting from a disaster event, assuming that it could occur at any given time	analytic models that relate level of maximum credible loss to damage state	domain expert, planner, community member, decision maker	DELPHI appraisal; HAZUS & CommunityViz (Scenario360)	☑	☑
Probable Loss	Capital stock and income-related losses resulting from a disaster event, assuming that the event could occur in any given year or over a iser-defined time horizon	event probability and analytic models that relate level of maximum credible loss to damage state	domain expert, planner, emergency manager decision maker	HAZUS & CommunityViz (Scenario360)	☐	☑
Expected Return on Investment	Total economic losses avoided by mitigation investment that have a potential to reduce vulnerability and/or risk	analytic models that compare the costs of mitigation with expected benefits for a given time interval	domain expert, planner, emergency manager, decision maker	HAZUS, LUPM & CommunityViz (Scenario360)	☐	☑

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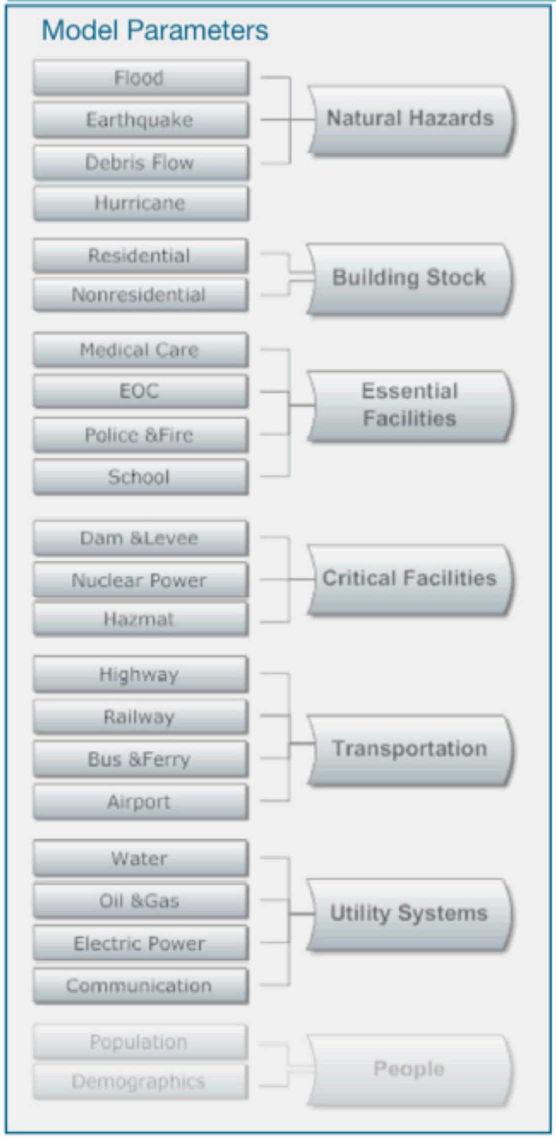
Assessment Criteria for Risk-Based Planning



System Functionality

Target Criteria: Maximize the capabilities of human-natural systems to withstand, respond to and recover from the impacts of a hazard event, and adapt to changing conditions of vulnerability and risk over time by optimizing functionality and service capacity in the event of a disaster.

Indicator	Description	Source	Relevance	Methods & Tools	*Qualitative Appraisal*	*Quantitative Analysis*
Resistance	Number of structures and/or the proportion of service capacity that remains functional following a disaster event	empirical models that relate functional capacity of engineered structures to damage state	emergency manager, domain expert, decision maker	HAZUS & CommunityViz (Scenario360)	☐	☑
Recovery Time	Capacity of system component to provide functional services in the days, weeks and months following a disaster event	empirical models that relate system functionality to damage state	emergency manager, planner, domain expert, decision maker	DELPHI appraisal; & CommunityViz (Scenario360)	☑	☑
Disaster Debris	Volume and type of waste material generated as a result of physical damage to buildings, contents or engineered structures.	empirical models that relate volume and type of disaster debris to damage state	emergency manager, planner, domain expert, decision maker	HAZUS & CommunityViz (Scenario360)	☐	☑
Adaptive Capability	Ability of an organization or community to withstand and respond to the impacts of potential hazard events	local knowledge, emergency management practitioners	emergency manager, domain expert, decision maker	DELPHI appraisal; & CommunityViz (Scenario360)	☑	☑

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- Transportation: Highway, Railway, Bus &Ferry, Airport
- Utility Systems: Water, Oil &Gas, Electric Power, Communication
- People: Population, Demographics

Social Equity

Target Criteria: Ensure the equity and fairness of risk management decisions by minimizing the extent to which vulnerable populations are exposed to hazard threats beyond their control, and maximizing their capability to respond and recover in the event of a disaster.

Indicator	Description	Source	Relevance	Methods & Tools	*Qualitative Appraisal*	*Quantitative Analysis*
Susceptibility	Geographic location and the physical characteristics that may pre-dispose a community to potential negative impacts of a hazard event	local knowledge, Statistics Canada: Community Profile Data	planner, emergency manager, community member, domain expert, decision maker	Principal Component Analysis; CommunityViz (Scenario360)	✓	✓
Agency	Disparities in household income and/or issues of race and ethnicity that may limit the ability of individuals and groups to make decisions that will directly influence their own well-being.	local knowledge, Statistics Canada: Community Profile Data	emergency manager, planner, community member, domain expert, decision maker	Principal Component Analysis; CommunityViz (Scenario360)	✓	✓
Coping Capacity	Demographic characteristics that may limit the ability of individuals and groups to cope with the impacts and consequences of a disaster event.	local knowledge, Statistics Canada: Community Profile Data	emergency manager, planner, community member, domain expert, decision maker	Principal Component Analysis; CommunityViz (Scenario360)	✓	✓

Table 4-5: An overview of the assessment criteria and associated indicators that collectively define the Pathways model for integrated risk assessment. The first two descriptive criteria (Community Profile and Hazard Exposure) provide situational awareness, while the remaining six target criteria (Public Safety, Socio-economic Security, Capacity, and Social Equity) are used to articulate a desired future state and to establish corresponding thresholds of risk tolerance.

significant role in determining the vulnerability of a place. Individuals and families that are new to the community are less likely to be familiar with the hazards of their new environment and therefore less aware of their vulnerability and risk. In addition, fast-growing communities with many new residents are often characterized by a large number of socially isolated households that have limited access to existing social networks during an emergency (Morrow, 1999). This lack of awareness and knowledge about the risk environment has the potential to influence decisions about housing location and general levels of preparedness. The ability to understand the official language of a community or region will determine the extent to which individuals and groups are able to respond to warnings and evacuation orders in the event of an emergency, and may limit their ability to make arrangements for their own safety and security during the recovery period.

Race and ethnicity may also contribute to vulnerability by increasing the potential for language and cultural barriers that can affect emergency response operations and the ability to access disaster relief funding through local, regional and federal agencies. Immigration status may also limit opportunities for occupational recovery and retraining.

Some occupations, especially those involving resource extraction, may be severely impacted by a hazard event. Those employed in resource industries suffer when production capabilities are lost and alternate means are not available to resume work in a timely fashion. Migrant workers engaged in agriculture and low-skilled service jobs (housekeeping, childcare, gardening) may similarly suffer as disposable income fades and the need for services declines. Reliance on single-sector employment for income generation promotes economic vulnerability by creating the potential for erratic cycles of boom and bust activity in resource, agriculture, and tourism industries and the communities and regions in which they operate. Cyclic variations or collapses in these industries can affect overall economic vitality and can compromise access to strategic community assets including food supply and basic services.

4.3 2..3 Built Environment

Physical elements of the built environment include such community assets as residential, commercial, and industrial structures and their contents; essential public and emergency response facilities; and natural features that provide ecosystem services. The built environment also includes critical infrastructure, such as the network of transportation, energy, water and communication systems and utilities that provide essential lifeline services for a community or region.

Provincial, territorial, and local or regional governments are responsible for maintaining detailed information on the physical environment for purposes of land and resource management and community planning. This includes information on land use (parcel fabric, zoning bylaws, etc.), property ownership, assessed value of land and building stock, and physical characteristics of residential, commercial and industrial buildings (location, address, age and type of construction, number of stories, etc.). Local and regional authorities share responsibilities with Crown corporations and private sector utility companies in maintaining information on critical infrastructure and lifeline services such as dam facilities, waterworks, transportation networks, energy, water, wastewater, and communication systems. Collectively, this information provides an essential baseline for describing key attributes of the physical environment.

Patterns of physical settlement are characterized on the basis of building types, occupancy classes, and forms of construction that are common in a North American context. Building types are classified in terms of the style and age of construction, and by the number of floors and overall square footage. Examples include light wood frame and un-reinforced masonry construction used for single storey and low-rise structures, and steel braced frame and reinforced concrete used in the construction of multi-storey and high-rise structures.

The general building stock inventory can include a description of individual building structures and/or building aggregates that represent the general form and character of larger chunks of the built environment such as neighbourhoods, planning areas, or census tracts. Age of construction provides an indirect measure of the level of protection and compliance with regulated safety thresholds for different hazard threats (ground shaking, severe wind, etc.). Older buildings that were constructed prior to the enforcement of modern building codes tend to be more susceptible to physical damage. Occupancy classes provide a means of characterizing overall building function. Examples include single and multi-family dwellings used for habitation, commercial and industrial buildings used for retail trade and fabrication, and public facilities such as churches, community halls, and government buildings.

Essential facilities represent a special class of building structures that provide emergency service functions during or after a hazard event. These include hospitals and related health care facilities, fire and police stations, dedicated emergency operation centres, and related facilities such as schools and community centres that provide shelter during and after a hazard event. In addition to describing these buildings in terms of construction type and form, they are further classified on the basis of specific functions or services they provide in support of emergency response and recovery operations.

Critical facilities are those engineered structures that if damaged by a hazard event would pose a particular threat in terms of the potential for loss or impacts on a community or region. They include storage facilities for industrial and hazardous materials, nuclear power generation plants, dams and related power generation facilities, levees and other protective structures (for floods, landslides, etc.), and military installations. Each of these structures are classified and described in terms of construction type, age, and specific attributes that are relevant with respect to the assessment of anthropogenic hazard threat (type and quantity of chemicals, level of safety, etc.).

Transportation infrastructure and related facilities represent key elements of the built environment. They are essential in maintaining the flow of goods and people to sustain local and regional economies, and in providing access to critical lifeline services in the event of an emergency. Transportation infrastructure includes highway and rail segments, bridge and tunnel structures, airport and public transit facilities, port facilities and related water-based transport infrastructure. Individual structures are classified on the basis of the type and form of construction, service capacity, and level of functionality in the event of an emergency.

Utility infrastructure and related systems provide services that are required to meet basic human needs and to support minimum levels of functionality in the event of an emergency. These include communication systems as well as physical installations, pipeline infrastructure and related distribution systems for potable water, wastewater, oil and natural gas. Each of these systems is classified in terms of type and year of construction, service capacity, and level of functionality in the event of an emergency.

Elements of cultural significance are those that are afforded value that cannot be directly measured in economic terms. Value can be attributed on the basis of historical significance, religious importance and cultural heritage, sense of place and aesthetics. Examples include heritage buildings, museum and rare library collections, churches and temples, religious and cultural artefacts that cannot be replaced, and landscape features and recreational amenities that are considered unique and that offer aesthetic value or contribute to the community's sense of identity. Although not often included in an assessment of direct economic losses, these features can represent a significant component of overall community wealth and often warrant special attention in terms of structural protection and safeguarding.

Elements of the natural environment that are likely to be of concern with respect to natural hazard threats include water resources, riparian zones, terrestrial and marine ecosystems and vulnerable species of animals, birds and plants that may be susceptible to the impacts of water inundation, slope instability, liquefaction, or sever weather conditions. Surface and groundwater resources are particularly vulnerable to the impacts of hazardous material spills or floodwaters that have inundated the built environment and have become contaminated with chemical or biological agents. The security of water resources encompasses the sustainable access to adequate quantities of water of acceptable quality, for human and environmental uses, on a watershed basis (Barnett, 2008). Access to potable water is of vital importance to response and recovery efforts and directly influences the longer-term resilience of a community. Loss of other key functions such as those provided by sensitive ecosystem habitat will have a direct bearing on overall environmental integrity and the capacity of natural systems to buffer the impacts of natural and anthropogenic threats.

4.3 3. *Hazard Threat*

Indicators of hazard threat provide insights on the likelihood, intensity, and probable impacts of natural processes that have a potential for damage to physical elements of the built environment. Information characterizing the severity and magnitude of a potential threat is referenced with respect to the probability of occurrence and spatial extent of a specific hazard event scenario. Indicators describing hazard potential are used to provide a common understanding of intrinsic physical vulnerabilities of the built environment and to assess the effectiveness and efficiencies of existing mitigation measures in providing overall protection to people and critical assets. The goal is to reduce credible threats to physical assets by developing mitigation strategies (e.g. building protective dykes and deflection berms) that minimize the extent or intensity of the hazard itself and that maximize the capability of critical assets to withstand the anticipated impacts of these hazard events over time.

Analyzing the exposure and susceptibility to natural hazards is typically the responsibility of domain experts working in science or engineering organizations, with specialized knowledge and a technical background in the analysis and predictive modelling of cause-effect relationships between natural and human systems. Assessments of hazard potential can be generated on the basis of existing knowledge about past events, deterministic modelling of cause-effect relationships, and statistical modelling of spatial relationships between event frequency and magnitude. Knowledge gained through observation and/or modelling is used to formulate hypotheses about natural processes that have a potential to trigger hazard events. Land use planners and emergency managers use the results of a hazard threat assessment to determine whether existing and proposed developments are safe for the use intended, and to identify strategies for further reducing vulnerability and risk through mitigation and emergency preparedness.

Physical vulnerability describes the extent to which elements of the built environment are able to withstand the impacts of a hazard event, and the expected levels of damage if a hazard event of known intensity occurs at some point in the future. Levels of vulnerability vary geographically as a function of hazard intensity (ground shaking, water depth, flow, velocity, etc.) and characteristics of building age and type of construction that influence structural fragility and overall damage potential. Level of protection describes the magnitude of a specific hazard event with respect to anticipated consequences. It is measured as the ratio of anticipated loss to asset value, and provides insights on how risks are distributed in a community or region and the effectiveness of existing mitigation measures.

4.3 3..1 *Hazard Potential*

The potential threat posed by a natural hazard is a function of *extent* (spatial footprint), *intensity* and *probability* of a specific event occurring over a specified time horizon. Each of these system variables represents a physical parameter that can be directly observed, objectively measured, or modelled. Knowledge of the earth system process and associated cause-effect relationships will influence decisions about who and what may be in harm's way, and whether site-level mitigation strategies are likely to be effective in reducing the areas impacted by a particular hazard threat.

The spatial extent of a natural hazard is a function of the scale at which earth system processes are operating, and is defined by the geographic area that could be impacted if an event were to occur at some point in the future. Earthquake ground shaking, volcanic eruption and flood hazards are controlled by large-scale earth system processes, and have a potential to impact areas that can encompass hundreds of square kilometres. Permanent ground deformation hazards such as liquefaction, landslides, and debris flows are controlled by more localized geologic processes with well-defined spatial extents that can be limited to individual structures or neighbourhoods.

Hazard intensity is a measure of the expected severity of physical processes at any given point on the landscape. For earthquakes, hazard intensity is measured in terms of seismic energy released as a result of sudden failure along zones of weakness in the earth's crust, and the resulting velocity, acceleration, and duration of ground shaking at the surface. The intensity of a flood event is measured by the depth of water at any given point. Depending on the capability to model impacts caused by the physical force of the water, intensity measurements for flooding may also include flow direction and velocity. Similarly, the intensity of a landslide, debris flow, or volcanic eruption hazard can be measured in terms of the depth and type of earth materials expected to be deposited at any given point along the path of the event, and the physical force of impact measured in terms of flow direction and velocity. Hazard intensities of hydro-meteorological events are measured in terms of the expected ground surface temperatures, the amount and duration of precipitation, and wind speed velocities at a given point on the landscape.

Hazard probability is an expression of the likelihood that a hazard event of a particular intensity or range of intensities will occur in a given area over a specified time horizon. It is measured as an expected level of uncertainty, where a minimum of 0 indicates an infinite level of error or uncertainty, and a maximum value of 1 indicates that the event will almost certainly occur over a specified time horizon. However, the interpretation and actual meaning of uncertainty, or the chance that a hazard event will occur, is a function of the time interval over which the hazard phenomenon is evaluated—a characteristic that can lead to significant confusion if not communicated clearly. For example, flood and landslide hazards are often reported in terms of an average recurrence interval, meaning that event(s) of a given intensity (or greater) are expected to occur on average within a specified period of time (e.g. a 1/200-year flood). Hazard likelihood may also be reported in the literature or in technical documents as a compound event probability. For example, an earthquake may be reported as having a probability of exceeding a minimum threshold of ground shaking over specified time intervals that can vary from 50 to 500 years (e.g. 2% in 50 years).

Depending on the time intervals used for reporting compound probabilities, hazard potential for a low-frequency/high-consequence event might appear to be comparable to the potential of a higher-frequency/lower-consequence event. Both may represent equivalent levels of risk, but for different reasons. Therefore, it is important to clarify the time horizon over which the hazard probability is reported, and to select a uniform time horizon for assessing the potential of multi-hazard events.

4.3 3..2 Physical Vulnerability

Physical vulnerability is a measure of the extent to which critical assets are likely to be damaged by the impacts of a hazard event with a known intensity and probability of occurrence. Physical damages will vary as a function of structural fragility and the effectiveness of mitigation efforts to increase structural resistance.

Fragility curves are calibrated for key elements of the built environment and are routinely used for analyzing and predicting damage states associated with the impacts of floods, earthquakes, and hurricanes (FEMA, 2004; Kircher *et al.*, 2006; Scawthorn *et al.*, 2006b; Schneider and Schauer, 2006; Vickery *et al.*, 2006b). Physical vulnerabilities associated with other natural hazards, such as landslides, forest fire and volcanic eruptions are not as well constrained by analytic models, but can be assessed on the basis of empirical observations that relate hazard intensity to measured states of damage in well-documented historic events.

4.3 3..3 Level of Protection

Level of protection is a composite indicator that measures the expected consequences of a hazard event on physical elements of the built environment. In the Pathways model, level of protection is assessed as the ratio between anticipated capital stock loss and dollar exposure for individual structures or selected elements of an asset portfolio. Anticipated capital stock loss represents the direct economic costs of replacing or repairing engineered structures and contents that are damaged by a hazard event. Dollar exposure represents the overall monetary value of the asset, measured in terms of total replacement costs. Level of protection can be determined on the basis of available knowledge and expertise using methods of semi-quantitative risk appraisal and quantitative risk analysis.

Resulting patterns of proportional loss provide insights on the capabilities of structures to withstand and recover from the impacts of a hazard event, and the effectiveness of existing or proposed mitigation measures in reducing levels of physical vulnerability and hazard potential. Areas with relatively high values of proportional loss might shed light on specific patterns of vulnerability related to age or type of construction, and on corresponding strategies that might be considered to mitigate the impacts of specific hazard threats. In some cases, these areas might be localized with a need for site-specific mitigation of individual structures. In situations where the pattern of proportional loss is driven by hazard potential, there may be a need to consider broader mitigation strategies that are effective in reducing the spatial impact or intensity of the hazard threat.

4.3 3..4 Induced Damages

In addition to direct damages caused by a hazard event, there is also the potential for induced damages caused by second-order hazard threats. Examples include inundation and fire following an earthquake, debris flows that are triggered by extreme weather events, and the release of hazardous materials from sites that have been compromised by the physical impacts of a disaster event. In some cases, such as earthquake-triggered tsunami, induced damages can exceed those sustained as a result of ground shaking by several orders of magnitude. In other cases, the extent of induced damage may be small by comparison but still have relevance in assessing overall hazard potential, physical vulnerability, and level of protection.

4.3 4. Public Safety

Ensuring the safety of citizens who are exposed to hazard threats beyond their control is perhaps one of the most fundamental public policy mandates for governments at all jurisdictional levels. In the context of land use planning, the overarching goal is to reduce the potential for loss of life by ensuring that existing and future development conforms to minimum thresholds of safety established through legislative guidelines or regulatory standards. For existing developments, the objective is to increase levels of protection through structural mitigation. For areas that have yet to be developed, the objective is to reduce physical vulnerability by ensuring that residential and commercial or industrial land use activities are situated out of harm's way. The consequences of these land use decisions will determine intrinsic levels of vulnerability for a community or region. Emergency managers address the implications of these decisions through preparedness and mitigation measures that seek to minimize potential threats to life and limb. In addition to reducing the potential for loss of life, the goal is to enhance the capability of people and systems to withstand and respond to the impacts of an unexpected hazard event.

Public safety indicators of the Pathways model provide insights on the anticipated human impacts of a hazard event to inform decisions for both land use planning and emergency management. Societal impacts are measured in terms of the probability of injury or death caused by physical impacts of a hazard event, and the anticipated level of emergency assistance that may be required to ensure the health and safety of individuals and groups who are displaced from their homes or do not have the capacity to provide for themselves. Management objectives and performance targets are expressed in terms of indicators that track the extent and severity of injuries and fatalities, anticipated levels of assistance or intervention required during or immediately after the impact of a hazard event (shelter requirements), and the requirement to provide basic and essential services through emergency management operations.

4.3 4..1 Injuries and Fatalities

Casualty scales provide a means of communicating the severity of a disaster event in terms of the anticipated number and type of injuries for a given hazard event, and the implications for medical care and emergency services. The US Federal Emergency Management Agency uses a graduated casualty scale that is defined by four levels of injury (Federal Emergency Management Agency, 2006b).

A Level 1 injury is characterized by severe cuts, first and second degree burns on a small part of the body, strained ligaments, and blows to the head not resulting in a loss of consciousness. These are injuries that would require observation, diagnosis and first aid treatment by qualified paraprofessionals. A Level 2 injury is one that would require a greater degree of medical care but is not likely to progress to life-threatening status. Examples might include severe cuts, second and third degree burns over large parts of the body, head injuries resulting in loss of consciousness, fractured bones, dehydration, and exposure to severe weather conditions. These types of injuries would likely require access to emergency care facilities for specialized medical services and surgery. Level 3 injuries pose an immediate threat to life if not treated in a timely manner, and are likely to require hospitalization for specialized medical treatment. Examples might include severe cuts resulting in uncontrolled bleeding, internal injuries, multiple bone fractures, spinal column injuries, and injures related to crushing. Level 4 injuries include those that exceed the capability for medical treatment, leading to instantaneous loss of life resulting from the sudden impacts of a hazard event.

The number and severity of injuries sustained in a disaster event will be influenced by the vulnerability of individuals and groups who are exposed to impacts of a hazard event by their physical location, their ability to respond to early warning to get out of harm's way prior to the event occurring, and the capacity of emergency services to respond with medical aid, shelter, and basic services. Land use decisions have the capacity to reduce the potential for loss of life by situating residential and commercial or industrial activities in areas where hazard impacts are not likely to result in injuries that exceed a Level 2 threshold. Emergency management decisions have the capacity to reduce the potential for loss of life by ensuring that medical care facilities are situated out of harm's way, and have the capability to provide both paramedical and specialized treatment for those in need.

4.3 4..2 Loss of Habitation

Sudden and unexpected natural hazard events have the potential to render homes and businesses uninhabitable as a result of direct physical damages to buildings and the indirect loss of essential lifeline services (water and power). Households and businesses may also be displaced as a result of induced damages, such as fire following an earthquake, the threat of inundation caused by the collapse of flood protection measures, and the uncontrolled release of hazardous materials.

The extent of physical damage and functional capabilities of lifeline services following a disaster event will determine the length of time that people are displaced from their homes and their requirement for short-term shelter or longer-term solutions. Emergency managers use this information in pre-event planning and preparedness operations to ensure there is a capability to address the anticipated needs for food and shelter. Local governments use this information to develop contingency plans for situations in which there may be a need to replace housing stock to support longer-term recovery operations.

4.3 4..3 Shelter Needs

Those who have been displaced from their homes as a result of a disaster event will seek alternate shelter in a variety of different ways. Some may seek temporary shelter with friends and family in neighbouring areas that have not been impacted, while others may opt for rental accommodation until they are able to return home. Those who do not have friends or family in the area, or who lack the means to arrange alternate accommodation on their own, are likely to seek short-term emergency shelter in public facilities. The proportion of individuals seeking short-term emergency shelter will be influenced by cultural norms and demographic variables that may vary widely from place to place. The ability to anticipate demands for public shelter is a basic requirement for pre-event planning and emergency preparedness operations.

Each of the public safety indicators in the Pathways model provides information relevant to the assessment of overall societal risk. Together, they offer a capability to assess whether existing or proposed land use activities are likely to be safe with respect to established legislative or regulatory guidelines, and to help make evident any gaps that may exist between anticipated needs for emergency services during response and recovery operations and the capabilities of local authorities to provide these services. In most cases, mitigation targets that minimize the potential for loss of life will trump all other public policy objectives. The choice of strategies for reducing societal risk through proactive land use activities and structural mitigation will also have significant implications for policy trade-offs that may need to be considered to establish a tolerable threshold of safety for both existing and future conditions.

4.3 5. Socio-economic Security

Socio-economic security is a measure of community wealth and the integrity of social, economic, and environmental assets that may be exposed to the impacts and consequences of a disaster event at some point in the future. Indicators of socio-economic security in the Pathways model track anticipated losses if the disaster event were to occur at some point in the future, the probable economic consequences of this same event over a specified planning horizon, and the relative costs and benefits of investing in mitigation measures over time. As a policy objective, the goal is to maximize the security of community wealth through strategic investments in mitigation measures that protect what is considered of value and that will yield a positive rate of return over time horizons of interest.

The level of socio-economic security for a community or region will vary as a function of intrinsic physical vulnerabilities, the economic value of community assets, and the vitality of social and economic networks following a disaster event. Community wealth is measured by investments in general building stock, physical contents, critical infrastructure and lifeline services that promote local or regional economic vitality, and by landscape features that provide environmental, historical and cultural value to a place and its people. Socio-economic security also encompasses the flow of goods and services and the human relationships that sustain a community or region. Target criteria for measuring socio-economic security might include minimum levels of economic loss that can be sustained by a community or region without external disaster relief, and the level of disruption that can be absorbed by human systems without affecting their capacity to respond and recover over time.

4.3 5..1 Anticipated Loss

Indicators of anticipated loss measure both direct and indirect economic consequences of a hazard event that is assumed to occur at some point in the immediate future. They provide insights on what could happen in a worst-case scenario, but do not account for the likelihood of these losses occurring over a given time horizon.

Direct losses include both anticipated capital costs of a hazard event and income-related losses sustained through reduced functionality and service capacity. Capital costs include investments that must be made to repair or restore buildings and infrastructure and to replace building contents and business inventory that have been damaged as a result of a hazard event. Income-related costs include loss of wages, relocation expenses and lost revenue from commercial and rental transactions that are disrupted by the impacts of a hazard event. Indirect economic losses include local impacts on the quality of life for a given community or region, and the anticipated upstream and downstream disruptions to employment and income flow within and between major economic sectors.

The magnitude of anticipated loss for a specific hazard event is a function of damage potential, asset value, and the effectiveness of existing or proposed mitigation measures in reducing both physical impacts and downstream economic consequences. Indicators of anticipated economic loss are used in the context of land use planning to inform decisions about where to locate critical assets, and to negotiate what may constitute a tolerable threshold of financial risk for a given community or region. In the context of pre-event planning and emergency preparedness, indicators of anticipated loss are used to assess the capability of a community or region to bear the financial consequences of a hazard event and the level of disaster relief assistance that may be required to restore economic viability of homes and businesses over time.

4.3 5..2 Probable Consequences

Indicators of probable consequence extend the scope of simple cause-effect loss estimates by taking into account the probability that an event of a given intensity or magnitude will occur over time frames that are relevant to the local planning process. For shorter planning horizons of 5–10 years, there may be little or no difference in expected losses between high-probability/low-consequence events such as a flood or extreme weather storm and lower-probability/higher-consequence events like an earthquake or landslide. For longer time horizons of 30–100 years, the probability of loss from disaster events increases exponentially to levels that have a potential to overwhelm the capabilities of local and regional governments to respond and recover.

This forward-looking assessment of probable loss provides valuable input to strategic planning decisions about land use and infrastructure development that must consider how to optimize investments in critical assets. Since the future pattern of economic risk is uncertain, investments in mitigation measures need to be justified economically on the basis of losses that are avoided on average every year or over a specified planning horizon. Depending on requirements of the risk management process, thresholds of risk tolerance can be evaluated on the basis of average annual loss (AAL) or probable maximum loss (PML).

Average Annual Loss (AAL) provides a measure of anticipated losses for all hazard events in a given risk scenario for a given year. It is based on the assumption that hazard events can be modelled as independent random events (Bernoulli random variables), and that the intensity and associated consequences of these events are uniform from year to year. An analysis of average annual losses for a community or region provides a baseline for determining thresholds of risk that can be managed on a year-to-year basis with available resources. By varying the planning horizon, average annual losses can be assessed for time intervals that might be relevant to a particular planning process. Comprehensive land use planning, for example, is often framed in terms of a 30- to 40-year time horizon. Strategic planning for critical infrastructure is typically framed in terms of a 100 to 150-year time horizon.

However, there is a danger that resulting hazard risk values based on cumulative average annual loss over a relatively short time interval may inadvertently bias the risk management and decision-making process by focusing attention on high-probability/low-consequence events. Because AAL is defined as the product of consequence and likelihood of occurrence, lower probability but potentially disastrous events can yield equivalent values of average annual loss that in some cases may even appear insignificant in comparison with those of higher-probability/lower-consequence events. Consider the portfolio of hypothetical hazard risks in Table 4-6. Those events with the lowest probability of occurrence (Hazard Events 1-5) represent tens of thousands of dollars in average annual losses, and appear to be on par with higher-probability/lower-consequence events. However, if one of these lower-probability events were to occur, there is potential that it could trigger hundreds of millions of dollars in direct economic losses, likely overwhelming financial capabilities of the community or region. The choice of time horizon will, therefore, have a direct bearing on what may be considered a tolerable threshold of risk.

Probable maximum loss (PML) is an alternate way of framing the overall risk profile for a portfolio of hazard threats that may vary widely in terms of their likelihood of occurrence and their potential for negative consequence (Kunreuther and Lerner-Lam, 2002; Grossi et al., 2005). PML is, by definition, the probability of *not exceeding* a specified threshold of loss for a collection of hazard events that may or may not occur over a time period of interest. As illustrated in Table 4-6, hazard events with lower probabilities of exceeding a specified threshold are less frequent, but have the potential for greater economic losses. More frequent events have a higher probability of exceeding a specified level of loss, but are likely to result in lower levels of damage and economic consequence.

There are several important ways in which a community might use information on probable consequences to inform strategic planning decisions. Information on expected average annual loss (AAL) is helpful in determining the level of investment that is required to ensure self-reliance on an ongoing basis. This might take the form of a local emergency relief fund that is budgeted on a year-to-year basis to invest in ongoing maintenance and upgrades of existing mitigation works or to manage the consequences of frequent but low-magnitude hazard events that may occur unexpectedly (riparian flooding, extreme weather, etc.).

Information on probable maximum loss (PML) is helpful in assessing where to situate critical community assets that are likely to establish patterns of land use over longer time frames, such as transportation and utility infrastructure, and the level of protection that may be required to ensure the security of financial investments in these critical assets over time. Indicators of probable maximum loss might also be used to

Quantitative Risk Analysis - *Multi-Hazard Risk Profile*

Hazard Event (EI)	Annual probability of occurrence (PI)	Loss (LI) dollars CDN	Probability of exceeding loss [EP(LI)]	E[L]=(p*LI) dollars
1	0.00011	$758,542,530	0.00011	$83,440
2	0.00011	$567,892,460	0.00022	$62,468
3	0.0002	$312,432,113	0.00042	$62,486
4	0.00045	$152,114,785	0.00087	$68,452
5	0.0009	$78,487,629	0.00177	$70,639
6	0.0042	$21,248,215	0.00596	$89,243
7	0.005	$12,567,321	0.01093	$62,837
8	0.015	$5,468,213	0.02577	$82,023
9	0.025	$3,465,981	0.05012	$86,650
10	0.05	$1,435,962	0.09762	$71,798
11	0.065	$750,623	0.15627	$48,790
12	0.08	$326,712	0.22377	$26,137
			Average Annual Loss (AAL) =	$814,962

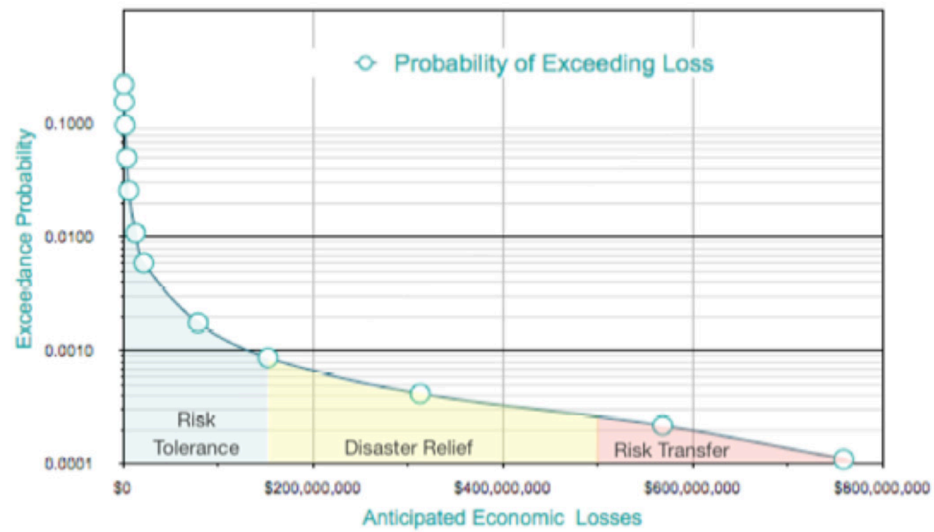


Table 4-6: Table and graph summarizing an assessment of Average Annual Loss (AAL) and Probable Maximum Loss (PML) for a hypothetical portfolio of hazard threats.

inform decisions about the location and overall design of proposed comprehensive neighbourhood development in areas that are exposed to natural hazard threats and the capacity of local governments to assume the risks of developing in these areas over the foreseeable future. In either case, there is a need to assess how patterns of community wealth are likely to evolve as conditions of vulnerability change and investments in critical assets continue to grow.

4.3 5..3 Return on Mitigation Investment

Return on investment (ROI) is a measure of overall financial risk—the balance between benefits gained and costs incurred by investing in mitigation to reduce underlying vulnerabilities or the consequences of hazard events with a potential to cause damage over planning horizons of interest. It is influenced by the effectiveness of mitigation measures in reducing probable consequences for a specific portfolio of community assets and the probability of recovering initial mitigation investments over a given period of time. Thresholds of resource efficiency provide a measure of overall financial risk and are usually expressed in terms of a minimum rate of return on the investment portfolio. The goal is to maintain or increase community wealth through the implementation of risk treatment measures that promote public safety and socio-economic security for existing and emerging hazard threats.

A mitigation portfolio is considered financially risky if the expected rate of return does not meet a designated threshold of performance. Examples of mitigation alternatives include direct capital investment in protective structures to reduce the probability of damage (levees, structural reinforcements, building retrofits, etc.), relocation of existing assets that can not be reasonably protected from hazard threats with available resources, and redirection of future development and associated infrastructure services to reduce vulnerability. Variables that influence the probable rates of return on a mitigation portfolio include scientific uncertainties regarding hazard potential (extent, intensity, and probability of occurrence), the effectiveness of existing and proposed mitigation measures to resist the physical impacts of a hazard threat, and the performance of local and regional economic markets that may be directly or indirectly influenced by risk management decisions.

Consider the example of a community that seeks to reduce financial risks by choosing a mitigation strategy from a set of policy alternatives that each offer potential benefits (Wein *et al.*, 2007). As illustrated in Figure 4-9, two options are considered and compared with respect to a business-as-usual baseline scenario. Option A represents a structural mitigation scenario that involves significant capital investment in protective measures (flood levees). The mitigation measures are assumed to protect community assets for flood depths that correspond with a 1/200-year event (PA = 0.005). The expectation is that investment in levee construction will have the effect of reducing damage potential and the likelihood of exceeding a minimum threshold of tolerable risk. Option B represents a mixed scenario that involves the removal of existing structures that exceed thresholds of tolerable risk, and the redirection of future growth and development into areas that are exposed to lower hazard threat. The direct costs of mitigation are significantly less than for Option A, but do not offer a consistent level of protection for the community. The expectation is that short-term capital investments of relocation and the future costs of building in less hazardous areas will reduce physical vulnerability through avoidance, thereby stabilizing the risk profile for flooding.

As illustrated in Figure 4-9, the more expensive mitigation scenario (Option A) yields the highest expected return on investment for low-frequency/high-consequence events, but is not an efficient choice for managing more frequent, smaller events. The underlying assumptions are that the levee is effective in protecting community assets up to the designated levels of safety for existing and future settlement, and that the levee will not be compromised or fail unexpectedly due to unforeseen design flaws or structural weaknesses. Option B is a more efficient choice for managing high-frequency/low-consequence events in

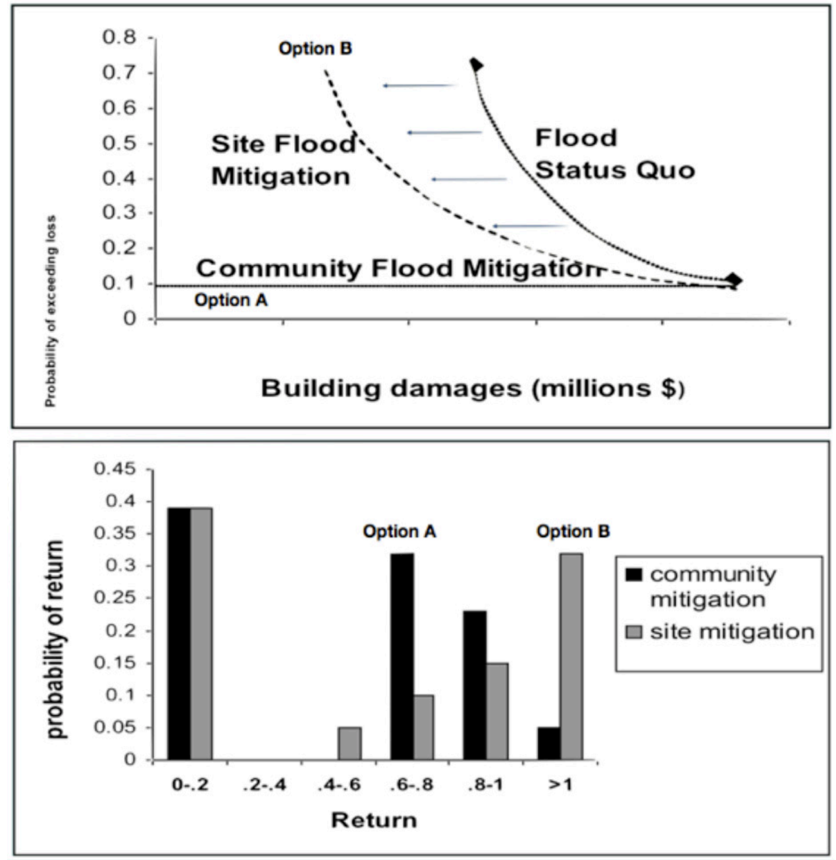


Figure 4-9: Expected rate of return on investment based on a comparison of mitigation alternatives for managing flood hazards (Wein et al., 2007)

the near term, and has the potential to yield equivalent or higher rates of return for future patterns of growth and development. The underlying assumptions are that high-risk assets are relocated before the next large flood event occurs, that risk avoidance policies are enforced through land use and local zoning bylaws, and that these policies are effective in redirecting future growth and development away from areas that are exposed to hazard threats.

A portfolio-based approach to financial risk management provides a measure of utility that is often required to justify the expenditure of public funds to pursue policy objectives. Community wealth is considered optimized if mitigation investments are shown to have a positive return on investment. An underlying assumption is that those benefiting from a specific mitigation investment should be able to compensate those that may be disadvantaged by it. The paradox of risk governance is that this is rarely the case (Burby, 2006)

4.3 6. System Functionality

As a policy objective, system functionality is used in the Pathways model to assess the capability of complex human-natural systems to absorb the impacts of sudden shocks that threaten structural coherence and functional integrity, and the capability of these systems to evolve and adapt to changing conditions of vulnerability over time. The goals are to increase the resistance of system components to potential hazard impacts, and to reduce the amount of time required to restore essential functions and lifeline services to pre-disaster levels. Performance targets are expressed in terms of indicators that track dimensions of resistance, debris generation, recovery time, and adaptive capacity.

The assessment of system functionality relies on domain-specific information and expertise provided by technical experts working in the fields of engineering and municipal operations. Knowledge gained through the assessment of system functionality helps inform land use decisions that promote structural resilience for existing and future developments, and emergency management operations that seek to increase capabilities for response and recovery in the event of a disaster. Depending on the availability of technical knowledge and expertise, system functionality can be assessed on the basis of empirical engineering models or a working understanding of how system components are likely to respond in the event of a sudden shock.

4.3 6..1 Resistance

Resistance is a measure of the capacity for buildings and engineered structures to withstand the physical impacts of a disaster event. The level of resistance for elements of the built environment is a function of hazard intensity and the physical vulnerabilities of both structural and non-structural elements of the system.

The resistance of buildings exposed to earthquake hazards is measured using engineering capacity curves that describe the expected response to ground shaking in terms of yield and ultimate strength. Buildings that are deformed beyond their capacity to respond and recover will sustain permanent physical damages that undermine structural integrity and that reduce system functionality. The level of resistance will determine the extent of damage, and the costs of restoring system functionality to pre-event levels through repair or replacement. In the case of floods, resistance reflects the capability of a building and its contents to withstand sustained periods of inundation without compromising structural integrity and functionality. Buildings that sustain flood damages of 10–50% are generally considered uninhabitable and in need of extensive repairs to restore baseline levels of functionality. Buildings that exceed 50% flood damage are considered beyond repair and would likely need to be replaced.

The resistance of transportation and utility systems is measured in terms of functional capacities that are retained following a disaster event, assessed with respect to baseline service levels prior to the event. In each system, there are components that will be more or less vulnerable than others. However, because they are connected and interdependent, damages to parts of a system are likely to compromise the integrity and functional capacity of the system overall. Bridges and tunnels that span waterways are particularly vulnerable elements of a transportation system. Damages sustained as a result of an earthquake, flood, or other natural hazard have the potential to cause major disruption and loss of functionality to the transportation system itself, and will have significant impacts on emergency response operations and the flow of goods and services that are required to sustain a community or region during the recovery process. The same is true for utility systems. Damages caused to water, gas, and oil pipelines may reduce overall functionality until segments can be repaired or replaced. While the disruptions can be significant, they do not necessarily undermine the overall functional capacity of the system. However, if components of a system that supply basic lifeline services are not resistant to the impacts of a hazard event, the entire system can be rendered non-functional. Water, gas, oil, and electrical power facilities are particularly vulnerable to the impacts of earthquake and flood hazards. Emergency response and recovery operations can be crippled in situations where these facilities are damaged beyond their capacity to respond and recover.

The capacity of engineered structures to withstand the physical impacts of a disaster event can be represented graphically by the loss of system functionality on a response-recovery curve. As illustrated in Figure 4-10, resistance is a measure of system functionality that is retained immediately after the hazard impact (red line in Figure 4-10). It can be enhanced through beforehand (*ex-ante*) efforts that minimize the exposure to hazard threats and minimize the vulnerability of system components through a blend of structural and non-structural mitigation measures (McDaniels *et al.*, 2008).

4.3 6..2 Recovery Time

Recovery is a measure of the rate at which system performance is restored over time (blue line in Figure 4-10). Recovery times for damaged buildings and critical infrastructure can range from several weeks to several years. The length of time required for recovery and the capacity to adapt to changing system conditions will have a direct bearing on overall resilience of a community or region. System resilience can be increased through *ex-ante* efforts that increase overall structural resistance through mitigation (deference between scenario 1 and 2 in Figure 4-10), and efforts after the fact (*ex-post*) that increase the efficacy of response and recovery operations through pre-event planning and early warning (dashed line in Figure 4-10). Both have the effect of reducing the amount of time required to restore system functionality.

Indicators that track system performance over time can be useful in assessing overall disaster resilience. Systems that are characterized by a higher level of resilience would experience relatively small levels of disruption, and would likely recover to baseline performance levels in a relatively short period of time. In some instances, these systems may even experience a net improvement as a result of *ex-post* mitigation measures that increase the adaptive capacity of the system during the recovery period. Systems that are characterized by lower levels of resilience would experience a relatively large drop in performance, would take longer to restore minimum thresholds of performance, and may never recover to pre-event states of functionality.

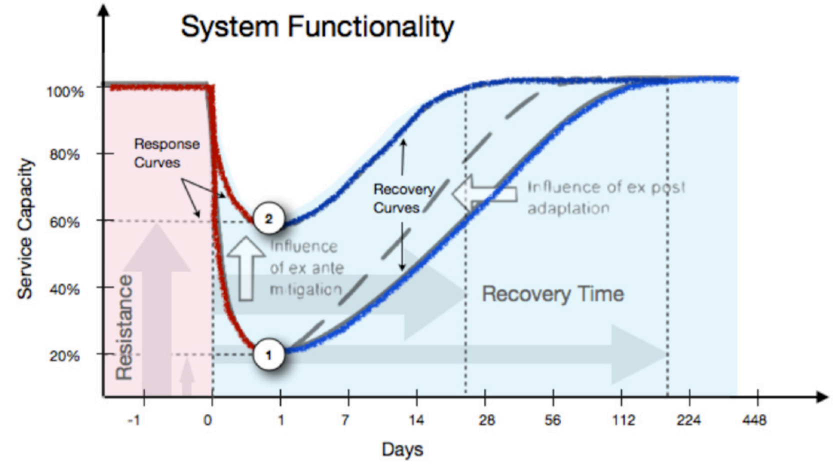


Figure 4-10: Response-Recovery profile for systems that are damaged in a disaster event. The proportion of service capacity that remains immediately after the event provides a measure of overall resistance. Recovery is measured by the time required to restore service capacity to pre-event baseline levels of system functionality. Scenario 1 describes the performance of a system that is characterized by low resistance and long recovery intervals. Scenario 2 describes performance characteristics of the same system as a result of ex-ante and ex-post mitigation. (adapted from: Miles and Chang, 2006; McDaniels et al., 2008, pg 312).

4.3 6..3 Disaster Debris

The capacity to respond and recover from a disaster event can be hampered by debris materials generated as a result of damages to buildings, contents, and critical infrastructure. Indicators used in the Pathways model provide insights on the type and volume of debris material that is likely to be generated for a given hazard risk scenario. Knowledge gained as part of the assessment process is used to inform land use decisions about building retrofits and special design considerations that may be required to reduce debris generation in areas exposed to natural hazards, and to make evident the requirements for debris removal to assist in post-event recovery planning and emergency preparedness operations.

The type and amount of debris material generated will vary as a function of the age and type of construction, the intensity of the hazard event, and the resistance of individual structures. Debris that is likely to be generated as a result of a natural hazard includes a mix of foundation materials and non-structural elements that are produced by shaking or collapse. Foundation debris includes a mix of brick, wood, and concrete materials that can be managed with bulldozers and other non-specialized machinery, and a second category of steel and reinforced concrete elements that may require special treatment in order to be broken into pieces that are small enough to be hauled away. Non-structural debris includes finish materials, building contents, and business inventory that are damaged beyond repair.

The amount of debris material generated in a single event can exceed the total volume of solid waste that is produced and sent to landfills by a community or region over the course of several years (Wojtarowicz, 2000; Brown *et al.*, 2010). In addition to undermining disaster response operations, the volume of disaster debris can easily overwhelm the capability of a community or region to manage the consequences during the recovery period.

4.3 6..4 Adaptive Capability

Capability is a measure of the extent to which an organization or community can anticipate and respond to the impacts of hazard events, and recover from the consequences of these events in order to realize potential net benefits over time. As defined, it is a relative measure that is often assessed in terms of levels of effectiveness and functionality. Pathways conforms to guidelines established by the Multidisciplinary Center for Earthquake Engineering Research (MCEER) for assessing capabilities of the human-natural system in terms of technical, organization, social and economic attributes (Bruneau *et al.*, 2003; Chang and Chamberlin, 2004; Chang and Shinozuka, 2004). The capability to respond and recover can be assessed using a blend of semi-quantitative and quantitative methods of analysis.

Technical dimensions of capability measure the extent to which structural systems and their components are able to withstand immediate and induced physical impacts of a hazard threat in accordance with accepted or desired levels of performance and efficiency, and their potential to recover these base levels of functionality over time. Organizational capabilities measure the extent to which public and private sectors are able to undertake appropriate levels of emergency preparedness and strategic planning to limit exposure to hazard threats (protection, regulation, land use zoning, etc.), to warn of impending threats (early warning systems), and to assist the community in responding to and recovering from the impacts of hazard events. Social capability measures the integrity, cohesiveness and robustness of social networks as evidenced by levels of communication and consultation, risk awareness and understanding, and by participation (volunteerism) in personal and community preparedness. Finally, economic capability refelcts available economic resources to implement risk treatment measures through dedicated organizational budgets and mitigation/capital improvement loans, and to respond to anticipated consequences of potential hazard events through risk transfer mechanisms including financial insurance/re-insurance markets and disaster relief funds.

4.3 7. Social Equity

Equity reflects intent to establish and maintain a balance in the distribution of risk across all sectors and demographic elements of a community, including individuals and groups of an existing population and those of future generations. Target criteria and indicators are expressed in terms of hazard susceptibility, the agency of individuals and groups to make decisions that will directly influence their own well-being, and the ability of these individuals and groups to cope with the impacts and consequences of a disaster event.

Patterns of social equity can change abruptly over time and are influenced by a wide range of scale-dependent variables including political stability, economic vitality, cultural norms, and shifting demographic patterns that reflect the passage of time and the movement of people from place to place. Target thresholds are generally referenced to baseline conditions of a community at a given point in time. They might include the level of exposure to known hazard threats across all neighbourhoods in a community or region, levels of social justice, and access to emergency response services.

Knowledge gained as part of the assessment process is used to inform long-range comprehensive planning to improve overall quality of life, and to provide situational awareness about the location and particular needs of vulnerable populations in the event of an emergency. The goals are to ensure the equity and fairness of risk management decisions by minimizing the extent to which vulnerable populations are exposed to natural hazard threats that are beyond their control and to maximize their capability to respond and recover in the event of a disaster.

4.3 7..1 Susceptibility

Susceptibility is a measure of physical exposure to natural hazard threats. Variables that influence the extent to which vulnerable populations are situated in harm's way include geographic location with respect to existing or emerging hazard threats; the age and condition of residential building stock; housing tenancy; and proximity to commercial or industrial activities that may pose second-order threats resulting from the impacts of a natural hazard.

Geographic location is perhaps the most important variable influencing patterns of susceptibility in a community. Residential settlements located in low-lying areas adjacent to coastlines and along river valleys are exposed to higher levels of damage caused by flooding and earthquake-triggered liquefaction. Older neighbourhoods in many communities reflect construction practices that pre-date modern building safety guidelines for natural hazards, and tend to be situated near commercial or industrial centres that can pose additional second-order threats such as fire and accidental release of hazardous materials. It is not uncommon for many of these neighbourhoods to be occupied by older citizens living alone, lower-income families, transients, and those seeking rental accommodation close to their place of work. In many cases, these are also the more vulnerable populations of a community.

4.3 7..2 Agency

Agency is the degree of influence an individual or group may have in dealing with the impacts or consequences of a hazard event, and disparities that may exist between them as a function of differences in social status or ability to make choices and take action based on prevailing cultural norms (Tierney, 2006). Variables that will influence characteristics of agency may include personal or family income, access to financial reserves and emergency services, sense of place and degree of connectedness in a community, literacy and the ability to communicate in the official language(s) used by local authorities, and overall understanding of natural hazard processes and what to expect in the way of potential impacts (through formal education or tacit knowledge gained through experience).

Levels of personal or family income and access to financial reserves will have a direct bearing on the ability of some individuals to take actions that provide access to emergency shelter and basic needs in advance of an impending hazard threat, or to relocate and make alternate living arrangements in response to the impacts of an unexpected disaster event. For those without the financial means to take actions on their own, proximity and access to emergency services will influence overall levels of agency. Knowledge about a place and a strong sense of belonging in a community will also have a bearing on self-reliance in the event of an emergency. Understanding what to do, where to go, and how to avoid the impacts of an unexpected hazard event can greatly reduce the likelihood and severity of personal injury, and will enhance the ability for groups in a community to mobilize and assist others who may be in need of help. The capacity to understand hazard threats in order to take actions necessary to avoid negative impacts and consequences is dependent on a working knowledge of natural processes through formal education or experience, and the ability to communicate with others in order to anticipate and respond to unexpected emergencies.

4.3 7..3 Coping Capacity

Coping capacity is a measure of the physical and psychosocial characteristics of a community that will determine the extent to which individuals and groups are able to withstand and respond to a disaster event (Kuban and MacKenzie-Carey, 2001; Davis *et al.*, 2004;

International Federation of Red Cross and Red Crescent Societies, 2006b). Variables that may influence the capacity to cope with negative impacts and consequences of a disaster event include age, physical ability, family structure, and access to support services.

The youngest and oldest members of a community are often the most vulnerable populations in the event of a disaster. Those under the age of 5 years are dependent on others to make decisions on their behalf that will keep them out of harm's way and reduce the potential for injury or disruption. Those over the age of 65 are equally vulnerable, but in different ways. They may lack the physical ability to evade or withstand the impacts of a hazard event on their own, or may lack clarity of thought to recognize and respond to an unexpected emergency. Caregivers acting on behalf of the very young, elders, and those living with physical or mental disabilities may also be disadvantaged in their abilities to withstand and respond to a disaster. The same may be true for those living alone or in physical isolation within a community.

The combined influence of these variables will determine intrinsic patterns of social disadvantage, who and where the most vulnerable populations are, and the manner in which risks are distributed across all members of society. Knowledge gained through an assessment of social vulnerability will inform land use and emergency management decisions that have a potential to increase self-reliance, quality of life, and overall resilience of a community or region.

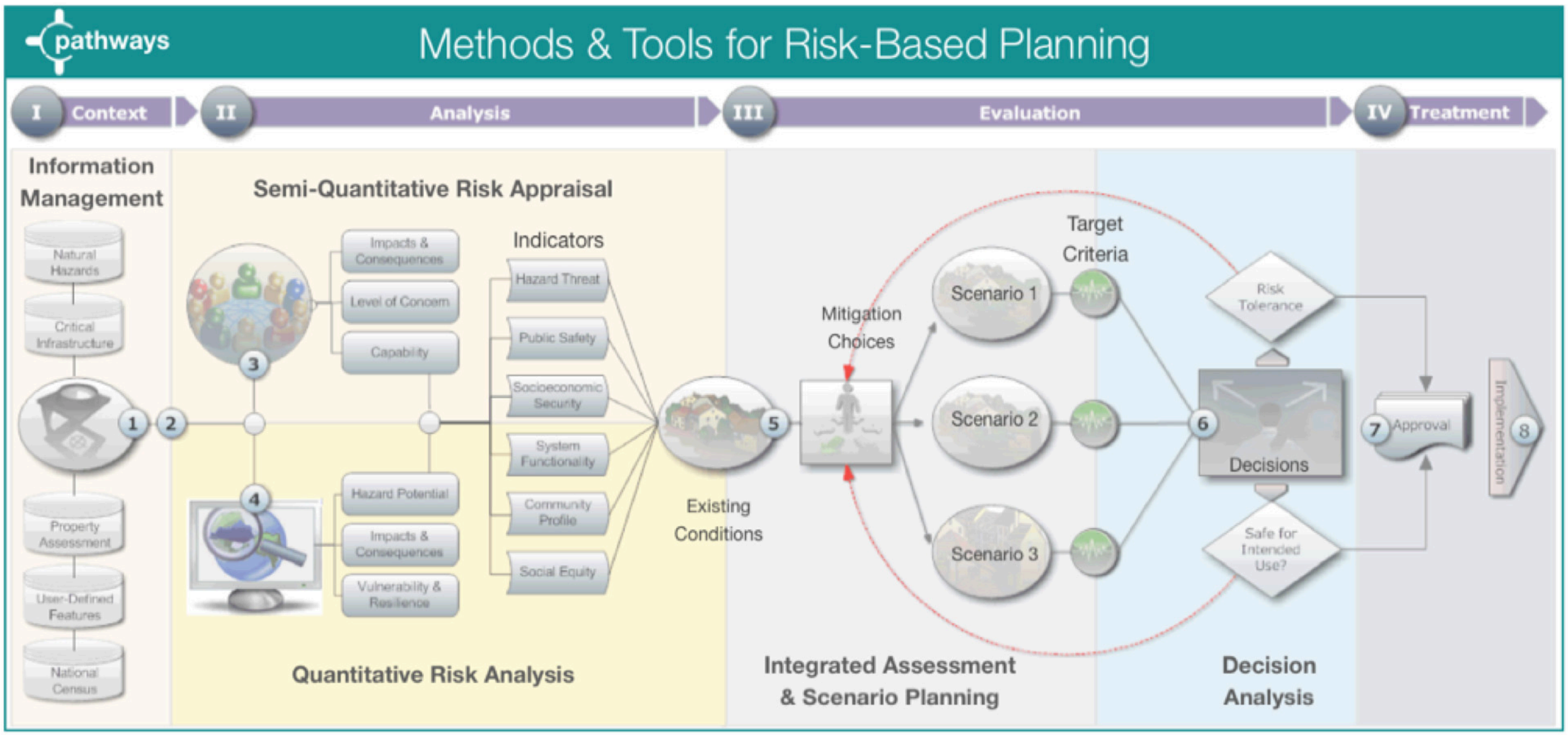


Figure 4-11: The constellation of methods and tools used to implement the Pathways model for integrated assessment and risk-based planning. The choice of implementation methods will be driven by the needs and operational requirements of the local planning process.

4.4 Methods and Tools for Risk-Based Planning

The Pathways model can be implemented as spatial decision support system using a constellation of quantitative and semi-quantitative methods and tools (see Figure 4-11). Choices about implementation methodology will be driven by the severity of the hazard threat, requirements for legally defensible assessments of impacts and consequences, the availability of scientific knowledge, and the level of technical expertise on hand to support the planning process.

Land use planners and emergency managers working in smaller municipalities or unincorporated rural and remote communities may not have access to scientific knowledge or technical expertise to support the use of quantitative risk assessment methods on an ongoing basis. For these communities, the process begins with the compilation of available information about natural hazards, patterns of human settlement, and characteristics of the built environment. Following the establishment of overall context, goals and objectives (Stage I), the process continues with a semi-quantitative appraisal of anticipated impacts and consequences, levels of concern, and capabilities for response and recovery using Delphi-based methods of risk appraisal (Stage II). In situations where the consequences of a hazard threat have the potential to overwhelm capabilities for self-reliance, there may be a need for some communities to solicit input from other groups and agencies in using quantitative methods of risk analysis to address issues of system complexity and scientific uncertainty.

Land use planners and emergency managers working in larger municipalities and regional planning authorities are more likely to have access to domain experts and technical planning systems to support the use of quantitative risk assessment methods and tools. For them, the process begins with the compilation and synthesis of available information and knowledge about the risk environment using industry-standard geographic information systems (GIS) and database management systems. Following the establishment of overall context, goals and objectives (Stage I), the process continues with support from a blend of semi-quantitative and quantitative risk analysis methods. In these situations, semi-quantitative methods of risk appraisal are used to solicit local knowledge about the risk environment and to gauge overall perceptions of risk in the community. A complementary suite of analytic methods and tools are used to measure hazard potential, the probability of damage, anticipated casualties and socio-economic losses, system disruption, and intrinsic patterns of social vulnerability (Stage II).

Outputs of the semi-quantitative risk appraisal and quantitative risk analysis process are then used to assess the system of Pathways indicators, and to develop baseline scenarios that describe available knowledge about the risk environment for each hazard threat of concern to the community. These baseline scenarios provide the necessary context and focus for assessing the overall risk profile for a community or region, and for evaluating the strengths and weaknesses of mitigation alternatives with respect to policy goals and objectives (Stage III).

Depending on available technical expertise, the scenario planning and decision-making process can be facilitated using a blend of design- and model-based methods and tools. Qualitative methods utilize narrative-based scenarios and target criteria to compare and evaluate the performance of mitigation alternatives with respect to the policy goals and objectives established in Stage I of the planning process. For those utilizing quantitative methods of risk analysis, the evaluation process is facilitated using methods of integrated assessment modelling and scenario planning.

Methods and tools used in implementing the Pathways framework were selected on the basis of current uptake and use in the domains of land use planning and emergency management, and their capacity to function in a loosely coupled manner to facilitate the full cycle of analysis and evaluation. While the applications described below provide an operational proof-of-concept for implementing the Pathways framework, they are not prescriptive. The standards-based architecture and modular design of the Pathways framework allows the substitution of equivalent applications that may already be used in local planning contexts, and the ongoing refinement of methods and tools as best practices continue to evolve and are made available in the public domain.

4.4 1. Semi-Quantitative Risk Appraisal

Risk appraisal is a semi-quantitative method of analysis that is used widely in the field of emergency management to support pre-event planning and preparedness operations (International Federation of Red Cross and Red Crescent Societies, 1999; Renn, 2001; Emergency Management Australia, 2002; Flax *et al.*, 2002; Klinke and Renn, 2002; BC Provincial Emergency Program, 2003; Ferrier and Haque, 2003; Pearce, 2003; Kohler *et al.*, 2004; Davis, 2005a; FEMA, 2009). The Pathways method for risk appraisal is adapted from available best practices, and is consistent with emerging national guidelines for capability-based planning that are part of the broader Canadian All-Hazards Risk Assessment Framework (Goudreau, 2009; Hales and Race, 2010).

As summarized in Figure 4-12, the methodology utilizes available information, knowledge and the collective judgments of local residents and domain experts to rank the likely impacts and consequences of existing or emerging hazard threats, the level of community concern for vulnerable populations and critical assets, and the capabilities required by the community to respond and recover from these threats using available time and financial resources. Outputs of these assessments are used to evaluate selected indicators and target criteria of the Pathways model, and to inform the evaluation of mitigation alternatives using

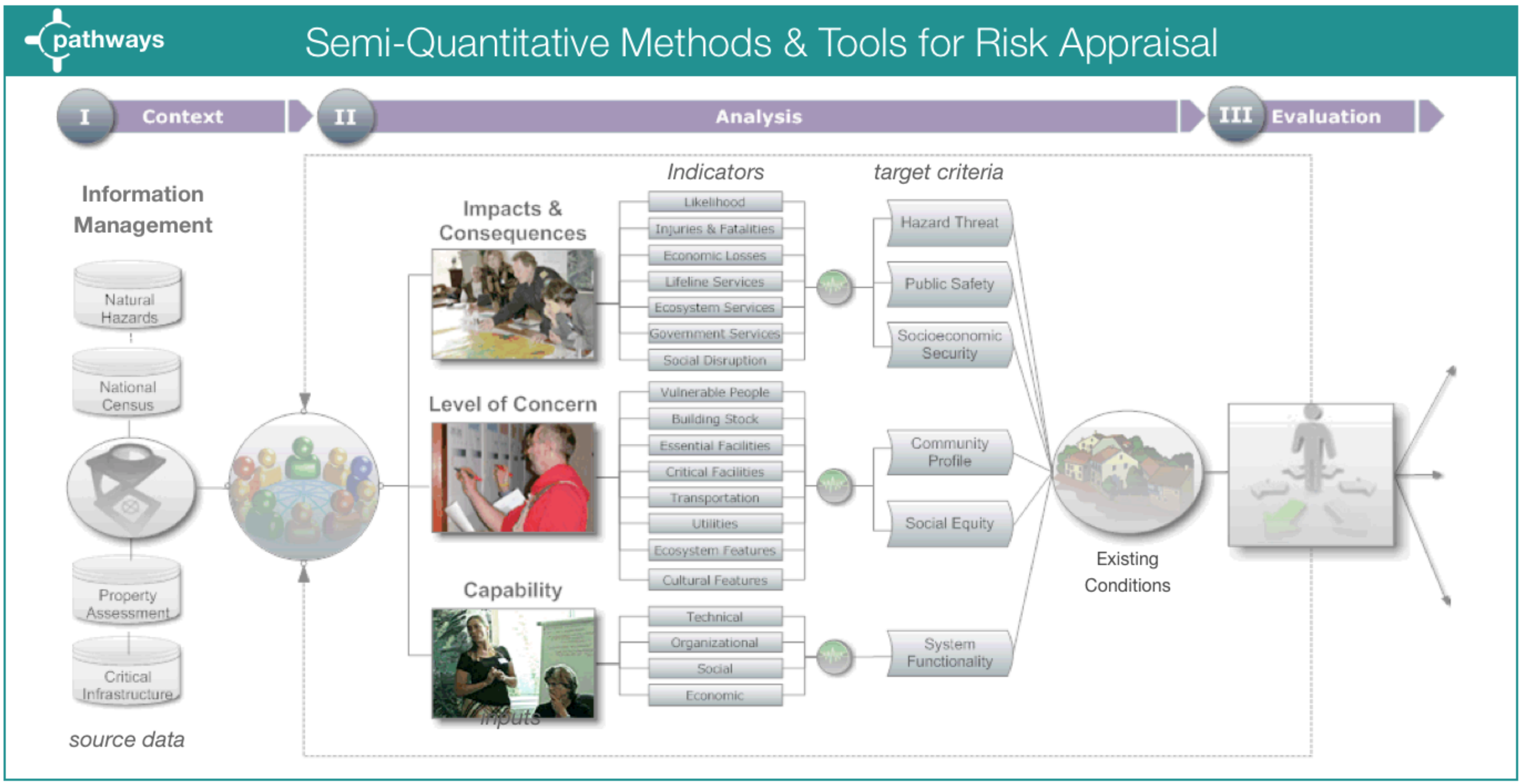


Figure 4-12: Semi-quantitative methods of risk appraisal used to assess target criteria and associated indicators of the Pathways model.

methods of integrated assessment and scenario planning.

4.4 1..1 Impacts and Consequences

Assessment of impacts and consequences is based on the type and number of hazard events that are likely to occur in a given region over a specified planning horizon, and the anticipated severity of these events in terms of damages, injuries, economic losses, environmental impacts, and social disruption. Available scientific assessments of intrinsic natural hazards and community-based mapping techniques are used to identify the spatial extents of potential hazard threats. Assessment of hazard severity is based on ordinal rankings that express relative degrees of likelihood that a hazard event will occur sometime in the future, and the anticipated magnitude of impact measured in terms of damage, injury, or disruption. The rating schema used in the Pathways framework is based on general guidelines established for risk management (Ferrier and Haque, 2003; Australia/New Zealand Standards, 2004; APEGGA, 2006) and recommendations currently under review for the assessment of natural hazard threats and accidents in a Canadian context (Public Safety Canada, personal communication, 2010).

As illustrated in Table 4-7, likelihood of occurrence is assessed on the basis of past occurrence, and is measured on an ordinal scale of 1 to 6 where values are ranked according to return periods that reflect what are considered to be maximum credible events for a range of natural hazard threats. For example, a frequency rating of 1 indicates a rare and extremely unlikely hazard event with an average return period of 10,000 years and a corresponding annual probability < 0.0001. A qualitative interpretation of this rating would be that similar events are known from the geologic record, occur in similar settings elsewhere in the world, and have the potential to occur in the area of interest. A frequency rating of 3 indicates an unlikely occurrence with an average return period of ~100 years and a corresponding annual probability of 0.01, suggesting that the event is known to occur in the region and could be expected within a single generation. A frequency rating of 5–6 indicates that the likelihood of occurrence for a specified hazard threat is very high, is known to occur in the region on an annual basis and could reasonably be expected to happen at least once over a 3-year period. The corresponding annual probability for such an event would range from 0.33 (could happen within the next three years) to 0.9999 (almost certain to occur).

The anticipated impacts and consequences of a particular hazard threat

pathways — Risk Appraisal Methods - *Hazard Likelihood*

Rank	Level	Description	Annual Probability
6	Very Likely	Event is known to occur in the region and likely to happen at least once per year	~ 0.9999
5	Likely	Event is known to occur in the region and likely to happen at least once in the next 10 years	0.9999 - 0.1
4	Moderate	Event is known to occur in the region and likely to happen at least once in the next 30 years	0.01 - 0.033
3	Unlikely	Event is known to occur elsewhere and could be expected to happen in the region at least once in the next 100 years	0.001 - 0.01
2	Very Unlikely	A previous event is recorded in the geologic history for the region and could be expected to happen at least once again in the next 1,000 years	0.0001 - 0.001
1	Extremely Unlikely	A previous event is recorded in the geologic history and/or is known to occur in similar settings elsewhere, and could be expected to happen at least once again in the next 10,000 years	> 0.0001

Table 4-7: Rating tables used in assessing the likelihood of occurrence for existing or emerging hazard threats.

are assessed on the basis of experience and an understanding of cause-effect relationships. As illustrated in Table 4-8, they are also measured on an ordinal scale of 1 to 6 where hazard severity is ranked in terms of the number and severity of injuries, the potential for loss of life, anticipated economic losses, environmental impacts, legal consequences, socio-cultural impacts and disruption of local government services. For example, a severity rating of 1 indicates that impacts of a specific hazard event are likely to be incidental at the scale of a community or region, resulting in minor injuries not requiring hospitalization, direct economic losses of up to $1 million, minor short-term environmental damage, possible legal action for non-compliance with bylaws or regulations, limited disruption to government services, and only minor social impacts and damage to structures and items of cultural significance. A severity rating of 3 indicates a moderate level of impact resulting in major injuries requiring hospitalization, economic losses of $10–50 million, loss of basic lifeline services for a period of 1–2 weeks, disruptions to local government services that do not require disaster assistance, and localized impact on the community resulting in isolated but persistent social disruption. At the other end of the scale, a severity rating of 6 would indicate a catastrophic event resulting in widespread major injuries, multiple fatalities, economic losses in excess of $1 billion, long-term environmental damage resulting in loss of ecosystem services, widespread disruption of government services requiring disaster assistance from higher levels of government, and significant socio-cultural impacts that are persistent for years. The rating scale used in this version of the Pathways framework is calibrated for impacts and consequences that are likely to occur in a moderate-size municipality with a population of less than 100,000 people. Modifications of the rating scale would be required to assess the risks of larger metropolitan areas that include multiple urban centres and/or that encompass broader exurban regions.

The Delphi method is used to assess overall hazard threat by first ranking frequency and severity based on a weighted average of individual responses, and then synthesizing results to reflect a collective judgment (mean value) of for all hazard threats of concern. In situations where there is significant variability of rank values, an effort is made to explore divergent opinions and perspectives through a structured process of dialogue and debate. The process is repeated until there is no significant change to mean rank values or the variance of individual responses.

As illustrated in Figure 4-13, outputs of the hazard threat assessment are summarized in the form of a qualitative risk profile that characterizes frequency-magnitude relationships for a portfolio of hazard threats that are considered credible for a given geography and planning horizon. In order to preserve meaning and integrity of the assessment process, results are plotted on a continuous ordinal scale to facilitate a comparison of relative frequency and severity. Hazard threats are then classified in terms low, medium, and high levels of risk. These designations reflect a preliminary assessment of what are considered to be acceptable, tolerable, and intolerable thresholds of risk for a community or region based on likelihood of occurrence and anticipated consequences.

4.4 1..2 Level of Concern

The second step in the appraisal process measures perceived levels of concern for elements at risk in the human-natural system. It is a way of assessing who and what are considered most vulnerable to the portfolio of hazard threats that have been highlighted in preceding steps of the appraisal process, and identifying mitigation strategies to safeguard these assets while pursuing potential benefits of a future course of action. Maps and associated tables are used to validate the location and classification of existing and/or proposed features that have been compiled as part of the asset inventory (see Section 4.3.2). As illustrated in Table 4-9, levels of concern are assessed on the basis of normative statements that summarize anticipated impacts and disruptions for a suite of credible hazard threat scenarios.

Assessment of overall concern can be based on the impacts of single or multi-hazard threats that are considered credible for a given geographic setting and planning horizon. Similarly, the impact statements can be tailored to specific elements at risk, or adapted to reflect a broader collection of assets in a community or region. Once context and focus have been established, community assets are then rated in terms of anticipated levels of impact and the extent of associated disruption.

Risk Appraisal Methods - *Impacts & Consequences*

Impact Indicators	Incidental	Minor	Moderate	Major	Severe	Catastrophic
	1	2	3	4	5	6
Public Safety	Some minor injuries, but no medical treatment required	Widespread minor injuries and some major injuries requiring hospitalization	Widespread major injuries requiring hospitalization and irreversible disability or impairment (<30%) to one or more persons	Single fatality and/or injuries resulting in severe irreversible disability (>30%) to one or more persons	Multiple fatalities and/or injuries resulting in severe irreversible disability (>30%) to several people	Multiple fatalities and/or injuries resulting in severe irreversible disability (>30%) to more than 50 people
Socioeconomic Security	< $1M	$1M -$10M	$10M - $50M	$50M - $100M	$100M - $1B	>$1B
System Functionality	Loss of service capacity for a period of less than 1 day	Loss of service capacity for a period of 1 - 7 days	Loss of service capacity for a period of 7-14 days	Loss of service capacity for a period of 14 days to 3 months	Loss of service capacity for a period of 3 months to 1 year	Loss of service capacity for a period of greater than 1 year
Environmental Services	Minor short-term environmental damage but not affecting ecosystem functions	Moderate short-term environmental damage but not affecting ecosystem functions	Serious medium-term environmental damage, ecosystem functions are disrupted but recoverable	Very serious long-term environmental damage and impairment of critical ecosystem functions	Very serious long-term environmental damage and potential loss of critical ecosystem functions	Loss of significant environmental features and associated ecosystem services
Governance & Accountability	No disruption of government services. Minor adverse public or media attention. No complaints Minor non-compliance & breach of regulation	Localized disruption of government services. Attention from media and/or heightened concern by local community. Criticism by NGO's Minor legal non-compliance	Disruption of local government services, but not requiring disaster assistance. Significant adverse national/public/ NGO attention. Serious breach of regulation resulting in fines and/or prosecution.	Widespread disruption of local government services requiring disaster assistance. Serious public outcry and international media coverage. Serious breach of regulation resulting in fines and/or prosecution.	Widespread disruption of local government services requiring disaster assistance. Serious public outcry and international media coverage. Major breach of regulation resulting in litigation	Widespread disruption of local government services requiring disaster assistance. Serious public outcry and international media coverage. Major breach of regulation resulting in litigation and class actions.
Social Disruption	Localized impact on community resulting in minor medium-term social impacts. Damages are repairable	Localized impact on community resulting in isolated but persistent social impacts. Permanent damage to structures and items of cultural significance	Localized impact on community resulting in isolated but persistent social impacts. Permanent damage to structures and items of cultural significance	Widespread impact on community resulting in serious and persistent social impacts. Significant damage to structures and items of cultural significance	Widespread impact on community resulting in serious and persistent social impacts. Significant damage to structures and items of cultural significance	Widespread impact on community resulting in serious and persistent social impacts. Significant damage to structures and items of cultural significance

Table 4-8: Rating tables used in assessing the likely impacts and consequences of a specific hazard event scenario.

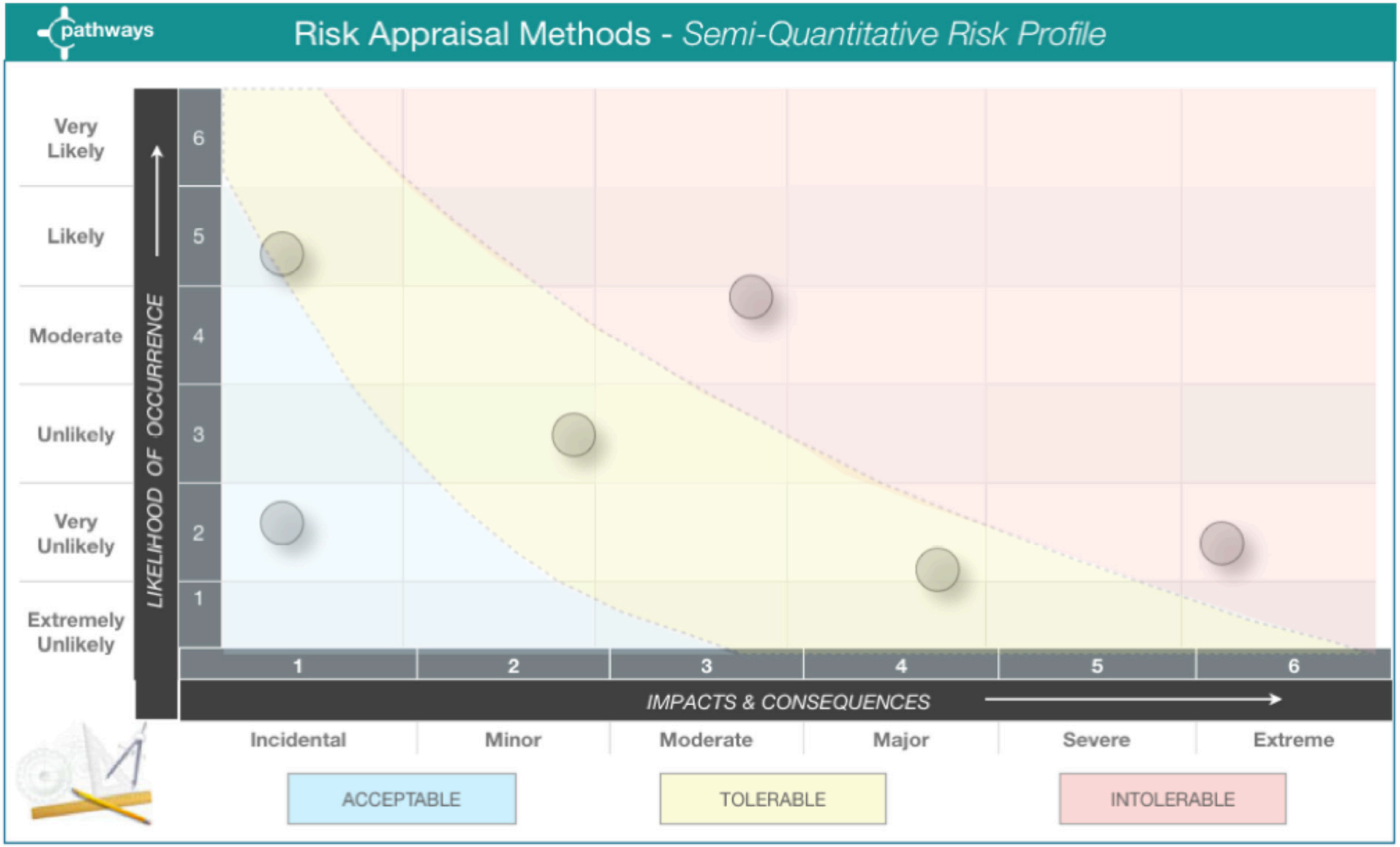


Figure 4-13: Qualitative risk profile used to summarize frequency-magnitude relationships for existing and emerging hazard threats, as determined using semi-quantitative methods of risk appraisal.

Levels of concern are measured on an ordinal scale of 1 to 6, where a value of 1 indicates relatively low levels of concern and a value of 6 indicates an extremely high level of concern.

Methods of ranking and normalization are similar to those described for the assessment of impacts and consequences. Results are summarized in the form of thematic maps and charts. Charting techniques will vary depending on the specific level of concern. One way of effectively summarizing overall perceptions of risk is with a two-dimensional plot that represents variations between anticipated impact and the extent of disruption for each of the major asset categories (See for example: Chang and McDaniels, 2007).

Risk Appraisal Methods - *Level of Concern*

Community Assets	Concerns Regarding Anticipated Damage/Loss	Level of Impact						Extent of Disruption					
		Very Low	Low	Mod.	High	Very High	Extr.	Very Low	Low	Mod.	High	Very High	Extr.
		1	2	3	4	5	6	1	2	3	4	5	6
Vulnerable Populations: • the very young & elderly • socially & economically disadvantaged • people living with disabilities • ethic minorities • people living alone	Public safety is influenced by levels of health and/or fitness. These susceptibilities may lead to increased load on emergency response/recovery operations and demand for critical health care and social services during and after a hazard event. Negative impacts may be balanced by tacit knowledge, judgment and life experience of community elders and others who may contribute significantly to response and recovery efforts by strengthening social fabric and assisting in the decision making process.												
General Building Stock: • residential • commercial & industrial • civic & institutional • cultural & historic	Physical damages/loss to structures and contents may require response/recovery and potential evacuation. Structural damage in excess of ~20% can result in displacement of individuals and families, causing significant financial/emotional hardship. Equivalent levels of damage for commercial and/or industrial structures will impact the provision of basic services during emergency response operations and can result in interruption/loss of institutional capacity with consequent impact(s) on local economy and social vitality.												
Essential Facilities: • hospitals & care facilities • emergency operation centres • fire & police stations • schools & emergency shelters	Physical damages/loss to structures and contents may require response/recovery and potential evacuation. Structural damage in excess of ~20% can result in interruption/loss of emergency services with consequent impact(s) on public safety and socioeconomic vitality. Reduction of local emergency response/recovery capacities below minimum thresholds of resilience would trigger a state of emergency and a call for assistance from higher levels of government.												
Critical Facilities: • dams, levees & protective structures • nuclear power plants • military installations • hazardous material faciltiies	Physical damages to critical facilities can undermine structural integrity and significantly reduce regulated levels of safety. Failure of critical structures have the potential to trigger disaster events that can easily overwhelm local and regional capacities for response and recovery. The consequences of these disaster can be several orders of magnitude greater than the those caused by the triggering event, and will impact long-term recovery.												
Transportation Systems: • highway networks • rail networks • airport facilities • bus, ferry & port facilities	Interruption and/or short-term loss of transportation services would impact emergency response & recovery operations, potentially threatening pubic safety and socioeconomic security and socioeconomic structures that rely on the upstream and downstream flow of goods and services. Significant structural damages to strategic transportation facilities, such as roads, railways and airport facilities may seriously impact local and Provincial/Federal response & recovery operations and impact the recovery of critcal system functions.												
Utility Systems • potable water systems • wastewater systems • oil pipelines & facilities • natural gas pipelines & facilities • electric power gneration systems • communication facilities	Structural damage to utility systems could result in the interruption of basic services, thereby compromising emergency response/recovery operations and self-sufficiency of individuals and families in the community. Damages to pumping stations, power generation facilities and/or distribution lines would reduce service capacity and the functionality of homes and businesses. As many of these systems are interconnected, damages to one part of the infrastructure is likely to have consequences elsewhere in the system. Sustained interruption to services would impact local economy and social vitality.												
Natural Environment • surface & groundwater resources • riparian zones & wetlands • sensitive terrestrial habitat • sensitive marine habitat • vulnerable species	Elements of the natural environment function as interconnected and interdependent systems that provide vital ecosystem services, and help shield communities from second-order impacts of disaster events. Surface and groundwater resources are particularly vulnerable to the impacts of hazardous material spills and/or floodwaters that have inundated the built environment and become contaminated with chemical and/or biological agents. Loss of water security and disruption of key ecosystem functions can have long-lasting impacts to a community or region.												
Cultural Features • heritage & religeousbuildings • aesthetic landscape features • recreational amenities	Though not considered strategic assets and often overlooked, these features are the means by which people make sense of the place in which they live and their relationship to community/ natural environment. Damages and/or loss of cultural artifacts can have long-lasting social impacts to both individuals and communities.												

Table 4-9: Rating table for summarizing level of concern for vulnerable populations and community assets.

Assessment of community concern provides a focus on populations and critical assets that are considered most vulnerable and in need of safeguarding through pre-event planning and mitigation. However, protection of community assets for the purpose of realizing potential gains requires a balancing of trade-offs between risks and benefits within the constraints of available time, resources, and political agency. Judgments on the relative value of assets involve a consideration of community values, goals, and beliefs. Judgments on which assets are most in need of safeguarding involve a consideration of both equity and utility, and an assessment of overall capabilities for response and recovery.

4.4 1..3 Capabilities for Response and Recovery

Assessment of capabilities for response and recovery shifts the focus of appraisal from a threat-based view of impacts and consequences to a more general consideration of what may be required to reduce outstanding vulnerabilities and promote resilience for a community or region. As outlined in the Pathways model, capability is a measure of the extent to which an organization or community can withstand and respond to the impacts of potential hazard events, and recover from the consequences of these events in order to realize potential net benefits over time. Levels of capability are assessed in terms of the effectiveness for technical, organizational, social and economic systems to withstand, respond to and recover from the impacts and consequences of a disaster event (Bruneau *et al.*, 2003; Chang and Chamberlin, 2004; Chang and Shinozuka, 2004).

As summarized in Table 4-10, capabilities for response and recovery are assessed on the basis of available knowledge in the local community using an ordinal rating scale of 1 to 6 to measure relative levels of effectiveness. A value of 1 indicates very low levels of perceived effectiveness and a value of 6 indicates an extremely high level of effectiveness. Depending on the needs and requirements of the planning process, the appraisal can be carried out in the context of an individual hazard scenario or a portfolio of credible hazard events for an area of interest. Appraisals for single-event scenarios help focus attention on specific capabilities that may be needed for response and recovery planning, whereas appraisals for composite multi-hazard event scenarios draw attention to broader issues of disaster resilience that may be relevant at the scale of the community or region.

The capability of technical systems to respond and recover is measured by the perceived level of effectiveness for existing mitigation structures to provide adequate levels of protection in the event of a disaster. The appraisal can focus on individual components of the mitigation system (early warning capability, dykes, back-up power, etc.) or on overall capabilities for response and recovery. The appraisal of organizational systems takes into account the effectiveness of pre-event planning and emergency management operations, the enforcement of building codes and regulated safety standards, and ongoing maintenance of existing mitigation structures. The appraisal of social systems focuses on the effectiveness of communication and outreach activities in promoting awareness and understanding of natural hazards and their likely impacts and the capabilities of individuals and groups in the community to work together to support emergency response and relief operations. Finally, the appraisal of economic systems measures the capability of a community or region to access financial resources required to invest in mitigation measures that will reduce underlying system vulnerabilities, to transfer outstanding risks through insurance markets, and to access emergency relief funds in the event of a disaster.

4.4 1..4 Evaluating Results of Target Indicators

The Pathways methodology for aggregating indicator values and evaluating target criteria conforms with technical guidelines and recommendations that have been established for multi-criteria analysis in the fields of environmental protection, risk assessment, and sustainable land use planning (Monnikhof and Bots, 2000; Costa, 2001; Janssen, 2001; Yoe, 2002; McDaniels *et al.*, 2004; Omann, 2004; Gregory *et al.*, 2005; Kiker *et al.*, 2005; Yalcin and Akyurek, 2005; Linkov *et al.*, 2006b; Jones and Andrey, 2007). Target criteria and indicators can be based on any or all variables that are considered relevant to a particular planning process. For example, public safety might be assessed solely on the basis of the likelihood for loss of life, or on a combination of indicators that track anticipated injuries and requirements for emergency services.

Risk Appraisal Methods - *Capabilities for Response & Recovery*

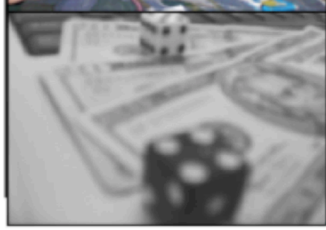
	Capability	Description	Level of Effectiveness					
			Very Low	Low	Mod.	High	Very High	Extreme
			1	2	3	4	5	6
	**Technical Systems** • preventive structures (levees, berms, etc.) • design guidelines • building codes for new structures • retrofits of unsafe structures • early warning systems • back-up power • secure supplies of potable water • *others that are relevant to community*	Technical dimensions of capability measure the extent to which structural systems (and their components) are able to withstand immediate and induced physical impacts of a hazard threat in accordance with accepted/desired levels of performance and efficiency, and their potential to recover these base levels of functionality over time.						
	**Organizational Systems** • pre-event emergency planning • emergency response & recovery • strategic land use planning • enforcement of regulated safety thresholds • enforcement of local building codes • public works & maintenance • *others that are relevant to community*	Organizational capabilities measure the extent to which public and private sectors are able to undertake appropriate levels of emergency preparedness and strategic planning to limit exposure to hazard threats (protection, regulation, land use zoning, etc.), to warn of impending threats (early warning systems), and to assist the community in responding to and recovering from the impacts of hazard events						
	**Social Systems** • communication & networking • risk awareness & individual preparedness • neighbourhood emergency response • participation in civic affairs • community organizations • *others that are relevant to community*	Social capability provides a measure the integrity, cohesiveness and robustness of social networks as evidenced by levels of communication and consultation, risk awareness and understanding, and by participation (volunteerism) in personal and community preparedness.						
	**Economic Systems** • resources for mitigation & preparedness • local emergency relief funds • disaster assistance loans • disaster relief funding • insurance markets • *others that are relevant to community*	Economic capability provides a measure of available economic resources to implement risk treatment measures through dedicated organizational budgets and/or mitigation/capital improvement loans, and to respond to anticipated consequences of potential hazard events through risk transfer mechanisms including financial insurance/ re-insurance markets and disaster relief funds.						

Table 4-10: Rating table for assessing capabilities for response and recovery.

Similarly, socio-economic security might focus on anticipated capital stock losses to buildings and contents, or on a broader consideration of direct and indirect economic losses. In situations where target criteria are assessed using multiple indicators, care must be taken to ensure that numeric or subjective values are aggregated in ways that preserve meaning and maintain integrity of policy targets.

The first step in this process is to normalize model outputs so that there is shared meaning (coherence) in measures of magnitude—larger numbers reflect bigger or better values—and conditions of state. This can be done by using the reciprocal of an indicator value to ensure that resulting measures have the same directionality and are consistent with the intent of the indicator and associated targets. Once the data have

Semi-Quantitative Risk Appraisal - *Aggregation Methods*		
Mode of Aggregation	**Description**	**Analytic Method**
Z-Score	the difference between each observation and the mean is calculated, and then divided by the standard deviation. The advantage of this method is that it minimizes any distortions that may occur when variables with different mean values are aggregated. Z-scores are used widely in the social sciences, but are not as common in the field of risk-based planning (Jones and Andrey, 2007)	$\frac{X_i - min(X_i)}{max(X_i) - min(X_i)}$
Linear Scaling (% of range)	the difference between each observation and the minimum value in the range is calculated, then divided by the difference between maximum and minimum values of the range. The advantage of this method is that resulting scores represent the relative percentage of the range of values between 0 and 1. However, the disadvantage is that linear transformation does not necessarily preserve the proportionality of the original values and may inadvertently distort the meaning of the indicator (Yoe, 2002).	$\frac{X_i - min(X_i)}{max(X_i) - min(X_i)}$
Unit Vector	the observed or measured value is divided by the square root of the sum of the squares of all the criterion measurements. The advantages of this method are that it: (i) preserves both proportionality and cardinality of the original values, and (ii) the modulus of the normalized vector always sums to one (Yoe, 2002). Disadvantages are that it may be more difficult to implement and not as familiar as the more common method of linear transformation.	$\frac{X_i}{\left(\sum_i x_i^2\right)^{1/2}}$

Table 4-11: Methods for aggregating results of semi-quantitative risk appraisal to evaluate performance with respect to Pathways target criteria.

been standardized in terms of meaning, the next step is to transform the data into a common scale of measure. There are several methods for transforming indicator values, each designed to optimize a particular outcome. All of these methods have particular strengths and weaknesses that need to be considered in building a coherent and internally consistent system of indicators (Yoe, 2002; Jones and Andrey, 2007). The most common methods of transformation are summarized in Table 4-11.

The decision to aggregate indicator values always strives for balance between precision of meaning and ease of use in support of real-world decision making. Indicators based on semi-quantitative measures are generally evaluated as the sum of their parts and can be either weighted or un-weighted (Cutter *et al.*, 2000; Jones and Andrey, 2007). Weighting of indicator values can be used to explore the influence of community values and preferences. As a rule of thumb, indicators in the Pathways model are un-weighted, aggregated only at the level of individual target criteria, and are not combined into higher-level composite indices. This ensures that scenarios are evaluated on the basis of a consistent set of assessment criteria that are internally coherent and that provide a reliable basis for comparing the strengths and weaknesses of mitigation alternatives.

Semi-quantitative methods of appraisal outlined above provide an effective means of structuring and integrating available knowledge about the risk environment for the purpose of establishing general thresholds of risk tolerance that are used to evaluate the strengths and weaknesses of mitigation alternatives. Outputs of the appraisal process can be summarized in the form of indicators that measure key dimensions of risk, vulnerability, and resilience for a community or region. When used in conjunction with outputs of a quantitative analysis, they also provide an effective means to evaluate differences that may exist between perceived and scientifically measured levels of risk.

4.4 2. Quantitative Risk Analysis

Quantitative methods of risk analysis provide a capability to predict the outcomes of complex system interactions, and to constrain uncertainties of analytic models within the limits of available information, knowledge, and resources. Outputs of a quantitative risk analysis are used by planners and decision makers to comply with regulatory thresholds for safety and security; to justify mitigation investments (cost-benefit analysis), and; to ensure that outcomes of the decision making process will withstand scrutiny if challenged in a court of law. A quantitative analysis does not take the place of a semi-quantitative risk appraisal. Rather, it offers a complementary view of the risk environment—one that is based on objective measures and an understanding of process interactions derived from theory, and validated through observation and modelling.

Quantitative risk assessment methods used to implement the Pathways model are summarized in Figure 4-14. They include public domain software applications for information management and structuring of asset inventory data (Beyond 20/20® and CDMS); FEMA's standardized damage and loss estimation methodology for assessing the impacts and consequences of floods, earthquakes, hurricanes, and related hazard threats (HAZUS); and commercial methods of multivariate statistical analysis for assessing dimensions of social vulnerability (SoVI).

4.4 2..1 Information Management

Methods and tools that are used in the Pathways framework to manage information used to describe patterns of human settlement and characteristics of the built environment are summarized in Figure 4-14. Community profile information is compiled from population and demographic data collected as part of the national census (Statistics Canada, 2006). The data are made accessible for customized modelling applications using Beyond 20/20®—an application developed by Ivation Datasystems to facilitate access to and manipulation of socio-economic data for purposes of statistical modelling and analysis. The application provides a capability to create custom views (tables, charts, maps) that can be exported to a variety of industry-standard data formats for use in third-party modelling applications. It is used by Statistics Canada to disseminate national census data for desktop and web-based viewing and analysis, and is used in the Pathways framework to prepare model inputs for quantitative risk analysis.

FEMA's Comprehensive Data Management System (CDMS) is a specialized application that is designed to transform location-based information about the built environment into a structured inventory of community assets that can be used for analyzing the impacts and consequences of natural hazard threats using HAZUS. The system comprises a data model that describes physical elements of the built environment in terms of geographic location, form, and function, and is implemented as an SQL database that can be deployed as a stand-alone desktop and/or web application.

The first step of the process involves the translation of available information from federal, provincial, and municipal sources into a standardized data format. The information is then categorized and transformed into a structured asset inventory (ontology) using the CDMS data model to characterize elements of the built environment and their relationships to one another. The inventory is characterized in terms of people, general building stock, essential facilities, critical facilities, transportation systems, and utility systems. By offering a comprehensive description of the built environment, CDMS provides a capacity to support a wide range of modelling applications. Formal documentation of the CDMS inventory is provided in a series of technical manuals developed by the US Federal Emergency Management Agency and the Polis Center (FEMA, 2006b; a; The Polis Center, 2006).

4.4 2..2 Hazard-Risk

HAZUS is a quantitative loss estimation method developed by the US Federal Emergency Management Agency (FEMA) and the National Institute of Building Sciences (NIBS). It is used to support risk-based planning activities that promote national disaster mitigation policies in the United States (National Institute of Building Sciences, 2002; FEMA, 2004; Schneider and Schauer, 2006; Bostrom *et al.*, 2008; FEMA, 2008). The HAZUS methodology encompasses an integrated suite of analytical models, decision-support tools and procedural guidelines for quantitative risk assessment of floods, earthquakes, and hurricanes. Models and tools are based on state-of-the-art scientific and engineering knowledge and industry standards for quantitative risk assessment. Although developed for use in the United States, the HAZUS toolset is robust and provides a standardized approach to loss estimation that is being adopted by organizations worldwide. The Earth

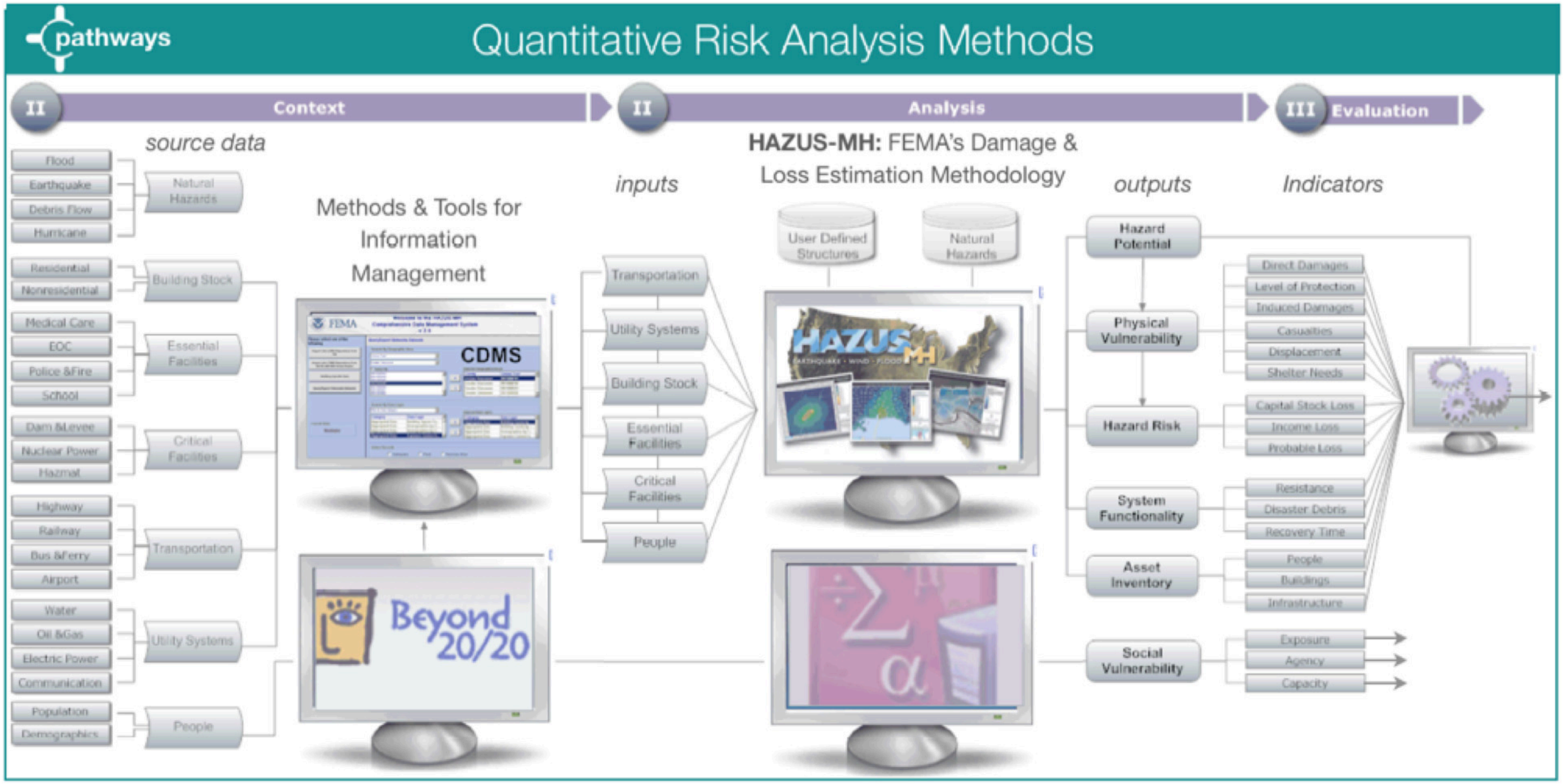


Figure 4-14: Methods of quantitative risk analysis used to evaluate target criteria of the Pathways framework.

Sciences Sector (ESS/NRCan) selected HAZUS as a best practice for quantitative loss estimation based on a suitability analysis of available risk assessment methods in the public domain.

As illustrated in Figure 4-15, HAZUS can be used to assess potential damages and losses caused by earthquakes, floods and hurricane at three distinct levels of analysis. A Level 1 analysis utilizes default asset inventory and hazard potential data and is typically run at the scale of an entire community or region. Outputs of a Level 1 analysis are aggregated at the scale of neighbourhoods or regions to characterize overall patterns of damage and loss. A Level 2 analysis makes use of parcel-level data from local and regional sources to describe characteristics of the built environment (type of construction, age, and primary land use activities) and incorporates available scientific knowledge to more accurately define hazard potential. Outputs of a Level 2 analysis are aggregated at the scale of individual neighbourhoods and are used to inform land use planning and emergency management operations. A Level 3 analysis incorporates site-level information about the built environment and knowledge provided by domain experts to define the hazard potential (spatial extent, intensity, and probability of occurrence) at specific locations on the landscape. Outputs of a Level 3

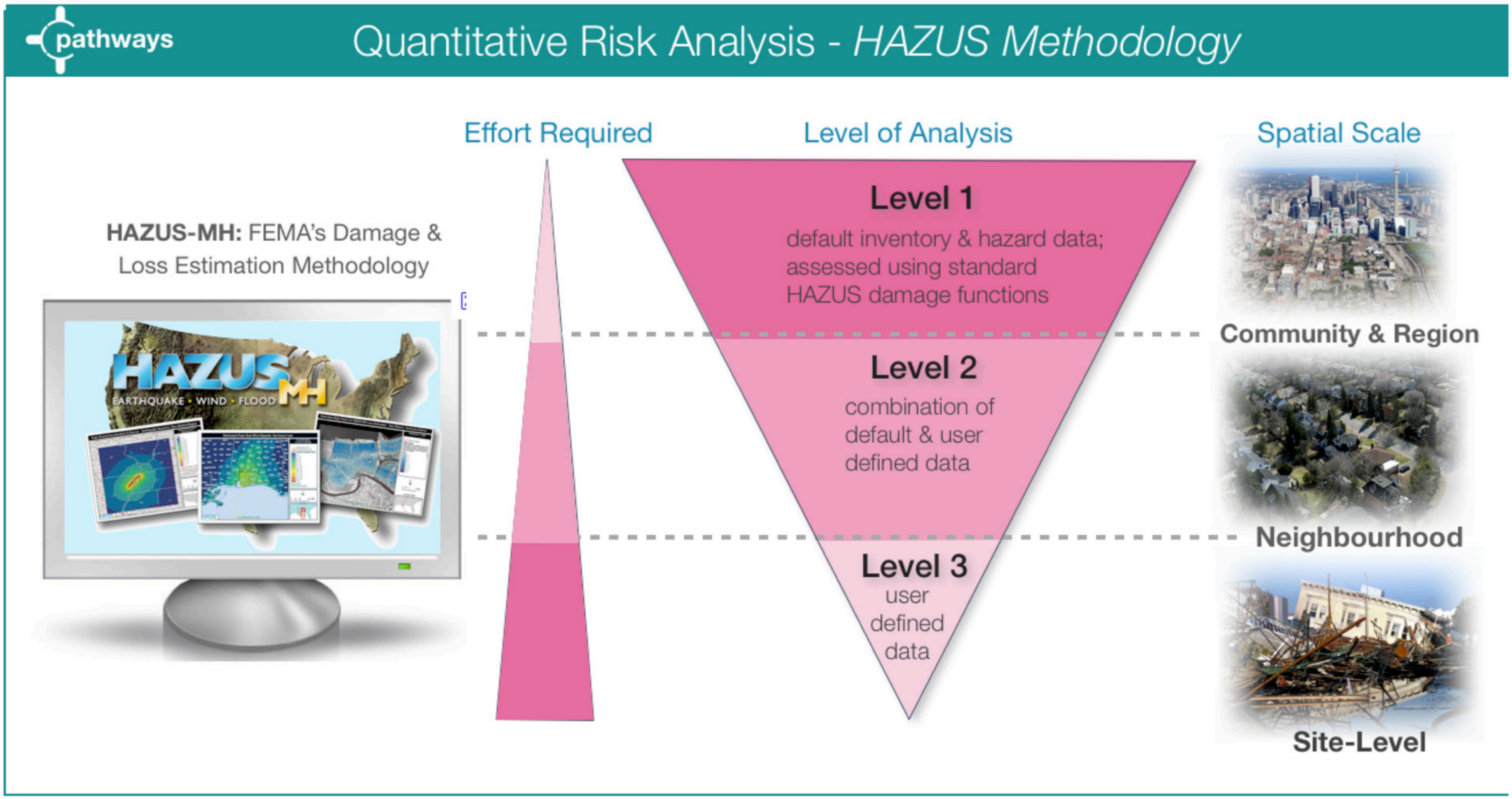


Figure 4-15: Levels of analysis that are used in HAZUS for different spatial scales

analysis are generated for individual features and are used to inform decisions about whether an existing or proposed development is considered safe for the use intended.

Quantitative methods of risk analysis used in the HAZUS methodology are based on linear cause-effect relationships that can be expressed mathematically in terms of hazard potential (threat), physical impacts (vulnerability), and socio-economic losses (consequence):

$$\text{Risk} = f\left(\text{Hazard Potential}, \text{Physical Vulnerability}, \text{Anticipated Loss}\right) \quad (1)$$

In this formulation, risk is expressed as a function of dependent variables that are evaluated separately and combined mathematically in ways that are consistent with risk theory and the circumstances of a given risk scenario. The scope of a quantitative risk analysis will vary with geographic setting and requirements of the decision-making process, but generally involves: (i) an assessment of spatial extent and frequency-magnitude relationships (hazard potential) for natural hazards of concern to the planning process; (ii) an assessment of expected damages and injuries (physical vulnerability) and anticipated socio-economic losses (hazard-risk) that may be caused by the hazard event; (iii) an assessment of the extent to which critical lifelines are able to withstand and recover from the impacts of a disaster event (system functionality), and (iv) an assessment of underlying causal structures that may pre-dispose a community or region to negative impacts of a hazard event (social vulnerability). The scale of analysis can be limited to site-specific assets or to a portfolio of assets over a wide geographic area. In either case, it is assumed that the scope and severity of a threat is well understood in terms of hazard potential, and that spatial extent, intensity, and rates of occurrence can be reasonably predicted from historical data or statistical relationships (Ayyub *et al.*, 2007; McGill *et al.*, 2007).

In the context of a quantitative risk analysis, vulnerability is defined as the probability of damage to a physical asset, the severity of injury to people, or the potential for loss of life. It is analyzed as a function of structural fragility with respect to a specified hazard threat and the effectiveness of relevant mitigation measures. Anticipated loss is defined as the maximum credible loss to a target asset and is evaluated in monetary terms as a replacement cost or loss of income resulting from direct physical damages. The risk associated with a specific hazard threat for a given scenario can be expressed as the Cartesian product of physical vulnerability, maximum credible loss for a collection of target assets, and the probability that the event will occur over a specified time horizon:

$$\text{Hazard - Risk}\left(R_h\right) = \left[\text{Vulnerability}\left(V_h\right) \times \text{Loss}\left(L_{MCh}\right) \times \text{Probability}\left(P_h\right)\right] \quad (2)$$

There are clearly limits to what can be analyzed and modelled. For this reason, it is common to reduce system complexity in order to assess hazard potential and probabilities of damage by framing the problem so that larger-scale influences are minimized, and by making assumptions of uniformity and independence to simplify the analysis of network interactions and feedback loops (Champion, 2005).

The assumption of uniformity is used in situations where detailed time series and probability distribution functions describing magnitude-frequency relations are not available. In these situations, it is assumed that the probability of occurrence for a hazard event over a specified planning horizon does not change with time. For example, if the likelihood of earthquake magnitudes for a given area (MMI > VII) is reported as 0.05 over a 30-year time horizon, it is assumed that this would be the likelihood of occurrence for the same earthquake magnitude over any equivalent 30-year period of time in the future. Independence is used to simplify the assessment of multi-hazard potential by assuming that individual hazard events are triggered by self-governing processes and do not affect the outcome of other co-spatial hazards in the same planning horizon. On the basis of these simplifications, models are then constructed to represent system behaviour and to predict specific cause-effect relationships. However, care must be taken to ensure that analytical scope, simplifying assumptions, and limits of scientific knowledge are made evident in reporting model results so as not to inadvertently bias the decision-making process. The following sections describe specific methods and tools that are used in the Pathways framework to support each stage of the quantitative risk analysis process.

4.4 2..3 Hazard Potential

Quantitative assessment of hazard potential is appropriate at local and regional scales where there is a need to analyze impacts and anticipated consequences (damages, injuries, and economic losses) of single or multi-hazard events in order to develop site-specific disaster mitigation strategies, land use bylaws, or design guidelines. Assessment methods include both standard deterministic and probabilistic techniques that are tailored to specific hazard threats. Hazard potential (K) for a specific event (h) is assessed as the Cartesian product of its intensity (I) and probability of occurrence (P):

$$\text{Hazard Potential}\left(K_h\right) = \left(I_h \times P_h\right) \quad (3)$$

In this formulation, geographic extent is used in assessing and mapping the spatial distribution of a hazard threat but is not included in the numerical model. It is evaluated through spatial analysis using a binary value of 1 to indicate whether a specific landscape feature (point, line, area, grid cell) has the potential of being impacted by a hazard threat that exceeds a minimum threshold value of intensity, and a value of 0 to indicate a condition where the landscape feature is either not affected or is below the specified intensity threshold.

Intensity and magnitude are two different ways of measuring the relative severity of a hazard threat. Intensity is a direct measure of hazard threat and is assessed in terms of physical attributes of velocity (earthquake ground motion, wind, etc.), depth (water, debris flows, etc.) and material properties. The intensity of an earthquake, for example, is measured by seismic energy released and propagated through the earth's crust (logarithmic seismic wave amplitude; Richter Scale) or by units of peak ground velocity or spectral accelerations at different frequencies measured at the earth's surface (PGV, PGA, Sa0.1, Sa0.5, etc.). Hazard event intensities for landslides, volcanic eruptions, floods, and storm surge are typically measured and reported in terms of the depths of earth materials and water at any given location, rates of travel over the land surface and/or aggregate values of physical force.

Magnitude is a function of intensity and is used to measure the relative severity of a hazard event in terms of anticipated impacts to the built environment and associated injury or loss of life. The Modified Mercali Index is an example of a hazard magnitude metric that translates intensity of a seismic event into corresponding dimensionless measures of impact. Seismologists and emergency managers use MMI values to communicate relative severity of a potential earthquake event over a range of potential outcomes. An MMI value of I reflects an event that is only barely felt, whereas an MMI value of XII reflects ground shaking intensities that would likely result in total destruction of the built environment.

Hazard probability is an expression of the likelihood that a hazard event of a particular intensity or range of intensities will occur in a given area over a specified time horizon. It is evaluated using the generalized probability function $y = \varphi(x)$, where a minimum p value (probability) of 0 indicates an infinite level of error or uncertainty, and a maximum p value of 1 indicates that the event will almost certainly occur over a specified time horizon. Values of uncertainty range from 0 to 1. Hazard likelihood is commonly reported in terms of the probability (P) of a exceeding a specific hazard intensity (h) over a defined interval of time (T_R). The mathematical expression for describing the compound event probability for a single hazard event is:

$$\text{Compound Event Probability}\left(P_{CEh}\right) = \left(\frac{P_h}{T_R}\right) \tag{4}$$

For multi-hazard event scenarios, it may be necessary to first convert compound event probabilities into a consistent unit of measure to ensure that likelihood of occurrence for different hazard events of equivalent intensity have the same meaning and can be compared. The approach used in Pathways is to assess each hazard event in terms of annual probability of occurrence. The annual probability (P_A) is defined as the likelihood that a specified level of hazard intensity (h) will be exceeded in any given year over a defined time interval. The conversion of compound probability for a hazard event of a given intensity (h) over a reported time interval (T_R) to a corresponding annual probability for a planning horizon of interest (P_H) is given by:

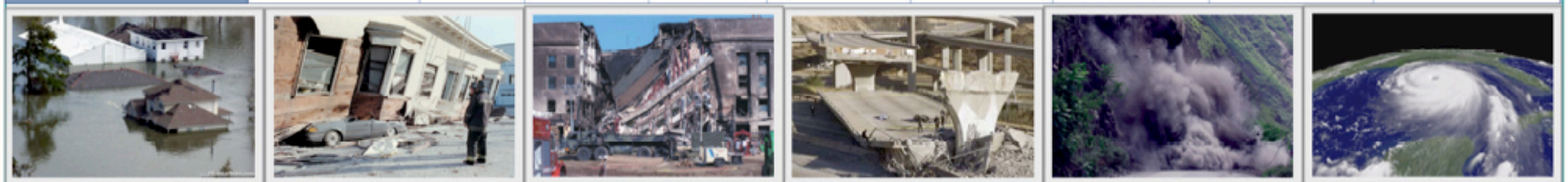
$$\text{Annual Probability }\left(P_{Ah}\right) = 1 - \text{power}\left(\frac{P_{CEh}}{T_R}\right)^{PH} \tag{5}$$

In this way, planning horizon can be used instead of recurrence interval to explore how annual probabilities compare for different hazard threats and how they will vary as a function of specific model assumptions. The relationships between compound and annual probability of a hazard event are summarized below in Table 4-12 for a range of planning horizons.

Up to this point, we have considered the probability of a single hazard event occurring over a given time interval. This is sufficient for situations in which land use planners and emergency managers need to focus on a

Quantitative Risk Analysis - *Assessing Hazard Probability*

Hazard Event (of specified intensity)	Reported Likelihood	P_{CEh}	T_R	P_{Ah} = 1 yr	P_{Ah} = 10 yrs	P_{Ah} = 30 yrs	P_{Ah} = 100 yrs	P_{Ah} = 500 yrs	P_{Ah} = 1000 yrs
Riverine Flood	1/200 years	.99999	200	0.00500	0.04889	0.13961	0.39423	0.91843	0.99335
Earthquake (PGA)	2% in 50 years	0.02	50	0.00040	0.00399	0.01193	0.03922	0.18130	0.32973
Earthquake (PGA)	1/2475 years	.99999	2475	0.00040	0.00403	0.01205	0.03961	0.18295	0.33243
Earthquake (PGA)	10% in 50 years	0.10	50	0.00200	0.01982	0.05829	0.18143	0.63249	0.86494
Earthquake (PGA)	1/475 years	.99999	475	0.00211	0.02085	0.06127	0.19002	0.65137	0.87845
Landslide	1/10,000 years	.99999	10000	0.00010	0.00100	0.00300	0.00995	0.04877	0.09517
Severe Storm	50% per year	.50	1	0.50000	0.99902	1.00000	1.00000	1.00000	1.00000



$$\text{Annual Probability } \left(P_{Ah}\right) = 1 - \text{power}\left(\frac{P_{CEh}}{T_R}\right)^{PH}$$

Table 4-12: Relationship between reported likelihood and annual probability for variable planning horizons.

particular hazard threat in order to develop a corresponding response plan or assess the level of safety for specific mitigation measures. But what about the cumulative probability of a risk scenario that may involve multiple hazard threats over the same planning horizon? Assuming that multiple hazard events of varying intensity occur independently of one another and the rates of occurrence are constant for any given interval of time, it is possible to assess the likelihood of exceeding a specified threshold of probability using the expression:

$$\text{Probability of Exceedance } \left(P_E\right) = 1 - \prod_{h=1}^{n}\left(1 - P_{Ah}\right) \quad \text{(Grossi } et\ al.\text{, 2005)} \qquad (6)$$

This is the approach used by the National Building Code of Canada (NBCC) in establishing safety thresholds for the design and construction of engineered structures in areas exposed to earthquake hazards. Maps and associated tables provide an assessment of the probability of exceeding a designated threshold of ground shaking intensity for a range of time intervals (Adams and Halchuk, 2003; Halchuk and Adams, 2008). A similar method can be used to assess multi-hazard potential for a risk portfolio that includes different types of threats. In addition to standardizing the unit of measure for assessing hazard, this involves a reconciliation of intensity measurements for the various hazard types. This is a challenge given that hazard intensities are assessed on the basis of physical attributes that vary from one hazard type to another (Douglas, 2007).

Pathways addresses this issue by assessing hazard potential in terms of intrinsic magnitude—a measure of probable impact with respect to a common structural element (e.g. single-family wood frame dwelling) that is used as a reference standard. The method allows an objective measure of relative severity between different hazard types and is independent of the actual characteristics of the built environment. More specifically, it provides a capability to characterize an internally coherent multi-hazard potential surface that accounts for the cumulative severity of multiple threats over variable planning horizons. In this approach, hazard magnitude is evaluated as the ratio of damage states between existing conditions and potential future patterns of settlement. As building structures are added to the model to simulate future conditions of growth and development, the measure of multi-hazard potential will increase proportionally. The approach is similar in concept to the damage index developed by Blong and co-workers to assess the magnitude of multi-hazard threats in Australia (Blong, 2003b; a). By combining equations (3) and (6), multi-hazard threat (K_{MH}) can be expressed in terms of magnitude (M):

$$\text{Multi - Hazard Potential } \left(K_{MH}\right) = \left[1 - \prod_{h=1}^{n}\left(1 - \left\{M_h P_{Ah}\right\}\right)\right] \quad \text{(this study)} \qquad (7)$$

Geographic variations in multi-hazard potential are assessed using standard methods of spatial analysis. For areas in which a particular hazard threat is either non-existent or below a specific threshold of impact, the corresponding hazard potential variable is excluded from the analysis. As illustrated in Figure 4-16, maps can be generated that portray composite patterns of hazard potential for a portfolio of hazard threats that may be of concern to the planning process. Results of the assessment provide a high-level screening tool to assist land use planners and emergency managers in identifying areas that may be currently at risk and areas of concern with respect to future growth and development.

This approach also provides a capability to explore the effects of changing assumptions about planning horizon. For example, high-frequency/low-consequence flood events may characterize the overall threat profile for planning horizons of less than 30 years. For planning horizons greater than 30 years, the effects of lower-frequency/higher-consequence threats, such as major earthquake or landslide events, become increasingly more evident. Establishing a common understanding of these relationships is vital in evaluating the strengths and weaknesses of mitigation alternatives. By not considering the effects of low-frequency/high-consequence events there is a danger that levels of structural protection may be set below what is considered a minimum threshold for public safety.

4.4 2..4 Physical Vulnerability

Information about the built environment and physical characteristics of hazard potential provide the necessary context for analyzing specific risk scenarios in terms of threat (physical vulnerability, level of protection, and induced damages), public safety (casualties, loss of habitation, and shelter needs), system functionality (resistance, disaster debris, and recovery time), and socio-economic security (anticipated economic loss, probable loss, and expected return on investment).

In the context of quantitative risk analysis, physical vulnerability provides a measure of the extent to which people and physical assets are impacted by potential hazard threats in terms of damages, severity of injury, and potential for loss of life. Physical impact is measured as a function of structural fragility (F) with respect to a specified hazard threat (h), and the effectiveness of mitigation efforts to increase resistance of the structure to physical damage (R_m). The vulnerability of physical elements in the built environment ($\in$) to impacts of hazard-specific threats is given by:

$$\text{Vulnerability } \left(V_{\in,h}\right) = \sum\left[F_{\in|h}\left(1 - R_{\in}\right)\right] \quad \text{(Ayyub } et\ al.\text{, 2007)} \qquad (8)$$

Fragility ($F_{\in|h}$) is a measure of direct physical damage and is assessed as a function of hazard intensity and the probability of exceeding a specified threshold of damage. Damage functions are represented in the form of lognormal fragility curves that reflect the uncertainty of anticipated damage states based on spatial variability of the hazard threat, and variability in the response of a physical structure to a specified level of hazard intensity. Fragility curves provide a means of predicting physical

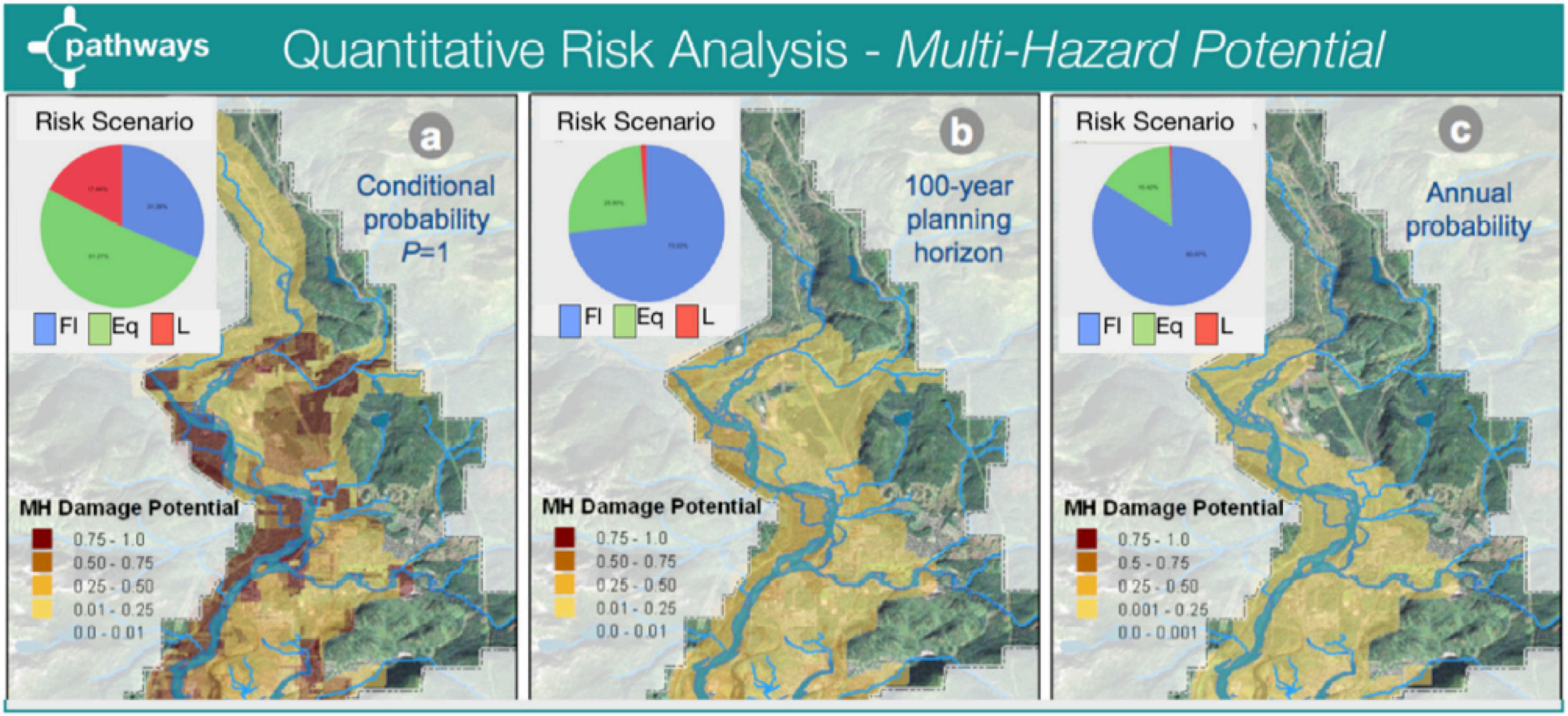


Figure 4-16: Sample outputs of a multi-hazard potential assessment for a portfolio of event scenarios. The maps provide a measure of relative hazard potential for flood, earthquake, and landslide events. Multi-hazard potential varies as a function of the time horizon used to assess multi-hazard probability.

impacts of a hazard event based on experimental studies of structural performance under simulated hazard conditions, or forensic studies of actual damages resulting from hazard events in which spatial variability and hazard intensity have been observed and measured. Injuries and fatalities are assessed on the basis of the extent and probability of physical damage to buildings, and take into account the temporal probabilities that specific groups of people will be in the building at a specified time of day. Modelling of resistance (R_e) is based on the extent to which structures conform to existing safety thresholds established by building codes and design guidelines, and or the expected level of resistance resulting from proposed mitigation measures.

HAZUS provides an extensive library of calibrated damage functions for earthquake, flood, and hurricane hazards. Fragility curves for earthquake hazards are based on performance models that relate the physical resistance of engineered structures to anticipated ground shaking intensities (PGA, PGV, Spectral Acceleration) and associated permanent ground failure (landslides, liquefaction, and surface fault rupture). Fragility curves are available for most key elements of the built environment (ACT-13, 1985; FEMA, 1997), including structural and non-structural components of buildings (residential, commercial, industrial), essential facilities (hospitals, care facilities, emergency operation facilities, schools), critical infrastructure (dams, power plants, military installations), transportation systems (roads, railways, bridges, tunnels), utility systems (potable water, wastewater, oil, natural gas and electric power), and

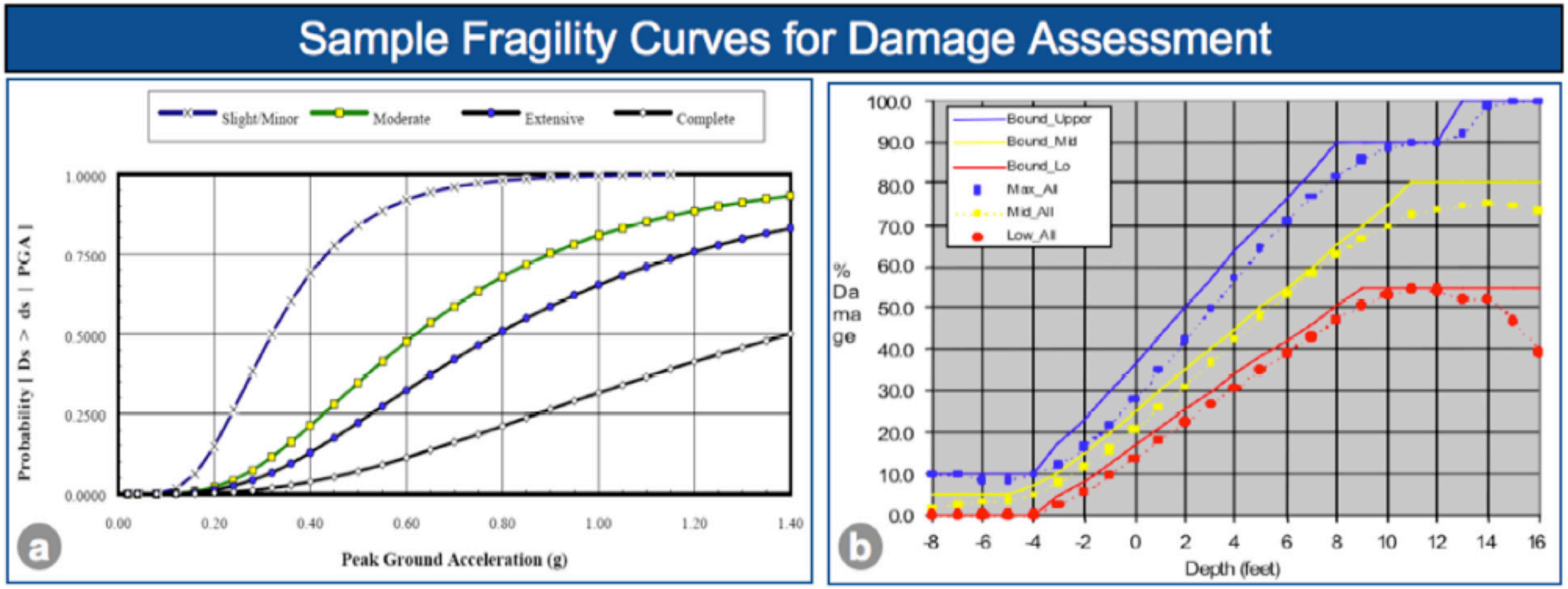


Figure 4-17: Fragility curves used to compute the probability of damage caused by a) earthquake ground shaking based on HAZUS methodology), and b) flooding based on DEFRA methodology.

communication systems. Figure 4-17 is an example of fragility curves that describe the likelihood of reaching or exceeding a specified damage state based on an estimate of ground shaking and flood intensities.

Human impacts of earthquakes are measured in terms of the probable severity of injury and the numbers of people that are likely to be displaced from their homes as a result of structural damage. Injury and displacement rates are assessed on the basis of physical damage state, not directly on the people occupying the building. The level of injury is estimated by multiplying the predicted damage rate for the facility by the number of people that are estimated to be in the building at the time of the earthquake event. The maximum potential number of people who are likely to be impacted is based on the occupancy class of the building (residential, commercial, industrial) and the time of day that the earthquake event occurs. The number of individuals displaced during an earthquake event is estimated by computing occupancy for buildings that exceed minimum thresholds of sustained damage (~20%).

Damage functions for floods, storm surge, and tsunami inundation include those developed by the US Federal Insurance Agency (FIA, 1970), the US Army Corps of Engineers (UCACE, 2003), and the UK Department for Environment, Food and Rural Affairs (DEFRA, 2003). The UCACE method utilizes measures of water depth, duration of flooding, construction type and elevation of the first floor to determine likely impacts to structures and contents at a given location. More than 900 fragility curves have been calibrated for key elements of the built environment including residential and commercial buildings and contents, vehicles, essential facilities, transportation and utility systems. The DEFRA method is similar in scope to that of UCACE but takes into account additional effects of water velocity and the presence of floating debris such as trees and building materials. Variables that influence the probability of damage include building type and construction materials, age, and the general state of maintenance. These factors will determine the overall resistance of a structure to a specific hazard threat.

The analysis of injuries caused by floods, storm surge, and tsunami inundation utilizes site-specific information on water depth and velocity, and the characteristics of vulnerable populations. Empirical studies have shown that even shallow flood events (10–20 cm) have the capacity to topple a person if the water is moving at a high velocity over the land surface. Full assessment of human vulnerability requires the capacities of agent-based spatial models that take into account detailed information on the hazard conditions (depth, velocity), a person's age, time of day (anticipated location), and whether they are likely to attempt finding shelter indoors or to evacuate on foot. If the person is indoors at the time of the hazard event, then the building damage function would determine the likely potential for injury. If the person is outdoors and attempting to escape through areas exposed to flood waters, then depth-velocity values (m2/sec) along the anticipated escape route would determine whether a person is likely to be swept away and lost.

Damage functions for other natural hazard types are less well developed. Fragility curves that relate wind intensity to expected levels of damage have been established for assessing hurricane hazard threats in North America and parts of Europe, but not for other types of hydro-meteorological hazards types (Vickery *et al.*, 2006a). Fragility curves for landslide and volcanic hazards are even less formalized due to a lack of detailed information on the physical response of specific buildings types and other structures to slope instabilities and material properties (Douglas, 2007). Existing damage functions are based primarily on the forensic analysis of actual damages associated with landslide events in a specific geographic setting (Guzzetti *et al.*, 2003; Glade and Bell, 2004; Galli and Guzzetti, 2007; Akbas *et al.*, 2009; Petrucci and Gulla, 2009).

4.4 2..5 *Hazard Risk*

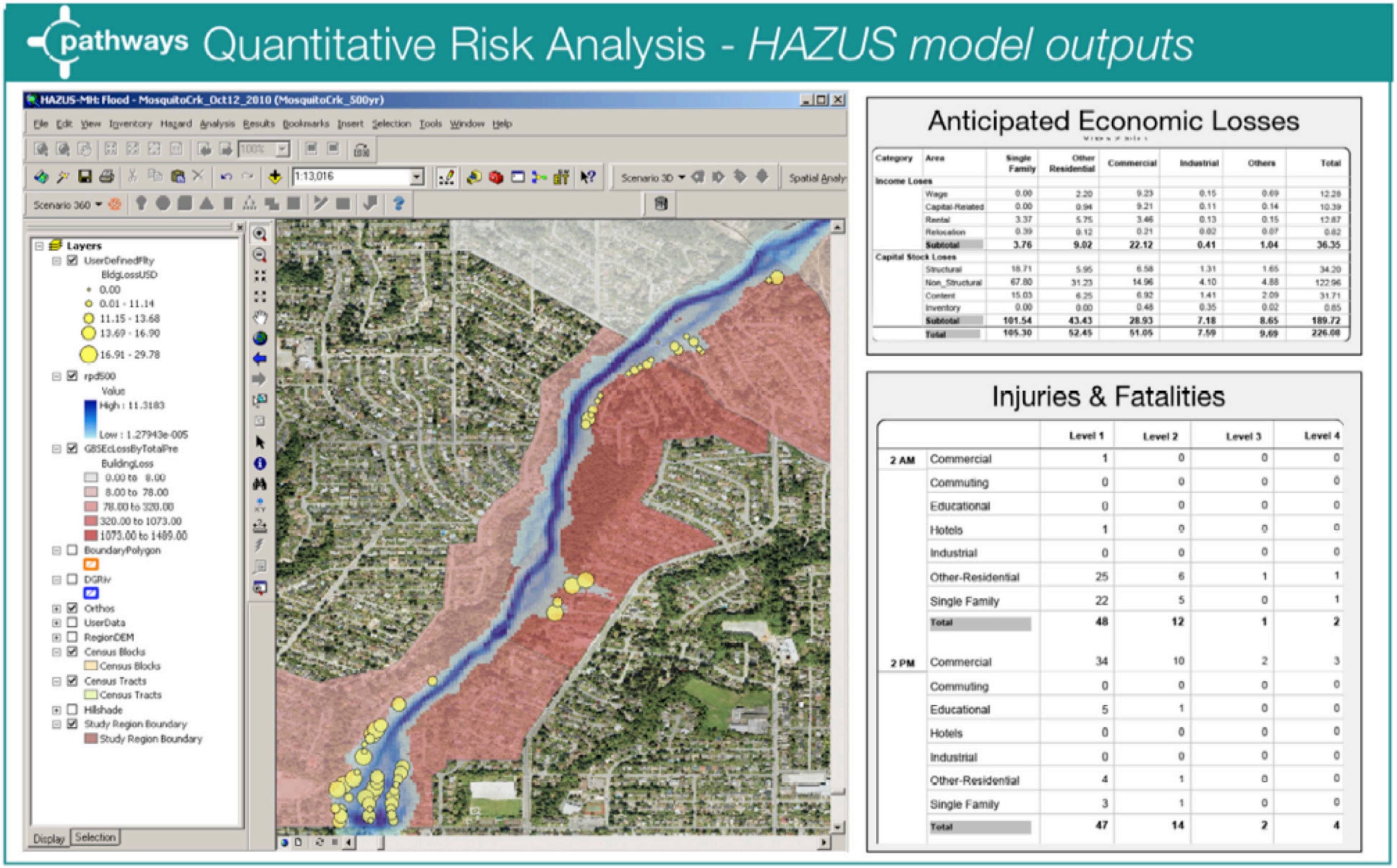
Hazard risk is a measure of the anticipated direct and indirect socio-economic consequences of a disaster event measured in terms of anticipated losses for a hypothetical event scenario, or the probable maximum loss for a portfolio of hazard threats (International Strategy for Disaster Reduction, 2002; ISO 31000, 2008b). Direct economic losses include capital costs for repair or replacement of physical structures, contents and inventory, and also business costs associated with loss of income and relocation. Indirect economic losses are those associated with ancillary consequences to socio-economic systems that do not sustain direct physical damage but are nonetheless impacted by the ancillary shocks of a hazard event. These can include upstream business costs associated with the loss of demand for goods and services, downstream business costs associated with the loss of production capacity, and losses to employment income caused by disruptions or business closures. Estimates of indirect economic losses are based on input-output models that account for interdependencies between different sectors of the economy at local and regional scales (Rose, 2004b; Rose, 2004a).

Direct economic loss is measured on the basis of damage potential (V) and value of a target asset (L), the probability that a hazard event will occur over a specified time horizon (P) and the effectiveness of emergency preparedness operations R). The anticipated loss for a specific hazard event scenario is given by:

$$\text{Hazard Risk } \left(R_{\epsilon,h}\right) = \sum\left[\left(L_{md} V_{\epsilon,h}\right) P_{Ah} \times \left(1 - R_{em}\right)\right], \quad \text{(Ayyub } et\ al.\text{, 2007) (9)}$$

In this formulation, P_{Ah} is the annual probability of the hazard event for a given planning horizon (equation 5), and R_{em} is the expected effectiveness of emergency preparedness, response and recovery operations. This is a variation of a general all-hazard risk equation developed for analyzing the security of assets that are exposed to a variety of natural and anthropogenic hazard threats (Ayyub *et al.*, 2007; McGill *et al.*, 2007). As illustrated in Figure 4-18, spatial patterns of risk are assessed using equation (9) to model anticipated losses for physical assets that can be represented as geographic features or areas on a map.

Risk profiles offer a means of graphically comparing frequency-loss relationships for a portfolio of disaster events over a range of time horizons (see Table 4-6). They are particularly effective in assessing the implications of model uncertainties (planning horizon and associated growth potential) in evaluating the effectiveness and efficiency of



Anticipated Economic Losses

Category	Area	Single Family	Other Residential	Commercial	Industrial	Others	Total
Income Losses							
	Wage	0.00	2.20	9.23	0.15	0.69	12.28
	Capital-Related	0.00	0.94	9.21	0.11	0.14	10.39
	Rental	3.37	5.75	3.46	0.13	0.15	12.87
	Relocation	0.39	0.12	0.21	0.02	0.07	0.82
	Subtotal	**3.76**	**9.02**	**22.12**	**0.41**	**1.04**	**36.35**
Capital Stock Losses							
	Structural	18.71	5.95	6.58	1.31	1.65	34.20
	Non_Structural	67.80	31.23	14.96	4.10	4.88	122.96
	Content	15.03	6.25	6.92	1.41	2.09	31.71
	Inventory	0.00	0.00	0.48	0.35	0.02	0.85
	Subtotal	**101.54**	**43.43**	**28.93**	**7.18**	**8.65**	**189.72**
	Total	**105.30**	**52.45**	**51.05**	**7.59**	**9.69**	**226.08**

Injuries & Fatalities

		Level 1	Level 2	Level 3	Level 4
2 AM	Commercial	1	0	0	0
	Commuting	0	0	0	0
	Educational	0	0	0	0
	Hotels	1	0	0	0
	Industrial	0	0	0	0
	Other-Residential	25	6	1	1
	Single Family	22	5	0	1
	Total	**48**	**12**	**1**	**2**
2 PM	Commercial	34	10	2	3
	Commuting	0	0	0	0
	Educational	5	1	0	0
	Hotels	0	0	0	0
	Industrial	0	0	0	0
	Other-Residential	4	1	0	0
	Single Family	3	1	0	0
	Total	**47**	**14**	**2**	**4**

Figure 4-18: Outputs of a quantitative risk analysis portrayed as a) a map showing spatial distribution of hazard risk for a given time horizon, and b) tables summarizing anticipated losses and casualties.

proposed mitigation measures, and in establishing corresponding thresholds of risk tolerance with respect to socio-economic security and public safety. Anticipated losses will increase for future scenarios in which time horizons are longer (increased probability of occurrence), or in which the asset portfolio is augmented through growth and development (greater number of assets exposed to consequences of a given hazard event). Mitigation measures have the potential to decrease anticipated losses but require the investment of capital resources up front.

As illustrated in Table 4-6, risk profiles are developed by first sorting the portfolio of hazard event scenarios in order of decreasing loss. Probabilities of exceedance are then calculated for each event using equation (6), beginning with the highest consequence event and progressing incrementally to the lowest consequence event. The resulting risk profile (shown in Table 4-6b) is delineated by the probable maximum loss for each of the hazard threats in the portfolio. The cumulative anticipated loss for a given community or region is represented graphically as the area under the risk curve and can be assessed mathematically by integrating losses over a specified range of probability. Probable maximum loss is the standard method used by the insurance industry to negotiate thresholds of risk tolerance for individuals and corporate entities. It explicitly accounts for uncertainty and the consequences of "worst-case scenarios," and provides the necessary context for developing efficient strategies to manage economic risks associated with multi-hazard threats (Kovacs and Seweeting, 2004; Grossi *et al.*, 2005; Kovacs and Hallak, 2005; Kovacs, 2010). In the context of land use planning and emergency management, risk profiles offer a synoptic view of the cumulative loss potential for a community or region. They are an effective means of evaluating thresholds of risk tolerance and strategies and the effectiveness of risk reduction strategies.

Consider the hypothetical example of a community that is interested in developing an actionable disaster mitigation plan to manage potential economic losses associated with a portfolio of hazard threats represented by the risk profile in Table 4-6b. Based on the potential for loss of life caused by natural hazard threats, they have selected an event recurrence interval of 1/10,000 (P_A =0.0001) as a target threshold for tolerable risk. The corresponding disaster event for this region is a major earthquake that has a potential to trigger direct economic losses of approximately $760 million . The community has determined that internal financial resources will only cover up to $150 million in direct losses to publicly owned assets. The balance of $610 million represents potential losses that would need to be managed by additional investment in mitigation measures, reliance on disaster relief funding, or the transfer of residual risk through insurance or re-insurance markets.

There are many ways in which the community might choose to mitigate risks associated with a portfolio of hazard threats. One option would be to invest a portion of the available resources into protective mitigation measures, such as structural reinforcement or retrofitting of existing buildings to increase levels of safety and reduce potential losses. This would have the effect of reducing the probability of exceeding minimum thresholds of tolerable loss, thereby shifting the risk curve to the left along the x-axis in Table 4-6b. Another option might be to establish a maximum threshold of tolerable loss that is managed by limiting the potential for future growth and development in areas that are exposed to earthquake hazards (non-structural mitigation). This would have the effect of maintaining existing levels of risk by ensuring that any new assets are not situated in harm's way. Each of these risk management strategies have particular strengths and weaknesses that would need to be evaluated in terms of efficiency (benefits and costs) and ancillary consequences with respect to other policy objectives.

Return on investment (ROI) is a metric of socio-economic security that is used to evaluate the performance and efficiency of a mitigation investment or to compare the efficiency of a number of different investments that are made for the purpose of promoting socio-economic security, public safety, and overall disaster resilience. It is defined as the ratio of benefits gained as a result of investing in the mitigation of hazard impacts to an asset (a_i), divided by the costs incurred by investing in these measures (C_i). For a collection of assets, the expected return on an investment is given by:

$$\text{Return on Investment } \left(ROI_A\right) = \sum_{i=0}^{I} a_i \left(\frac{V_{\epsilon,h} L_{mcl}}{C_i} - 1 \right) \qquad (10)$$

In this formulation, a benefit or financial return is interpreted to mean losses that are avoided by implementing a proposed mitigation measure (Bernkopf *et al.*, 2001; Rose, 2004b). Mitigation costs include direct capital expenditures as well as the indirect economic costs of implementing and maintaining a given set of protective and avoidance measures. Pathways utilizes a portfolio-based approach to analyzing financial risk that extends conventional methods of risk-benefit analysis using principles of financial portfolio theory (Bernkopf *et al.*, 2001; Ayyub *et al.*, 2007). Portfolio modelling seeks to optimize the performance of securities that have an uncertain rate of return. Financial security is defined to be an investment in which an expenditure is made and a future benefit or financial return is expected (McKenna, 1986; Bernkopf *et al.*, 2001).

The analysis of financial risk can be facilitated using available cost-benefit tools, like the USGS Land Use Portfolio Model (LUPM). It begins with the grouping of assets considered "at risk" by the community into mitigation portfolios that are then analyzed in terms of expected probabilities of loss with and without mitigation measures in place using methods described above. Mitigation alternatives to safeguard these asset collections are then modelled as investment portfolios, where performance and efficiency are measured in terms of probability of financial return. A mitigation portfolio, like an investment portfolio, can include a collection of assets that vary widely in terms of anticipated losses and expected rates of return.

The objective is to provide information that will assist decision makers in formulating actionable risk reduction strategies and in assessing trade-offs between policy alternatives. A mitigation portfolio is considered financially risky if the expected rate of return does not meet a designated threshold of performance. Examples of mitigation alternatives include direct capital investment in protective structures to reduce the probability of damage (levees, structural reinforcements, building retrofits, etc.), relocation of existing assets that can not be reasonably protected from hazard threats with available resources, and redirection of future development and associated infrastructure services to reduce vulnerability. Variables that influence the probable rates of return on a mitigation portfolio include scientific uncertainties regarding hazard potential (extent, intensity, and probability of occurrence), the effectiveness of existing and proposed mitigation measures to resist the physical impacts of a hazard threat, and the performance of local and regional economic markets that may be directly or indirectly influenced by risk management decisions.

4.4 2..6 System Functionality

The analysis of system functionality in the Pathways framework makes use of models in HAZUS to predict the response and recovery characteristics of critical lifeline facilities and related services over time. The approach is consistent with engineering-based methods developed by the Multidisciplinary Center for Earthquake Engineering Research (MCEER; Bruneau *et al.*, 2003; Chang and Chamberlin, 2004; Chang and Shinozuka, 2004; Miles and Chang, 2006), but less hearty in terms of their capacity to model interdependence and system feedbacks. A mathematical expression of system functionality is given by:

$$\text{Functionality (F)} = \int_{t}^{t_1} \left[\left(1 - V_{\epsilon,h}\right)\left(1 - R_{em}\right) \right] dq \quad \text{(Bruneau } et\ al.\text{, 2003),} \qquad (10)$$

where (Q) represents a measure of system performance that varies with time, and (R_{em}) represents the expected effectiveness of emergency preparedness, response and recovery operations. Levels of performance can be measured on the basis of service throughput (rates of flow for lifeline services), the proportion of service connections that are active at any given point in time, and the expected level of disruption caused by a hazard event (Chang and Chamberlin, 2004). Performance levels following a modelled hazard event can range from no reduction in system functionality (F=1) to complete system failure (F=0).

The MCEER framework defines robustness as the ability of a system to withstand a given level of stress without suffering degradation or loss of function. It is assessed as a function of damage potential. Correlations between damage potential and expected system performance are calibrated using forensic data or results of empirical studies (Chang and Chamberlin, 2004; Chang and Shinozuka, 2004). Baseline thresholds are used as a point of reference to measure differences between system functionality before and after a hypothetical hazard event. Recovery time is defined as the capacity to meet priorities and achieve goals in a timely manner in order to contain losses and avoid future disruption. It is assessed using predictive models that anticipate the number of days or months required to restore functionality to baseline performance levels during response and recovery phases.

The adaptive capacity of the system is measured by the extent to which the system is expected to respond and recover to the hazard impact with time. Adaptive capacity can be enhanced by the implementation of mitigation measures that increase the resistance to physical damage prior to the hazard event (R_{ϵ}) or by response and recovery efforts that increase performance of the system after the disaster event (R_{em}).

Systems that are characterized by a higher level of functionality would experience relatively small levels of disruption as a result of *ex-ante* mitigation, and would likely recover to baseline performance levels in a relatively short period of time. In some instances, these systems may even experience a net improvement as a result of *ex-post* mitigation measures that increase the adaptive capacity of the system during the recovery period. Systems that are characterized by lower levels of functionality would experience a relatively large drop in performance, would take longer to restore minimum thresholds of performance, and may never recover to pre-event states of functionality.

4.4 2..7 Social Vulnerability

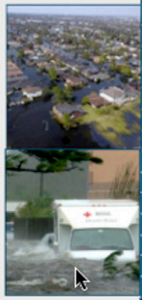
The quantitative analysis of social vulnerability involves the detection of statistically significant patterns of correlation within a collection of population and demographic variables. The assessment utilizes methods of multivariate analysis that are based on principles of inductive reasoning. Outputs are evaluated in terms of correlation factors that are not easily reconciled with numeric models of risk. While there is value in comparing spatial patterns of hazard risk and vulnerability, they are conceptually distinct.

Vulnerability emphasizes root causes that create unsafe conditions or predispose a community or region to negative consequences of a hazard event. The capacity to analyze and map patterns of vulnerability is a requirement for pre-event emergency planning and is a priority of the National Disaster Mitigation Strategy for Canada (NDMS; Hwacha, 2005) Vulnerability can be analyzed in terms of physical susceptibility to hazard threats that are external to the system (exogenous variables; UN/ISDR,2002), and in terms of human factors and socio-economic processes that are internal to the system and that have a potential to amplify the impacts and consequences of a hazard threat for a particular community or region (endogenous variables; UNDP, 2006). Exogenous variables describe physical aspects of a system that can be predicted on the basis of causal relationships that are known and that can be assessed mathematically using principles of deductive reasoning. Endogenous variables are particular to the characteristics of a particular place and population. They describe the human and socio-economic aspects of a system at a given point in time that must be discovered through observation, measurement, and inductive reasoning. The selection of model variables is known to have a significant influence on the assessment of vulnerability, and will vary according to geographic setting, scope, and requirements of the risk management process (Chakraborty *et al.*, 2005; Jones and Andrey, 2007).

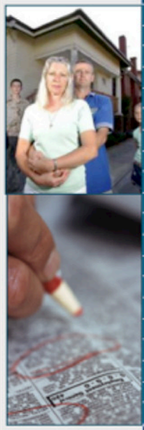
As illustrated in Table 4-13, Pathways reconciles these two approaches by integrating physical and human dimensions of susceptibility into a general model of vulnerability that addresses: (i) underlying causal structures and driving forces that determine the extent to which people and places are likely to be exposed to hazard threats; (ii) socio-economic factors that enable some to withstand the impacts of a hazard event and that force others to succumb; and (iii) factors that influence the capability of individuals and groups to cope with and recover from the impacts and consequences of a hazard event.

The Pathways model for social vulnerability is implemented using standard methods of geostatistical modelling and multivariate principal component analysis (PCA), and information that can be derived from community profile data collected as part of the national census (Statistics Canada, 2003a; 2006). It extends capabilities of the well-known Hazards-of-Place model (Burton *et al.*, 1993; Coburn *et al.*, 1994; Cutter *et al.*, 2000; Kuban and MacKenzie-Carey, 2001; Flax *et al.*, 2002; BC Provincial Emergency Program, 2003; Cannon *et al.*, 2003; Cutter *et al.*, 2003; Ferrier and Haque, 2003; Pearce, 2003), and is consistent with recommended best practices for the assessment of vulnerability in a Canadian context (Jones and Andrey, 2007; Andrey and Jones, 2008).

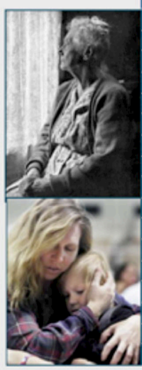
Social Vulnerability Model



Exposure to Natural Hazard Threats		
StatsCan Variable	**Influence**	**Description**
DU_HEC	(+)	dwelling units per hectare
P_CON_LT85	(+)	% housing units constructed before 1985
P_MOB_HOME	(+)	% mobile home units
DU_SIG_DAM	(+)	% dwelling units exposed to potential of significant damage
MHP_HEALTH	(+)	% buildings damaged that provide essential medical services
MHP_BASIC	(+)	% buildings damaged that provide basic services
MHP_COMM	(+)	% buildings damaged that provide commercial/industrial service
MHP_SOC	(+)	% buildings damaged that provide social services
P_RESOURCE	(+)	% employed in primary resource extraction industries
P_TRANS	(+)	% employed in transportation, communication & public utilities
P_SERVICE	(+)	% employed in service industries
P_TEN_OCC	(+)	% tenant-occupied housing units
A_RENT_TEN	(+)	average rent of tenant-occupied housing units
P_IND_OCC	(+)	% employees working in industrial sector



Agency & Ability to Influence Decisions		
StatsCan Variable	**Influence**	**Description**
P_HHI_LT80	(+)	% households earning <$80,000
P_L_INC_F	(+)	% low-income families
A_HH_INC	(-)	average household income
P_L_INC_I	(+)	% low-income individuals
P_TEN_GT30	(+)	% tenant-occupied households spending >30% on shelter
P_OWN_GT30	(+)	% owner-occupied households spending >30% on shelter
A_OWN_PAYM	(+)	average payments for owner-occupied housing units
P_DU_MAJOR	(+)	% housing units in need of major repairs
P_VIZ_MIN	(+)	% visible minority
P_ABORIG	(+)	% aboriginal community
P_PARTIC_N	(+)	% population not participating in labour force
P_UNEMPL	(+)	% civil labor force unemployed
P_MOB_LT1	(+)	% population that has moved within the last year
P_MOB_LT5	(+)	% population that has moved within the last 5 years
P_MIG_I	(+)	% population that has migrated from within BC
P_MIG_E	(+)	% population that has migrated from elsewhere in Canada
P_HISCH_N	(+)	% population with no high school diploma
P_LANG_N	(+)	% population without knowledge of official language
P_IMMIGRNT	(+)	% recent immigrants (within last 5 years)
P_PSEC_N	(+)	% population with no post-secondary degree



Capacity for Response & Recovery		
StatsCan Variable	**Influence**	**Description**
IN_NO_VEH	(+)	% population without access to a vehicle
P_AGE_LT5	(+)	% population under 5 years of age
P_AGE_GT_65	(+)	% population 65 years and older
P_SEN_ALON	(+)	% senior population living alone
P_FEM_POP	(+)	% female population
P_FEM_LAB	(+)	% female population participating in labour force
P_LFP	(+)	% lone female parent households
P_POP_ALON	(+)	% population living alone
P_CHD_GT30	(+)	% families spending > 30 hours of unpaid childcare
P_SEN_GT10	(+)	% families spending > 10 hours of unpaid care to seniors
P_S_PARNT	(+)	% lone parent households
P_HC_OCC_N	(+)	% population not in health care occupations
A_PROX_HC	(+)	proximity to hospitals and health care facilities
P_BSER_OCC	(+)	% employees in basic service industries
A_PROX_BS	(+)	proximity to basic service facilities
P_SOC_OC_N	(+)	% population not participating in social service occupations
A_PROX_SOC	(+)	proximity to social service facilities

Table 4-13: Pathways model for assessing intrinsic patterns of social vulnerability in a community or region.

4.4 3. Integrated Assessment and Scenario Planning

Existing methods of risk assessment emphasize the analysis of impacts and consequences based on static models of the human-natural system. They provide a snapshot of anticipated damages and losses for existing conditions, but are not designed to assess how the risk profile of a community or region is likely to evolve over time, or to evaluate the strengths and weaknesses of mitigation alternatives in terms of policy goals and management objectives.

Principles, goals, and targets that are embedded in the planning process will have a direct influence on land use allocation and evolving patterns of vulnerability and risk. As characteristics of the community profile change, so too will associated patterns of vulnerability and risk. For example, comprehensive land use plans that are geared toward compact and dense urban forms that emphasize efficiencies in transportation, resource management, and energy reduction can inadvertently increase the physical vulnerabilities of people and critical assets, thereby reducing overall disaster resilience and longer-term sustainability of the community. Similarly, emergency management plans that focus primarily on strategies of structural mitigation to reduce risk can in some cases promote a false sense of security that encourages future growth and development in harm's way. It is important, therefore, that land use planners and emergency managers have a capability to anticipate and visualize how changes in land use are likely to occur, and to make evident how these changes may influence the resilience of a community or region over time.

The capability to model landscape evolution and the underlying system dynamics that influence patterns of vulnerability and risk through time is well established in the fields of global environmental change and integrated assessment (Jaeger, 1998; Rotmans and Van Asselt, 2000; van der Sluijs, 2002; Turner *et al.*, 2003; Verburg *et al.*, 2004). At the same time, methods of integrated assessment and scenario planning are becoming more widely available and are increasingly used on a routine basis by land use planners to inform decisions about growth management and sustainable development at regional and local levels of government (Boyd and Chan, 2002; Condon, 2003; Durbach and Stewart, 2003b; Swart *et al.*, 2004; Verburg *et al.*, 2004; Girling *et al.*, 2006; Montibeller *et al.*, 2006; Alcamo, 2008; Condon *et al.*, 2009; Walker and Daniels, 2011).

4.4 3..1 Bridging the Gap Between Risk Analysis and Risk Evaluation

CommunityViz® is an integrated system of scenario modelling and visualization methodologies developed by the Orton Family Foundation to assist planners in adopting an evidence-based approach to land use that is informed by the best available science and governed by community values and preferences (Walker and Daniels, 2011). The application is implemented as an extension to the well-known ArcGIS® platform and comprises modelling tools for integrated assessment and scenario planning (Scenario360), and specialized tools for landscape modelling and visualization (Scenario3D).

Scenario360 is the analytic modelling engine of the CommunityViz® application. It is designed to create, analyze and display multiple hypothetical landscape scenarios (land use plans, growth patterns, project plans, etc.), compare alternate scenarios to assess potential impacts of decisions on the basis of user-defined assessment criteria, and evaluate the sensitivity of assumptions and external influences using dynamic, formula driven attributes and indicator charts. In addition to providing an open modelling development environment that is directly coupled with ArcGIS, the Scenario360 application also provides pre-programmed wizards for a range of common planning and decision-making functions (see Table 4-14). Scenario3D extends the capacity and impact of CommunityViz® by enabling users to render photo-realistic and interactive landscape visualization models from outputs of a Scenario360 analysis, thereby promoting deeper understanding of what the impacts of various choices will look like on the ground over time. Outputs of a Scenario360 analysis can be published as stand-alone web applications, and exported as standard 3D project files for use in freely available landscape viewers such as GoogleEarth. CommunityViz® is used for a wide range of planning activities by an active network of more than 10,000 researchers and practitioners worldwide, and is considered a best practice for place-based planning at the local and regional level (Boyd and Chan, 2002; Girling *et al.*, 2006; Salter *et al.*, 2007; Condon *et al.*, 2009).

As illustrated in Figure 4-19, CommunityViz® is used in the Pathways framework to bridge the gap between risk analysis and risk evaluation stages of the planning process. RiskMap is the prototype for a Scenario360 decision support tool developed as part of this project to assist planners and emergency managers in developing and evaluating mitigation scenarios based on performance indicators of the Pathways model. Information and knowledge generated as part of the risk appraisal and quantitative risk modelling process is transformed into a corresponding system of interactive maps, indicators and charts that are modelled using custom scripts in Scenario360. RiskMap can be used to generate and compare mitigation scenarios for both single and multi-hazard event scenarios, and provides a basis for identifying a preferred course of action that reflects available scientific knowledge, community values and planning preferences. It can be used in conjunction with HAZUS and other decision support tools in the Scenario360 suite to model land use change and evolving patterns of vulnerability and risk over time, and with third-party external models that are integrated through the CommunityViz® platform.

The Land Use Portfolio Model (LUPM) is a statistical model developed by the US Geological Survey for analyzing the costs and benefits of selected mitigation strategies and expected rates of return on investment. It is used in conjunction with HAZUS to evaluate the efficiency and expected rates of return on mitigation investments over time. Indicators of social equity are assessed using commercial methods of multivariate statistical analysis that are based on best practices developed as part of the Social Vulnerability Index (SoVI).

By integrating existing best practices of risk analysis with emerging new methods of scenario modelling and landscape visualization, the Pathways framework offers a capacity to explore dimensions of vulnerability and risk in the broader context of evolving human-natural systems, and to

communityviz®
RiskMap Wizard: A customized application that facilitates the integrated assessment and modelling of hazard-risk indicators that are derived from HAZUS - FEMA's standardized damage and loss estimation methodology for analyzing the impacts and consequences of earthquakes, floods and hurricanes in North America
Common Impacts Wizard automatically creates GIS-based impact analyses to evaluate the most commonly used indicators of economic, environmental, and social outcomes associated with alternative growth scenarios. The wizard facilitates the creation of formulas, indicators, charts, reports, and variable assumptions with default values to serve as a starting point
The Custom Impacts Wizard sets up analysis models for impacts that are not covered in the Common Impacts Wizard or elsewhere. The wizard facilitates the development of formulas, attributes, indicators, assumptions and charts that can can be used to evaluate the consequences of decision alternatives
The Land Use Designer Wizard facilitates the development of land use models that are used to create and evaluate 'what-if' scenarios on the fly. Each land use model is associated with a set of impacts. As land-use models are added to the analysis, the cumulative impacts are summarized through a system of indicators and charts.
The Optimizer Wizard is used to maximize the performance of selected target criteria to facilitate the decision making process. Features are combined according to a set of user-defined rules to identify patterns that support pre-defined policy goals and objectives. The assessment is facilitated using a modified Simplex Method algorithm.
The Suitability Wizard facilitates the identification of planning areas that are most suitable for a designated land use activity based on user-defined indicators and target criteria. The assessment combines objective measures of system conditions with user-defined values and preferences to make evident land use choices that promote policy goals and objectives
The Allocator Wizard helps determine where growth is most likely to occur over time. It uses a supply-demand model to sequentially assign occupancy classes and associated density to areas that have a potential to accommodate future growth. Allocation can be based on strict -order or probability-based models.
The Build-Out Wizard steps the user through a formal build-out analysis using land use policies and guidelines to determine the number of future residential dwellings and the amount commercial/industrial floor space that can be accommodated, where these structures are likely to be located on the ground, and what the resulting form and massing of buildings will look like in 3D.
The TimeScope Wizard model incremental changes to the landscape over time. Elements of the built environment are allocated according to user-defined rules and assumptions. Indicators, charts and map features are updated automatically to help visualize the impacts associated with anticipated land use changes on a year-by-year basis.

Table 4-14: Decision support tools that have been developed for use in the CommunityViz Scenario360 application to assist in a wide array of planning functions. The RiskMap application was developed as part of this study to facilitate implementation of the Pathways model in support of both land use planning and disaster mitigation.

develop risk management strategies that minimize negative impacts of growth while promoting overall resilience and principles of sustainable land use. Whether using results of semi-quantitative risk appraisal or quantitative risk analysis, the steps involved in developing a scenario model are:

- Establish Context: geographic extent of the scenario, the scale of analysis and the interval of time that will be used to explore system changes, and the indicators that will be used to measure associated impacts over time.
- Describe Baseline Scenario: an assessment of the initial system state at a reference year or interval of time based on observations, measurements, or model outputs.
- Describe Endpoint Scenario(s): an assessment of anticipated system conditions at the endpoint of the scenario based on choices about intended outcomes (targets), judgments of uncertainty, and assumptions about cause-effect relationships.
- Analyze System Dynamics: incremental and step-wise changes to the system that are assessed over specified intervals of time based on choices about intended outcomes (targets), judgments of uncertainty, and assumptions about cause-effect relationships.
- Develop Working Hypotheses: an examination of model uncertainties (sensitivity analysis) for the purpose of exploring and evaluating causal linkages and driving forces that may explain observed system dynamics and scenario outcomes. Working hypotheses are then formulated as narratives or storylines that are tested on the basis of available knowledge and understanding. The evaluation incorporates both expert knowledge about system processes and context-based knowledge about a specific place and how it has evolved over time.

As illustrated in Figure 4-20, spatial and temporal patterns of risk can be made evident through the use of traditional maps and emerging new techniques of landscape visualization. Both offer a means of engaging people in an active exploration of landscapes that are familiar to them,

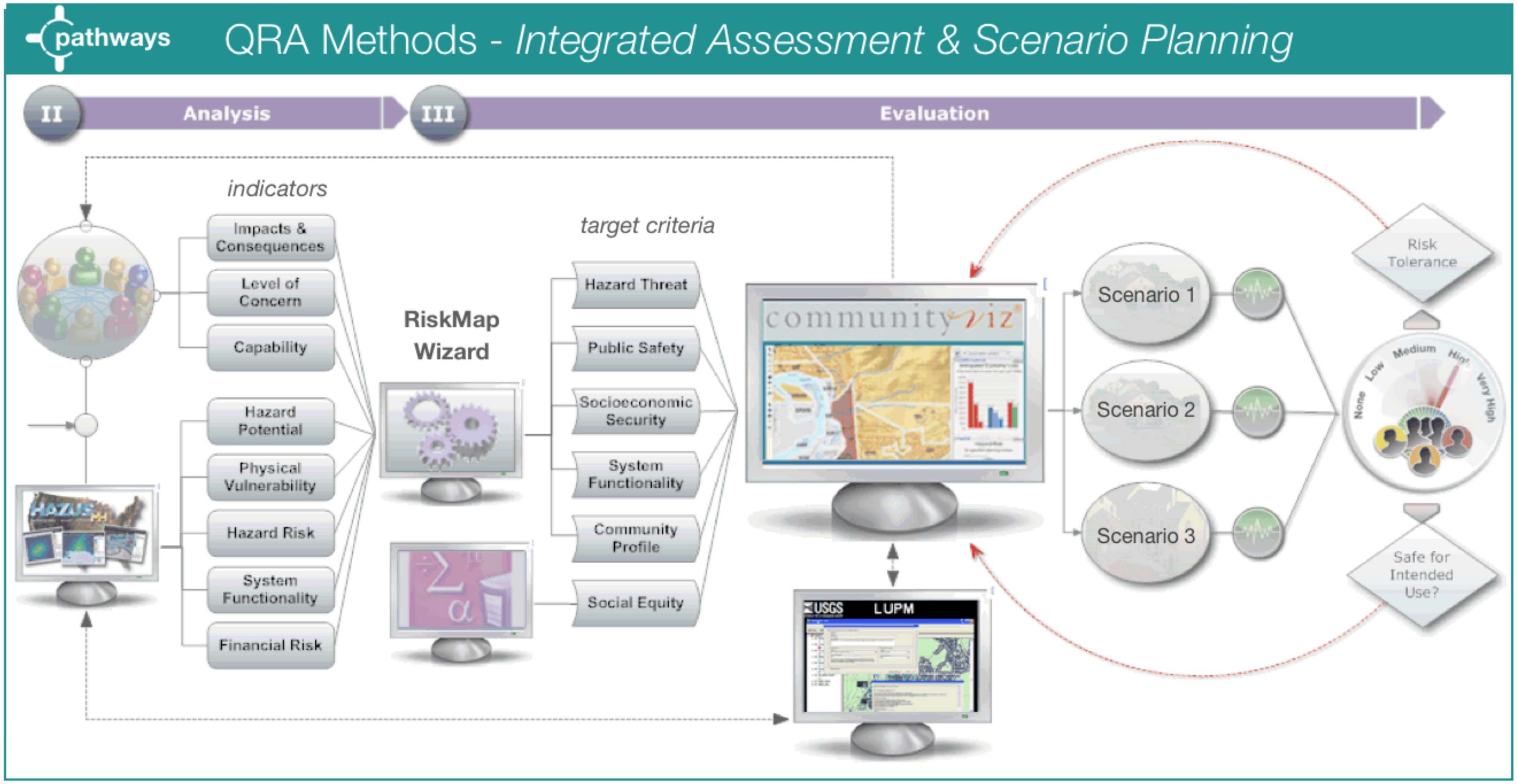


Figure 4-19: Methods and tools used in the Pathways framework to transform knowledge about the risk environment into actionable mitigation scenarios that are evaluated using the performance indicators and target criteria of the pathways model.

but in ways that trigger rapid cognition and analytical thinking about concepts and system dynamics that may not have a physical expression or otherwise be evident (Gahegan, 1999; Gahegan and Brodaric, 2002; Sheppard, 2006; Salter et al., 2007).

Traditional two-dimensional maps can be used to visualize spatial dimensions of vulnerability and risk. They have the advantage of being familiar to most people. Hazard potential maps, for example, are routinely used to communicate spatial extents, magnitudes and probabilities of potential hazard events, thereby providing a context for examining and assessing potential impacts to physical assets and people. Vulnerability maps are used to communicate variations in damage to building stock, patterns of displacement, and levels of anticipated injury. This information is invaluable in assessing the requirements for emergency preparedness and formulating detailed plans for response and recovery. Risk maps are used to communicate spatial patterns of expected loss, and provide a foundation for assessing the potential effectiveness of mitigation strategies. Exploration of these various map layers in a geographic information system (GIS) provides additional capacities for analyzing topological relations, and formulating hypotheses

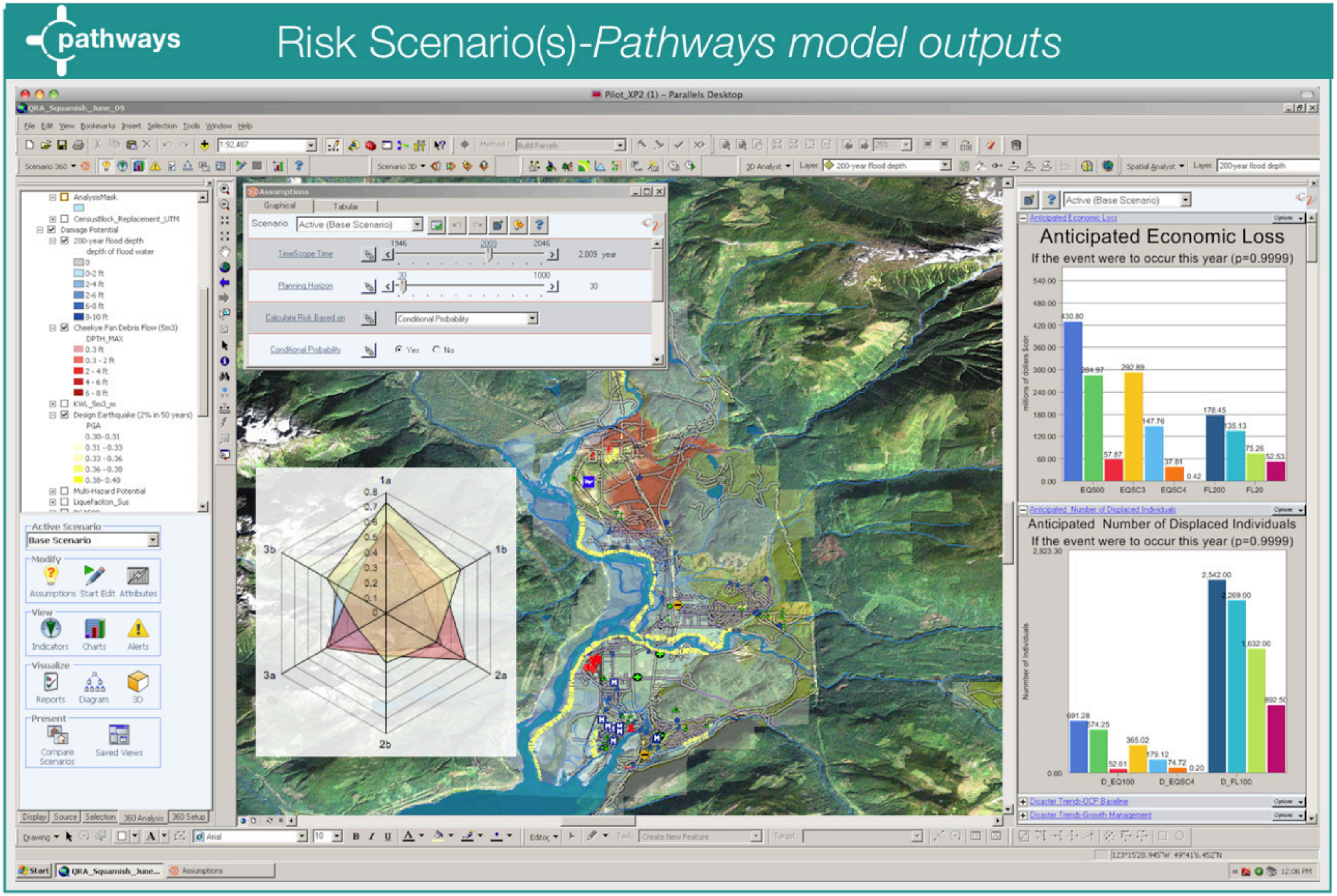


Figure 4-20: Example of a Pathways risk scenario developed using Scenario360 that utilizes outputs of a quantitative risk analysis from FEMA's standardized loss estimation methodology to portray patterns of vulnerability, and using indicators and target criteria of the Pathways model.

to explain underlying system behaviour.

Scenarios enhance these capabilities by using narrative or numerical models to simulate how these systems might change through time. As illustrated in Figure 4-20, outputs of a scenario-based landscape model can be effective in communicating changing patterns of vulnerability associated with incremental growth and development, and in promoting an understanding of the underlying socio-economic and political forces that may be driving these changes. Scenario outputs are made evident and spatially explicit through a combination of graphing, mapping, and visualization techniques. Normalized risk metrics can be graphed as charts of various types to facilitate comparison of values, or represented through information visualizations that draw out and promote understanding of intrinsic patterns and causal structures of underlying vulnerability and risk.

4.4 3..2 Modelling Changing Patterns of Vulnerability and Risk

Scenario models developed using CommunityViz® provide an overarching context that can be used to describe, analyze and compare the state of a system at various stages in its evolution, and to evaluate the linkages between choices and their consequences. Scenario models are critical in helping people understand the dynamics of vulnerability and risk over time, and assess changing levels of disaster resilience. As illustrated in Figure 4-21, the temporal horizon used to model land use change and associated patterns of resilience can vary depending on whether the focus is on understanding historical trends (forensic analysis), assessing the impacts to existing system performance during response and recovery phases of a disaster event (diagnostic analysis), or exploring potential future states of system resilience ("what if" analysis).

Historical patterns of land use provide a window into the societal values and preferences that drive change over time and a retrospective view of the potential outcomes of these choices with respect to disaster risk. The analysis of disaster risk assists in addressing the questions of what are the driving forces of vulnerability for a given place and population, and what might have been the consequences of a disaster event had it occurred sometime in the past. The objectives are threefold: first, to establish a correlation between historical growth trends, patterns of development and resulting states of vulnerability at given points in the past; second, to analyze these trends for the purpose of discovering potential linkages between policy choices that were made in the past, and resulting patterns of land use change and associated states of vulnerability; and third, to analyze what the impacts and consequences of these choices might have been had a credible disaster event occurred at some point over this time horizon.

Establishing baseline conditions and incremental trends in vulnerability involves the analysis of multi-hazard threats over specified time horizons using methods outlined in Section 4.4.2. As illustrated in Figure 4-21, conditions of physical vulnerability at specific intervals of time are normalized with respect to cumulative total damage for endpoint conditions of the scenario and plotted as a function of time. Trends in vulnerability are then used to detect underlying causal structures and driving forces. In the example shown in Figure 4-21, physical vulnerability mirrors a gradual population growth rate for the period 1945–1965, increases abruptly in the period between 1965 and 1975, then

Figure 4-21: Sample outputs of a Pathways risk scenario designed to evaluate historic patterns of vulnerability and the effectiveness of "what if" mitigation strategies in reducing risk and promoting overall disaster resilience.

continues to increase at varying rates up to 2009. The escalation in vulnerability over the period 1965–1975 could reflect a rapid period of growth and development in the region overall. Alternatively, it could record the effects of land use decisions that incrementally situate new development in areas exposed to natural hazard threats. The interpretation of results can be facilitated by utilizing methods of geospatial analysis to examine historical trends in the context of evolving patterns of human settlement (demographics, density, location of structures, etc.) and other factors that are known to influence the dynamics of vulnerability and risk over time.

The influence of underlying driving forces on overall system resilience can be further assessed by modelling the impacts and consequences of a hazard event as if it had occurred at some point in the past. Analytical methods are the same as those used in assessing impacts and anticipated consequences for existing conditions (see Section 4.4.2), and are facilitated using the TimeScope decision support wizard in Scenario360. Site-specific characteristics of the built environment derived from property assessment data (year of construction, building type, and occupancy class) are combined with hazard intensities for a specified portfolio of hazard threats to assess fragility and overall damage potential. Conditional probabilities are then used to assess what the impacts and consequences might have been had one of the hazard events occurred at a specific point in time. Model outputs provide a basis for assessing causal linkages that may be influencing patterns of vulnerability and risk in a community over time. They also provide an important baseline for diagnosing the likely impacts and consequences of a disaster event in terms of overall system resilience.

4.4 3..3 Suitability Analysis

Scenario modelling also provides a capacity to assess the suitability of future land use changes and the consequences of mitigation choices with respect to evolving conditions of vulnerability and risk. Scenario alternatives are developed on the basis of "what if" propositions that are designed to explore alternate pathways toward disaster resilience. Rather than rely solely on rational analysis and predictive modelling to forecast the most probable outcome of a policy alternative, scenario modelling considers system uncertainty in the context of longer planning horizons and poses the questions of what is the desired outcome of the decision-making process (the ends), and what is the most plausible combination of alternatives (means) that will meet expected management objectives.

As illustrated in Figure 4-22, the process of developing alternate "what if" scenarios involves a step-wise process of modelling the supply of land that is available to accommodate future development, the anticipated demands of population growth and local economic development that are likely to drive patterns of vulnerability and risk, and development preferences (values, goals and beliefs) that will influence land use priorities and associated rules that govern how future growth is likely to be accommodated. The modelling process is facilitated using Allocator, Buildout, and TimeScope decision support wizards in Scenario360.

The assessment of available land supply is based on existing or anticipated constraints to development. These can include legislative bylaws that direct the location, type, and density of land use for a given area, as well as non-negotiable regulatory setbacks that restrict development in designated parks, reserves, or ecologically sensitive areas. Development constraints are combined with existing conditions to determine a build-out capacity, which represents a physical description of land supply that is available to accommodate future growth and development for a given area. The anticipated demands for development are determined by considering current trends and expected variations in population and commercial growth over time. Growth trends are then used to predict the rates at which residential and commercial development are likely to occur in the future. The final step in the process involves the modelling of development preferences, often expressed as normative goal statements in land use and comprehensive planning documents. These are expressions of intent that reflect collective judgments of how future growth and development ought to be accommodated with respect to environmental integrity, economic vitality, and quality of life.

Variables that influence environmental integrity might include the level of protection for environmental features, ecosystem services, and

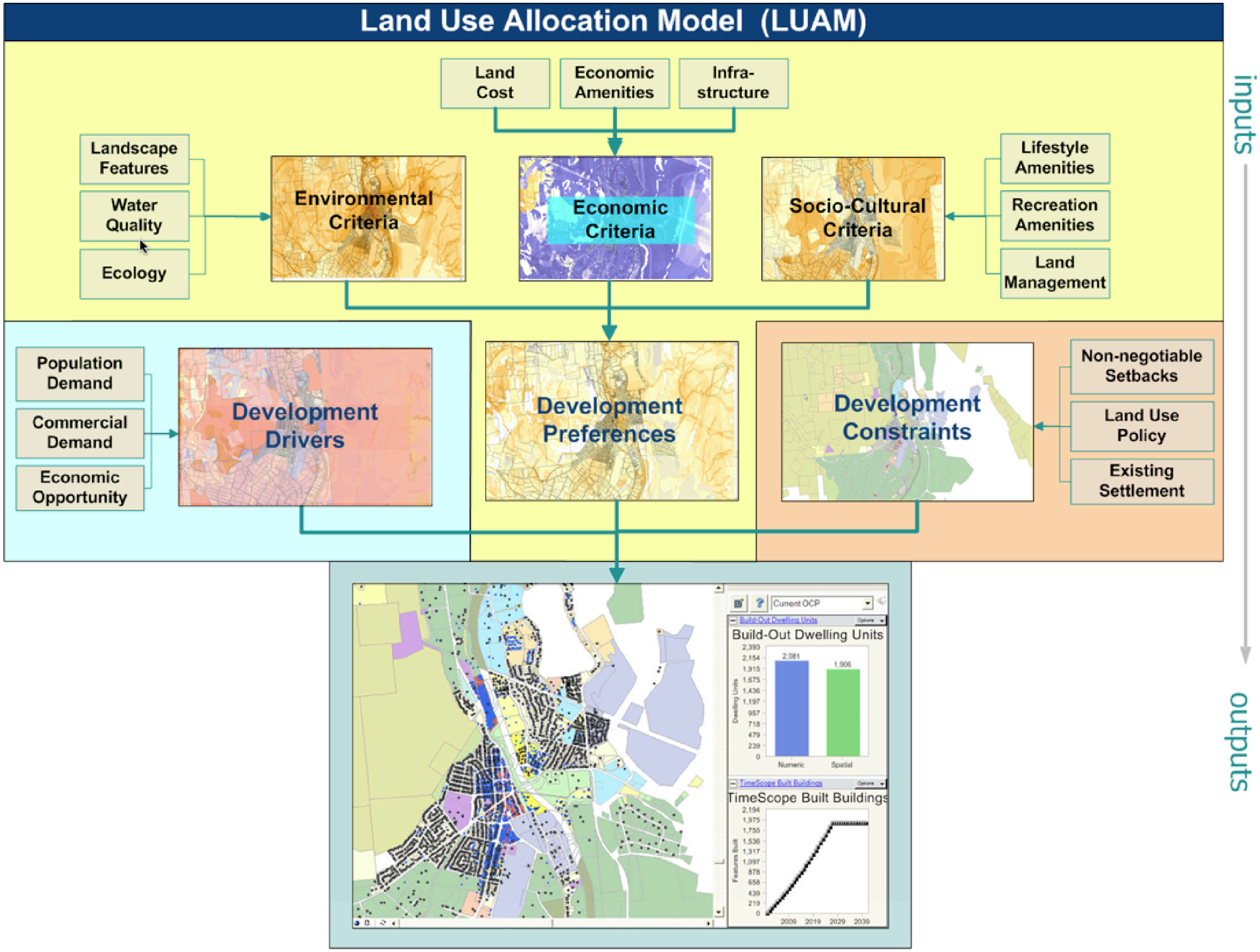


Figure 4-22: Steps in developing "what if" scenarios for evaluating the suitability of existing and proposed land use activities and the efficacy of various mitigation strategies.

species that may be vulnerable to the impacts of continued growth and development. Variables that influence economic development might include private land values, proximity to basic services, and market opportunities that are needed to support growth and development. Variables that influence social vibrancy might include individual quality of life, access to community amenities, and overall sense of place. The balance between these diverse and often competing public policy goals will ultimately determine how a future development pathway may unfold and the implications of these changes in terms of overall system resilience. A planning paradigm that emphasizes opportunities for local economic development would likely focus on development pathways that enhance utility (effectiveness and efficiency). A planning paradigm that emphasizes sustainable land use would likely seek balance between utility and equity.

4.4 3..4 Evaluating Mitigation Alternatives

Methods of integrated assessment and scenario planning are also effective in making evident the implications of mitigation alternatives with respect to policy goals and objectives by portraying key landscape and design elements in a context that people are familiar with, and from a range of different vantage points for both analysis and evaluation. They are critical in helping people understand the spatial-temporal dimensions of vulnerability and risk, and to more effectively negotiate a range of potential disaster mitigation and adaptation strategies that promote disaster resilience.

The integration of analytic, cognitive, and visual capabilities helps people to think about and literally see the linkages between choices and consequences (scenario hypotheses), and the implications of value trade-offs. As such, scenario-based landscape visualization and integrated assessment modelling hold the promise of promoting deep contextual understanding of underlying cause-effect relationships and offer a means of negotiating a common understanding of what these patterns might mean. These are the necessary foundations for effective science-policy integration and for bridging the gap between knowledge and action (Gahegan and Brodaric, 2002; Engels, 2005; Sheppard, 2006; Bishop *et al.*, 2009).

By varying assumptions about land supply, growth demands, development preferences and mitigation strategies, it is possible to construct a series of scenarios that portray plausible alternatives for the future. Scenarios can be developed to explore: the implications of mitigation alternatives that emphasize protective measures that reduce damage probability by maximizing resistance and capacities to withstand the impacts of a hazard event; avoidance measures that reduce underlying system vulnerability and ensure equity in the distribution of residual risk; and adaptive measures that increase the capacity of the system to respond and recover after a disaster event.

The evaluation of scenario alternatives is based on their performance with respect to target criteria established in Stage I of the planning process, and thresholds of risk tolerance that are negotiated as part of the decision-making process. In the face of complexity and ambiguity, many practitioners fall back on intuitive or heuristic methods that reduce problems to their simplest form in order to streamline the decision-making process. In these situations, there needs to be some form of mediation to clarify and provide structure to the decision-making process and an accompanying set of methods to help guide the analysis and evaluation of policy choices. This is the realm of science-policy integration and governance; it is here where the guidelines and standards for risk assessment are negotiated and decided.

One approach to decision making under conditions of uncertainty is to disaggregate the risk problem into a set of smaller components that can be measured and compared in terms of a performance matrix. The strengths and weaknesses of alternate policy choices are assessed by first ranking their relative level of performance against assessment criteria (indicators), then weighting alternatives through preference solicitation. This approach of comparative risk assessment (CRA) is a semi-quantitative method that is often used for evaluating policy alternatives in the field of environmental assessment. It assesses the strengths and weaknesses of individual decision criteria by aggregating assessment scores across the various alternatives (Lin et al., 2004).

Though effective in streamlining the decision-making process, it does not provide rigorous methods for evaluating the relative influences of system variables since they are often described with a wide range of measures. This limitation can be overcome by transforming indicator values into a common frame of reference through a process of normative ranking, similar to that described in Section 4.4.1.4. However, the transformation and aggregation of indicator values can unintentionally subdue or amplify the relevance of assessment criteria in ways can adversely influence the decision-making process.

Cost-benefit analysis (CBA) provides a more structured and transparent method for evaluating policy alternatives by integrating expert knowledge of system dynamics and uncertainty (probability theory) with stakeholder values and preferences (Mechler, 2003; Most and Wehrung, 2005). In the context of risk-based planning, CBA is used to evaluate the efficiency of investment decisions (portfolios) that seek to balance the costs of implementing hazard mitigation and risk reduction measures with the accrued benefits to overall community wealth. In this context, community wealth and the effectiveness of mitigation measures are assessed in terms of socio-economic security.

CBA requires explicit accounting and monetary valuation of all relevant community assets, mitigation costs, and potential losses resulting from a proposed course of action. The strength of this approach is that it provides an internally consistent and legally defensible metric against which policy alternatives can be evaluated and compared in absolute terms. Assets can be adjusted in value against anticipated future costs to derive discount rates for tracking economic flows over variable planning horizons. This provides an important capability for evaluating trade-offs between short- and long-term policy alternatives. However, the selection of decision criteria and the scope of policy alternatives is often limited by performance measures that can be assigned a market value or an equivalent value that reflects a willingness to pay for non-market goods or services (Gamper et al., 2006).

As discussed in Chapter 3, multi-criteria decision analysis (MCDA) extends the capabilities of CRA and CBA by allowing a broader selection of assessment criteria that more completely reflect available knowledge about complex human-natural systems, and that make evident underlying value-based judgments that are likely to influence the decision-making process. MCDA methods used in the Pathways framework are rooted in choice theory and systems-based thinking, and are used widely in the fields of human and ecological risk assessment (McDaniels and Thomas, 1999; Costa, 2001; Omann, 2004; Linkov et al., 2006a). Instead of focusing on a set of criteria that can be evaluated in absolute terms of market value, MCDA strives for balance across a broader set of considerations that can be evaluated in relative terms of utility and value-based goals (Yoe, 2002; Linkov et al., 2004; Ely, 2005; Kiker et al., 2005).

4.4 4. Decision Analysis

Methods of integrated assessment and scenario planning provide the spatial-temporal context for understanding risk and evaluating plausible mitigation alternatives. They also provide a means of structuring the decision-making process and a capability to integrate objective and value-based measures of risk to support strategic decisions about mitigation choices and their likely consequences (Goodwin and Wright, 2001; Belton and Stewart, 2002; Swart *et al.*, 2004; Montibeller *et al.*, 2006). Choices are based on decision criteria that reconcile tensions between a "*willingness to pay*" for investment in risk treatment options and a "*willingness to accept*" trade-offs between objectives in order to achieve a desired set of outcomes that balance collective risks and benefits. The first is based primarily on rational analysis and optimization while the latter is based on principles of integrated assessment and adaptive planning. Both involve the use of scenario planning and multi-criteria decision analysis (MCDA; McDaniels and Thomas, 1999; Costa, 2001; Omann, 2004; Linkov *et al.*, 2006a).

4.4 4..1 Goal-Based Decision Making

Optimization emphasizes values of effectiveness and efficiency (utility), and is well suited to risk management decisions that are focused on issues of safety or security over relatively short time horizons. Constrained optimization is all about trying to make something as perfect, effective, or functional as possible given anticipated constraints of time and resources (Yoe, 2002). Optimization decisions are geared toward maximizing utility outcomes for selected risk reduction principles and goals. Outcomes are measured in terms of progress toward or away from performance targets that are negotiated through deliberation. Defining an anticipated outcome for a particular risk scenario involves a process of prediction modelling and is equivalent to asking the question of where does the organization expect to be at some point in the future with respect to policy goals and management objectives (target criteria). The goal is to optimize the net benefits of a decision in terms of absolute numbers that can be justified on the basis of available information and knowledge, and that can be legally defended.

In practice, optimization involves the evaluation of target criteria that are arranged into a matrix form to facilitate a comparison of key risk metrics. Scenarios can be designed to validate or falsify predictions about causal linkages between policy choices and resulting consequences. An example of a constrained optimization analysis might be to test a hypothesis that upgrading seismic building codes will result in lower levels of structural damage and economic loss, and that implementation of these structural mitigation measures will justify the investment costs. In this case, simulation models would be run using updated parameters of susceptibility for selected buildings to determine damage potential, expected losses, costs of investment, and a rate of return on investment. The outcome of this process determines an overall willingness to pay, either through financial investment in risk treatment options or by optimizing the performance of priority objectives by removing others from consideration. Evaluation of anticipated outcomes also involves a process of making trade-offs, but the determination is driven by principles of utility and determined largely through market rationality. Management objectives that have been given priority through a formal process of preference solicitation are used to evaluate an appropriate course of action.

4.4 4..2 Value-Based Decision Making

Value-based decision making emphasizes the achievement of desirable outcomes based on a willingness to make trade-offs between varied and often competing management objectives (e.g. public safety, socio-economic security, lifeline services, and equity). In this context, trade-offs are defined as choices that involve giving up one thing to gain another (Yoe, 2002).

The process of evaluating decision alternatives involves reconciling tensions between fundamental principles and policy objectives, and a negotiation of risk tolerance thresholds. In some cases, this may mean that previously established performance targets might not be achievable for all management objectives. This approach is well suited to longer-term planning horizons that require the balancing of multiple and often competing public policy objectives, System variables and assumptions are evaluated using scenario-modelling techniques to monitor dimensions of risk and to explore changing patterns of vulnerability over time. This is equivalent to asking the question of where does the organization want to be in the future with respect to policy goals and management objectives. These preferred outcomes then become the new reference level against which alternatives are compared and evaluated to determine thresholds of risk tolerance and to select a preferred course of action.

Trade-off analysis is the method used to evaluate policy alternatives that result in the greatest overall value across the full spectrum of criteria. Depending on the circumstances, this may mean that very poor performance on one criterion may eliminate a policy alternative from consideration, even if it is compensated by good performance on other criteria. The underlying assumption is that decisions involving complexity and value trade-offs are best addressed using relative judgments on the most desirable overall scenario outcome, rather than absolute judgments based on fixed performance targets. An example might be reconciling demands for "safe development" through structural mitigation to promote economic vitality versus growth management and sustainable land use to promote disaster resilience and socio-economic well-being. The most appropriate mix of analytical approaches will vary from place to place and is determined through deliberation as part of the planning and decision-making process.

4.5 From Concept to Practice

Use case profiles are used widely in the fields of communication and design. They are narrative accounts that help answer the fundamental questions at the heart of any business or design process—who are the priority end users for a product or service, and what are their needs and operational requirements in terms of information (structure and content) and modes of communication (format and style). User profiles are framed around core functions, decisions, evaluation criteria, and operational requirements that are likely to be of concern to those involved in a risk-based planning process.

Each of the profiles described below is defined by a combination of personas and use case scenarios that reflect insights and lessons learned through consultation with a broad cross-section of case study partners and project collaborators. Personas are fictional archetypes that portray a representative end-user in terms of perspective, background, goals, and expectations. They are based on the "faces of risk-based planning" used to frame overall needs and operational requirements for the Pathways framework (Section 4.1.1). The accompanying use case scenarios are presented as hypothetical but plausible essays that emphasize how methods and tools of the Pathways framework might be used by individuals or groups to support specific planning functions and associated workflows.

4.5 1. Operational Land Use Planning: Development Permit Application

The review of development permits is a regulatory process through which proposed changes to buildings, infrastructure, and associated land use activities are assessed on the basis of compliance with existing legislation and alignment with policy goals for the community. The process is structured around the submission of a development proposal to the local planning authority. Details about the location, form and function of the proposed development will establish overall context and scope for the planning process. Proposed developments or changes to land use activities in areas that are exposed to existing or emerging hazard threats are subject to a technical review by a qualified professional to determine if the site is safe for the use intended.

In these instances, the assessment of risk is focused on potential impacts that may pose a threat to public health and safety or that may otherwise undermine existing regulatory standards and guidelines, thereby creating a liability for local authorities. The following use case scenario illustrated in Figure 4-23 profiles a development permit review process in which elements of the Pathways framework are used to support the analysis of potential impacts and consequences, and to evaluate mitigation strategies that might be considered by a developer to meet regulatory guidelines and standards for public safety.

4.5 1..1 Use Case Profile

Renee Deluth is a community planner with the town of Le Havre in rural Nova Scotia. She grew up in southern Quebec and learned the ropes of small business management by helping her family establish a regional farm cooperative for the valley. A graduate from the School of Planning at McGill University, she was one of the first in her class to incorporate Geographical Information Systems into her thesis research on changing land use patterns in rural Quebec. Renee joined the planning department for the township of Le Havre in 1995, and took over the job of senior planner in 2005. She is responsible for operational and strategic planning activities for the community, and has primary authority for reviewing and recommending development applications in accordance with relevant legislation and policies that have been adopted as part of the Official Community Plan. She and her family run a small maple sugar farm on the east bank of Le Havre River. They witnessed first hand the devastating impacts and consequences of a major flood in 2007 that forced many of their neighbours to evacuate homes and businesses for more than a month. Although many returned to clean up and rebuild, a few of the families were not able to cope and have since sold their homes and moved on.

4.5 1..2 Use Case Scenario

The planning department received a development permit application from the Springwood Group to begin Phase I construction of a proposed residential-commercial neighbourhood complex on land adjacent to the highway bridge crossing Le Havre River. Although consistent with existing land use zoning bylaws, community concerns over recent flood events and the future impacts of climate change have drawn attention to the potential risks of encouraging growth and development along the valley bottom. The issue was highlighted in a recent town hall meeting where members of the public challenged the town's council on their support for development proposals within the designated 1/100-year floodplain established by the Province of Nova Scotia. To address these issues, Renee hired a geotechnical consulting company to assist with a quantitative risk assessment of the proposed Springwood development.

As illustrated in Figure 4-23, the process begins with a review of the development proposal with respect to overall form and function, alignment with land use zoning and design guidelines, and compliance with provincial building codes and environmental setbacks. Site plans and architectural drawings are then passed on to the geotechnical consultants to assess the risks associated with the proposed development, and to recommend mitigation strategies that might be effective in reducing potential impacts and consequences.

Given the scale of the proposed development and the potential for litigation, the consultants opted to use methods of quantitative risk analysis to assess indicators of hazard potential, physical vulnerability and hazard risk. They used available digital terrain and river gauge data to model expected water depths associated with flood event scenarios. Based on observed river levels during the 2007 flood event, they ran both scenarios with the assumption that existing dykes could be compromised by structural failure and/or overtopping. An asset inventory was deverloped based on preliminary site plans and property assessment data for areas surrounding the proposed Springwood development. The asset inventory and detailed flood depth grids were combined in HAZUS to run a Level 3 risk analysis with user-defined depth-damage functions to assess damages and anticipated economic losses to building stock and critical infrastructure in the study area. Model outputs for the 1/100-year and 1/200-year flood scenarios were then compiled into a baseline CommunityViz® analysis using the RiskMap wizard to model indicators and related target criteria for hazard threat and socio-economic security.

After reviewing results of the risk analysis, Renee organizes a meeting with the developers to discuss preliminary findings. The consulting team is asked to present results of their quantitative risk analysis and to facilitate a discussion about potential mitigation alternatives. The baseline scenario for the proposed Springwood development indicates relatively low levels of expected flood damage for commercial buildings situated adjacent to the highway, but moderate levels of damage for both single- and multi-family dwellings in low-lying areas near the central wetland area. After reviewing the projected loss ratios for 1/100-year and 1/200-year flood scenarios, the development team agrees to explore potential mitigation strategies to reduce financial risks and potential liabilities down the road.

The consultants use scenario modelling tools to present two potential mitigation strategies for consideration. The first involves site-level mitigation to elevate the area identified for residential development above flood construction levels for a 1/100-year flood event, and below minimum thresholds of tolerable damage and loss for a 1/200-year event. Although effective in reducing loss ratios to acceptable levels for the developers, the construction of an elevated terrace in low-lying areas of the site would impede the flow of water along the floodway, thereby increasing upstream flood depths and transferring risk to adjacent properties that include a mix of lower-income single-family and mobile home dwellings. Renee considers this an untenable position as it increases the burden of risk to those most vulnerable in the community, and would not likely receive support from council.

The second option involves a clustering of mixed-use residential-commercial buildings on an elevated glacial terrace in the northern half of the property, and dedication of areas adjacent to the wetland as protected open space to be incorporated into the municipal greenways strategy. The strategy minimizes the potential for damage to proposed buildings and reduces overall loss ratios to tolerable levels. Although density allocations are maintained for the site overall, the clustering of mixed-use and residential units results in a higher proportion of duplex and multi-family townhouse buildings that exceed building-level density thresholds in the existing land use bylaw. It is agreed that increasing residential densities and clustering of multi-storey buildings on prominent high ground will be a hard sell in a community that is concerned about loosing its rural character through variances to existing

pathways

Land Use Planning - *Development Approval*

Renee Deluth, BA Arch., MAP, Age: 47

Community Planner: Responsible for both operational and strategic planning processes for the community. Has primary authority for reviewing and recommending development applications in accordance with relevant legislation and the Official Community Plan; provides guidance on environmental planning in the department and works closely with council.

> *"The flood last spring was certainly a wake-up call for all of us . If this is the level of safety and security we can expect from our levee system in the future, then maybe our growth management strategy is not as sustainable as we all thought. Like the guy at the conference said, Smart Growth - Yes, but not in dumb places."*

Context & Focus: Once a quite farming community, Le Havre has become an outdoor recreation hub for the region and the target for land developers vying for the remaining valley bottom tracts that have been zoned for municipal expansion. In addition to reviewing development permit applications and preparing staff reports for council meetings every monday evening, Renee is in charge of strategic land use and community planning for the township. In 2007, she assembled an advisory group to assist in the development of a growth management strategy, and to make final revisions to the new land use bylaw. The process was stalled by council earlier this year following torrential spring floods that over-topped the levee and flooded low-lying farms on the outskirts of town.

Use Case Scenario: In July, the planning department received a development permit application from the Springwood Group to begin Phase I construction of an 80 unit residential neighbourhood and commercial building complex on land adjacent to the main highway. Although consistent with existing land use zoning, the proposed development is exposed to riverine and storm water flood hazards.

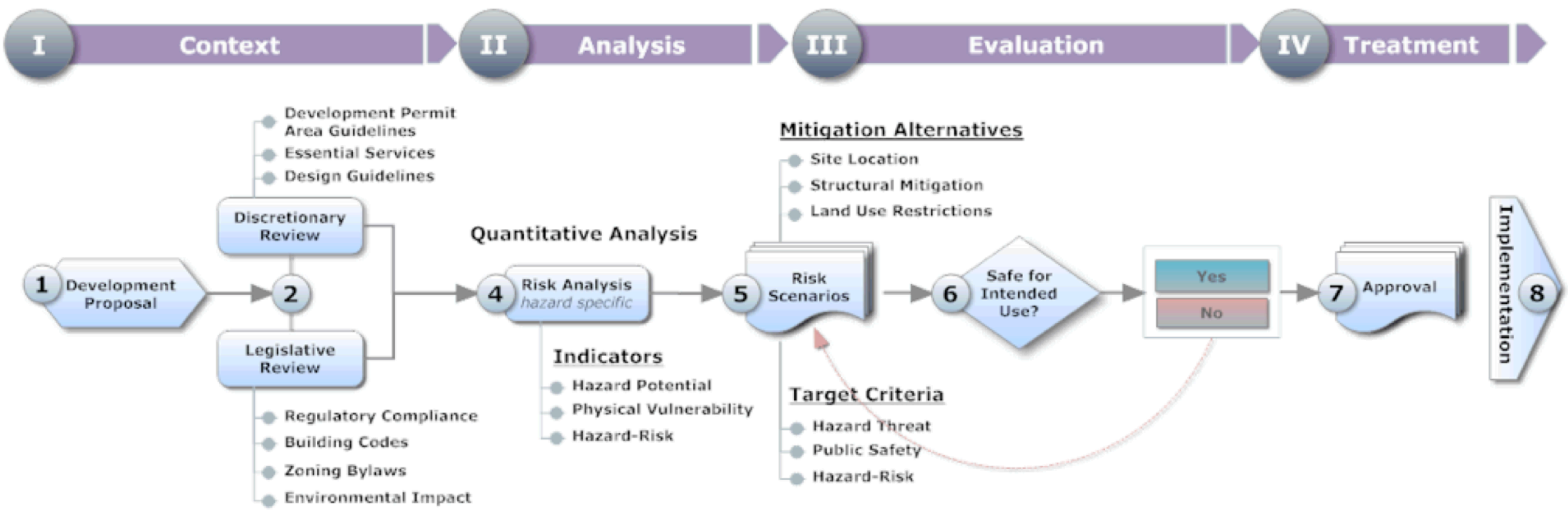


Figure 4-23: Use case profile and workflow scenario for a hypothetical land use planning process that is focused on the review of a development permit application for a small community in Nova Scotia. Elements of the Pathways framework are used to support the analysis of potential impacts and consequences of flooding, and to evaluate mitigation strategies that might be considered to meet regulatory guidelines and standards for public safety.

land use policies. The decision is made to revise the proposed site plan based on results of the risk scenarios, and to solicit input from the community before proceeding with a formal proposal and recommendations to council.

Turnout at the community workshop was better than expected, including several councillors who showed up to gauge public support. The Springwood Group had prepared map and poster displays outlining three different scenarios for consideration. They also facilitated small group discussions around each of the displays for the first part of the workshop. Following a formal presentation of each development scenario, the consultants were asked to present results of their risk assessment and to address questions from the community. The second half of the workshop was facilitated using roundtable discussions in which members of the community were asked to comment on each of the proposals. As expected, those opposed to increasing residential densities dominated the discussion with concerns about encouraging urban-style development and the erosion of rural character that had defined Le Havre for generations.

It was Edie Smith, the last surviving granddaughter to one of the original farming families in the valley, who swayed the discussion. She spoke in the closing plenary about the changes she has seen over the years and the underlying ethic of resilience that has defined the heart and soul of Le Havre since the early days when farming was the way of life. She reminded people of the many floods that have occurred in the valley over the years, and asked them to consider the consequences of knowingly increasing the burden of risk to the most vulnerable members of the community. Although it took several more months for the development permit application to receive third and final reading, it was Edie's profile of the community that Renee remembers each day as she drives past the new Springwood development on her way to work.

4.5 2. Pre-Event Emergency Planning: Shakeout Scenario

The primary focus for emergency management is to protect the safety and security of citizens by raising awareness about existing and emerging threats, and by investing in measures that strengthen resiliency through an integrated program of prevention and mitigation, preparedness, response and recovery. Prevention and mitigation encompass higher-level strategic planning functions within the broader realm of emergency management. They are focused on eliminating or reducing the impacts and risks of hazards through proactive measures in advance of an emergency or disaster event. Examples include the characterization of existing or emerging hazard threats and investment in mitigation measures that will reduce associated impacts and consequences (prevention), and the development of public outreach and education programs to increase awareness about hazard threats for an area and strengthen the capability of individuals and groups to withstand, respond and recover using available knowledge and resources (mitigation). Preparedness represents the tactical component of pre-event emergency planning; it is focused on strategies to manage the impacts and consequences of a disaster event through the preparation of detailed emergency response plans, capability assessments, resource inventories, training exercises, and mutual assistance programs. Emergency response encompasses actions taken during or immediately after a disaster to manage its consequences through search and rescue efforts, emergency medical assistance, and evacuation to minimize suffering and losses. Finally, recovery is the implementation of measures on the ground to restore conditions to an acceptable level through reconstruction, financial assistance, and social programs geared toward improving quality of life and addressing underlying conditions of vulnerability that will increase the resilience of communities and regions to future disaster events.

The use case outlined below in Figure 4-24 is focused on prevention, mitigation and preparedness components of the emergency management cycle. It profiles the development of a shakeout scenario for the Ottawa River Valley in which elements of the Pathways framework are used to facilitate semi-quantitative risk appraisal, quantitative risk analysis, and scenario-based evaluation of earthquake threats in the region. Hazard threats of concern include ground shaking in the urban centres and earthquake-triggered landslides in surrounding rural townships that are underlain by unstable Leda clay deposits. Semi-quantitative methods of risk appraisal are used to gauge levels of risk perception and capabilities for integrated response and recovery across all levels of government, while outputs of the quantitative risk analysis are used to evaluate the efficacy of existing mitigation measures and to prepare a coordinated disaster debris response plan for urban municipalities in and around Ottawa.

4.5 2..1 Use Case Profile

Steve Bose is a pre-event emergency planning coordinator for the Province of Ontario. A graduate from the School of Planning at Dalhousie University, Steve spent the winters in Halifax and his summers fighting forest fires as a smoke jumper in Western Canada. His background in planning and on-the-ground tactical experience as a fire fighter led him to his first job with the Office of Emergency Management for the City of Toronto. While there, he helped develop and implement methods for community-wide risk assessment as part of the Safe City project. In 2003, Steve joined the Risk Management Division for Emergency Management Ontario. He is part of a team responsible for implementing and evaluating Canada's All-Hazard Risk Assessment Framework for use at local and regional scales in the province.

4.5 2..2 Use Case Scenario

With passage of the revised Ontario Emergency Management Act in 2003, the responsibility for risk management was devolved from the Province to municipal governments and regional planning authorities. As part of the Community Emergency Management Program, municipalities and unincorporated regions in Ontario are directed to establish a capability for comprehensive risk-based planning that includes the development of prevention or mitigation strategies for hazard threats of concern, the implementation of guidelines for risk-based land use planning, public outreach and training, and the publication of detailed response and recovery plans for identified high-risk threats. In order to support the new policy directive, the Emergency Management Ontario program has created a division of risk management comprising a team of planners and GIS specialists. Steve and two of the junior planners have been tasked with a mandate to establish a liaison and training extension program to help build institutional capacity for community-based risk management across the province. It has been a steep learning curve for everyone, but the hard work is starting to pay off.

Following a magnitude 5.0 shallow earthquake in the Val-des-Bois region of southern Quebec in June of 2010, Steve and his group put together a proposal to develop a shakeout scenario for the Ottawa River Valley region—similar in scope, but a more modest version of the very successful shakeout scenario established in 2008 for the State of California (Jones *et al.*, 2008). They have partnered with the Institute for Catastrophic Loss Reduction and with domain experts from the Canadian Seismic Research Network to assist with technical aspects of the scenario development process.

As summarized in Figure 4-24, the process began with a roundtable workshop to review available information and knowledge about earthquake hazards in the Ottawa River Valley, and to assess capabilities for developing a shakeout scenario that will address policy objectives of Ontario's Community Emergency Management Program. Representatives from Statistics Canada and Ontario's ministries of Economic Development and Trade and Municipal Affairs were on hand to share information on how to access community profile and socio-economic data that will be required to support the risk assessment process.

In the months following the workshop, Steve and his team worked with project partners to assemble a Level I asset inventory and a folio of maps that will be used to support the community risk appraisal workshops and quantitative risk analysis planned for later that year. Emergency Management Ontario has used available Geographic Information System (GIS) capabilities and FEMA's Comprehensive Data Management System to create a library of Level I study regions for Ottawa, surrounding urban centres, and most of the rural Ontario townships along the Ottawa River Valley. The process of creating and aggregating study regions was facilitated through the use of a new North American version of HAZUS developed through a partnership between NRCan and the US Federal Emergency Agency.

Results of the quantitative risk analysis were used to frame a series of risk appraisal workshops throughout the Ottawa River Valley in which

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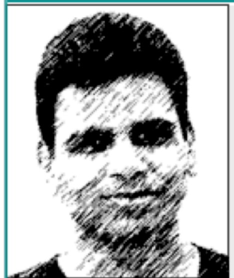
Emergency Management - *Pre-Event Planning & Preparedness*



Steve Bose, BSc., MAP., Age: 39

Emergency Manager: Responsible for the development and coordination of regional emergency planning activities and response plans across the Province; provides support to emergency response & recovery operations and manages community outreach program

> *"It's definitely a hard sell. The new policy requires all municipal and regional governments to develop a risk management plan, but there are no obvious incentives or guidelines for how to do this beyond standard protocols for emergency preparedness. Every community is different, so I have to make it up as I go."*

Context & Focus: With passage of the Emergency Management Act in 2003, the responsibility for risk management was devolved from the province to municipal governments and regional planning authorities. In order to support the new policy directive, the Provincial Emergency program created a division of risk management comprising a team of planners and GIS specialists. Steve and two of the junior emergency managers have been tasked with a mandate to establish a liaison and training extension program to help build institutional capacity for community-based risk management across the province. It has been a steep learning curve for everyone, but the hard work is starting to pay off.

Use Case Scenario: The Ottawa Valley includes the Nations capital, surrounding urban centres of Kanata, Nepean and Gatineau, and a network of small rural communities that extend from the Laurentian Hills in the west to the St. Lawrence River in the east. Following a magnitude 5.0 earthquake in the Val-des-Bois region north of Ottawa, Steve and his group are asked to develop a shakeout scenario to assist with pre-event planning and emergency preparedness operations by the province.

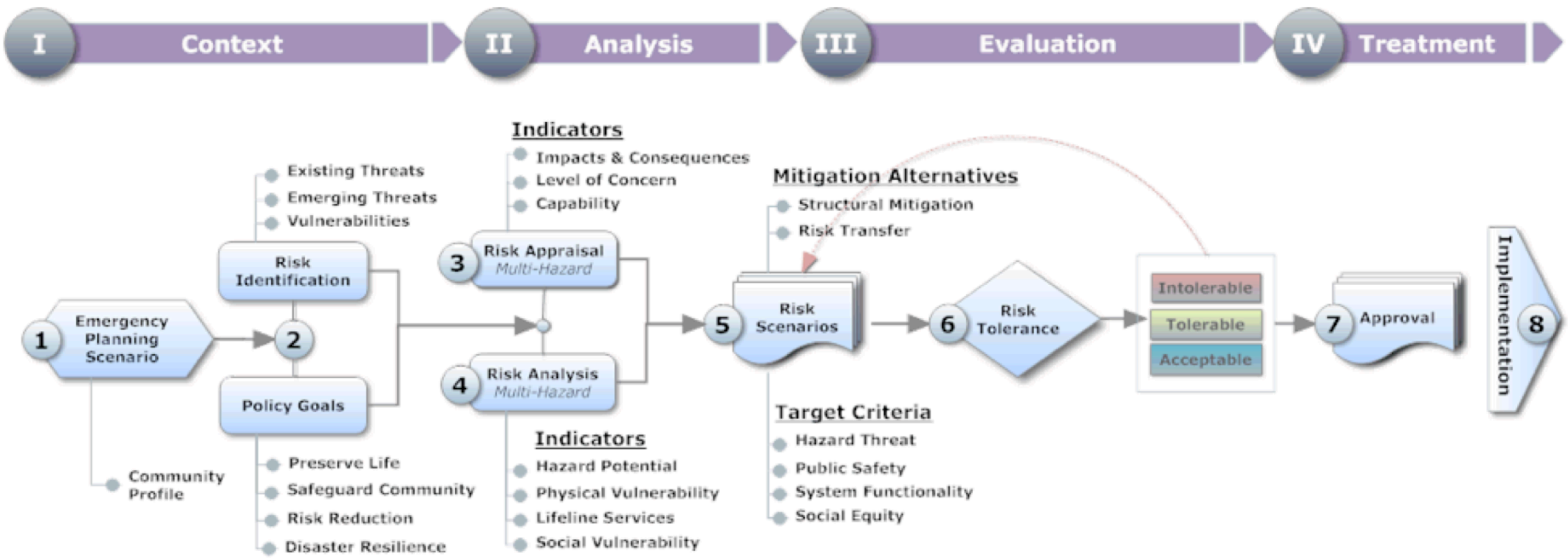


Figure 4-24: Use case profile and hypothetical workflow scenario for a pre-event emergency planning process aimed at developing a shakeout scenario for the Ottawa River Valley. Elements of the Pathways framework are used to support the appraisal of risk perceptions and the analysis of potential impacts and consequences of a magnitude 6.1 earthquake in the Ottawa-St. Lawrence valley region.

community members and critical infrastructure owners and operators were asked to characterize (using a survey) the likely impacts and consequences of a hypothetical but plausible magnitude 6.2 earthquake along a buried fault zone north of Ottawa. Results of the survey were compiled during the workshop mid-break, and then presented to workshop participants along with comparative results from a risk analysis using HAZUS. Most participants were surprised to learn that their expectations of likely impacts and consequences were several orders of magnitude less than what are predicted using quantitative risk analysis methods. The differences were most evident when comparing indicators of physical vulnerability, anticipated loss, and disruption of lifeline services.

Of particular concern was the level of damage to older masonry buildings in the urban centres, and the extent of damage resulting from permanent ground deformation caused by earthquake-triggered landslides in the surrounding rural townships. Although some workshop participants questioned the underlying science and validity of the risk assessment models, the results provided a common framework of understanding for assessing levels of concern and capabilities for emergency response and recovery at the community level. Most of the communities represented at the risk appraisal workshops agreed to participate in a regional shakeout exercise that will be planned for the following year.

Following a presentation to the Canadian Risk Hazard Network in Ottawa, Steve and his group were asked if they could share results of the quantitative risk analysis to support the development of a disaster debris management and business continuity plan to complement the existing shakeout scenario. Using results of the California Shakeout Exercise as a guide, the project team met again in December to review aggregate results of the quantitative risk analysis for the greater Ottawa River Valley region, and to sketch an outline for the scenario script that will be used to inform the shakeout exercise. As a group, they decided to use target criteria for hazard threat, public safety, socio-economic security and system functionality to track aggregate levels of disaster resilience.

Turnout for the shakeout exercise in the following year was disappointing, but did catch the attention of the media who ran a series of documentaries outlining anticipated impacts and consequences of a magnitude 6.1 earthquake scenario. The documentaries included interviews with domain experts who explained the underlying causes and history of earthquakes in the Ottawa-St. Lawrence region, members of the Canadian Seismic Research Network and Institute for Catastrophic Loss Reduction who outlined expected physical impacts, losses and disruptions to lifeline services, and representatives from the Ontario Association of Emergency Managers who stressed the importance of mitigation and preparedness for individuals, families and businesses in the region.

It was during the debriefing session several weeks later that Steve learned that there was interest from the federal government in running the shakeout exercise again the next year—with a focus on assessing the effectiveness and return on investment for mitigation strategies that could be implemented at different jurisdictional levels. Looking around the room at the network of project partners, it became evident that the issue of earthquake risk in the Ottawa valley had finally gained some traction. Steve was actually looking forward to gearing up for another cycle of planning, but not before taking that bike trip in the desert that he had been promising himself all winter.

4.5 3. Comprehensive Land Use Planning: Disaster Resilience

Comprehensive land use planning is focused on the development of a vision that articulates a desired future outcome for a community or region, and the actions required on the ground to realize policy goals and management objectives that reflect local values and preferences. At higher levels of government, comprehensive land use plans are the means by which strategies are developed to accommodate future growth and associated economic development, and to ensure compliance with environmental protection guidelines and standards.

Increasingly, comprehensive land use planning is the context in which social, economic, and environmental issues are reconciled to promote longer-term sustainability at local and regional scales. With greater understanding of climate change impacts and the need for adaptive management strategies, many communities are extending the scope of their comprehensive land use planning processes to include a consideration of anticipated natural hazard threats and the capabilities required to promote disaster resilience for both existing and future generations.

With this gradual shift toward risk-based planning comes the challenge of establishing institutional capabilities and the necessary partnerships across public, private, and academic sectors that will be required to address the complexities of integrated assessment and scenario-based planning. In addition to balancing trade-offs between economic vitality, environmental integrity and quality of life, the challenge becomes how to strengthen the resilience of communities and regions to unexpected future shocks that may be triggered by earth system processes operating at much larger geographic scales and over longer time horizons. As discussed earlier in this chapter, the ability to anticipate and take the necessary actions to build disaster resilience requires an understanding of how patterns of human settlement are likely to change over time, and the implications of these changes in terms of both vulnerability and risk.

The use case outlined in Figure 4-25 describes a hypothetical scenario that combines current best practices of sustainable land use planning with methods and tools that have been developed as part of the Pathways framework. The focus is on managing future growth and development in a region of southern Vancouver Island that is expected to double its population in the next 40 years and that is exposed to a combination of earthquake, flood, and landslide hazards. Semi-quantitative methods of risk appraisal are integrated with participatory planning workshops that have been designed to support an update of the Official Community Plan (OCP) for the hypothetical municipality of Creighton. Quantitative risk analysis, integrated assessment and scenario modelling are used to evaluate the implications of existing land use policies with respect to future levels of vulnerability and risk, and to explore the strengths and weaknesses of mitigation alternatives that balance trade-offs between a diverse suite of policy goals and objectives.

4.5 3..1 Use Case Profile

Marianne Azumi is a community planner for one of the regional districts on southern Vancouver Island. She is responsible for overall coordination and support of comprehensive planning activities for municipalities and unincorporated regions within the district, and has a lead role in the development of a growth management strategy to address anticipated demands for housing and infrastructure services over the coming decades. Marianne grew up listening to stories from her grandmother about their family home along the north coast of Japan, and has long been fascinated with patterns of human settlement and how people achieve a sense of place. She graduated with honours from the department of civil engineering at Queen's University in Kingston Ontario, and moved to the west coast in the 1990s to pursue a Master's degree at the School for Community and Regional Planning at the University of British Columbia. It was there that she was introduced to the ideas of sustainable land use planning and decided to continue on with PhD studies at the Institute for Sustainable Resource Development. Though she returns home often to visit family, she considers the west coast her home and playground. She moved to a small coastal community in 2005, where she lives with her family.

4.5 3..2 Use Case Scenario

Southern Vancouver Island enjoys a Mediterranean climate for much of the year and is a magnet for people relocating from other parts of the country in search of opportunity and a more active lifestyle. The demand for housing and amenities has fuelled a steady growth rate over the years, particularly in communities along the coast that offer quality of life and recreational amenities while still being within commuting distance to neighbouring urban centres. Creighton is one of those communities. It has seen a steady demand for new housing and increased municipal services as young professional families move into neighbourhoods once dominated by people working in the local sawmill or family-run fishing businesses.

In December of 2010, Creighton launched a 12-month program to update their existing community plan. Inspired by a workshop on risk-based planning at the recent Federation of Canadian Municipalities conference, the Chief Administrative Officer for Creighton approached Marianne to ask if she could help coordinate technical aspects of a planning process that would integrate principles of smart growth and climate change adaptation. The timing was uncanny, as Marianne had planned to meet the very next week with her former thesis supervisor and a group of researchers at the university who had received funding from the federal government to pilot a new methodology for climate change adaptation planning.

As it turned out, it was Marianne's thesis supervisor who had given the presentation at the FCM conference. He had been following recent trends on the international stage and was interested in combining principles of adaptation planning coming out of the Intergovernmental Panel on Climate Change (IPCC) with those adopted by the UN as part of their International Strategy for Disaster Risk Reduction (ISDR). After reviewing goals and objectives for the Creighton OCP update process, the decision was made to meet with staff at the Creighton planning department to sketch out a work plan for the case study. The meeting was held a week after the devastating earthquake and tsunami in northern Japan. With images of the unfolding disaster fresh in everyone's mind, all agreed that it would be prudent to expand the scope of study to incorporate an assessment of risks associated with future growth and development in areas exposed to earthquake and flood hazards.

Marianne was asked to brief the district planning staff on the proposed OCP update project for Creighton. She used a figure similar to that illustrated in Figure 4-25 to describe what the planning team has come up with in terms of a workflow and anticipated outcomes. The process would begin with a series of community workshops facilitated by municipal planning staff to solicit input on the overall vision and expectations for the OCP update in terms of policy goals and objectives. Based on results of a preliminary online survey, it was anticipated that much of the focus would be on issues of environmental integrity, quality of life, economic vitality and disaster resilience. Semi-quantitative methods of risk appraisal would be used to assist in identifying hazard threats of concern to the community, and to develop a composite risk profile for characterizing thresholds of risk tolerance and prioritizing mitigation strategies. Methods of integrated landscape modelling would be combined with a Level 3 analysis of flood and earthquake risk using HAZUS. Regional climate change models would be used to assess changing frequency-magnitude relationships for riparian and storm surge flooding, while recently updated earthquake models published by the Geological Survey of Canada would be used to assess ground shaking and associated permanent ground deformation hazards.

The modelling team decided on a time horizon of 40 years to assess the impacts of changing land use on underlying patterns of vulnerability and probable loss. They plan on using CommunityViz to develop a suite of "what if" land use scenarios that would provide a basis for evaluating the relative strengths and weaknesses of proposed growth management and infrastructure servicing strategies. Based on results of the initial online survey, it is likely that land use and mitigation scenarios would be evaluated in terms of their overall performance with respect to standard smart growth principles and target indicators of disaster resilience that address issues of public safety, socio-economic security, system functionality and social equity.

The presentation sparked a vigorous debate among district planning staff about the potential liabilities of assessing natural hazard risk as part of an OCP update process. There were concerns that knowledge about the potential impacts and consequences of natural hazards may sidetrack what many consider to be a more important and immediate discussion about sustainable land use and how to meet greenhouse gas reduction targets set by the Province. Marianne reminded her colleagues that while adaptation and disaster resilience are core elements of the OCP update process, there are other priorities that are likely to take centre stage when it comes to balancing the demand for future growth and development with values and preferences of the community. The exchange reminded her of those days in graduate school when she argued at length with colleagues about the merits of deliberative engagement, integrated assessment and scenario-based planning. It felt very much like this collaborative OCP planning project with Creighton was going to be a replay of her PhD thesis. However, this time around it would be the community not a review committee that

Land Use Planning - *Comprehensive Land Use Strategy*

Marianne Azumi, BSc Eng., MAP, PhD. Age: 46

Community Planner: Responsible for long-range planning processes in the district, including; overall coordination of growth management strategy, input on policy updates to Official Community Plans (OCP) in the region, and review of proposed sub-area plans for areas that have been identified for future growth and development as part of a broader economic revitalization strategy.

" I remember hearing stories from my grandmother about losing their home following a devastating earthquake and tsunami in their fishing village along the north coast of Japan. The stories had a big influence on my decision to go into planning. I enjoy the technical parts of the job, and the opportunity to work with domain experts to better understand the potential consequences of policy decisions. However, I've come to the realization that if you're not measuring what people care about then what's the point?"

Context & Focus: The southern coast of Vancouver Island is a magnet for young and old alkie seeking opportunity and a more active lifestyle. For many communities, the demands for growth and amenity-driven development are overwhelming local capabilities to anticipate and plan for change. Marianne was hired to provide overall coordination for a regional climate change adaptation plan to assist communities in meeting policy targets recently established by the Province.

Use Case Scenario: Marianne was asked by the municipality of Creighton to assist them incorporate a risk-based approach to their upcoming review and update of their Official Community Plan (OCP). At the same time, she was approached by a group of researchers at the University who had received funding from the Federal Government to pilot a new methodology for climate change adaptation planning at the regional scale. With images of the recent disasters in Japan fresh on everyone's mind, the focus has now shifted to an assessment of risks associated with managing growth and development in using principles of smart growth and disaster resiliience.

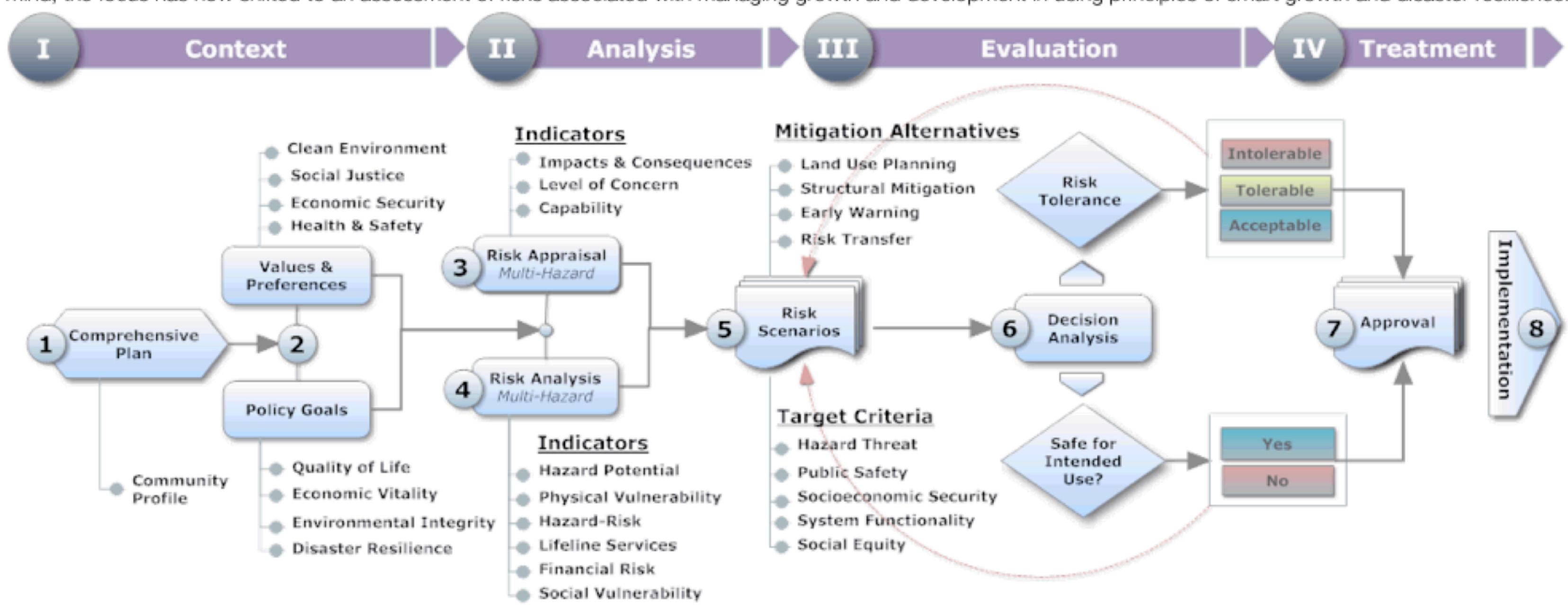


Figure 4-25: Use case profile and hypothetical workflow scenario for a comprehensive land use planning process that incorporates elements of climate change adaptation and disaster risk reduction. Methods and tools developed as part of the Pathways framework are used to support the assessment of increased flood risks caused by a changing climate and land use strategies that might be considered to mitigate the impacts of a large magnitude earthquake along the Cascadia subduction zone.

would ultimately decide whether these methods and tools are useful in helping navigate a path toward disaster resilience and sustainability.

pathways

Chapter Five:

On Risky Ground: Disaster Resilience Planning in the Mountain Community of Squamish, BC

"The kind of town that Squamish grows into over the next twenty or thirty years will have a lot to do with the negotiations that happen now between local residents and those bringing new development to town. There are still serious flood issues in the Squamish Valley that must be considered in terms of future development. In a flat valley bottom where so many rivers converge, building density is not only a matter of aesthetics, but of how much development a low-lying silt delta can support. While the people of Squamish work toward a vision of the town that maintains the quality of life that drew them there, the landscape itself might well have the final say in the shape and size of human habitation in the valley."

Excerpted from Top of the Pass (Vogler, 2007; Top of the Pass: Whistler and the Sea to Sky Country)

5. On Risky Ground: Disaster Resilience Planning in the Mountain Community of Squamish, BC

5.1 Introduction

It was a routine day for Jeff Dumont, a timber cruiser hired to assess forest resource potential in the upper Elaho Valley. He was slogging his way up a steep slope in the late afternoon of Friday, October 17, 2003 when he decided to turn back because of snow cover. It had been raining steadily for the past three days and his patience was running thin. Extreme weather is part of the job in this part of BC, but Jeff had not seen rain like this for some time. It was dark by the time he made it back down to the truck, and the rivers were running high. The windshield wipers could hardly keep pace with the driving rain. It was only luck that he was able stop before hitting the pile of rubble that had come down onto the road in front of him. It was not a big slide, mostly mud and debris from the logging cut above. He was able to navigate around the worst of it after several hours, clearing a path with a shovel and chain saw as he went.

He was back on the main hauling road just before midnight when he got the message from regional search and rescue. It was a priority call-out for RCMP special units and volunteer search and rescue teams along the Sea-to-Sky corridor. Floodwaters had swept away the bridge over Rutherford Creek and several people were reported missing. As he rounded the last bend headed down into the Squamish River valley, it was clear that he was not going anywhere that night. Floodwaters were running fast and had overtopped the riverbank blocking access to the bridge into town. He tested the waters, but the current knocked him down twice as he approached the bridge. He phoned his wife with the news, only to learn that the neighbourhood they had moved into last year was already flooded, and other low-lying areas of Squamish were on evacuation alert. She and the kids were heading down to Vancouver to stay with her folks. The next few days would be both long and worrisome for everyone….

As the news came in from communities along the Sea-to-Sky corridor, it would become evident that this was one of the most intense rainfall events to hit the coast of Brsitish Columbia in recent memory. In all, more than 350 mm of rain fell in just a few days from a storm that no one saw coming. The storm triggered flooding on all major rivers and forced more than 1000 residents to evacuate their homes. Pemberton and Squamish both declared a State of Emergency.

Several people lost their lives as raging floodwaters swept away highway bridges and destroyed transportation infrastructure along the Sea-to-Sky corridor. Emergency spillways were opened on the Daisy Lake Dam to keep reservoir levels below safety thresholds for fear of overtopping or catastrophic failure. River dykes in the town of Squamish were nearly compromised in several critical locations by scouring and erosion. Although considered a moderate 1/100 intensity flood event in statistical terms, freeboard along critical sections of the dyke protecting low-lying areas of Squamish was less than 55 cm at the height of the storm, threatening to overtop or undermine protective structures designed to withstand much larger events with return frequencies of 1/200 years. Homes, businesses, and vehicles were inundated as flood control systems struggled to keep pace with larger than expected volumes of storm water trapped behind the dykes. Major highway and secondary transportation corridors were impassable for days causing significant impacts on homeowners and businesses alike. More than 360 people were forced to seek refuge with local emergency services. Direct economic losses caused by this one flooding event are estimated to have been in excess of $30 million.

This is a story that is becoming all too familiar for communities across Canada. It underscores the challenges of managing risks associated with growth and development in areas exposed to natural hazards and the consequences of not adopting a proactive and balanced approach to disaster mitigation. For Squamish, the experience of being flooded during a strategic land use planning process provided the opportunity to reflect on the intrinsic vulnerability of living on an active floodplain. Knowledge of what could happen was the impetus to explore an alternate path forward—one that incorporates principles of disaster resilience into the broader paradigm of sustainable land use planning and community development.

This chapter describes a collaborative study involving the District Municipality of Squamish (DMOS) and the Earth Sciences Sector of Natural Resources Canada (ESS/NRCan). The intent of the partnership was to investigate the challenges and operational requirements for disaster mitigation planning at a municipal level, and to use insights gained from this study to inform the design and development of a framework for integrated assessment and risk-based planning that could be adapted for use by other communities across Canada.

Goals for this chapter are to:

- Highlight the challenges of risk-based planning in an archetypal mountain community exposed to multiple natural hazards.
- Characterize the risk environment and review existing municipal strategies to mitigate the impacts and consequences of natural hazard threats to the community.
- Present results of a semi-quantitative risk appraisal to assess perceptions of risk, capabilities for response and recovery, and to identify mitigation strategies that have potential to reduce future risks.
- Present results of a quantitative risk analysis to measure the physical impacts and anticipated socio-economic losses caused by flood, earthquake, and debris flow hazards that threaten the community.
- Evaluate the effectiveness of alternate land use planning strategies in reducing natural hazard risks, and in increasing longer-term disaster resilience of the community.
- Reflect on lessons learned and the implications for further development of the Pathways framework.

5.1 1. Living With Risk

Squamish is no stranger to the impacts and consequences of natural hazards. The town is located at the head of Howe Sound—a glacial fjord flanked by rugged mountain peaks that rise to elevations of more than 2500 m. The community lives at the confluence of five major mountain watersheds and in the shadow of earthquake and volcanic hazards related to active tectonic processes along the west coast of North America. Residential neighbourhoods and critical infrastructure facilities in North Squamish are situated in the path of one of the largest known debris flow hazards in Canada, the Cheekye Fan. Low-lying areas in the valley bottom are subjected to periodic flooding and the entire community is vulnerable to wildfire hazards along the interface between the built and natural environments. As a coastal community, Squamish is also vulnerable to emerging threats associated with the impacts of a changing climate. These include sea-level rise and related storm surge hazards in the downtown waterfront area, and extreme weather events that exceed the capacities of existing infrastructure for storm water management.

In addition to natural hazards, Squamish is exposed to a variety of anthropogenic threats caused by accidental chemical spills along major highway and rail corridors in the Squamish and Cheakamus valleys, and by outburst floods associated with catastrophic failure of critical dam facilities at Daisy Lake. Damages, injuries, and losses from any of these natural and human-induced hazard events would have lasting impacts on the community, and on transportation and utility systems that provide essential lifeline services for communities, businesses, and industries in the Sea-to-Sky region and neighbouring parts of Metro Vancouver.

5.1 2. Challenges of Risk-Based Planning in BC

Over 80% of the land base in British Columbia is publicly owned and maintained by the Province of British Columbia as Crown Land for its natural resource and agricultural land use potential. An additional 15% of the land base is protected under federal or provincial legislation and set aside through a network of parks and ecological reserves. That leaves less than 5% of the land base available to accommodate existing and projected growth demands (Condon, 2003). Most of these privately owned lands are located in the southwest portion of the province. It is clear that the demand for developable lands in the next 40 years will be intense, sustained, and likely contested as supplies diminish over time.

Squamish is situated within commuting distance of Metro Vancouver, one of the largest and fastest growing urban centres in Canada (see Figure 5-1). Annual growth rates for Squamish have been on the rise since 1985, spurred on by a regional economy that is rapidly shifting from a reliance on traditional resource-based industries (forestry, agriculture) to

Figure 5-1: Location and geographic setting of Squamish, BC. The community is located along the Sea-to-Sky corridor, midway between Metro Vancouver and the resort community of Whistler.

a more diverse portfolio of recreational tourism, trade, and related commercial and retail services. The community of ~16,000 people is expected to double its size in the next 20 years. However, the land base required to accommodate anticipated growth demands is constrained by rugged topography and by exposure to a wide range of natural hazard threats.

The Emergency Program Act for British Columbia (RSBC 1996, c111) establishes the legislative framework for emergency preparedness and disaster risk management for all levels of government in British Columbia. In accordance with principles of the National Disaster Mitigation Strategy (2007), it directs local governments to take a lead role in undertaking risk assessments and in developing emergency preparedness measures that address aspects of pre-event planning, hazard mitigation, response and recovery. Although not explicitly stated, the legislation implies that disaster mitigation ought to be coordinated through existing emergency management and land use planning activities.

The Local Government Act for British Columbia (RSBC 1996, c323) provides the legislative framework for governance and land use management in the province. The act recognizes municipalities and regional districts as independent and accountable orders of government, and establishes the authority and powers to assist them in improving service delivery, managing finances locally to meet policy objectives, and in developing land use management plans that embrace the underlying principles of sustainable development (Local Government Act, 1996). The Act stipulates that responsible agencies should "support settlement patterns that minimize risks of natural hazards." However, no guidelines or best management practices have yet been identified that make clear what might constitute a tolerable level of risk for a given community or region.

The Land Title Act (RSBC 1996, c250) and the Community Charter of British Columbia (RSBC 2003, c26) further direct land use planning and zoning bylaws that govern the location, design and form of the built environment at a site level. They require that public and private lands suitable for development be certified by qualified professional scientists and engineers as "safe for the intended use." They also grant authority to refuse approval of development permits "if the approving officer considers the land subject to, or reasonably expected to be subject to flooding, erosion, land slip or avalanche." With the notable exception of the National Building Code of Canada, there are no provincial guidelines that define thresholds of safety for development in hazardous terrain (Kuan, 2007). Following a fatal landslide event in 2006, the District Municipality of North Vancouver adopted a risk-based approach to disaster mitigation, establishing safety thresholds corresponding to a probability of death of 1/10,000 (10^{-4}) for existing development, and 1/100,000 (10^{-5}) for new development (Porter *et al.*, 2007). Although comparable to levels established for many settled areas in Europe, these thresholds exceed current standards of protection for natural hazards for most communities in North America.

Herein lies the challenge. Provincial land use regulations administered by the BC Emergency Program Act and the Local Government Act direct municipal and regional governments to manage risks associated with growth and development through existing emergency management, disaster mitigation, and sustainable land use planning operations at the scale of individual communities. Definitions of what constitutes a tolerable threshold of safety or risk are left to the interpretation of municipal and regional government. For reasons of liability, this judgment is often deferred to qualified professionals (geoscientists, geotechnical engineers, and planning consultants). However, there are no provincial standards for the level of technical expertise required to assess hazard threats, and no internally consistent guidelines for how thresholds of safety and risk tolerance ought to be determined (Friele *et al.*, 2008).

Thresholds of safety can be recommended on the basis of objective measures that are substantiated by theoretical knowledge and engineering models that establish minimum levels of protection for people and community assets (see for example the guidelines established by the Australian Geomechanics Society, 2000). Other thresholds of risk tolerance, such as socio-economic security, return on mitigation investment, and social equity must be established on the basis of what is considered vulnerable and in need of safeguarding for each individual community or region. Levels of risk tolerance are fundamental questions of governance that must be addressed by authorities responsible for land use planning and emergency management at local and regional scales.

If the potential for a natural hazard event with capacity for damage or injury is known or can be determined through scientific and geotechnical studies, then:

- What are the underlying system dynamics driving conditions of vulnerability and risk, and how will these conditions change with ongoing growth and development?
- How safe is safe enough, and who decides?
- What other factors are considered in establishing tolerable thresholds of risk for a community or region?
- How are thresholds of risk tolerance determined in the context of scientific uncertainty, competing political interests, and ethical perspectives?
- What is the most effective mode of planning to address these questions and how do agencies responsible for developing risk management strategies choose the most appropriate course of action?

These questions reflect principal design challenges for this study and are likely relevant to communities large and small, across Canada. Insights gained through on-the-ground experience help to highlight critical gaps that may exist between the concepts and practice of disaster risk management in North America and have the potential to inform broader efforts to establish national frameworks that promote disaster resilient communities (United Nations, 2005).

5.1.3 The Strategic Planning Process for Squamish

Recognizing the challenges ahead, the District Municipality of Squamish initiated work in 2005 to establish a comprehensive planning framework that would guide future growth and development in the community. As a first step in this process, the District commissioned a growth management study to explore how best to accommodate anticipated demands for housing and related infrastructure services (Urbanics Consultants *et al.*, 2005). The purpose of this strategic planning study was to identify the challenges and opportunities associated with projected growth trends and to analyze capabilities of the District to accommodate future growth and development in terms of serviceable land areas, transportation, and community facilities. The study also evaluated the strengths and weaknesses of various land use strategies to manage anticipated growth and development over a 30-year planning horizon, and provided recommendations on a preferred approach to development. This approach would incorporate New Urbanist principles of Smart Growth and sustainable development featuring compact and dense neighbourhood forms that make efficient use of limited land availability and infrastructure services while promoting environmental integrity, economic vitality, and an enhanced quality of life (Congress of New Urbanism, 2001; Arigoni *et al.*, 2002).

Baseline information and insights gained through the growth management study were used by the District to inform a series of neighbourhood planning sessions aimed at redeveloping the commercial waterfront and related port facilities, revitalizing the downtown core, and improving connectivity with surrounding neighbourhood nodes (Design Centre for Sustainability, 2005). Results of these planning processes were used to frame a review of the District's Official Community Plan (OCP; 2007), a policy document that establishes broad goals and objectives concerning the form and character of existing and future patterns of human settlement.

The OCP review process involved extensive consultations with individuals and groups in the community to assess community values and preferences, and with other government agencies to identify key issues of concern. The Earth Sciences Sector (ESS) contributed to this process by providing knowledge and expertise to assist planners in drafting policies to address risks associated with natural hazards in the region (Journeay and Talwar, 2005). This work led to a subsequent proposal to undertake an integrated risk assessment study to inform land use policies under consideration as part of the OCP revision process. The proposal formed the basis of a formal partnership agreement between the Earth Sciences Sector and the District, and was approved by both parties in June of 2007.

5.1.4 Case Study Goals and Objectives

Collaboration with the District Municipality of Squamish (2007–2009) provided a unique opportunity to examine how methods of integrated assessment and risk-based planning might be incorporated into the broader context of a comprehensive land use planning process framed by principles of sustainable development and community resilience. The study was focused on three primary goals. First, to better understand the challenges of community-based risk assessment through the lens of a comprehensive land use planning process led by the District Municipality of Squamish. The planning process explicitly addressed principles of disaster resilience and sustainable development in the context of a complex and dynamic risk environment that is influenced by multiple natural hazards and system vulnerabilities. Second, to use the findings of this research to inform the design and development of a framework for integrated risk assessment that provides a capacity for disaster resilience planning at local and regional scales, and that is adaptable for use in support of emergency management and comprehensive land use planning across Canada. And finally, to evaluate how results of the integrated risk assessment process might be used to inform the planning and decision-making process in a mid-sized community exposed to a variety of natural hazard threats.

The scope of work for this study was focused on the first three stages of risk-based planning (Context, Analysis, and Evaluation), and did not include the development of formal policy recommendations for disaster mitigation (Treatment). The study provided an opportunity to address the needs and requirements for bridging the gap between knowledge about the risk environment and the evaluation of actionable mitigation strategies. Though focused on the interface between science and policy, the study did not include a mandate to develop formal policy recommendations for disaster mitigation, or to address the challenges of bridging the gap between intent and the actions that are required on the ground to promote disaster resilience for the community of Squamish.

Our premise in undertaking this project was that case-based research with practitioners who are actively working on the ground will lead to a better understanding of the underlying challenges and requirements for risk-based planning and to the discovery of general principles and solutions that can be adapted for use in other communities across Canada. Insights gained so far suggest that Pathways is effective in transforming knowledge about risk environment into actionable mitigation strategies that have a potential to reduce system vulnerabilities and promote disaster resilience. The framework can be used to support integrated risk assessment and scenario-based planning at local and regional scales, and contributes to broader efforts in Canada to develop a capability for all-hazards risk assessment and disaster resilience planning.

5.2 Our Process at a Glance

Figure 5-2 is an overview of the risk-based planning process used in the Squamish case study. The process was facilitated through a series of collaborative planning workshops involving an informal working group of ~35 volunteers who freely contributed their time, knowledge, and expertise to guide the risk assessment and scenario planning activities. In

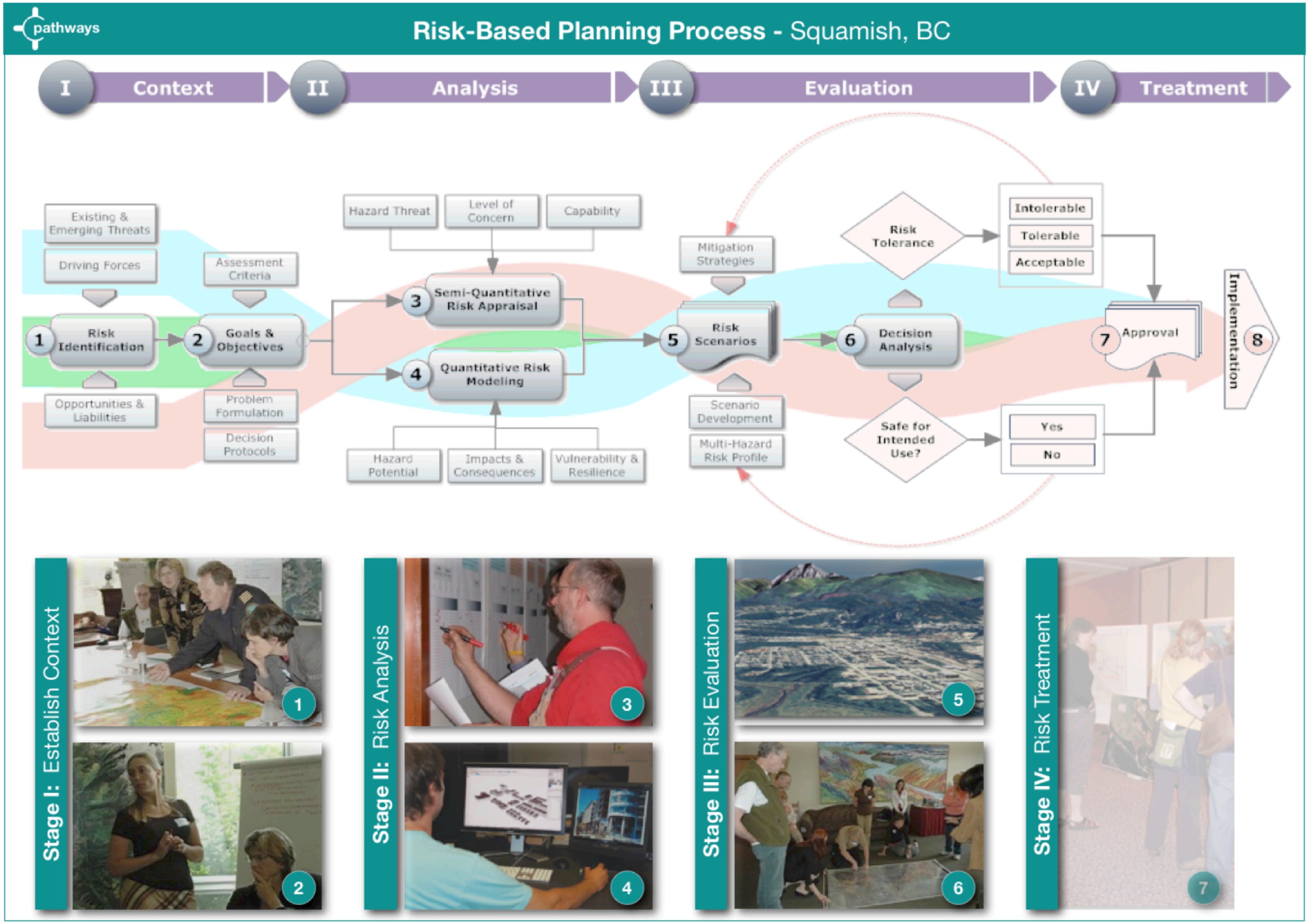


Figure 5-2: An overview of the risk-based planning process used in the Squamish case study.

addition to the Pathways team (District planners, ESS researchers, and facilitators), the working group included emergency management professionals working in the broader Sea-to-Sky region, community representatives from local business, stewardship groups and neighbourhood resident associations, regional health authorities and community service organizations, and regional government staff from the broader Squamish-Lillooet Regional District.

5.2.1 Context

The process began with the compilation and synthesis of available information and knowledge about existing and proposed patterns of settlement within the District Municipality of Squamish, including planning and assessment authority information describing land use policies governing the form and character of the built environment, and census data describing the population and demographic profile of the community. It also included the compilation of existing geotechnical and scientific studies describing known hazard threats for the District and recommendations for both structural and non-structural mitigation. This information was used to diagnose opportunities and liabilities associated with current and proposed patterns of land use, and to assess factors external to the system that may influence changing patterns of vulnerability and risk over time. These included growth and densification in the downtown core and surrounding neighbourhood nodes, proposed new developments to accommodate anticipated housing and business demands, changing demographics, and patterns of social disadvantage. Community values and preferences identified as part of the broader comprehensive planning process for the District were used to guide the identification of study goals and objectives.

On the basis of these considerations, the study area was defined to encompass all private and public lands within the municipal boundary (see Figure 5-1). Additional lands and physical assets within the District but not under municipal jurisdiction were included to allow for a more complete description of the risk environment. These included regional transportation infrastructure assets managed by the Province of BC (highway, rail, and port facilities), and lifeline facilities managed by private and Crown corporations (energy and communications facilities). Based on a diagnosis of hazard threats and priority issues of concern, a planning horizon of ~30 years was chosen to coincide with that of the growth management study, the OCP review process, and associated neighbourhood planning initiatives focused on revitalization of the downtown core and associated waterfront areas. The primary goal was to identify mitigation strategies for reducing risk that could be incorporated into ongoing planning and policy development activities by the District. Assessment criteria selected for the study included indicators that could be used to characterize the overall risk environment (community profile and hazard threat), and a consideration of performance indicators that could be used to develop policy targets with respect to public safety, socio-economic security, and social equity. Although we considered issues of system functionality and recovery planning, these were not identified as priority issues for this initial phase of work.

5.2.2 Analysis

Subsequent workshops provided the opportunity to validate available knowledge about the risk environment and to undertake a semi-quantitative risk appraisal of hazard threats, community assets and capabilities. Workshop deliberations utilized a combination of asset mapping, collaborative GIS and Delphi-based methods to determine:

- Which hazard threats are of greatest concern in terms of expected physical impacts and consequences?
- Who are the most vulnerable members of the community and where are they located?
- What are the community assets considered most vulnerable and in need of safeguarding, and where are they located?
- What are the capabilities of people, systems, and mitigation structures to withstand, respond to and recover from the impacts of hazard threats of concern?
- What additional capabilities are needed to increase levels of disaster resilience in the community?

During the workshops, hazard threats were ranked on the basis of available knowledge about frequency-magnitude relationships for flood, landslide, and earthquake event scenarios. Vulnerability was assessed and ranked on the basis of levels of concern for people and assets in the community, and adaptive capabilities were ranked on the basis of perceived levels of effectiveness.

Outside of the workshops, a parallel process was undertaken by ESS researchers to quantitatively measure the expected impacts and consequences of the same portfolio of hazard threats based on available knowledge about cause-effect relationships and underlying driving forces. We used FEMA's Comprehensive Data Management System (CDMS) to build an asset inventory for the District, and HAZUS to carry out a Level 3 analysis of damage potential, casualties, and anticipated socio-economic losses associated with flood and earthquake hazards. EmerGeo was used to model ground shaking associated with near-source earthquake hazard threats (shakemaps), and to assess probable damages and losses associated with debris flow hazards on the Cheekye Fan. Dimensions of social vulnerability were assessed using a modified version of the SoVI index and available census data. Principal component analysis was used to detect spatial correlations between hazard exposure in the community and patterns of social disadvantage.

5.2.3 Evaluation

The risk evaluation component of the process involved the compilation and synthesis of analytical results for the purpose of generating scenario-based models that could be used to explore spatial-temporal dimensions of the risk environment, and to assess the strengths and weaknesses of mitigation alternatives. CommunityViz® was used for the scenario modelling and visualization of the risk environment and the assessment of target indicators. Composite risk profiles similar to those utilized by the insurance industry for appraisal purposes were to used to compare the impacts and consequences for the selected portfolio of hazard threats. These results were then combined with spatial buildouts of existing and proposed settlement patterns to examine changing patterns of vulnerability over time, and to evaluate the efficacy of proposed mitigation alternatives in terms of risk reduction and overall disaster resilience.

The scope of work for this part of the study was dictated by requirements of the OCP revision process. Mitigation scenarios were developed to evaluate the effectiveness of proposed structural mitigation measures, and the extent to which disaster resilience could be enhanced by risk avoidance strategies that reduce underlying system vulnerabilities through sustainable land use policies and Smart Growth design guidelines. Scenarios were evaluated on the basis of selected target indicators that tracked progress toward or away from priority goals and management objectives.

5.2.4 Treatment

The District of Squamish has yet to complete the final stages of establishing thresholds of risk tolerance to select actionable mitigation strategies for approval and implementation. However, provisions have been made in the updated 2010 OCP that establish a framework of guiding principles, objectives and policies for moving forward. They include the following intentions:

1. To understand, asses and manage the multiple natural hazards in Squamish in a manner that takes into account publicly acceptable levels of risk
2. To minimize and mitigate the risk of loss of life, property damage, and economic impacts from natural hazards, including:
    - Flood hazards
    - Debris flow hazards
    - Slope instability
    - Rock falls
    - Snow and mud avalanches
    - Seismic hazards
    - Wildfire hazards
3. To adapt to climate change impacts that are already occurring or anticipated to occur, minimize the adverse impacts, and take advantage of positive impacts and opportunities

5.3 Characteristics of the Risk Environment in Squamish

The District Municipality of Squamish is a mountain community of

~16,000 people. It encompasses more than 29,000 acres (11,730 hectares) of private and public lands that extend 26 km northward along the Squamish and Cheakamus valleys. The community comprises 14 distinct neighbourhood nodes, a downtown commercial area along the waterfront, and several industrial areas scattered throughout the District. Critical infrastructure includes municipal road, water and waste facilities, an extensive levee system, natural gas pipelines, electrical transmission facilities, and major port, rail and highway facilities that provide essential transportation services between urban and rural centres in southwest British Columbia.

The natural environment is characterized by a wide range of natural and human-induced hazards. These include riparian and storm water flood and liquefaction hazards along the valley bottom, landslide and debris flow hazards along steep valley walls and run-out zones on the Cheekye Fan, ground shaking, ground deformation and liquefaction hazards related to near-source earthquake events, interface fire hazards in forested lands within and along the perimeter of the community, and less likely high-consequence events related to volcanic eruptions along active centres located on Mt. Garibaldi, Mt. Cayley, and Mt. Meager.

Human-induced hazard threats include catastrophic outburst floods related to upstream failure of the Daisy Lake Dam and hazardous material spills along major rail and highway corridors that run through the heart of the community. The impacts of climate change and sea-level rise are uncertain, but will likely influence the frequency and intensity of hydro-meteorological threats such as rain-triggered debris flow, storm surge, and interface fire. Additional factors that will have a direct influence on future patterns of vulnerability and risk in the community include population growth and densification, amenity-driven development in areas exposed to natural hazard threats, and a changing demographic that is increasingly vulnerable to the impacts and consequences of hazard events.

5.3.1 Natural Hazards

Historical accounts of natural hazards in the Squamish Valley reveal that the most frequent threats are those triggered by severe weather events (Blais-Stevens and Septer, 2008). These include more than sixteen riparian and debris flood events caused by intense multi-day rainfall, four tidal flood events caused by high wind and storm surge, and three landslide (debris flow) events caused by rain-induced slope failure (see

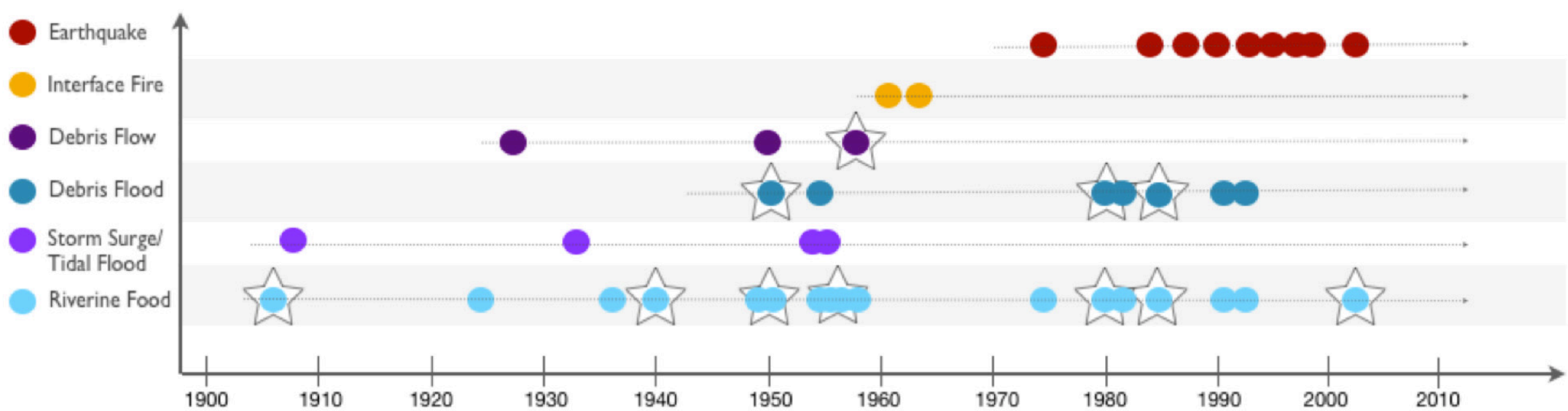


Figure 5-3: A timeline of natural hazard events that have impacted Squamish since the arrival of European settlers in 1885. Records of earthquake events in the surrounding area have been monitored only since 1975. See Table 5-1 for details, and Appendix III for a complete record of natural hazard events. Based on data compiled by Blais-Stevens & Septer, (2008).

Event	Hazard Threat	Impacts
1906-09-08	Extreme weather/riverine flooding	164-218mm rain over 5 days resulted in significant flooding along the Cheakamus and Squamish rivers. 3.6m of flood water in the Squamish valley caused significant damage to farms and related infrastructure in the Brackendale/Garibaldi Estates areas and washed away primary bridges over the Cheakamus and other major rivers in the valley
1940-10-18	Extreme weather/riverine flooding	~212mm of rain over 4 days with intense 1-day downpours resulted in heavy flooding along the Mamquam River and ~1.5 meters of inundation in the Dentville/Downtown areas. Flooding elsewhere in the Squamish Valley (Brackendale/Garibaldi Estates) resulted in significant damage to farms and residential properties. Nearly all livestock in the valley were drowned and 20 families were evacuated to higher ground. Up to 6 meters of floodwater was trapped behind the main sea dyke and smaller river dykes upstream, several of which had to be blasted with dynamite. Rail and road infrastructure, including several bridges were severely damaged.
1950-10-07	Flooding/debris flow	~283mm of rain over 8 days resulted in flooding of the Squamish and Mamquam Rivers. Impacts included significant bank erosion along the Squamish River and up to 3 meters of flooding in low-lying areas of North Yards and Dentville. Several families were evacuated. Torrential rains triggered two separate debris flow events along the Cheakamus River valley, disrupting rail service for 4 days.
1957-09-05	Extreme weather/riverine flooding	~96mm of rain over 3 days resulted in extensive flooding on all major rivers in the Squamish valley. Overtopping of dykes along the Squamish River resulted in up to 4.2 metres of flooding and associate damage to residential buildings. Overtopping of a flood protection structure above a new powerhouse facility along the Cheakamus River caused significant damage.
1958-08-28	Debris flow	Following a sudden rainstorm, ~100,000 m3 of rock debris and logs rushed down the Cheekye River building a 4.5 meter temporary dam across the mouth of the Cheakamus River. The debris flow is reported to have been up to 3 meters deep and moving at a velocity of up to 8 km/hour. A debris flow event of similar intensity is reported to have occurred in the same located ~30 years earlier.
1980-12-26	Riverine flooding/debris flooding	~212mm of rain over 5 days, combined with melting snow conditions resulted in streamflows along the Squamish, Mamquam and Stawamus Rivers that corresponded to intensities associated with flood events with a 130-190 year return interval. BC Hydro was again forced to open spillways on the Daisey Lake dam, contributing to flooding along the Cheakamus and Squamish valleys. Dykes prevented flooding in Downtown Squamish, but unprotected low-lying areas north of the Mamquam River were extensively flooded, resulting in significant damage and/or destruction of ~200 homes. 6 people were evacuated by air. Reported losses are estimated to have been $313, 670 CDN.
1984-10-08	Riverine flooding/debris flooding	~352mm of ran over 5 days resulted in record-level river discharge of 2,610 m3/second on the Squamish River, resulting in a significant change to the river course and extensive damage to flood protection works. As with earlier major flood events, water depths in low-lying residential areas were several meters deep, resulting in significant damages to homes and related infrastructure. The Cheakamus highway bridge was washed out during the same event. Losses associated with flood damages for the Squamish area are reported to have been ~$623,000 CDN. Total losses in the Sea-to-Sky corridor were ~$1,946,700 CDN.
2003-10-18	Extreme weather/riverine flooding	~480mm of rain over a 7 day period resulted in significant flooding and debris slide events along the Sea-to-Sky corridor. All major rivers in the Squamish valley were running high, but did not overtop their banks. Bank erosion caused significant damage to flood protection measures. Storm water runoff trapped behind dyke structures in low-lying areas of the valley caused extensive flood damage to buildings. More than 360 people were forced to seek refuge with local emergency services. Losses associated with flood damages are estimated to have been ~$30,000,000CDN

Table 5-1: Historical accounts of the more severe natural hazard events to have impacted the community of Squamish since 1885.

Appendix III for a full account of past hazard events). Major flood and debris flood events are by far the most frequent, and have caused the most damage in the community to date. The most severe of these events are shown with a star in Figure 5-3.

In addition to hydro-meteorological hazards, there have been at least four major forest fires (>500 hectares of area burned) in the region surrounding Squamish, though none have directly threatened the community. Seismic activity has only been monitored since ~1975. Over a 35-year period, there have been over 17 small earthquakes (M2.0 –M4.6) within a 50 km radius of Squamish. The largest of these would have been felt, but none have posed a direct threat. While historical accounts can be useful in characterizing natural hazard threats, they have the potential to bias perceptions of risk toward more frequent but of lower consequence events. This is certainly the case for the community of Squamish, where recorded landslide, flood, and earthquake events are several orders of magnitude smaller than those known by the scientific community to have a potential to occur in the region. Areas exposed to natural hazard threats in the Squamish valley are summarized in Figure 5-4, and are briefly described below.

5.3.1.1 Landslides

Squamish is exposed to a wide range of landslide hazards related to steep topography, high rainfall, and the potential for collapse of weakly consolidated volcanic deposits perched at high elevations along the valley walls. Multiple volcanic eruptions from a composite cone in the Mt.

Garibaldi Complex (13,500–11,500 years ago) resulted in thick deposits of loosely consolidated sediments along the margins of glaciers that partially filled the Squamish Valley. With retreat of the glaciers and subsequent inundation of the valley fjord, the volcanic edifice was de-buttressed and collapsed over time sending large volumes of volcanic sediment down slope through a combination of rock avalanches, slope failure and debris flow events. Deposition and reworking of these debris flow deposits resulted in the construction of a large (~25 km^2) alluvial fan-delta known as the Cheekye Fan (Friele *et al.*, 1999; Clague *et al.*, 2003). Large-magnitude landslide events associated with collapse of other nearby volcanic centres in the region are known to have resulted in damming and alteration of the Squamish and Cheakamus river valleys. Smaller-magnitude landslide events are common along the steep valley walls and have resulted in significant alterations to river grades over the past several hundred years.

Discoveries of thick debris flow deposits on the Cheekye Fan in the 1970s led to what has become one of the most thorough assessments of landslide hazard risk in Canada. The extent of historic debris flow deposits encompassed an area slated for residential development and revealed that critical infrastructure facilities maintained by the District of Squamish and the Province of British Columbia may also be susceptible to landslide hazards. Following a series of exploratory studies, a team of consultants was commissioned by the Province to determine overall landslide hazard potential and to recommend strategies to mitigate future landslide events in the Cheekye River basin (Thurber Engineering & Golder Associates, 1993). More recent studies have refined frequency-magnitude relationships for debris flow events on the Cheekye Fan and the geographic extent of areas that are likely to be impacted (Clague *et al.*, 2003; Kerr Wood Leidal, 2003; Jakob and Friele, 2009). On the basis of these studies, it is estimated that as much as 3–5 million cubic metres (3–5 Mm^3) of material could be triggered in a single landslide event, resulting in a catastrophic debris flow that would extend out onto the Cheekye Fan. For reference, 3 Mm^3 is approximately the volume of concrete that was used to construct the Hoover Dam in the Black Canyon of the Colorado River between Arizona and Nevada.

Areas exposed to significant debris flow hazards include upper portions of the Cheekye Fan, industrial lands in North Squamish, First Nation settlement of Cheekye, and northern portions of Brackendale (see Figure 5-4 Map A). Approximately 260 homes are currently exposed to debris flow or debris flood hazards (~5% of existing building stock), and there is potential for an additional ~230 residential units to be built in areas of significant hazard threat. Other assets of concern include CN Rail and provincial transportation infrastructure crossing the Cheekye Fan, BC Hydro transmission lines and power generation stations, and elementary school facilities in northern Brackendale. Areas that are susceptible to small-scale landslides include steep valley slopes underlain by unstable surficial materials outside the municipal boundary, ridge features that extend into the Garibaldi Highlands and Westbank regions, and part of the Smoke Bluffs in the Northridge, Valleycliffe and East Squamish neighbourhoods (see Figure 5-4 Map A). Approximately 22 homes are exposed to potential hazard threats, which represents less than ~0.5% of the total building stock.

5.3.1.2 Floods

The Province of British Columbia completed initial phases of floodplain hazard mapping for the District of Squamish in 1983. Areas exposed to threats of 1/20-year and 1/200-year flood events were identified on the basis of hydrologic modelling of river dynamics and available 1:20,000 geodetic measurements of valley floor topography (Canada-British Columbia Floodplain Mapping Program, 1983). Flood hazard assessments were updated by Klohn-Leonoff and Graham Farstad in 1994 to account for the potential of dyke failure (Klohn Leonoff LTD & Graham Farstad, 1994). Information gained from this study was used to generate flood construction levels (FCL) and to develop a flood hazard management plan to guide local land use policy (zoning regulations) and flood-proofing measures for new construction within the 200-year floodplain (Klohn Leonoff LTD & Graham Farstad, 1994). In 2003, the Province of British Columbia updated their delineation of the 1/200-year floodplain to support implementation of proposed land use and building design guidelines (Province of British Columbia, 2004).

For reference, a 1/200-year recurrence interval means that there is a

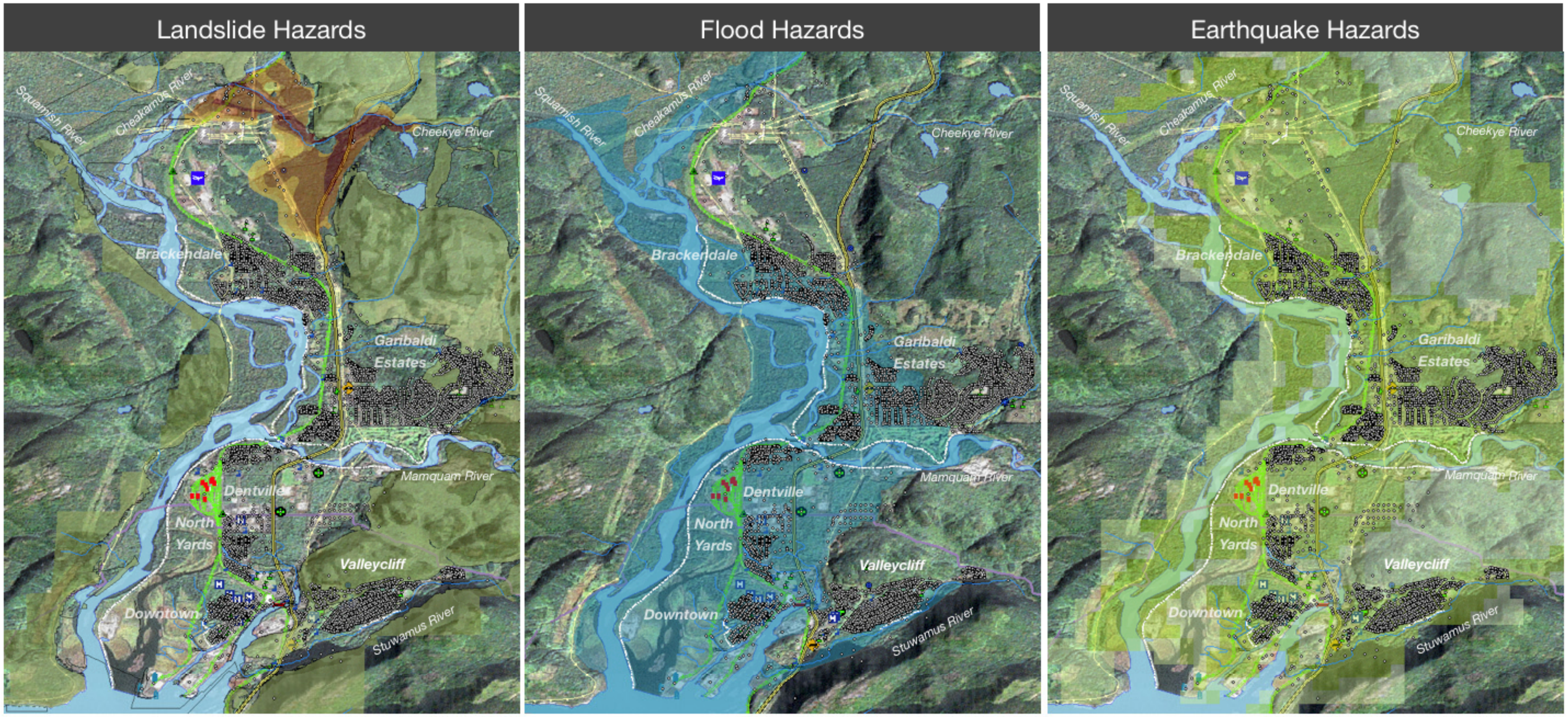


Figure 5-4: Map A: The extent of areas considered more highly susceptible to small-scale landslides (green) and to more severe debris flow hazards on the Cheekye Fan (orange). Debris flow scenario is based on results of Kerr-Wood Leidal (2003) for a 1/20,000 2.8 Mm^3 event. Map B: The extent of areas considered to be part of the 1/200-year floodplain along the Squamish, Cheakamus, Cheekye, Mamquam and Stawamus rivers. Map C: Areas exposed to seismic hazard threats associated with a probability of 2% in 50-year (1/2,500-year).

0.5% chance that a major flood event could occur at some point in the future. The amount of water represented by a 1/200-year flood event would be enough to fill all five major river channels up to the height of existing dyke structures, which in places stand nearly 10 m above the river channel. While the likelihood of the flood event itself is 0.5%, the probability of local flood defences being overtopped for a 1/200-year event over the design lifetime of a dyke (~50 years) is closer to 20%.

Areas of the Squamish Valley exposed to threats of a 1/200-year design flood event are shown in Figure 5-4 Map B. The floodplain represents the extent of land that could be inundated in a 1/200-year flood scenario in which dykes and other flood protection measures are overtopped by the volume of water or otherwise compromised by scouring, erosion, or seepage resulting in structural failure. The floodplain area includes all of the Downtown Squamish commercial and industrial areas and surrounding residential neighbourhoods of Dentville, North Yards, and significant portions of Garibaldi Estates and Brackendale. The area of potential inundation encompasses ~3,235 residential buildings, nearly 60% of the total building stock. An additional 941 parcels that are currently zoned for residential development are exposed to potential flood hazards. The majority of existing buildings that would be impacted include older homes built before flood construction levels and other on-site mitigation measures were established, and mobile home structures located in some of the more vulnerable low-lying areas of the valley. Other structures that would be impacted include essential facilities in the southern portion of the valley (health care, police, fire, and emergency operation centres and schools), transportation infrastructure and vulnerable bridge connections over the Mamquam and Stawamus Rivers, waste water facilities, and a power substation.

5.3.1.3 Earthquakes

Southwest British Columbia is exposed to a wide range of seismic hazard threats related to active tectonics along the North American plate margin. Source zones for earthquake events include the interface between oceanic crust of Juan de Fuca Plate and overriding continental crust of the North American Plate (Cascadia subduction zone), the down-going slab of oceanic crust as it sinks beneath western North America (Benioff zone), and interlocking networks of faults in the overriding North American Plate that accommodate incremental strain and displacement along the Cascadia subduction zone boundary (Crustal Faults).

Earthquake hazards include ground shaking caused by sudden release and propagation of seismic energy through the earth's crust; the amplification of seismic energy caused by undulations in the bedrock surface and physical properties of overlying surficial materials; liquefaction and related permanent ground deformation caused by shaking and subsequent failure of water-saturated sediments; and landslides triggered by ground shaking and surface rupture along active faults. Of these, ground shaking, liquefaction, and earthquake-triggered landslides represent the most significant hazard threats for Squamish. Figure 5-4 Map C depicts seismic hazards associated with an earthquake event in which the intensity of ground shaking exceeds a 2% in 50 years' probability of occurrence (~1/2,500 years). This the design event used as a reference for assessing safety thresholds as part of the National Building Code for Canada (Adams and Atkinson, 2003; DeVall, 2003; Halchuk and Adams, 2008).

More than ~4000 buildings (~74% of total stock) are exposed to ground shaking hazards capable of causing at least slight levels of structural damage in the Squamish region (peak ground velocity; PGA > 8.1 cm/second). Amplified ground motion in these regions, many of which are settled, would result in a moderate to strong level of perceived shaking with the potential for structural damage corresponding with a Modified Mercali Index value (MMI) of VI to VII. For reference, an MMI value of VI corresponds with a level of shaking that would be felt by all. It would be difficult for a person to walk steadily and buildings would sustain light levels of structural damage. Most of the damage would be related to shifting of furniture and non-structural building components with some cracking of weak masonry and concrete. An MMI value of VII corresponds with a level of ground shaking that would make it difficult for a person to stand. Although newer buildings would sustain only minor levels of damage, there would be potential for considerable structural and non-structural damage to badly designed or poorly built buildings. Non-structural building components and furniture would be broken and there would likely be damage to masonry structures and chimneys.

Areas of greatest exposure include the Downtown Squamish commercial-industrial core and surrounding neighbourhoods of Dentville, North Yards, Garibaldi Estates, and Garibaldi Highlands. Nearly all the essential facilities in Squamish are exposed to similar levels of ground shaking. These include the main hospital, health care facilities in the downtown core and Dentville areas, the majority of school buildings, and police, fire, and emergency operation centres along major transportation corridors.

5.3.1.4 Other Threats of Concern

Other natural hazards of concern to the District of Squamish include catastrophic failure of the Daisy Lake Dam on the Cheakamus River, interface wildfire, the eruption of volcanic centres in adjacent parts of the Garibaldi Arc, and potential impacts of climate change (sea-level rise, severe storm events). Wildfire is an imminent threat to Squamish and has the potential for significant impact, comparable in magnitude to many of the other natural hazard types considered as part of this study. For this reason, the District commissioned a study in 2007 to identify areas most susceptible to naturally occurring fire hazards, and to recommend long-term land use strategies to reduce risks associated with interface wildfire (Davies and Coulthard, 2007). Results of the study included a detailed analysis of wildfire hazard potential and a list of 78 specific recommendations for mitigation. Wildfire threat was assessed on the basis of available fuel sources, fire behaviour characteristics (slope, aspect, winds, etc.), potential for ignition, susceptibility of the built and natural environment, and the capacity for fire suppression. Areas of particular concern include existing and proposed residential developments along the east side of the Squamish River valley that lie adjacent to forest stands and for which there is limited access.

5.3.2 Patterns of Human Settlement

The pattern of human settlement in Squamish reflects its long history as a resource-based industrial hub (agriculture, forestry, mining), and its role as a gateway community for the transportation of goods and services between Vancouver and rural communities to the north. While the density, form, and function of individual neighbourhoods have evolved over time, the underlying pattern of settlement has remained relatively constant over the years. The rugged mountain setting, environmental sensitivities, and a limited supply of available private lands all place significant physical constraints on where future growth and development will likely occur in the District. As a result, choices about the location and density of future development have and will continue to play a significant role in establishing intrinsic patterns of vulnerability to natural hazards in the community.

5.3.2.1 Historical Trends and Driving Forces

The abundance of natural resources, proximity to the ocean and access to inland travel routes for commerce have been the primary drivers of human settlement in the Squamish Valley for more than 5,000 years. The rugged coastal valley encompasses traditional lands belonging to Coast Salish people of the Squamish Nation, and was home to the Sko-mish tribe at the time of first contact with European explorers in 1772. By 1882, the valley had been settled as a farming community with 35 families living in what is now Brackendale. Other early migrants included trappers, loggers, and prospectors who settled in homesteads throughout the valley, and a small community of Sikhs who settled in the downtown waterfront area to work sawmills that serviced a growing logging industry. Chinese labourers constructed the first protective levee structures to safeguard low-lying agricultural lands against flooding,

After the construction of port facilities and rail lines to Pemberton in 1914, the downtown waterfront area and surrounding industrial lands of Squamish became a major hub of commerce, connecting resource-based communities in the BC interior with the growing urban centre of Vancouver. Between 1914 and 1946, many of the residential neighbourhoods of Squamish had been established to support a growing industrial base of logging, mining, rail transportation, and shipping. Additional dykes were constructed to protect industrial assets and surrounding residential neighbourhoods from the impacts of tidal storm surge and river flooding.

In the period between 1946 and 1956, rail-based commerce gave way to emerging new forestry practices that relied on truck logging and the construction of road networks into surrounding mountain valleys to access large and lucrative tree farm licenses granted by the Province. The community doubled in size from 582 to 1,292 residents, many settling into existing mid-valley farming neighbourhoods of Brackendale and Mamquam (now known as Garibaldi Estates) and industry-based neighbourhoods of Downtown Squamish, Dentville, North Yards, and Valleycliffe (see Figure 5-5). During this period, the Daisy Lake Dam was constructed upstream along the Cheakamus River, providing electricity to support the demands of industrial and residential growth.

The focus of growth and development shifted dramatically in 1958 with the completion of the Sea-to-Sky Highway. By 1964, neighbourhoods that had previously been managed by local farm, water and sewer boards were incorporated as the District Municipality of Squamish, thereby consolidating governance, infrastructure services, and land use planning activities under a single authority. In the decade between 1956 and 1966, the population of Squamish tripled in size from 1,292 to 4,240 residents, many of whom began commuting daily to Vancouver for work. This period of transition marked the beginning of a new era for Squamish.

As illustrated in Figure 5-5, the period between 1961 and 1981 witnessed an unprecedented rate of growth and development in the community—a trend that was driven largely by economic opportunities in the forest sector and by outdoor recreational amenities that began to attract individuals and families seeking a more rural lifestyle. The population doubled in size to over 10,000 people, with residential development and associated infrastructure services expanding into new areas along the valley floor and adjacent highlands. It was during this time that debris flow deposits were discovered along the Cheekye Fan. With additional research on the extent and magnitude of previous landslide events in the area, it became evident that areas identified for residential growth and further infrastructure development were in the path of one of the largest known landslide hazard threats in Canada.

The recession in the early 1980s had a significant impact on resource-based communities throughout British Columbia. Unemployment rates in Squamish during this period rivalled those of the Great Depression in 1930 and had a significant influence on growth and development. By 1986 the forest industry had rebounded and the community experienced a renewed period of growth that lasted until the early 1990s. Between 1996 and 2006, growth rates slowed again in response to globalization and a regional economy that was undergoing a gradual transition away from resource-based industries.

5.3.2.2 Community Profile (2006)

Squamish is a vibrant and diverse community of more than 16,000 residents that is expected to double in size over the next 30 years (Urbanics Consultants *et al.*, 2005). The demographic profile of the community reflects both the rural mountainous setting and strong metropolitan influences from the Metro Vancouver region (Statistics Canada, 2006). The focus of commercial activity is gradually shifting from its industrial roots to service-oriented sectors that support the community's vision of itself as The Outdoor Recreation Capital of Canada and a gateway to the Sea-to-Sky region.

Squamish is one of the smaller urban fringe communities in the lower mainland area of Metro Vancouver. However, the rate of population growth over the period 1985 to 2006 was 2.1%, well above the provincial average of 1.9% per year. The gender mix is 49% female and 51% male, a pattern that is opposite to that of most communities in BC. The age profile is also opposite to that observed in British Columbia and many other parts of Canada. The number of younger cohorts, including all age categories less than 20 years of age and between the ages of 20 and 39 is nearly 3% above the national average. The median age of the population is 35.9, 3.5 years below the national median and almost 5 years below the provincial median age. At the other end of the spectrum, the percentage of retirement-age (60-74 years) and elderly cohorts (>75 years) is 6% below the provincial average, 2.3% and 3.4% below the national averages for these same age categories.

Family structure characteristics are also different in Squamish than in other parts of the province. While 85% of the families in Squamish include parents with children (matching the provincial average), there a fewer married-couple families (9% below the provincial average) and more common-law families (9% above the provincial average). The total number of lone-parent families in Squamish is on par with other parts of British Columbia (~15%). However, the number of female lone-parent families exceeds that of male lone-parent families by a factor of nearly four. Significantly, the numbers of elderly living alone and families who spend a significant amount of their time caring for dependents are above the provincial and national averages.

The statistics also indicate that Squamish is a community on the move, with a significant proportion of the population either migrating from other parts of Canada or emigrating from other countries. Over a five-year period between 2001 and 2006, nearly 24% of the population moved their place of residence within Squamish. During this same time interval, 17% arrived from elsewhere in British Columbia, 5% arrived from elsewhere in Canada, and 4% emigrated from other countries. Nearly 36% of the District's immigrant population is from India. Although dramatic, the trends in mobility are similar to those observed in other parts of BC. Nearly 20% of the total Squamish population report languages other than English or French as their mother tongue. It

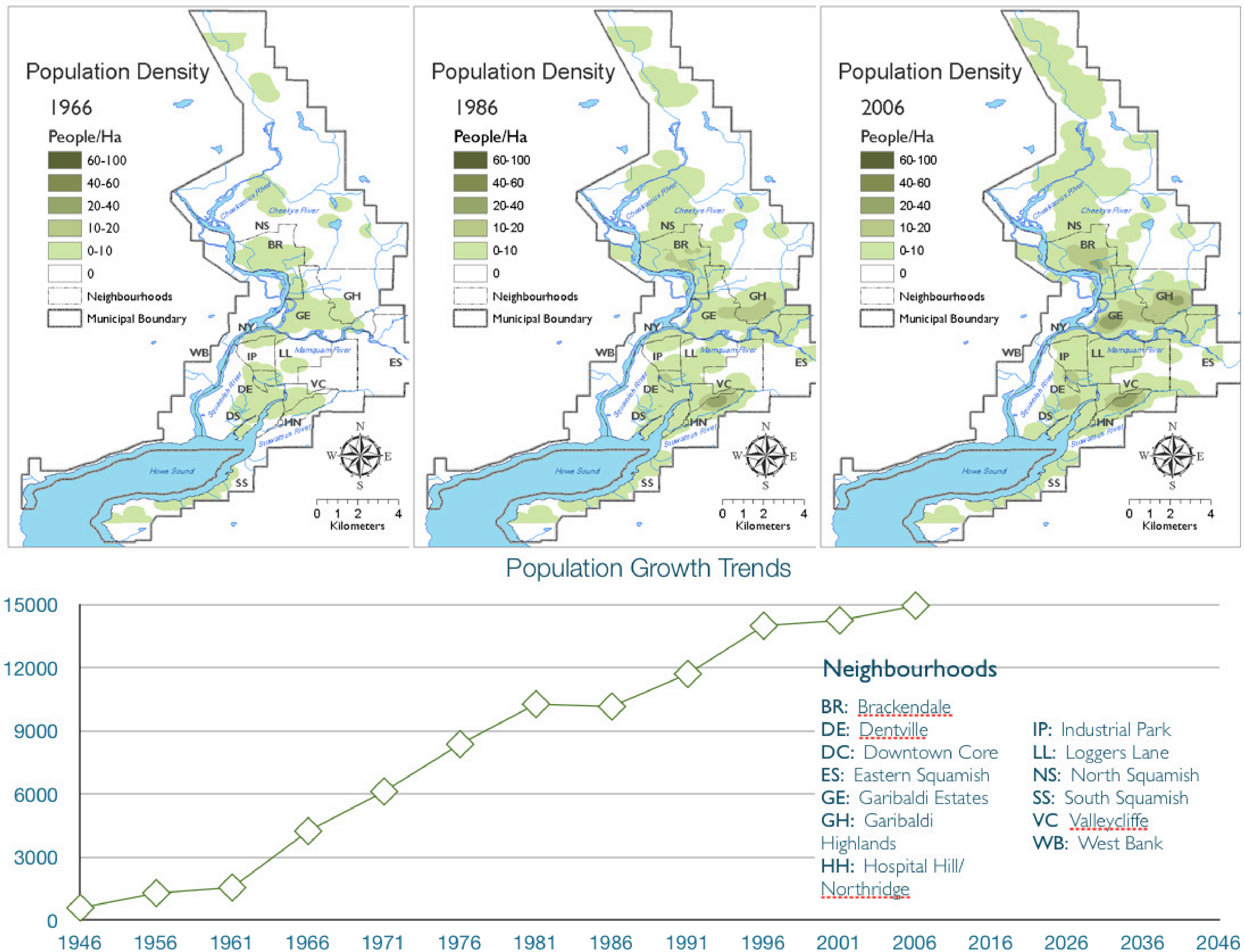


Figure 5-5: Growth trends and corresponding patterns of human settlemenet in Squamish over the period from 1946-2006.

is estimated that more than 300 individuals do not have a working knowledge of either official language.

Housing characteristics in Squamish are on par with other parts of British Columbia, with some notable exceptions. Of the 5,620 dwellings in 2006, more than 76% were owned as compared with only 68.7% nation-wide. Over 50% of the population lives in single-detached homes, with an additional ~22% living in row houses and semi-detached multi-family dwellings. Less than 18% of the population lives in duplex or multi-storey apartments, nearly 20% below that of the provincial average, and 6.4% of the population lives in other types of dwellings, including a significant number of mobile homes. The benchmark price for a single-family detached house in 2006 was ~$406,500 (value of land and building assets), more than $175,000 below that of a comparable home in the lower mainland region. However, the rates of increase are on par at 14–16%.

The median 2005 household income for Squamish ranges from $79,337 (provincial average) for couple households with children to $32,629 for one-person households (~$5,000 above the provincial average). Nearly 3.5% of households in Squamish earn less than $10,000. The cost of living is slightly higher than in other parts of the province at ~$800 per month for rented dwellings and ~$1,275 for owner-occupied dwellings. Employment earnings account for nearly 70% of the total income in Squamish as compared with the BC average of 66%. All other sources of reported income (pension, investment, self-employment) are at levels of 1% to 3.5% below the corresponding provincial averages.

As illustrated in Figure 5-6, the labour force in Squamish is dominated primarily by accommodation and food services, construction, and retail trade sectors. Other important employment sectors include health care and social assistance, professional scientific and technical services, educational services, public and private sector administration services, transportation, and warehousing. Nearly one third of the experienced labour force is in sales and service occupations (30%), with an additional 22% working in the trades as transport and equipment operators and in related occupations. The pattern is different to that of Metro Vancouver, where occupations in business, finance and administration dominate the employment profile.

Major employers in the community include School District #48, the District Municipality of Squamish, Save-on-Foods, the Squamish Nation, Home Depot, Furry Creek Golf & Country Club, and Squamish Terminals (Squamish Sustainability Corporation, 2008). Nearly 47% of the workforce is employed in the community of Squamish with an additional 28% commuting to jobs elsewhere in the Sea-to-Sky region or in Vancouver. Almost 25% of those employed either have no fixed place of work or work form home. Less than 1% work outside the province or outside of Canada. Nearly 75% of the adult population drive themselves to work with the remaining 25% either riding as passengers, walking, cycling or using public transit.

5.3.3 The Physical Environment

The form and function of the built environment reflects the history of settlement in Squamish and is one of the primary factors influencing patterns of physical vulnerability in the community. The location, year of construction and type of structure all have a direct bearing on the extent and magnitude of damage associated with a given portfolio of natural hazard threats. Like many resource-based communities in British Columbia, Squamish is organized around an industrial-commercial core that is surrounded by residential neighbourhood nodes. As illustrated in Figure 5-7, the primary industrial-commercial core extends northward from the downtown waterfront areas of Howe Sound and the Mamquam Blind Channel, along the alluvial floodplain of the Squamish River to its confluence with the Mamquam River. A second industrial node that includes the airport and electrical power facilities is located at the north end of the community near the confluence of the Squamish, Cheakamus and Cheekye river valleys.

Though loosely connected by a rectilinear network of roads and rail lines, the industrial-commercial core and surrounding neighbourhood nodes are largely separated from one another along the narrow valley bottom. Highway 99, a major north-south transportation corridor in British Columbia, bisects and effectively separates the downtown core and industrial-agricultural neighbourhoods of Dentville, North Yards, Brackendale, and North Squamish to the west from the largely

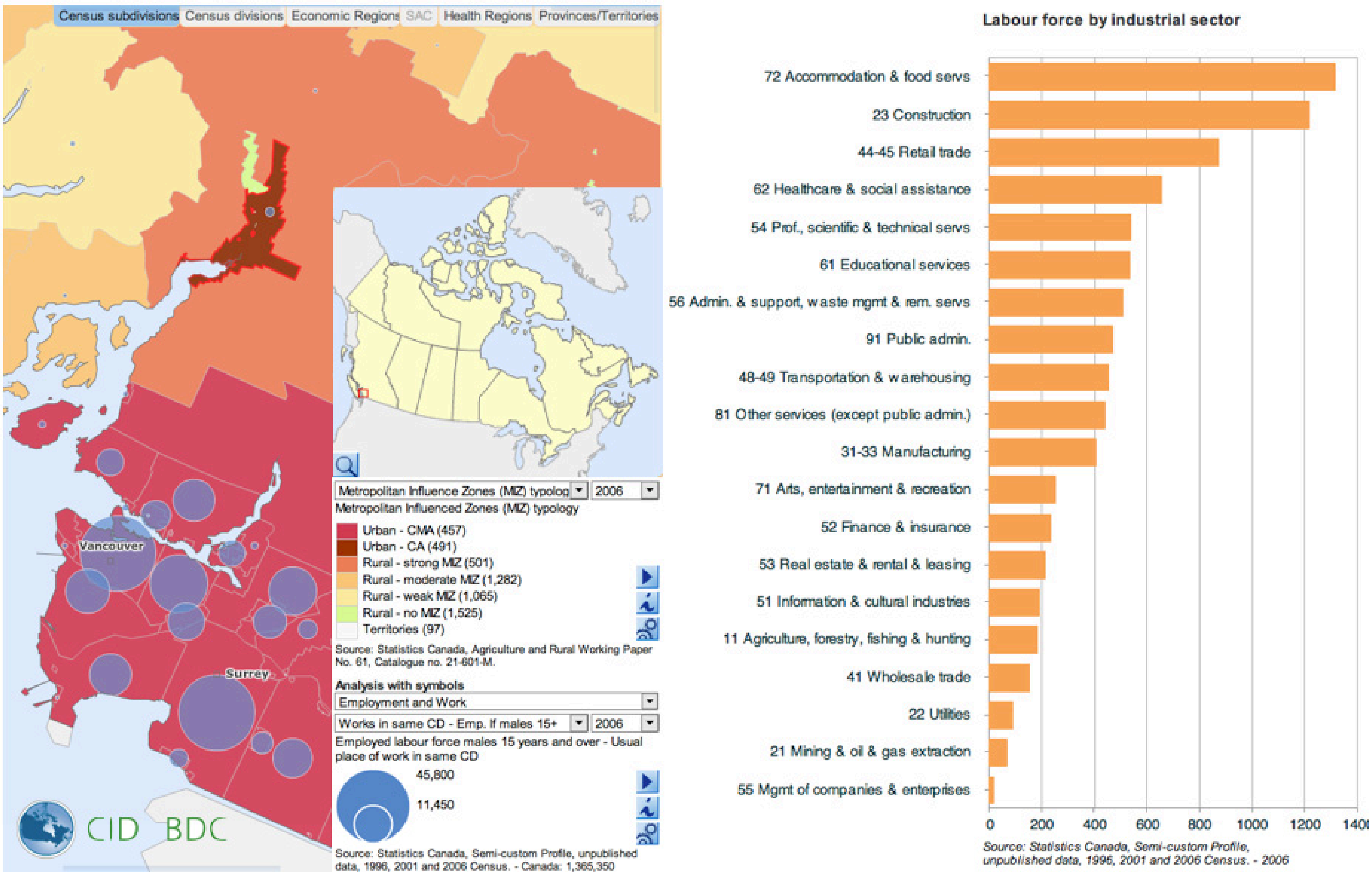


Figure 5-6: Labour force statistics by sector for the community of Squamish. Maps and graphs are based on community profile data provided by Statistics Canada (2006) through the Community Information Database for Canada.

residential neighbourhoods of Hospital Hill-Northlands, Valleycliffe, Garibaldi Estates, and Garibaldi Highlands to the east. In addition to facilitating the flow of people, goods and services in the community, road and rail networks also serve as distribution corridors for major utility services including water, energy, and communications.

5.3.3.1 General Building Stock

There are more than 5,620 building structures in Squamish. The majority

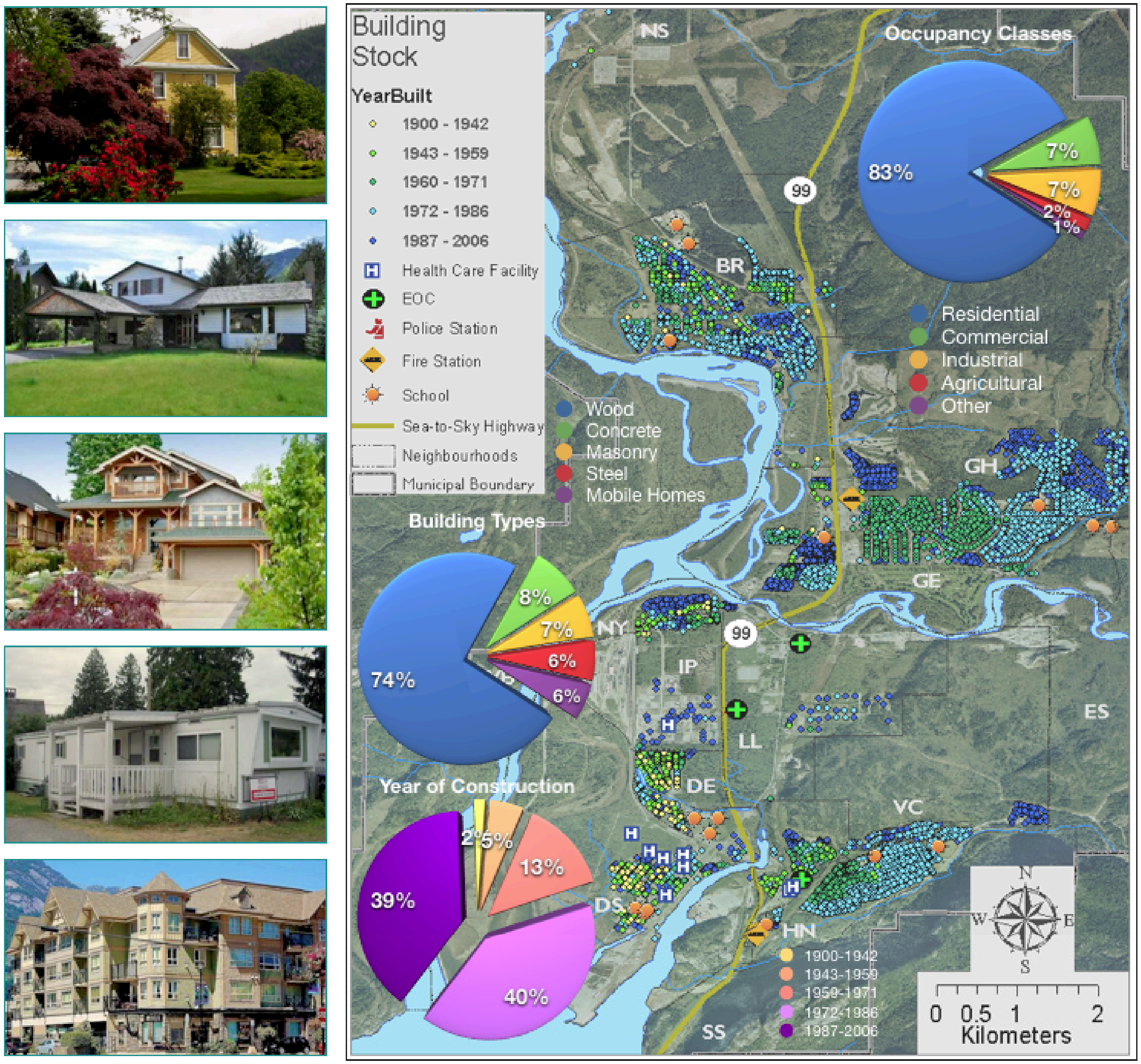


Figure 5-7:Distribution, age, and physical characteristics of building stock in the community of Squamish, BC. Designated neighbourhood areas include North Squamish (NS), Brackendale (BR), Garibaldi Highlands (GH), Garibaldi Estates (GE), North Yards (NY), Industrial Park (IP), Loggers Lane (LL), Dentville (DE), East Squamish (ES), Valleycliffe (VC), Hospital Hill-Northlands (HN), Downtown Squamish (DS) and South Squamish (SS).

of these are residential buildings (83%) with equal proportions of commercial (7%) and industrial (7%), and smaller numbers of agricultural, government, religious and school buildings. As illustrated in Figure 5-7, structures built prior to 1960 are concentrated primarily along the valley bottom in Downtown Squamish, Dentville, North Yards, and northwest portions of Brackendale. Buildings constructed during rapid growth in the 1960s are concentrated primarily in Hospital Hill-Northridge, Garibaldi Estates and western portions of Valleycliffe. Buildings constructed in the interval 1970–1980 and those constructed to more modern building code standards (post-1985) are distributed throughout the community with concentrations in eastern Valleycliffe, North Yards, Garibaldi Estates, Garibaldi Highlands, and the southeast portions of Brackendale.

Nearly 75% of the buildings are wood frame construction with smaller but equal proportions of steel, masonry or concrete, and mobile home structures. They include a mix of single-family detached houses (~61%); semi-detached houses, multi-family row houses, and duplexes (~22%); multi-family apartment complexes (~12%); and single-attached houses and mobile home dwellings (~5%). In addition, there are more than 1,400 non-residential buildings including industrial (41%), commercial (39%), agricultural (12%), and a mix of public facility (8%) structures, all totalling more than 120,000 m^2 of floor space. The total assessed value of the building stock in Squamish is ~$1.1 billion with a replacement value for structures and contents that is estimated to be ~$1.27 billion (HAZUS; default replacement cost ratio).

5.3.3.2 Essential and Critical Facilities

Essential police, fire, health care, and emergency operation facilities are concentrated primarily in the southern portion of the District. There is one hospital with a bed capacity of 25 that serves the community and broader Sea-to-Sky region, and an additional 8 facilities that provide health care services to the community. In addition to 20 elementary and secondary schools in proximity to major neighbourhood nodes, there are a number of new school facilities established as part of the Quest University campus in the Garibaldi Highlands area. The combined replacement value of essential facility assets is estimated to be $49 million. Critical facilities include an extensive dyke/levee system and hazardous material storage sites in the downtown waterfront area and in major industrial centres.

5.3.3.3 Transportation and Utility Systems

Major transportation infrastructure in Squamish includes the provincial Sea-to-Sky Highway (Highway 99), approximately 340 km of secondary roads maintained by the municipality, a deep-water port and related facilities, rail lines and related facilities operated by Canadian National (CN), and an airport that provides general (non-scheduled) aviation services to the community and surrounding regions (see Figure 5-8). There are 19 highway bridges and 9 railway bridges crossing all of the major river systems in the valley.

Major utility systems are distributed throughout the District and provide lifeline services to the community and broader Sea-to-Sky region (see Figure 5-8). They include an extensive network of potable water and waste water facilities (pipelines, pump stations, and storage tank facilities) that follow major and minor transportation corridors; electrical power substations and power transmission lines for industrial, residential and commercial use; natural gas pipelines that traverse the valley bottom; and a variety of regional communication broadcast, antenna, and switching stations.The total value of the lifeline inventory is estimated to be in excess of $527 million.

5.3.3.4 Elements of Environmental and Cultural Significance

Because of its physical setting and relatively long history of settlement, Squamish is endowed with a wealth of natural and cultural assets, many of which are considered by the community to be vulnerable and in need of safeguarding. Environmental assets include ecologically sensitive riparian and wetland areas throughout the District, the most notable of which include the Squamish Estuary, the Baynes Island Ecological Reserve, and critical fish habitat along the Mamquam Blind Channel. Over 26% of the District has been designated as park, reserve, open space, or greenway corridor to help protect ecological assets. An additional five provincial parks have been established in the Squamish area—Alice Lake, Murrin, Stawamus Chief, Shannon Falls, and the

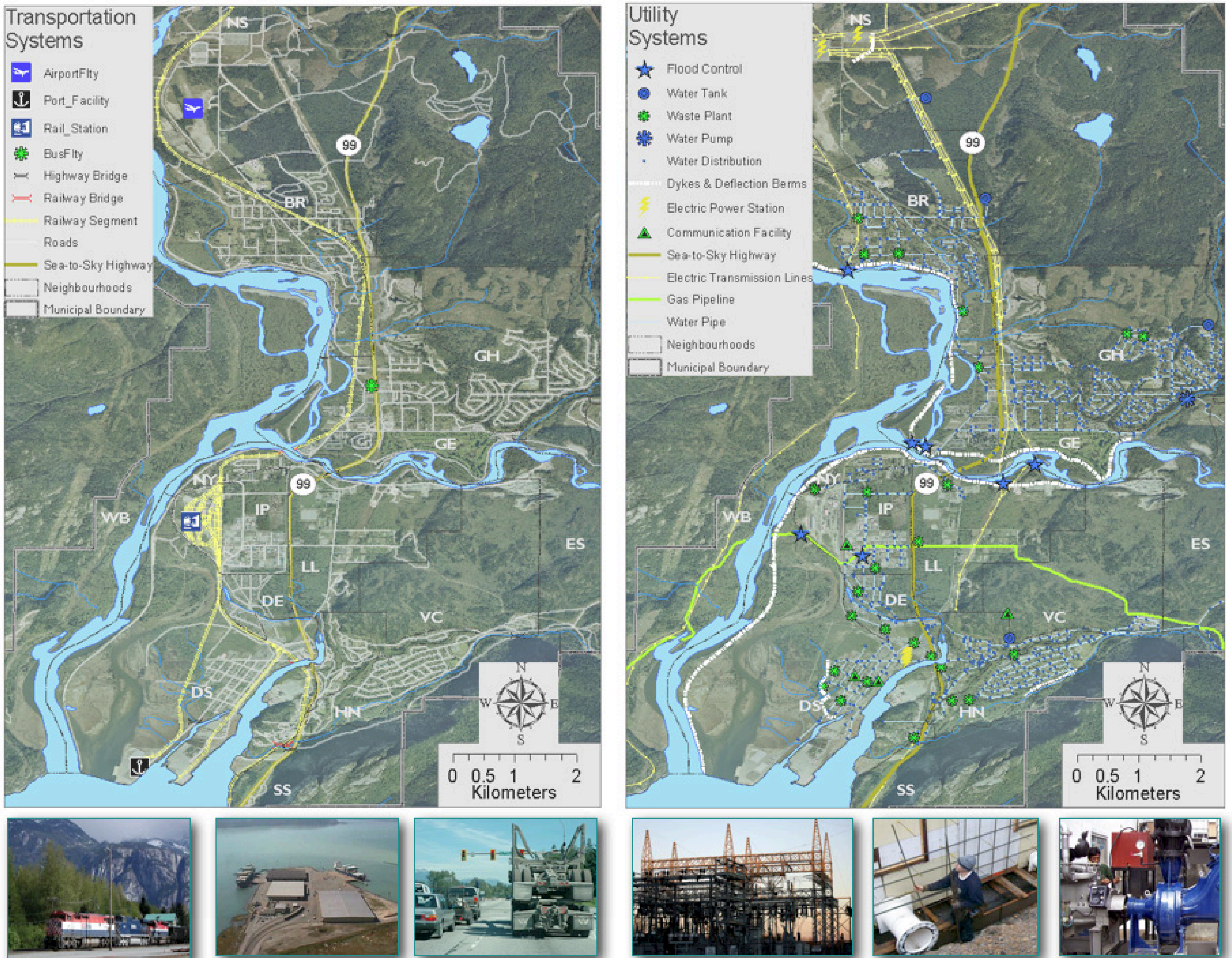


Figure 5-8: Critical infrastructure and related lifeline services in Squamish. The map on the left shows the distribution of transportation system infrastructure and related facilities. The map on the right shows the distribution of utility infrastructure and related facilities.

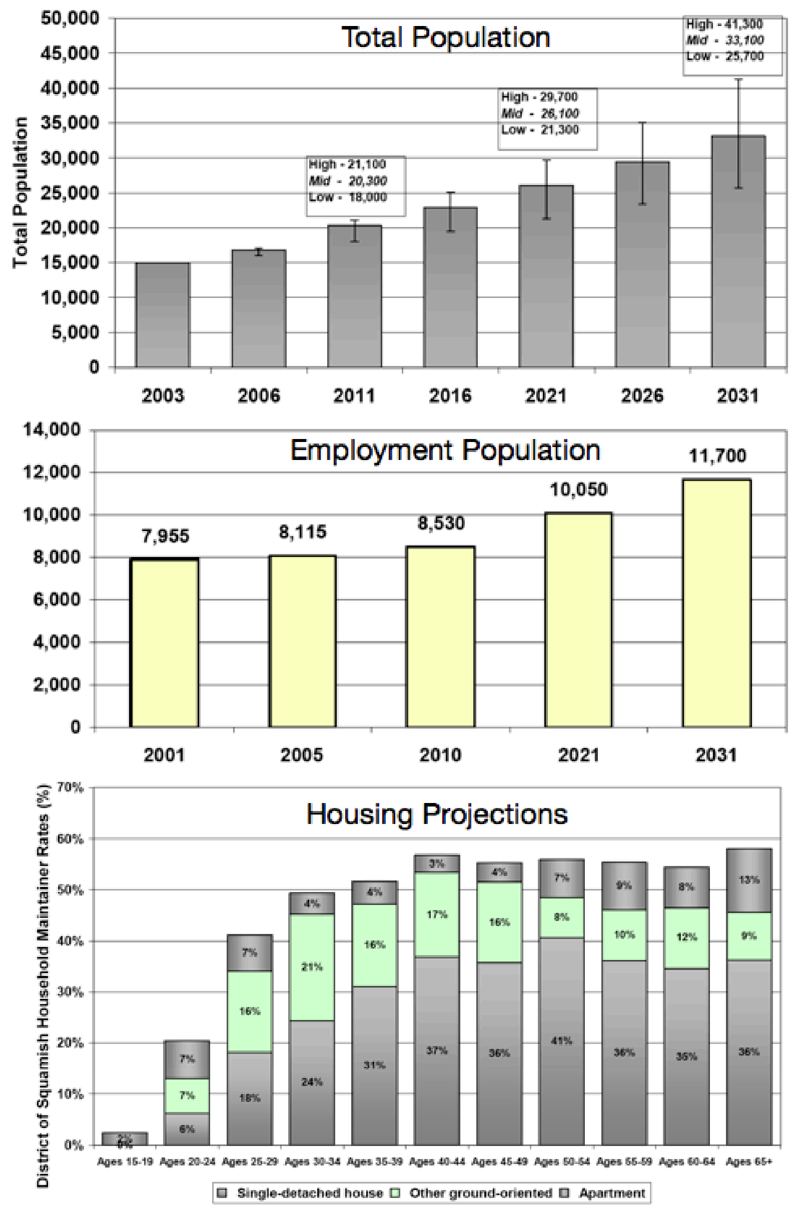


Figure 5-9: Projections for population and employment growth and associated residential housing demand for the District of Squamish (Urbanics Consultants et al., 2005; District Municipality of Squamish, 2007b).

Brackendale Eagles provincial parks. Many natural assets also feature world-class outdoor recreational opportunities for hiking, wind surfing, mountain biking, and rock climbing. Although providing essential ecological services that are of value to the community, these assets have not as yet been assessed in terms of their monetary contribution to community wealth.

5.3.4 External Drivers and Future Trends (2006-2031)

Drivers of growth and change in the District of Squamish include proximity to one of the largest and fastest growing urban centres in Canada; a regional economy that is in transition from traditional resource-based industries to emerging new industries based on recreational tourism, green technologies, and business services; a transportation system that includes a deep-water port facility, rail and highway infrastructure; and a physical setting and access to recreational amenities that are considered highly desirable in choosing a place to live in British Columbia. Any one of these factors has the potential to significantly influence rates and patterns of change in the community; together they are contributing to one of the fastest growth rates for a community of its size in British Columbia.

5.3.4.1 Population and Employment Growth

Forecasts of population growth for the District of Squamish (see Figure 5-9) suggest a non-linear rate of growth of 2.6% for the period 2006–2021, with numbers increasing from current levels of approximately 16,000 to more than 26,000 (Urbanics Consultants *et al.*, 2005; District Municipality of Squamish, 2007a). By the year 2031, the population of Squamish is expected to double its current size with an anticipated population of ~33,000. Projections that take into account the uncertainties associated with external and internal influences suggest an anticipated population range of between 26,000 and 41,000 people.

Over the roughly 30-year time period, it is anticipated that the age and demographic characteristics of the population are likely to change significantly. As with many communities in proximity to metropolitan centres in southwest British Columbia, the proportion of individuals over the age of 65 is expected to double from current levels of ~8% to

~15% by the year 2031. Of these, the numbers of people between 65 and 74 years of age will increase by ~21%. The number of elderly individuals over the age of 75 is anticipated to increase by 33%. Demographic characteristics such as family structure, income, and employment are more variable and were not included in the population forecasts. Nonetheless, it is clear from the history of the community that current trends are likely to persist. All of these factors will have a bearing on patterns of employment, demand for new housing in the District, and intrinsic levels of social vulnerability.

The projected growth in employment for the period 2010-2021 is expected to increase at a rate of ~1.5%, slower than the corresponding population growth rate of ~2.6%. This corresponds to an employment forecast of ~10,000 for the year 2021 and ~12,000 for the year 2031 (Urbanics Consultants *et al.*, 2005). The corresponding labour participation rate of ~40% is expected to remain, 10% below current levels of ~50% for the period 2010-2031. This is due in large part to an aging local population and expectations that Squamish will continue to attract new residents seeking to retire in a vibrant community that offers a wide range of lifestyle amenities.

5.3.4.2 Implications for Future Development and Land Use

Commercial development is expected to mirror employment trends with a corresponding demand for ~75,000 m^2 (800,000 ft^2) of commercial floor area, and ~24,000 m^2 (255,000 ft^2) of office space. Studies undertaken in support of the regional growth strategy process suggest that demands for commercial and industrial floor area will likely be accommodated by the available supply of land that is designated for these uses in the Official Community Plan (Design Centre for Sustainability, 2005; Urbanics Consultants *et al.*, 2005; District Municipality of Squamish, 2007b). In contrast, growth in the residential housing sector is expected to double over the next 30 years with population growth rates that translate into a demand for an additional ~8800 single- and multi-family residential dwellings by the year 2031 (Design Centre for Sustainability, 2005; Urbanics Consultants *et al.*, 2005). Figure 5-9 provides a breakdown of anticipated new residential building stock by occupancy class.

The variable rates of growth for each occupancy class reflect anticipated changes in population and demographics described above. Although the demand for single-family detached homes is likely to remain strong, the proportion of overall residential building stock is expected to decrease from current levels of ~61% to less than 53% between 2021 and 2031. At the same time there is likely to be an increase in the proportion of multi-family dwellings from current levels of ~12% to approximately 25% between 2021 and 2031. The anticipated trend in housing toward multi-family dwellings and mixed-use residential-commercial structures reflects both a shift toward an older population seeking smaller house size and proximity to amenities, and Smart Growth planning principles that encourage higher density and more compact urban neighbourhood forms to help reduce environmental impacts and promote quality of life.

While the demand for residential housing is large, the supply of private lands available to accommodate expected growth and development is small and highly constrained by geographic setting. Buildout analyses undertaken as part of the community's growth management study indicate that less than 27% of the land base within the municipal boundary is available to accommodate anticipated needs for residential development. In addition to designated parks, ecological reserves, greenway corridors, and regulatory setbacks on riparian and wetland areas along the valley floor, there are additional physical and financial constraints to residential development. These include lands that exceed designated safety thresholds for flood and landslide hazard threats and lands that encompass steep slopes at higher elevations where the costs of mitigation and municipal servicing exceed projected resources for infrastructure development (Urbanics Consultants *et al.*, 2005; District Municipality of Squamish, 2007b).

Given the limited land supply, the options for managing anticipated growth demands are to designate existing limited use lands for residential development, or to increase the density of available residential lands in the downtown core and in surrounding neighbourhood nodes. Both of these options have the potential to increase physical exposure to natural hazards, and corresponding levels of vulnerability and risk to the community. A third option would be to adopt land use policies that limit the capacity for future growth and development in areas that are exposed to natural hazards.

5.3.5 Existing Risk Management Policies

Squamish was one of the first communities of its size in Canada to establish a municipal risk management policy based on empirical thresholds of safety for natural hazards. Over the past 15–20 years, the municipality has commissioned a number of scientific and geotechnical studies to better define the threats posed by debris flow and flood hazards in the valley, and to assist in defining thresholds of safety to help guide mitigation works and land use planning. The scope of work for these studies included an assessment of hazard potential and the delineation of risk management zones relating to the collapse of landslide-generated dams along the flanks of Mount Garibaldi and catastrophic outburst of debris flow landslides and related floodwaters onto the Cheekye Fan (Thurber Engineering & Golder Associates, 1993; Kerr Wood Leidal, 2003), The studies also looked at riparian and coastal surge flooding accompanied by structural failure of levee and dyke systems along the Squamish, Cheakamus, and Mamquam rivers (Klohn Leonoff LTD & Graham Farstad, 1994), and wildfire along the interface between areas of human settlement and surrounding forested slopes in the Squamish Valley (Davies and Coulthard, 2007)

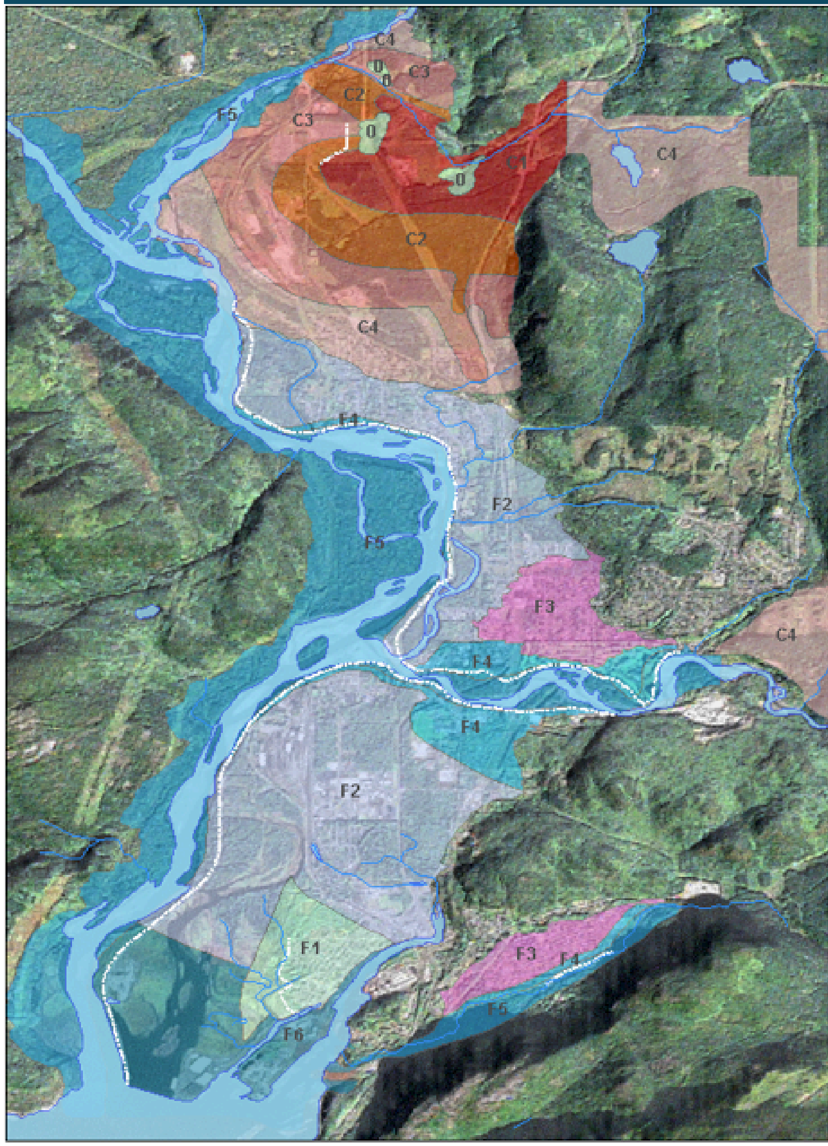
In addition to characterizing hazard potential, these studies have collectively established a risk management framework for the District of Squamish that is based on the principle of maximizing public safety. In the context of this framework, safety is defined in terms of hazard intensities that that pose a threat to life and limb and that correspond with event probabilities of 0.0001 (1/10,000). Risk management zones that have been established on the basis of these tolerance thresholds are summarized in Figure 5-10.

Based on the results of detailed geotechnical studies that were available in the 1990s, the District used a 1/10,000 7 Mm^3 debris flow event to identify four risk management zones on the Cheekye Fan (Zones C1-C4 in Figure 5-10). For each zone there is a corresponding set of planning guidelines and risk mitigation strategies to minimize potential consequences in terms of both socio-economic security and public safety. Risk management areas were identified on the basis of hazard potential and probability of death to individuals and groups. Existing thresholds of safety follow protocols established elsewhere in British Columbia (Cave, 1992), and are defined by the probability of damage exceeding 1/2500 (pa > 0.0004), and/or the probability of death exceeding 1/10,000 (pa > 0.0001).

Zones C1 and C2 exceed these risk thresholds and are considered unacceptable for habitable land use. Zones C3 and C4 make provision for existing development through a wide range of additional risk reduction measures including early warning systems, land use zoning, and structural mitigation (deflection berms) to protect existing private and public investments (buildings and transportation infrastructure). Subsequent geotechnical studies by Kerr Wood Leidal (2003) provided a more refined assessment of likely debris flow scenarios, both in terms of frequency-magnitude relationships and areas of potential impact (see Section 5.5.1). Results of this work indicate that a 1/10,000-year debris flow event is more likely to be in the range of 2.8–5.4 Mm^3 with associated run-out zones that do not correspond with those identified in the initial Thurber-Golder study. However, results of these more current studies have not yet been incorporated into the hazardous area map used to inform land use planning for the District.

The Klohn Leonoff study (Klohn Leonoff LTD & Graham Farstad, 1994) identified six additional risk management zones to account for flood hazard threats (Zones F1–F6 in Figure 5-10). Zones F5 and F6 represent the river floodway and coastal storm surge areas and are considered unacceptable for habitable use. Recommended safety thresholds were based on the probability of exceeding water depths and velocities associated with a flood event with a 1/200-year frequency (pa > 0.005) in which existing levees are breached. Zones F1–F4 represent areas exposed to increasingly higher levels of flood hazard threat, and in which site-specific flood proofing measures are recommended. The study identified areas that would be suitable to accommodate future growth and development, and suggested site planning and mitigation guidelines to reduce potential flood impacts on buildings and critical lifeline infrastructure. Policy recommendations identified land use zoning, diversion dykes, and warning systems as the most appropriate measures for reducing flood risk, and a

Risk Management Zones for the District Municipality of Squamish



Hazard Zone	Annual Probability of Damaging Event	Probability of Death	Risk Management Strategies
Zone C1	0.02	0.0625	Designate only for uses that involve no significant habitation. Silviculture, outdoor recreation (requiring no significant improvements), and resource extraction are examples of appropriate uses. Include alluvial fan flood-proofing measures
Zone C2	0.001	0.0011	Similar to Zone 1, but because of less destructive effects, policy could allow more intensive forms of outdoor recreations such as golf course, without residential facilities, particularly if the probability of death approach indicates acceptable risk. No habitable uses. Include alluvial fan flood-proofing measures.
Zone C3	0.0004	0.00011	Designations should reflect existing uses and should allow limited infill. However, large tracts of vacant land should be designated as for Zone 2. Include alluvial fan flood-proofing measures.
Zone C4	0.0001	0.00005	Designations should be determined primarily by general community planning and servicing conditions, because exposure to hazard is not so great as to be the primary determinant of land use. Include alluvial fan flood-proofing measures.
Zone F1	0.005	NA	All new development to conform with designated Flood Construction Levels. No erosion protection required
Zone F2	0.005	NA	All new development to conform with designated Flood Construction Levels. Erosion protection required for fill.
Zone F3	0.005	NA	Approved Site grading plan required to provide flood-proofing. Erosion protection required for fill.
Zone F4	0.005	NA	All new development to conform with designated Flood Construction Levels. Erosion protection required for fill and foundations
Zone F5	0.005	NA	River Floodway. No development permitted
Zone F6	0.005	NA	All new development to conform with designated Flood Construction Levels that are refined on the basis of site-specific wind/wave analysis.

Figure 5-10: Existing risk management zones for the District Municipality of Squamish are based on the results of dated geotechnical studies carried out in the 1990s to assess hazard potential and to establish thresholds of safety for debris flow, flood, and wildfire hazards (Thurber Engineering & Golder Associates, 1993; Klohn Leonoff LTD & Graham Farstad, 1994)

comprehensive set of mitigation strategies to be evaluated on the basis of resource efficiency (costs versus benefits) and social equity.

Outcomes of the 1993 Thurber-Golder study have been incorporated into the existing Land Use Bylaw for Squamish, which provides regulatory constraints against development in areas that are considered to exceed the 1/10,000-year safety threshold for probability of death resulting from natural hazards. Safety thresholds for landslide and flood hazards are based on the 1/2500-year and 1/200-year event frequencies. The Official Community Plan for the District is also specific with respect to landslide and flood hazards (District Municipality of Squamish, 2010). It acknowledges the need to work towards managing multiple natural hazards in a manner that takes into account acceptable thresholds for public safety and socio-economic security; however, it does not specify what these thresholds are or how they might be negotiated. Nonetheless, the plan does identify a set of management objectives and charts a path toward an integrated risk management plan for the District. Policies outlined in the OCP bylaw (Section 2.5; pages 111-115) include provisions to:

- Maintain 1/200-year flood protection standards along the Squamish, Stawamus, and Cheakamus rivers, and develop sea dykes that provide continuous protection to Downtown Squamish
- Develop a comprehensive flood hazard plan or bylaw to address land use and mitigation strategies
- Review the existing Zoning Bylaw to restrict or minimize the intensity of potential development for areas that are subject to high flood and/or debris flow hazards
- Identify land uses and mitigation strategies on the Cheekye Fan that are compatible with assessed levels of hazard potential and risk
- Minimize building construction and fill placement in the corridor between Highway 99 and Loggers Lane in order for the area to serve as an emergency floodway and enable reduced Flood Construction Levels (FCLs) to be established in Dentville and Downtown Squamish
- Exempt non-residential uses in the downtown from the required Flood Construction Level (subject to other mitigation measures endorsed by a qualified professional engineer) in order to preserve historic streetscapes
- Encourage periodic gravel removal within riverbeds to maintain existing channel capacity and dyke protection

5.4 Results of Risk Appraisal for Squamish

Risk appraisal methods outlined in Chapter 4 (see Section 4.4.1) were used to characterize levels of knowledge and perceptions of natural hazard risk in the community. Objectives of the risk appraisal process were to: (i) identify a portfolio of credible hazard events to include as part of the risk assessment process and rank the severity of these events in terms of likelihood and expected physical impacts, (ii) gauge levels of concern about the potential consequences of these hazard events on the community, (iii) assess existing capabilities for mitigation, response and recovery, and (iv) to identify additional mitigation strategies that would promote increased levels of disaster resilience for the District of Squamish. Results of the risk appraisal were analyzed on the basis of both individual and group responses. While there was variation at the individual level, the group response was internally coherent and reflected a high level of understanding about natural hazard risks and their likely impacts on the community.

5.4.1 Perceptions of Hazard Threat

Six hazard risk scenarios were identified as part of the appraisal process, two each for floods, landslides and earthquakes. Each of these hazard risk scenarios was then ranked in terms of their perceived likelihood of occurrence and expected physical impacts on people and community assets. A scale of 1 to 6 was used to rank perceived event frequency and magnitude, using narrative statements to assess relative levels of frequency and magnitude. Results of the hazard threat appraisal are summarized in Figure 5-11.

5.4.1.1 Landslide Hazard Scenarios

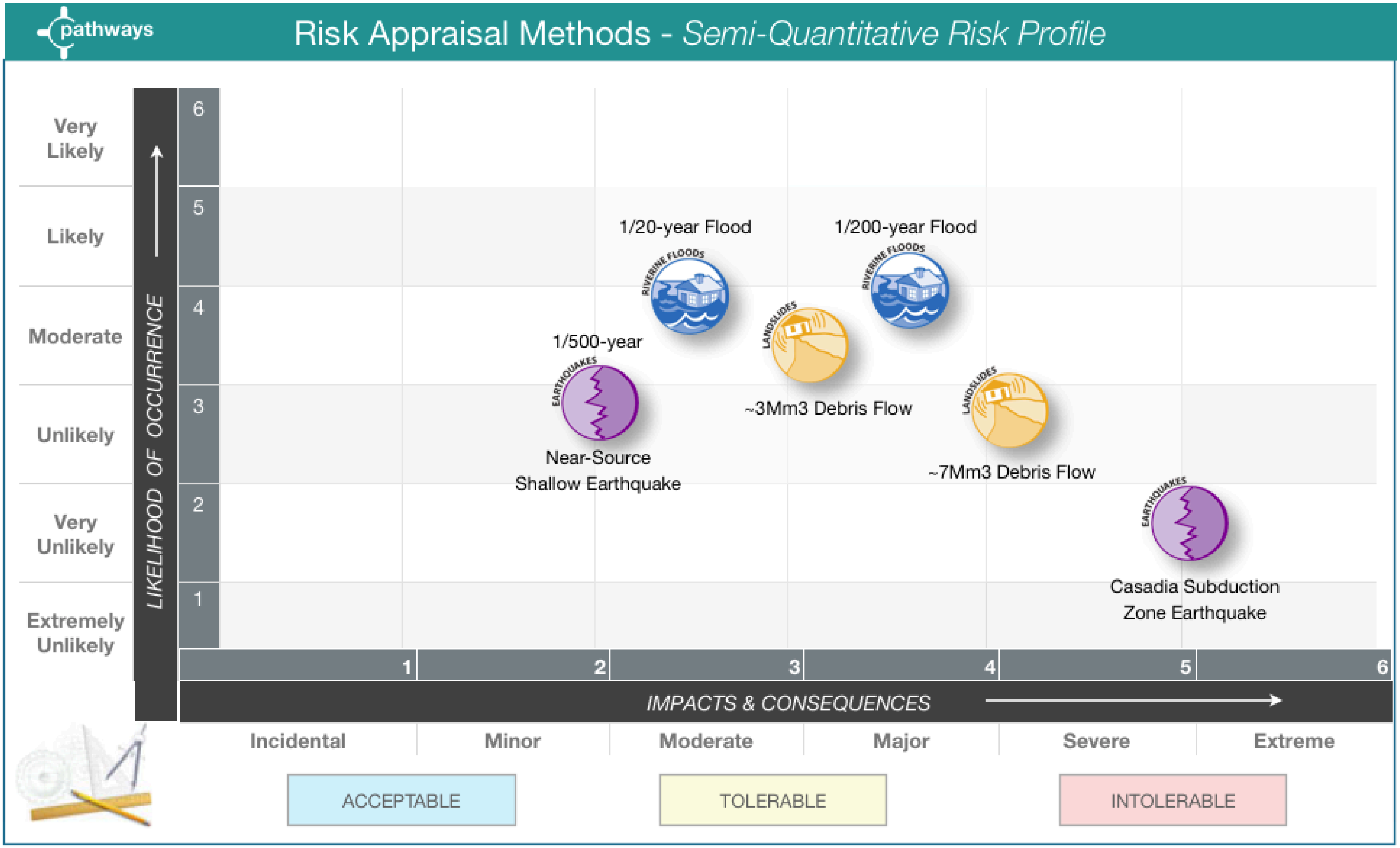


Figure 5-11: Risk profile reflecting local knowledge of natural hazard threats for the District Municipality of Squamish. The portfolio of hazard scenarios includes: 1/20-year and 1/200-year flood event), small and large magnitude debris flow events on the Cheekye Fan, a near-source shallow earthquake , and a more distant Benioff or subduction zone earthquake along the west coast of North America

While it was recognized that there was potential for slope failure along the valley margins in many parts of the community, the working group identified debris flows on the Cheekye Fan as the primary landslide hazard of concern. Two separate debris flow scenarios were considered, both triggered by landslide dam outbursts along the upper reaches of the Cheekye River. The first scenario is defined by an event involving 3.0–5.4 Mm^3 of debris material, considered by experts to be a credible event scenario based on known debris flow deposits preserved in the geologic record (Clague *et al.*, 2003; Kerr Wood Leidal, 2003; Friele and Clague, 2005; Jakob and Friele, 2009). The second is defined by a ~7 Mm^3 event, considered by provincial authorities to be a maximum credible scenario for mitigation of critical infrastructure assets that are situated along portions of the Sea-to-Sky corridor that cross the Cheekye Fan (Thurber Engineering & Golder Associates, 1993; Kerr Wood Leidal, 2003). The smaller of the two debris flow event scenarios was ranked by the working group as a moderate-probability/moderate-consequence event (rank scores of 3.3 and 3.1, respectively) that is likely to occur sometime over the next 30 years with a potential to cause minor economic losses ($10 million to $50 million) and localized disruptions to municipal utilities and services. The larger magnitude event was ranked as a moderate- to low-probability/moderate-consequence event (2.73 and 4.09, respectively) that is likely to occur sometime in the next 100 years with a potential to cause loss of life, economic losses of ~$100 million, and major disruption to municipal services resulting in the declaration of a state of emergency.

5.4.1.2 Flood Hazard Scenarios

Flood scenarios included 1/20-year and 1/200-year events triggered by severe weather storms in which protective dyke structures are compromised by structural failure, overtopped by rising floodwaters, or act as barriers to surface water flow causing inundation in low-lying areas of the valley. Many of the workshop participants were familiar with the history of flooding in the region, had witnessed the October 2003 flood in Squamish, and had first-hand knowledge of flood hazard potential throughout the valley. As a group, they ranked the 1/20-year flood as a relatively high-probability/low-consequence event (rank scores of 3.9 and 2.3, respectively) that is likely to occur sometime in the next 10 years resulting in relatively minor economic losses ($1 million to $10 million) and localized disruptions to municipal utilities and services. The 1/200-year flood was ranked as a moderate- to high-probability/moderate-consequence event (4.0 and 3.65, respectively) that is likely to occur sometime in the next 30 years with a potential to cause significant economic losses ($10 million to $50 million) and localized disruptions to municipal utilities and services.

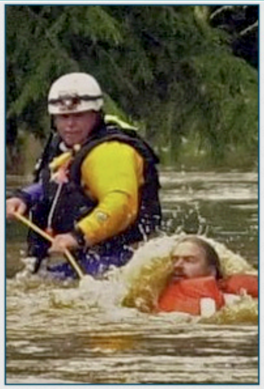
5.4.1.3 Earthquake Hazard Scenarios

The working group was less familiar with earthquake hazards in the region, but did identify two event scenarios for consideration as part of the risk appraisal process. The first was a near-source earthquake event triggered by displacement along a shallow fault with in a 50 km radius of Squamish. The second was a more distant earthquake event triggered by displacement along the Benioff zone deep beneath Georgia Basin and/or a "Cascadia event" along the subduction zone southwest of Vancouver Island. The near-source shallow earthquake scenario was ranked as a low-probability/low-consequence event (2.9 and 1.9, respectively) that is likely to occur sometime in the next 100 years with a potential for isolated damage, minor losses, and no disruption to municipal utilities and services. The more familiar Cascadia subduction zone event was ranked as a very-low-probability/high-consequence event (1.7 and 5.0, respectively) that is likely to occur sometime in the next 1000 years with a potential for multiple fatalities, economic losses in excess of $100 million to $1 billion and major disruption to municipal services resulting in the declaration of a state of emergency.

5.4.2 Levels of Concern

Assessing levels of concern about the potential impacts and consequences of credible hazard scenarios involved a three-step process. In the first step of the process, we used methods of participatory community mapping to identify, locate and describe vulnerable populations and assets that were considered to be most at risk and in need of safeguarding. For each of the population and asset groups identified, members of the working group were asked to rank their relative level of concern on a scale of 1 to 6, where an interval value of 1 indicated a very low level of concern and a value of 6 indicated an extremely high level of concern. Participants were then asked to prioritize each of the asset categories both in terms of individual and group response. The priority setting exercise was framed by a consideration of: (i) who and what must be protected at all costs (non-negotiable assets), (ii) who and what must be protected in order for the community to thrive (negotiable assets), and (iii) who and what must be protected in order to achieve a balance between safety, socio-economic security and equity between those who ultimately bear the risk of natural hazard in the community. Ranking scores for individual

Level of Concern



Vulnerable Populations	Rank
People with disabilities	5.5
Seriously ill	5.5
Elderly	5.4
Young children	5.4
Economically disadvantaged	4.7
First Nations People	4.6
Homeless	4.6
Non-english speakers	4.5
Single parent families	4.2
Tourists	3.9
Large families	3.7
Pets	1.1
Transients	0.4
Wildlife	0.3

Community Assets	Rank
Gas pipeline	6.0
Recreational areas (trails, lakes)	6.0
Critical infrastructure	5.9
Critical facilities	5.5
Dangerous goods storage facilities	5.5
Residential buildings	5.1
Daisy Lake dam	4.8
Public safety buildings	4.8
Ecosystem features	4.3
Commercial buildings	4.1
Industrial buildings	4.1
Culturally significant buildings	3.9
Historically significant buildings	3.3

Table 5-2: Assessed levels of concern for vulnerable populations and community assets considered at risk and in need of safeguarding by the working group. The overall assessment of vulnerability was determined by assigning a weighting factor to ranking scores for individual assets to reflect the level of priority assigned at the group level.

assets were then weighted by overall level of priority to assess relative levels of vulnerability. Results of the appraisal process are summarized in Table 5-2.

5.4.2.1 Vulnerable Populations

Populations identified by the working group to be most at risk and in need of safeguarding included people living with disabilities, the seriously ill, the very young (<5 years of age), and seniors living alone or together in care facilities that are exposed to flood hazards. Other populations of high concern included those living in neighbourhoods comprising a higher proportion of single-parent families and those caring for children and the elderly. Because the working group included representatives from the regional health authority, there was a relatively high level of knowledge about the locations and particular vulnerabilities of these population groups. First Nation communities and lower-income neighbourhoods were identified as being vulnerable due to their physical location and exposure to flood and debris flow hazards. Other populations of concern included the homeless, non-English speaking residents, tourists, and larger families with dependents. The final category identified by the working group included pets, livestock, and wildlife situated in low-lying areas of the valley that would likely be stranded in the event of a major flood.

5.4.2.2 Critical Infrastructure and Community Assets

Critical infrastructure and community assets considered most at risk and in need of safeguarding by the working group included utilities and transportation systems, both of which were considered vital in terms of longer-term disaster resilience. Utility systems were acknowledged as being vulnerable and in need of protection because of the role they play in providing basic water and energy services to the community. Other assets of high concern included critical facilities (dams and hazardous waste storage); residential, commercial, industrial, and municipal buildings that provide economic stability to the community in terms of goods and services; and essential facilities that provide emergency response capabilities in the event of a disaster. Additional assets of concern included buildings and other features that have cultural or historical significance, and environmental features such as wetlands and riparian areas that provide critical habitat and ecosystem services to the community.

5.4.3 Disaster Resilience

For purposes of the appraisal process, we defined disaster resilience as the capability of an organization or community to withstand and respond to the impacts of potential hazard events, and to recover from the consequences of these events in order to realize potential net benefits over time. As defined, it is a relative measure that is assessed in terms of levels of effectiveness or functionality. The first part of the process focused on an assessment of existing capabilities for response and recovery in terms of mitigation measures currently in place as part of the municipal risk management plan. The second part of the workshop provided an opportunity for participants to reflect on their assessment of existing capabilities, and to identify strategies that would further reduce vulnerabilities in the community and promote disaster resilience over time.

5.4.3.1 Existing Capabilities for Response and Recovery

The appraisal process considered existing capabilities for response and recovery through the lens of technical, organizational, social, and economic measures that are already in place in the community. In addition to providing a general list of risk treatment measures for each category, we also asked members of the working group to identify specific mitigation measures that had been adopted by the municipality. Participants were then asked to rank the perceived level of effectiveness of existing risk treatment measures on a scale of 1 to 6, where a score of 1 indicated a very low level of effectiveness and a score of 6 indicated an extremely high level of effectiveness. Final scores were based on a weighted average of individual responses for each category. Results of the appraisal process are summarized in Table 5-3.

Technical measures include structural mitigation works and geotechnical engineering systems (including guidelines for building safety) that are designed to increase capabilities of the community to withstand immediate and induced physical impacts of a hazard threat in accordance with accepted or desired levels of performance and to recover base levels of functionality over time. For the community of Squamish, these include an extensive network of protective dykes and deflection berms to mitigate the impacts of floods and debris flow hazards, and the enforcement of design guidelines and building codes that are intended to reduce the physical impacts of ground shaking in the event of an earthquake. Overall, the working group considered these technical measures to be only moderately effective in mitigating the impacts of natural hazard threats. Protective dyke and deflection berm structures were given an overall ranking of 3.6, while early warning systems were given a relatively low ranking of effectiveness at 2.3.

Capacity for Response & Recovery

Technical	Rank
Preventive Structures	3.60
Design/Building Guidelines	3.51
Building Codes	3.05
Retrofits	2.77
Early Warning	2.30

Organizational	Rank
Emergency Preparedness	4.25
Emergency Response	4.15
Public Works	3.50
Land Use Planning	3.05
Institutional Capacity	2.80
Bylaw Enforcement	2.77

Social	Rank
Risk Awareness	3.32
Communication	3.10
Public Participation	2.68

Economic	Rank
Provincial/Federal Disaster Relief	3.60
Insurance Market	3.10
Mitigation /Reconstruction Loans	3.00
Local Emergency Funds	2.80

Table 5-3: An assessment of existing capabilities of the community to withstand, respond to and recover from the impacts of a potential disaster event over time. The assessment reflects the weighted average of individual responses that were ranked on a scale of 1 to 5, where a score of 1 indicates mitigation measures that are considered to have a very low level of effectiveness, and a score of 5 indicates mitigation measures that are considered to have an extremely high level of effectiveness.

Organizational measures are those that increase the extent to which public and private sectors are able to undertake appropriate levels of emergency preparedness and planning to limit exposure to hazard threats (protection, regulation, land use zoning, etc.), and to assist the community in responding to and recovering from the impacts of hazard events. The list of organizational measures considered relevant for this study included: response and recovery operations managed by municipal protective services and the Squamish Emergency Program; public works and operations managed by the municipal Parks and Recreation Department and land use planning and bylaw enforcement services managed by the municipal Community Services Department. Of these organizational measures, the working group ranking existing emergency management services to be most effective in reducing the potential impacts of disaster events (4.3), and the enforcement of existing land use policies for hazardous areas to be the least effective (2.8).

Social measures that have a capability to increase the disaster resilience of a community include those that promote a greater degree of communication and consultation, risk awareness and understanding, and participation in neighbourhood-level emergency preparedness. For the community of Squamish, these include public education and outreach programs to increase the awareness and understanding of natural hazard threats in the valley, the development of neighbourhood-level emergency preparedness and communication plans, and active participation in the community planning process. Overall, the working group ranked existing social system capabilities as having a low to moderate level of effectiveness (2.7–3.3) in reducing the potential impacts of natural hazard threats.

Finally, economic measures are those that increase the capability to leverage available financial resources to: implement risk treatment measures through dedicated organizational budgets and mitigation or capital improvement loans; and to respond to anticipated consequences of potential hazard events through risk transfer mechanisms including financial insurance/re-insurance markets and disaster relief funds. Given the size of the community and the available tax base, the working group ranked existing measures as having a low to moderate level of effectiveness in reducing the socio-economic consequences of a disaster event (2.8–3.6).

5.4.3.2 Mitigation Targets and Strategies for Disaster Risk Reduction

After reflecting on the strengths and weaknesses of existing capabilities to mitigate the impacts of natural hazard threats in Squamish, we then asked members of the working group to establish goals and set performance targets for additional measures that would have the potential to reduce underlying vulnerabilities and increase disaster resilience of the community over time. At the time of the workshop, we did not have the capability to run the HAZUS loss estimation model to evaluate the full spectrum of target criteria and indicators in the Pathways framework. As a result, the selection of target criteria was limited to five indicators that address level of protection to residential buildings, essential facilities and critical infrastructure, and that address the safety of vulnerable populations including school-age children and the elderly. Benchmark values that reflect current conditions were assessed for each of the indicators using preliminary damage estimates for flood, debris flow, and earthquake scenarios. For each of the five indicators we asked members of the advisory group to identify a desired level of performance with respect to a specific risk management goal (performance target). The focus for this part of the process was on establishing an overall set of objectives to guide future discussions about potential mitigation strategies.

The level of protection to residential buildings (performance target #1; Figure 5-12) was assessed by the number of buildings for which the extent of physical damage caused by a flood, landslide, or earthquake is likely to exceed 30%. Benchmark values for expected levels of damage to existing structures and those that would be present at a future buildout date of 2038 were assessed at ~46% and 53%, respectively. Performance targets identified by individual members of the working group ranged in value from 25–50% with an average value of ~38%. The target represents an 8% reduction in physical vulnerability, suggesting that additional measures be taken to reduce potential impacts on residential development in the future.

As with residential building stock, the level of protection to essential facilities (performance target #2; Figure 5-12) was assessed by the proportion of structures that are likely to sustain physical damages in excess of 30% as a result of impacts sustained during a flood, landslide and/or earthquake. Essential facilities were defined to include schools, police and fire station facilities and emergency operation centres. The

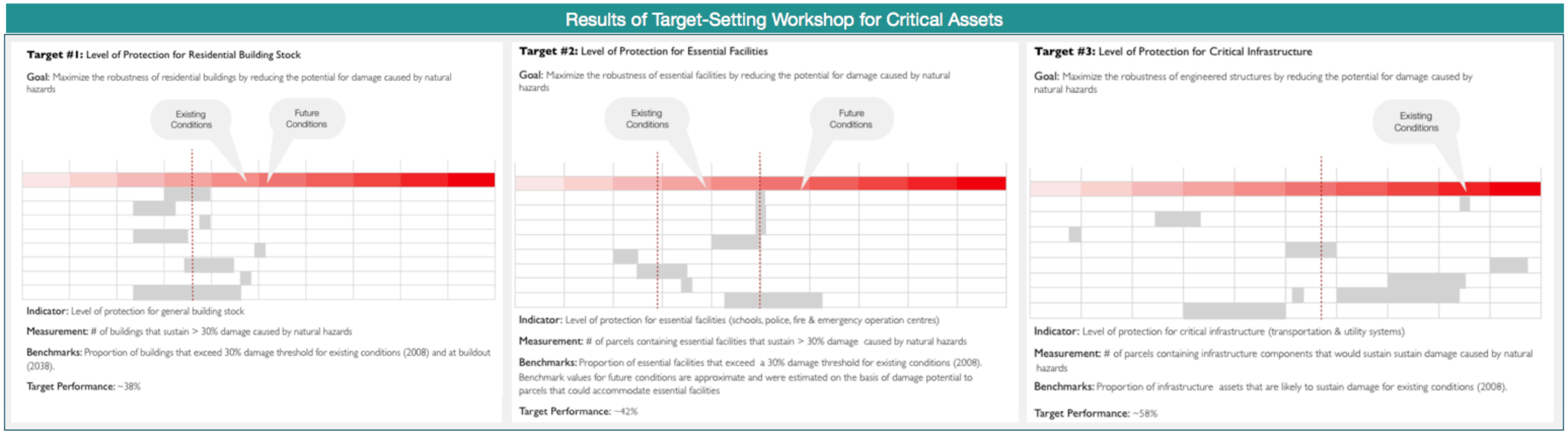


Figure 5-12: Results of target setting workshop. Benchmarks are based on preliminary results of a quantitative risk analysis using analytical methods available at the time of the workshop. The grey bars indicate the range of performance target values suggested by individual working group members, while the average value is shown with a red dotted line,

benchmark value for existing conditions was assessed at ~39%. Benchmark values for future conditions are unknown, but were estimated to be approximately 59% based on the proportion of land that could be developed for civic use. As illustrated in Figure 5-12, performance targets identified by the working group fell into two distinct categories. Values for the first category ranged between ~40-63% with an average of 50%, suggesting no preferred shift in the direction of current trends. Performance values for the second category ranged between 20-36% with an average of 29%, indicating a desire to reduce damage potential from existing conditions by nearly 10%. Unfortunately, we were not able to interpret or reconcile the differences between these two viewpoints.

The level of protection for critical infrastructure (performance target #3; Figure 5-12) was assessed by the proportion of facilities that are likely to sustain physical damages as a result of impacts sustained during a flood, landslide, or earthquake. Critical infrastructure was defined to include major transportation and utility systems. The benchmark value for existing conditions was assessed at ~85%, but did not specify a minimum threshold for damage. Benchmark values for future conditions could not be assessed with available information. As a result, there was little guidance to working group members in terms of what to expect for current trends. Not surprisingly, performance targets were quite variable, ranging from a minimum value of 8% to a maximum value of 97%. On average, the group recommended that damage potential be reduced through mitigation by 39% from existing conditions.

The last two performance targets address levels of safety for what many considered to be the most vulnerable populations in the community—children attending school during the day, and elders in senior care homes and assisted living facilities. The safety of children in public schools (performance target #4) was assessed by the proportion of school facilities that were likely to sustain >30% of physical damage from the impacts of natural hazards. The benchmark value for existing conditions was assessed at ~27%. Performance targets identified by the working group ranged in value from 16–51% with an average of 30.8%, very near that of existing conditions. The safety of community elders (performance target #5) was assessed by the proportion of senior care facilities that were likely to sustain >30% of physical damage from the impacts of natural hazards. The benchmark value for existing conditions was assessed at ~86%. Although performance targets of the working group ranged in value from 29–91%, the average of 72.9% clearly indicated a desired reduction in damage potential from existing conditions and anticipated future trends.

After reflecting on results of the target setting exercise, the working group identified a number of strategies that could be pursued to reduce risk and promote disaster resilience of the community. These strategies included maintaining and/or increasing levels of protection for flood and debris flow hazards by upgrading dyke and flood control measures and constructing deflection berms on the Cheekye Fan; increasing levels of public safety through education and enhanced emergency preparedness measures; increasing socio-economic security through land use planning and risk avoidance; ensuring that mitigation measures address the needs of the most vulnerable and socially disadvantaged members of the community. Recommendations of the working group were used to inform the development of disaster mitigation scenarios (see Section 5.6), and the selection of a much broader set of indicators with which to assess levels of safety and thresholds of tolerable risk for the community (see Section 5.5).

5.5 Results of Quantitative Risk Analysis for Squamish

A quantitative analysis of flood, debris flow, and earthquake risks was undertaken to analyze the impacts and likely consequences for a

	Hazard Scenario	Source of Hazard Assessment Information	Hazard Assessment Methodology	Recurrence Interval (years)	Annual Probability P_A
Debris Flow Events					
1	3 Mm³ debris flow- unmitigated	KWL (2003); Jacob & Friele (2009)	FLO-2D	10,000	0.000100
2	5 Mm³ debris flow- unmitigated	KWL (2003); Jacob & Friele (2009)	FLO-2D	10,000	0.000100
Flood Events					
3	1/20 year riparian flood	This Study	HAZUS-FIT	20	0.050000
4	1/100 year riparian flood	This Study	HAZUS-FIT	100	0.010000
5	1/200 year riparian flood	This Study	HAZUS-FIT	200	0.005000
Earthquake Events					
6	~1/500 year M7.3 'design' event	Halchuk & Adams (2008)	GSCFRISK	476.2	0.002100
7	1/1000 year M7.3 'design' event	Halchuk & Adams (2008)	GSCFRISK	1000	0.001000
8	~1/2500 year M7.3 'design' event	Halchuk & Adams (2008)	GSCFRISK	2,475.2	0.000404

Table 5-4: A summary of information about hazard event scenarios used for quantitative risk assessment in the Squamish study area.

portfolio of credible hazard threats in the study area. The analysis builds on the results of previous studies commissioned by the District of Squamish and the Province of British Columbia to assess frequency-magnitude relationships for floods and debris flows in settled areas of the valley (Thurber Engineering & Golder Associates, 1993; Klohn Leonoff LTD & Graham Farstad, 1994; Kerr Wood Leidal, 2003), and regional seismic hazard assessment studies of ground shaking potential undertaken by the Geological Survey of Canada to support revisions to seismic engineering guidelines for the National Building Code for Canada (Adams and Atkinson, 2003; Adams and Halchuk, 2003; Halchuk and Adams, 2008). On the basis of this work, a portfolio of eight hazard event scenarios was selected for quantitative risk analysis (see Table 5-4).

In addition to compiling available information on natural hazard potential, this study has also contributed to the understanding of landslide, flood, and earthquake hazards by conducting a series of directed scientific studies. The scope these studies included an assessment of landslide probability for a variety of slope failure hazards in the region, recalibration of existing flood hazard assessments to reflect higher-resolution ground surface elevation models (Lidar and bathymetric survey data), hydrologic analysis of riparian flood hazards for 1/20, 1/100 and 1/100-year events using HEC-RAS modelling capabilities of HAZUS, and a seismic microzonation study using a combination of subsurface geology and available geophysical information to characterize the potential for site amplification, liquefaction, and earthquake-triggered landslides. All of this work was undertaken in an effort to reduce scientific uncertainties in the assessment of hazard potential, and to increase reliability of the risk assessment.

With this as a foundation, FEMA's Comprehensive Data Management System (CDMS) was used to compile an asset inventory describing the location, physical characteristics and exposure of buildings, essential facilities, critical infrastructure (transportation, utility, and communication systems), and vulnerable populations in the community. Characteristics of the built environment were compiled at the parcel level using data obtained from provincial assessment and municipal planning authorities. Information on vulnerable populations was compiled at the neighbourhood scale (census dissemination areas) using community profile data obtained from Statistics Canada (Statistics Canada, 2003c)

An important contribution of this study has been quantitative risk modelling of expected damages and anticipated losses for each of the hazard event scenarios listed in Table 5-4. Analytical results discussed in the following sections provided an opportunity to compare expert understanding and objective measurement of cause-effect relationships with local knowledge and perceptions of risk in the community. The study incorporated an all-hazards approach and extended the scope of previous risk analyses for the community.

The assessment of damages and socio-economic losses was carried out for existing and future conditions using methods described in Chapter 4 (see Section 4.4.2). The analysis of physical vulnerability for debris flow hazards utilized empirical damage functions derived from case studies in mountainous areas of Italy and Austria (Fuchs *et al.*, 2007; Akbas *et al.*, 2009). Losses were calculated on the basis of replacement costs for buildings and other structures impacted by the debris flow. The analysis of damage probabilities and anticipated socio-economic losses for flood and earthquake hazards was based on an extensive library of fragility curves and standardized loss estimation methods developed as part of the HAZUS model (FEMA, 2004). Results of this multi-hazard risk analysis were used to evaluate dimensions of vulnerability and risk for 14 of the 25 indicators that were used to characterize levels of protection, public safety, socio-economic security, and social equity.

5.5.1 Landslide Risk

The Cheekye Fan is situated almost completely within the municipal boundary of Squamish and is perhaps one of the most extensively studied debris flow deposits in Canada. The extent, frequency, and magnitude of known landslide deposits—and the proximity of these deposits to human settlement and critical infrastructure—have been of concern to municipal and provincial authorities for more than 40 years. Over this time, more than 16 separate studies have been commissioned to understand the underlying geological processes that have triggered major debris flow events in the past, and to refine frequency-magnitude relationships that are needed to assess the risks of landslide events in the future. The evolution of knowledge about hazard potential and associated risks of debris flows on the Cheekye Fan is well documented in a recent paper by Jakob and Friele (2009)

Quantitative risk analysis of debris flow hazards on the Cheekye Fan was initially driven by the need to understand the potential impacts and consequences of a major event on existing and proposed residential development in the communities of Brackendale and North Squamish, and on major transportation and utility infrastructure systems that are built on the Cheekye Fan (Thurber Engineering & Golder Associates, 1993). The probability of death to individuals (PDI) and groups (PDG) was used to establish minimum thresholds of safety for land use, and to inform the design of structural mitigation works to protect existing and future development on the Cheekye Fan. We extended the scope of this earlier risk analysis work by undertaking a preliminary assessment of damage potential and anticipated socio-economic losses for debris flow hazards, and an analysis of how these risks vary as a function of planning horizon.

5.5.1.1 Hazard Assessment

Early assessments of hazard potential for a large-magnitude debris flow event on the Cheekye Fan were based on a series of geotechnical reports by Crippen Engineering LTD (1975; 1981) in which the potential for a large debris flow (~5 Mm3) was identified, but with a relatively low probability of occurrence (1/10,000 years; p = 0.0001). The discovery and subsequent radiocarbon dating of buried debris flow deposits beneath the municipal landfill in 1990 confirmed the potential for a large magnitude event on the fan, and led to the suggestion that the extent of the area impacted could be much larger and potentially more frequent than initially proposed in the Crippen report of 1981. These observations, coupled with development proposals for residential housing and related service infrastructure on the southern portions of the Cheekye Fan, led the BC Ministry of Environment, Lands and Parks to commission follow-up studies to determine thresholds of safety for residential development and other land uses.

On the basis of available frequency-magnitude relationships established for past events, the Thurber-Golder study identified the potential for a large magnitude event (~7 Mm3; 1,700 m^3/s) originating from a breached landslide dam on the Cheekye River with an estimated return period of 10,000 years. Potential run-out zones were modelled for low- and high-magnitude event scenarios (~3 Mm^3 and ~7 Mm^3), for existing conditions and for mitigation scenarios involving the construction of protective berms to deflect debris flow material away from existing and proposed development structures. Results of this work were used to identify areas that exceeded tolerable thresholds of safety for proposed residential development based on annual probability of death to both individuals and groups (PDI > 1/10,000; Thurber Engineering & Golder Associates, 1993). Recommendations of the Thurber-Golder study were subsequently incorporated into District land use and zoning bylaws for the 1996 Official Community Plan (see Figure 5-10) and have served as a point of reference for growth management strategies developed by the municipality as part of their long-range strategic plan for sustainable development (Urbanics Consultants *et al.*, 2005).

Deterministic models of landslide hazard potential were revised by Kerr Wood Leidel in 2003 to account for new scientific information suggesting that magnitude-frequency relationships for debris flow events on the Cheekye Fan may have been previously overestimated (Clague *et al.*, 2003; Kerr Wood Leidal, 2003). Geologic studies indicated that observed debris flow deposits on the Cheekye Fan were not produced by a single event, but rather by a series of several smaller magnitude events over a period of time. On the basis of this new information, it was suggested that a maximum credible event scenario was more likely to be on the order of ~2.8 to ~5.4 Mm^3 with an estimated return interval of 10,000 years (Friele *et al.*, 1999).

This interpretation has since been corroborated by the geological and geotechnical investigations of Jakob and Friele (2009). Results of these investigations have established detailed frequency-magnitude relationships for two distinct classes of debris flow hazards on the Cheekye Fan (see Figure 5-13). The first is characterized by smaller events (<1 Mm^3) that are likely triggered by severe storms with return periods of ~30 to 125 years. The second is a larger and potentially devastating class of debris flow events (2.8 –5.4 Mm^3) that are thought to be triggered by rock avalanches traveling down from higher elevations of the Cheekye basin with a return period of ~3,000 to 12,000 years (Jakob and Friele, 2009).

The Kerr Wood Leidel study was commissioned to determine landslide hazard potential on the Cheekye Fan and to develop design guidelines for the construction of a series of deflection berms that would mitigate the impacts of a low-probability/high-consequence event. Rheological models were developed for what the BC Ministry of Environment, Land and Parks considered at the time a maximum credible design event (7 Mm^3/15,000 m^3/s), and for what is now considered by the geotechnical community to be a more likely range of event magnitudes and probabilities (2.8 and 5.4 Mm^3/9600–15,000 m^3/s). Run-out zones for 2.8 Mm^3 and 5.4 Mm^3 event scenarios are shown in Figure 5-15. Both are defined by lobes of debris flow material that extend northwest from the fan apex to the Cheakamus River, and southwest toward the community of Brackendale.

Run-out models for the smaller of the two event scenarios suggest that northwest portions of the Cheekye Fan would be inundated with 0.3–6 m of debris flow material traveling at velocities of 2–6 m/sec. Areas impacted include road and railway sections along the Cheakamus and Cheekye rivers, bridge facilities, and residential neighbourhoods in the Waiwakum Indian Reserve (IR 14). The amount of debris material flowing into the Cheakamus valley would likely result in damming of the river for a period of hours or days, causing significant dam outburst flood hazards downstream along the Cheakamus and Squamish Rivers. The southern lobe of the debris flow extends 2.5–3.0 km southwest from the Cheekye River bridge along Highway 99 to Brackendale, encompassing residential lands at the north end of the community, forested lands of the Eagle Reserve, and power transmission lines leading to the BC Hydro substation. Hazard intensities range from minimum values of 0.3 m and 2 m/sec along distal parts of the fan to a maximum of ~6 m and 6 m/sec near the fan apex.

Run-out models for the 5.4 Mm^3 event indicate similar hazard characteristics for the northern lobe, but suggest that a much higher proportion of debris flow material would likely be directed southward along Highway 99 and across the BC Rail line in northern Brackendale. Areas of particular concern include existing and proposed residential development in the northern portion of the community that could potentially receive up to 4 m of debris material traveling at a velocity of up to 4 m/sec. More distal portions of the fan, encompassing the Brackendale Elementary School, would likely be inundated with 0.3–2 m of muddy water.

5.5.1.2 Physical Vulnerability

Physical impacts and damage potential associated with debris flow hazards on the Cheekye Fan were estimated using vulnerability functions derived from field investigations of recent landslide events in mountain villages of Austria and Italy. These studies have led to the development of a preliminary set of empirical functions that relate the intensity of debris flows (depth) to expected levels of physical damage (Fuchs *et al.*, 2007;

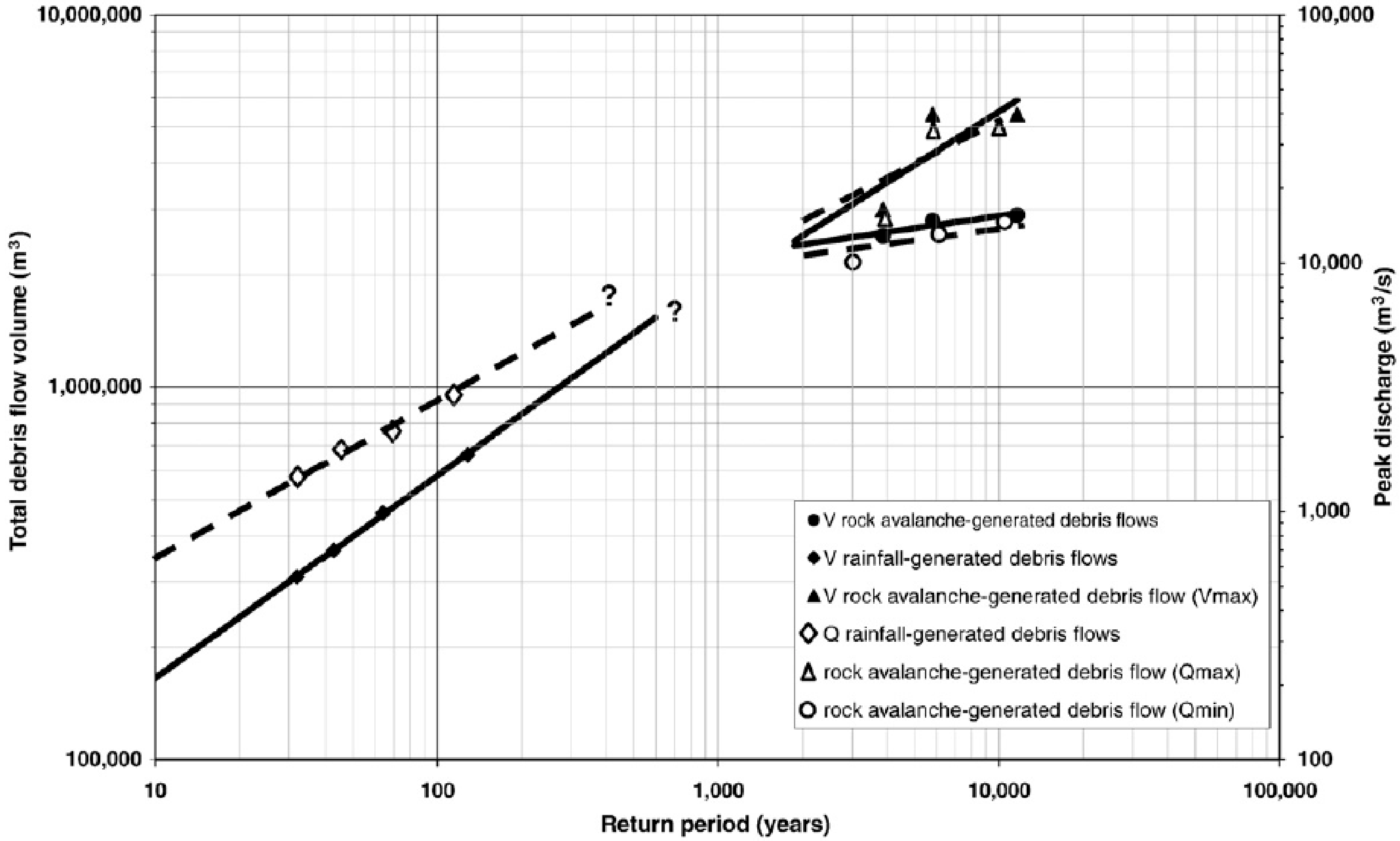


Figure 5-13: Frequency-magnitude relationships for rain-generated events that occur regularly on a scale of hundreds of years, and rare but potentially devastating events that are known to have occurred in the last 10,000 years on the Cheekye Fan that have the potential to occur again in the future. Figure taken from Jakob and Friele (2009)

Akbas *et al.*, 2009). Although based on a relatively small sample of forensic data for residential buildings, both studies demonstrate a non-linear relationship between hazard intensity and damage potential (K_{DF}) that can be expressed as a second-order polynomial function in which the variable (h) is the estimated depth of debris flow material (see Figure 5-14).

The correlation between observed and expected damage states is reasonably well established for debris flow depths of up to 2.5 m (R^2 is between 0.86 and 0.995). For debris flow depths of greater than 2.5 m, the damage state for building structures is assumed to be equal to 1.0,

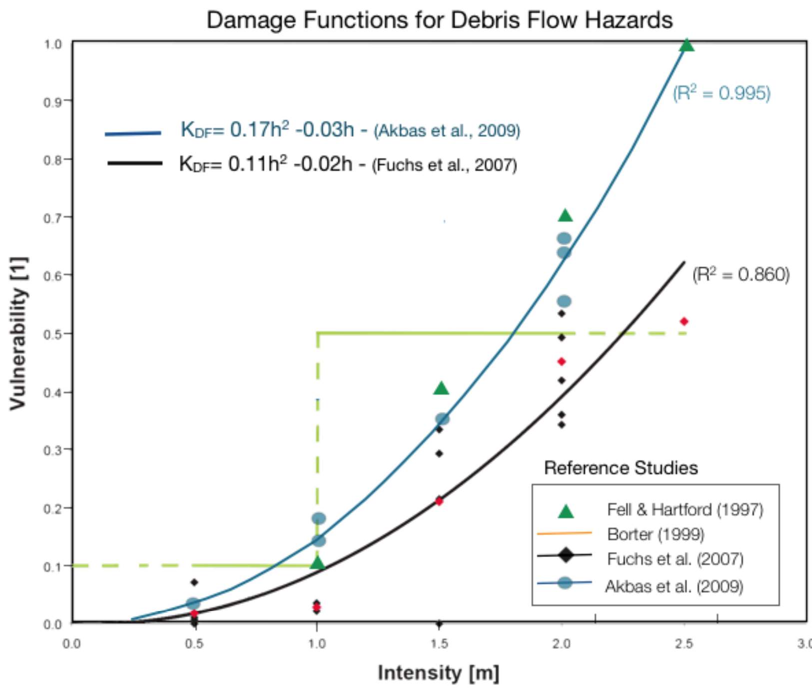


Figure 5-14: Observed and modelled relationships between debris flow intensity (depth) and physical vulnerability (damage potential) based on empirical studies by Fuchs et al. (2007; in black) and Akbas (2009; in blue). Figure is adapted from Fuchs et al. (2007), and includes results of previous reference studies.

meaning that the structure is almost certain to be destroyed by the force of the debris flow (K_{DF} = 1.0). As illustrated in Figure 5-14, estimates of damage state using the vulnerability function developed by Akbas *et al.* (2009) are ~5% higher than those obtained in the Fuchs *et al.* study (2007). The differences are small and likely reflect physical variability in debris flow characteristics, variations in the type of building construction between the two sites, or analytical uncertainties associated with a relatively small sample of empirical observations (Akbas et al., 2009).

Damage potential for residential and non-residential buildings on the Cheekye Fan was assessed using values of maximum depth derived from numerical modelling of 3 Mm^3 and 5.4 Mm^3 debris flow events (Kerr Wood Leidal, 2003), and vulnerability functions developed by Fuchs *et al.* (2007) and Akbas *et al.* (2009) that relate hazard intensity to expected levels of physical vulnerability. Both methods of vulnerability assessment yield similar results for general building stock and are consistent with qualitative estimates of damage potential used in the original Thurber-Golder study (1993). Although empirical damage functions are not yet developed for critical infrastructure, the Thurber-Golder study does provide general guidelines for assessing damage state. In accordance with these guidelines, we have assumed that critical infrastructure would be completely destroyed if exposed to debris flow depth in excess of 4 m.

Results of our damage assessment for the 2.8 Mm^3 debris flow event are summarized in Figure 5-15. Of the 35 buildings exposed to debris flow hazards, it is estimated that 10 structures would sustain moderate damage and the remaining 25 would be substantially damaged or destroyed. Nearly all of the exposed structures are located on the north flank of the Cheekye Fan with the majority being residential buildings (22) and the remainder comprising a mix of industrial and commercial buildings (13). Approximately 2.7 km of Highway 99 and an additional ~25 km of secondary roads would be engulfed by debris flow deposits in excess of 4 m. Major highway and railway bridges on the north flank of the fan would likely be destroyed, as would a ~1 km section of the BC Rail line that runs along the Cheakamus River.

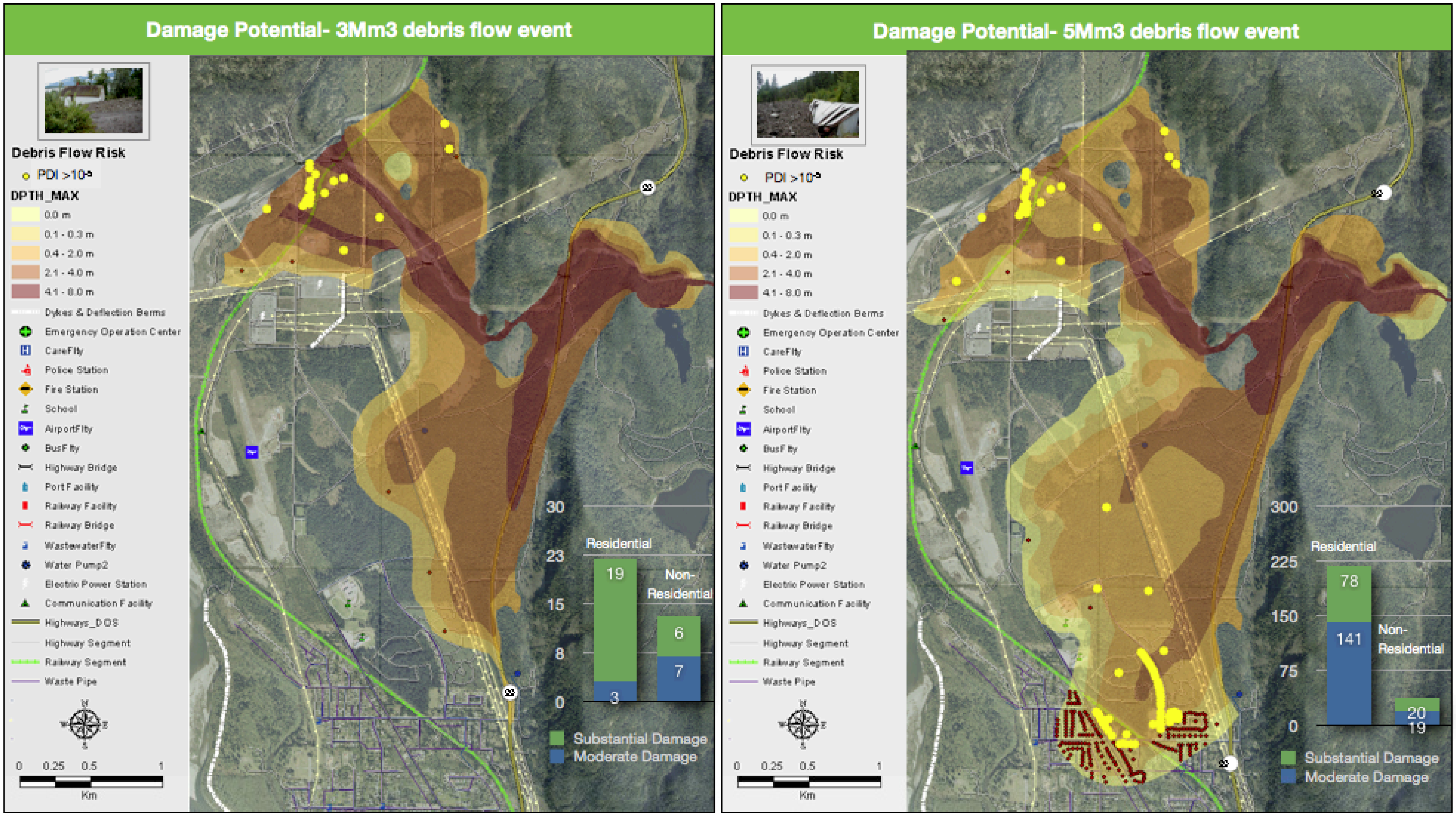


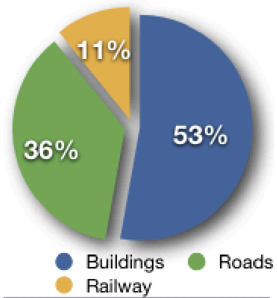
Figure 5-15: Damage potential for modelled 2.8 Mm^3 and 5.4 Mm^3 debris flow events on the Cheekye Fan. The extent and magnitude of the debris flow hazard (depth and flow velocity) is based on model results of Ker -Wood Leidal (2003), while estimates of damage potential are derived from vulnerability relationships of Fuchs et al. (2007) and Akbas et al. (2009).

As expected, the 5.4 Mm^3 debris flow event results in a significantly higher level of physical damage to residential neighbourhoods in Brackendale and North Squamish (see Figure 5-15). Of the ~258 residential and non-residential buildings impacted by the debris flow, 160 would sustain damages of up to 40%, and 98 would be completely destroyed. Residential buildings make up the majority of damaged structures (85%) with the remainder comprising a mix of industrial, commercial, and institutional buildings. The level of damage to Highway 99 and major bridges is similar to that for the 3 Mm^3 debris flow event. However, an additional 10 km of secondary roads and ~1.7 km of BC Rail lines would sustain significant damage in the 5.4 Mm^3 event. The BC Hydro substation and related power generation facilities are currently protected by a deflection berm on the lower Cheekye Fan and would not likely sustain significant damage. While methods for assessing the

Damage & Losses for 3Mm³ Debris Flow

Buildings & Essential Facilities	Physical Vulnerability (# of buildings)		Economic Losses (thousands of dollars -CDN)	
	Moderate Damage	Substantial Damage	Building Loss	Total Loss
‣ Residential Buildings	3	19	$5,747	$5,747
‣ Non-Residential Buildings	7	6	$26,941	$26,941
Totals:	**10**	**25**	**$32,688**	**$32,688**

Critical Infrastructure	Physical Vulnerability	Economic Losses
	# of Facilities	Total Loss
‣ Highway 99	2.7 km	$4,314
‣ Secondary Roads	21 km	$11,185
‣ Highway Bridges	3	$7,000
‣ Railway Segments	1.1	$1,688
‣ Railway Bridges	1	$5,000
Totals:	**5**	**$29,188**

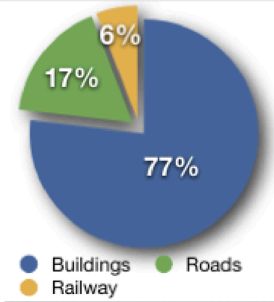


Societal Impacts	Physical Vulnerability
	# of features exceeding threshold
‣ PDI > 10^{-4}	2
‣ PDI > 10-5	25
‣ Fatalities (PDG; F-N)	29
‣ Fatalities (PLL)	24

Damage & Losses for 5Mm³ Debris Flow

Buildings & Essential Facilities	Physical Vulnerability (# of buildings)		Economic Losses (thousands of dollars -CDN)	
	Moderate Damage	Substantial Damage	Building Loss	Total Loss
‣ Residential Buildings	141	78	$17,988	$17,988
‣ Non-Residential Buildings	19	20	$105,029	$105,029
Totals:	**160**	**98**	**$17,988**	**$123,017**

Critical Infrastructure	Physical Vulnerability	Economic Losses
	# of Facilities	Total Loss
‣ Highway 99	2.7 km	$4,314
‣ Secondary Roads	31 km	$16,512
‣ Highway Bridges	3	$7,000
‣ Railway Segments	2.8	$4,275
‣ Railway Bridges	1	$5,000
Totals:	**7**	**$37,101**



Societal Impacts	Physical Vulnerability
	# of features exceeding threshold
‣ PDI > 10^{-4}	32
‣ PDI > 10-5	106
‣ Fatalities (PDG; F-N)	137
‣ Fatalities (PLL)	122

Table 5-5: Anticipated socio-economic losses and societal risks associated with impacts of 2.8 Mm³ and 5.4 Mm³ debris flow events on the Cheekye Fan. Estimates are based on hazard assessment models of Kerr Wood Leidal (2003) and best practice methods of assessing risks to community assets (Ayuub et al., 2007) and vulnerable populations (Porter, 2006b)

physical impacts of debris flow hazards are evolving, they have not yet matured to the level of those established for floods and earthquakes. For this reason, we consider the damage assessment presented in this study to be preliminary and subject to revision as the state of knowledge is refined over time.

5.5.1.3 Anticipated Losses

The assessment of socio-economic loss provides a measure of anticipated financial consequences if a landslide event were to occur (P_{AA}=1). Loss estimation is not equivalent to an assessment of hazard risk, which takes into account the probability of the hazard event occurring over planning horizons of interest. Nonetheless, it is useful in gauging the severity of a hazard event in terms of potential financial impacts and for comparing the patterns of loss between different hazard scenarios.

Direct capital losses associated with impacts of debris flow hazards on the Cheekye Fan were estimated on the basis of damage potential and replacement costs for individual buildings exposed to debris flows of up to ~2.5 m (structures, contents, inventory), and full replacement value of buildings and critical infrastructure components that are likely to be destroyed by the impacts of debris flows that exceed 2.5m and 4m. Not included in our assessment of landslide risk for the Cheekye Fan area were additional direct economic losses associated with business interruption (income, costs of relocation), indirect economic losses associated with financial disruption to local and regional economies, and the psycho-social impacts of the event itself on those directly affected and on the broader community. The indirect losses are likely to be equivalent or greater in magnitude than those sustained by the event itself. Results of our analysis are summarized below for both 2.8 Mm^3 and 5.4Mm^3 debris flow events (see Table 5-5).

Socio-economic losses associated with the 2.8 Mm^3 debris flow event are estimated to be ~$61.9 million with replacement costs of buildings and contents accounting for 53% of the total loss. Replacement costs for transportation infrastructure are estimated to be $29.2 million, with the majority of losses related to impacts to major bridges on the Cheekye and Cheakamus rivers and secondary road systems.

Direct capital losses associated with the 5.4 Mm^3 debris flow event are estimated to be $164.7 million with replacement costs of buildings and contents accounting for ~77% of the total loss. Replacement costs for critical infrastructure are estimated to be $37.1 million. Although anticipated losses to Highway 99 and major bridges are comparable between the two hazard event scenarios (~$16.3 million), replacement costs for BC Rail lines and secondary road segments are incrementally higher ($4.3 and $16.5 million, respectively) for the larger 5.4 Mm^3 event.

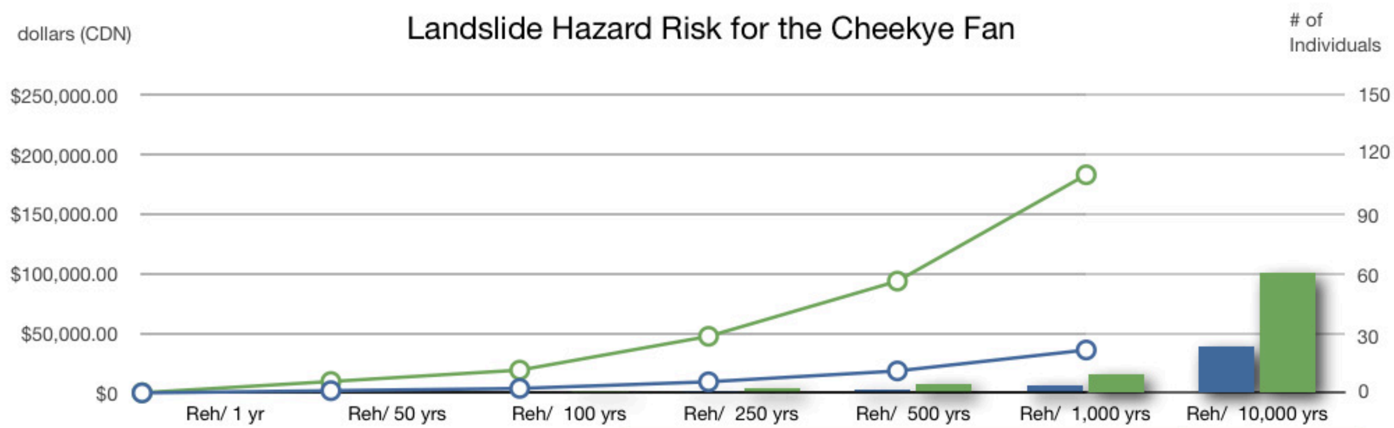
5.5.1.4 Hazard risk

Landslide risk is a measure of the probable consequences resulting from the impacts of a specific hazard event, measured in terms of economic loss or potential for loss of life (ISDR, 2002; ISO 31000, 2008b). Our analysis of landslide hazard risk for debris flow hazards in the Cheekye Fan is consistent with professional guidelines established by the Association of Professional Engineers and Geoscientists of British Columbia (APEGBC, 2010), and best practice methods for quantitative risk analysis developed by the Australian Geomechanics Society (AGS, 2000). The scope of analysis includes an assessment of probable economic loss based on general risk assessment methods described in Section 4.3.5.3 (Ayyub *et al.*, 2007; McGill *et al.*, 2007), and an assessment of the probability of death to individuals (PDI) and to groups (PDG) using AGS guidelines and methods developed by Porter (2006) for analyzing societal risk in the context of residential development.

Results of our analysis of landslide hazard risk for the Cheekye Fan are summarized in Table 5-6. The trends are characteristic of low-probability/high-consequence hazard event scenarios in which probable losses and the differences between losses associated with events of different intensities are relatively small for short time horizons of 1-500 years and increase exponentially for long time horizons of 500-10,000 years. Our estimates of financial risk reflect existing conditions of structural mitigation and do not take into account any additional capabilities for loss reduction. The analysis of societal risk incorporates a loss reduction rate of ~20%, which reflects an average capability for emergency response and recovery given an advanced forecast warning time of up to 12 hours for channelled flood and debris flood hazards (USACE, 1984; Scawthorn *et al.*, 2006c)

Probable economic loss is a method of determining the overall financial risk profile for a portfolio of hazard threats that vary in terms of their likelihood of occurrence and their potential for negative consequence. As illustrated in Table 5-6, the profile of financial risk associated with debris flow hazards on the Cheekye Fan is similar for 2.8Mm^3 and 5.4Mm^3 debris flow events over relatively short time horizons of 1-500 years. Values of average annual loss range from a minimum of $6,200 over a time horizon of 1 year to a maximum of ~$7.8 million over a time horizon of 500 years. The overall trend and differences between losses for 2.8 Mm^3 and 5.4 Mm^3 events increase for longer time horizons, ranging from a minimum value of $7.8 million for time horizons of 500 years to a maximum of ~$100 million for time horizons of 10,000 years.

Our analysis of risk to life conforms to established best practice guidelines that suggest a tolerable threshold of 1/10,000 (10^{-4}) for the probability of death to individuals most at risk to the impacts of landslide hazards in existing structures, and a threshold of 1/100,000 ($10^{-5)}$ for individuals in new developments (AGS, 2000; APEGBC, 2010). As illustrated in Figure 5-15, it is estimated that ~25 buildings on the north flank of the Cheekye Fan would exceed minimum thresholds of tolerability for probability of death to individuals most at risk to the impacts of a 2.8 Mm^3 debris flow event. Based on methods described by Porter (2006), the estimated number of fatalities where the



$$\text{Hazard Risk } (R_{\epsilon,h}) = \sum\left[\left(L_{md}V_{\epsilon,h}\right)P_{AAh} \times \left(1 - R_{em}\right)\right],$$

Model Variables	Value
L_{mci}: Replacement costs for buildings, contents, inventory and CI	See Table 5-5 & 5-6
$V_{e,h}$: Physical vulnerability, measured as a function of hazard intensity	See Table 5-5 & 5-6
R_{em}: % losses avoided through emergency management measures	10.00%

Probable Maximum Loss (PML)								
Hazard Event (of specified intensity)	Capital Loss $P_{AA}=1$	R_{eh}/ 1 yr	R_{eh}/ 50 yrs	R_{eh}/ 100 yrs	R_{eh}/ 250 yrs	R_{eh}/ 500 yrs	R_{eh}/ 1,000 yrs	R_{eh}/ 10,000 yrs
2.8 Mm3 debris flow	$61,876.09	$6.19	$308.62	$615.71	$1,527.80	$3,017.88	$5,888.56	$39,114.26
5.4 Mm3 debris flow	$160,118.23	$16.01	$798.63	$1,593.28	$3,953.52	$7,809.43	$15,237.97	$101,216.91
Probable Loss of Life (PLL)								
Hazard Event (of specified intensity)	Loss of Life $P_{AA}=1000$	R_{eh}/ 1 yr	R_{eh}/ 50 yrs	R_{eh}/ 100 yrs	R_{eh}/ 250 yrs	R_{eh}/ 500 yrs	R_{eh}/ 1,000 yrs	R_{eh}/ 10,000 yrs
2.8 Mm3 debris flow	24.00	0.02	1.13	2.26	5.60	11.07	21.60	-
5.4 Mm3 debris flow	122.00	0.12	5.75	11.48	28.49	56.27	109.80	-

Average Annual Probability (P_{AA})									
Hazard Event (of specified intensity)	$P_{CE\,h}$	T_R	P_{AA}/ 1 yr	P_{AA}/ 50 yrs	P_{AA}/100 yrs	P_{AA}/ 250 yrs	P_{AA}/ 500 yrs	P_{AA}/ 1,000 yrs	P_{AA}/ 10,000 yrs
2.8 Mm3 debris flow	.999999	10000	0.00010	0.00499	0.00995	0.02469	0.04877	0.09517	0.63214
5.4 Mm3 debris flow	.999999	10000	0.00010	0.00499	0.00995	0.02469	0.04877	0.09517	0.63214

$$\text{Average Annual Probability } (P_{AAh}) = 1 - \text{power}\left(\frac{P_{CEh}}{T_R}\right)^{PH}$$

Capital Losses (3Mm3) Capital Losses (5Mm3)
Loss of Life (3Mm3) Loss of Life (5Mm3)

Table 5-6: Hazard risk for 2.8 Mm³ and 5.4 Mm³ debris flow events on the Cheekye Fan evaluated using methods described in Section 4.4.3 of this study (Ayyub et al., 2007; McGill et al., 2007). Estimates of financial risk are based on probable economic loss for time horizons that range from 1-10,000 years, and are measured in thousands of dollars (see bar graph). Estimates of societal risk are based on probable loss of life values (PLL) for time horizons that range from 1-1,000 years, and are measured in numbers of individuals (see line graph).

cumulative frequency exceeds 1/1000 (10^{-3}) is ~29. The estimated number of fatalities based on an assessment of probability for loss of life (PLL) is ~24.

Risk to life for the 5.4 Mm^3 debris flow scenario is nearly four times larger than that associated with the 2.8 Mm^3 event, even though the likelihood of occurrence is considerably less. Of the ~258 structures impacted by the debris flow, it is estimated that ~32 would exceed the PDI tolerability threshold of 1/10,000 (10^{-4}) and 106 would exceed the minimum tolerability threshold of 1/100,000 (10^{-5}). As illustrated in Figure 5-15, the majority of these structures are located in residential neighbourhoods in northern Brackendale and along the north flank of the Cheekye Fan. The estimated number of fatalities where the cumulative frequency exceeds 1/1000 (10^{-3}) is ~137. The estimated number of fatalities based on an assessment of probability for loss of life (PLL) is ~122.

Risk to life is considered unacceptable if the number of expected number of fatalities for a group of individuals exceeds 1 for cumulative frequencies of 1,000 years or less (AGS, 2000; APEGBC, 2010). These thresholds are consistent with those established in 2009 by the District of North Vancouver to manage risks associated with debris flows hazards in an urban residential setting (Porter, 2006; Porter *et al.*, 2007). As illustrated in Figure 5-15, the expected number of fatalities due to debris flow hazards on the Cheekye Fan exceeds the minimum threshold of risk tolerance for the probability of death for a group (PGD). The probable loss of life for the smaller 2.8 Mm^3 debris flow event is ~1 for a time horizon of 50 years and increases to an estimated value of ~17 over a time horizon of 1,000 years. Probable loss of life for the 5.4 Mm^3 event increases from ~4 over a time horizon of 50 years to an estimated value of ~85 over a time horizon of 1,000 years. These estimates take into account a 10% reduction in loss that is likely to be gained through existing capabilities for response and recovery including pre-event planning and advanced notification of impending danger. See Section 5.6.3 for a discussion of additional risk reduction potential that could be realized through structural mitigation (deflection berms) and debris flow early warning systems.

5.5.2 Flood Risk

The Squamish Valley is situated at the confluence of five major mountain river systems, all of which are capable of generating flood conditions at lower elevations. Carved by glaciers and shaped by weather-driven erosion over tens of thousands of years, the valley is part of an extremely active and dynamic geologic setting. The adjacent Coast Mountains rise to elevations of more than 4000 m and are the first barrier to storm events that sweep in from the Pacific Ocean throughout the year. Melt water from snow pack and receding ice fields in mountain headwater regions combine with atmospheric disturbances and extreme weather events to produce a wide range of flood conditions in the valley. Watershed gradients are relatively high and most of the major rivers transport large volumes of bed load sediment. Deposition of sediment loads over time can result in elevated riverbeds, leading to an increase in water levels and associated flood hazard threat for the same amount of flow. The community is also exposed to flood hazards associated with storm surge and sea-level rise.

The combination of geologic setting, environmental conditions and historical patterns of settlement in fertile agricultural lands along the valley floor have led to significantly high levels of flood risk that have etched their way into the communal consciousness. Many people living in Squamish today have either directly experienced the impacts and consequences of a flood, or live with the memory of previous flood events that have been passed along through stories from generation to generation (see Appendix III for a chronicle of historic flood events). The knowledge of damages and losses caused by previous flood events has led to a number of geotechnical studies that have been commissioned over the years by the Province of British Columbia and the District of Squamish to better understand and characterize the hazard threat, and to develop strategies to mitigate the risk associated with future events. Our work has built on these earlier studies, and focuses primarily on an assessment of physical vulnerability and potential socio-economic losses associated with future flood events in the valley.

5.5.2.1 Hazard Potential

The initial assessment of flood hazard potential for the Squamish Valley was carried out in the 1980s by Environment Canada and the Province of British Columbia to identify and map areas exposed to hazard threats associated with a 1/200-year flood event, and to establish flood construction levels to guide land use planning by the community. In 1994, the municipality commissioned a study by Klohn-Leonoff Ltd. and Graham Farstad Associates Ltd. to refine the existing provincial flood hazard assessment and to develop a flood hazard management plan for the community (Klohn Leonoff LTD & Graham Farstad, 1994).

Background geotechnical studies established new elevation and flood construction level (FCL) baselines for 1/20-year and 1/200-year design flood events. Hydraulic models were developed to account for overtopping and structural failure of existing flood protection works (levees and dykes), and for geomorphologic changes to the valley floor caused by river processes (erosion and deposition) and infilling for industrial development since the initial 1983 flood hazard assessment by the Province (Klohn Leonoff LTD & Graham Farstad, 1994). In 2003, the Province of British Columbia updated their delineation of the 1/200-year floodplain to support implementation of proposed land use and building design guidelines (Province of British Columbia, 2004). Although results of the Klohn-Leonoff-Farstad study have been used to inform the designation of hazardous areas in the Official Community Plan, many of the recommendations put forward in the flood management plan have yet to be fully implemented in terms of strategic planning or development guidelines.

To meet regulatory obligations for safe operation of the Daisy Lake Dam, BC Hydro initiated an independent study in 2008 of hazard potential along the Cheakamus and Squamish river valleys. The study focused on several hypothetical scenarios in which seismically induced failure of the dam facility resulted in a catastrophic outburst flood along lower reaches of the Cheakamus and Squamish river valleys. The study included the development of a high-resolution ground surface elevation model based on GPS and bathymetric survey data, and the generation of several outburst flood scenarios based on 2D numeric models of river dynamics (BC Hydro, 2008; personal communication). Although model outputs for the dam outburst scenarios are proprietary, geodetic data acquired by the BC Hydro study were made available to us to help in establishing a common geodetic baseline for refining existing flood hazard assessments in the Squamish Valley.

In addition to refining existing flood depth grids from the Klohn-Leonoff-Farstad study with higher resolution surface elevation data, we used the HAZUS Flood Information Tool (FIT) to develop a suite of deterministic hazard assessment models for 1/20, 1/100 and 1/200 flood scenarios. FIT is a modified version of the US Army Corps of Engineers 1D HecRas program, which provides a capability to model frequency-magnitude relationships, spatial extent, and the expected height of floodwaters for river and coastal flood scenarios (Scawthorn *et al.*, 2006a; Scawthorn *et al.*, 2006b). River profile and flow velocity data were compiled from the 1994 Klohn-Leonoff-Farstad study and the BC Ministry of Environment to model flood inundation resulting from overtopping and dyke failure scenarios.

Model results for 1/100-year and 1/200-year flood scenarios for the Squamish, Cheakamus and Mamquam river systems are shown in Figure 5-16. All scenarios are based on the assumption that existing flood protection works (dykes & pumping stations) are compromised by overtopping and/or structural failure. We did not have sufficiently detailed information to model flood hazards for the Cheekye or Stawamus rivers, though both have the potential to cause significant inundation. Also not included in our assessment is an analysis of coastal flooding caused by storm surge and/or sea-level rise.

The extent of flooding for the 1/100-year scenario encompasses much of the valley bottom with water depths that range from 0–0.3 m along the edge of the floodplain and high-standing areas in the southern part of the valley to broad areas of 0.3–1.5m in Garibaldi Estates and Downtown Squamish. There are also a number of areas outside the designated 1/200-year floodplain boundary that would likely be susceptible to 1m of flooding. Isolated pockets of deeper flooding (>5 feet) are expected in North Garibaldi Estates and along the confluence between the Squamish and Mamquam rivers. The combination of water depth and flow velocities in these areas is of particular concern to residential neighbourhoods and transportation infrastructure including Highway 99, the BC Rail line, and connecting bridges over the

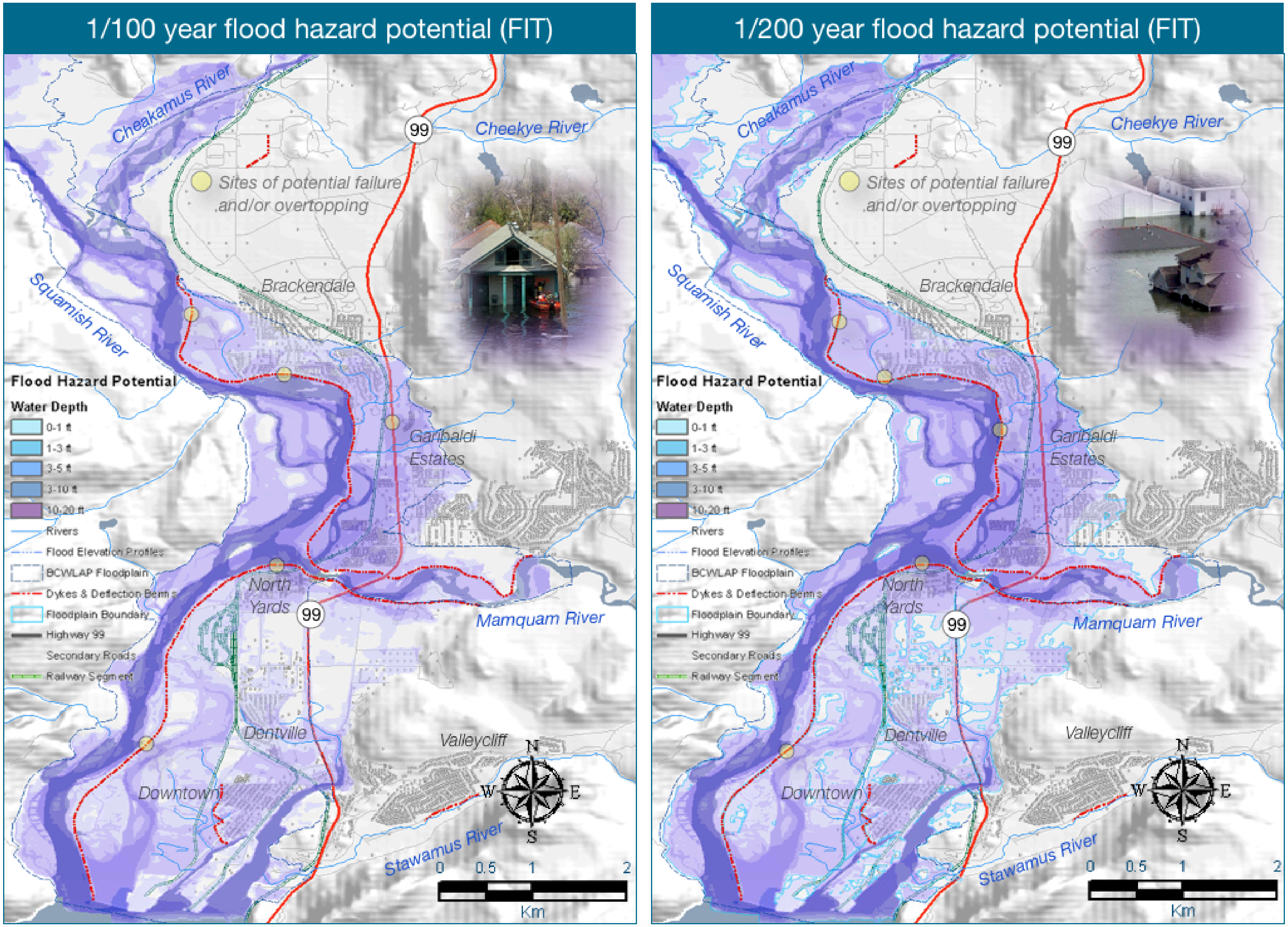


Figure 5-16: Depth grids showing the extent and intensity of hazard potential for 1/100-year and 1/200-year flood scenarios along the lower Squamish, Cheakamus and Mamquam river valleys. The assessment of hazard potential is based on a 1D hydraulic model (FIT) that is included as part of the HAZUS flood module. Data sources include river profile and flow velocity data compiled from the Klohn-Leonoff-Farstad study (1994) and the BC Ministry of Environment, and high-resolution ground surface elevation and bathymetric data provided by BC Hydro (2008). For reference, the 1/200-year floodplain boundary designated by the Province for planning purposes is shown as a blue dashed line.

Mamquam River.

As expected, the 1/200-year scenario encompasses a much broader area and results in deeper flooding throughout the valley. Brackendale is inundated with 0.3-1m of water, as are parts of Downtown Squamish, Dentville, the industrial park, Loggers Lane, and Brennan Park neighbourhoods that extend beyond the limits of the designated 1/200-year floodplain boundary. Areas of particular concern include much of Garibaldi Estates (1-1.5 m), and low-lying areas in North Yards and along the confluence of the Squamish and Mamquam rivers where water depths are 1.5 m or deeper.

Though we cannot independently validate our flood hazard models, the results for 1/100-year and 1/200-year scenarios are consistent with major flood events that are known to have occurred in the period 1908–1958, prior to the construction of modern dykes and flood protection measures in the valley. Seven of these events are reported to have resulted in inundation of ~1-2 m in parts of Downtown Squamish, Dentville, and North Yards, and greater than 2m in low-lying agricultural lands that are now the residential neighbourhoods of Garibaldi Estates and Brackendale.

During the October flood of 2003, floodwaters along the Squamish River came to within 50 cm of overtopping existing dykes and caused significant scouring and piping of dykes at several locations in Brackendale and Garibaldi Estates (see Figure 5-17). In addition to posing an extreme riparian flood hazard threat, the storm also resulted in significant overland flood hazards. Intense rainfall over a relatively short duration resulted in surface run-off that exceeded the capacity of existing storm water drainage systems in several parts of the valley. As a result, surface run-off was trapped behind protective dyke structures leading to significant flooding in low-lying areas.

To assess the flood hazard posed by severe storm events, we examined historical weather data and records of past floods in the Squamish Valley to establish frequency-magnitude relationships and predict the probability and intensity of future events (Chung and Journeay, 2007). As illustrated in Figure 5-18, empirical data on cumulative two-day precipitation associated with storm events since 1959 were correlated

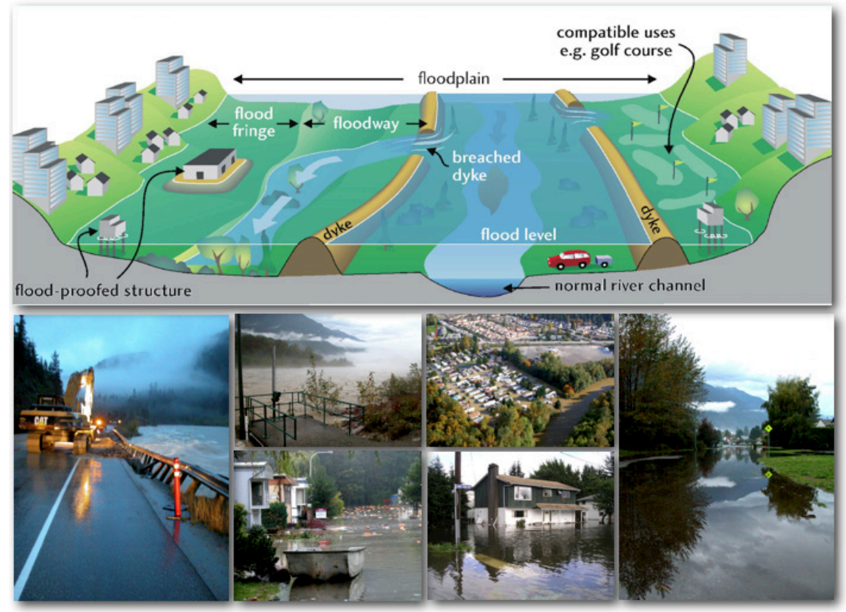


Figure 5-17: Setting and characteristics of the 2003 Squamish Flood

with historic flood occurrences for this same time interval. The observations were then used to compute the probability of past flooding events, and to derive corresponding frequency-magnitude functions that relate measured storm intensity with flood hazard potential. By correlating flood frequency with empirical data on flood intensity, it was then possible to forecast the frequency-magnitude relationships of future flood events caused by extreme weather events of variable intensity.

The prediction models suggest that extreme storm events resulting in ~180 mm of rain over a two-day period would be capable of generating hazard potential equivalent to a 1/20-year river flood event. Storm events resulting in ~220mm of rain over a two-day period would be capable of generating flood hazard potential equivalent to a 1/200-year river flood event. Without detailed forensic data on the depths of previous storm water floods, there is no way to independently validate model results in terms of areas that might be inundated or the anticipated depths of flooding for any given storm event. Water depths

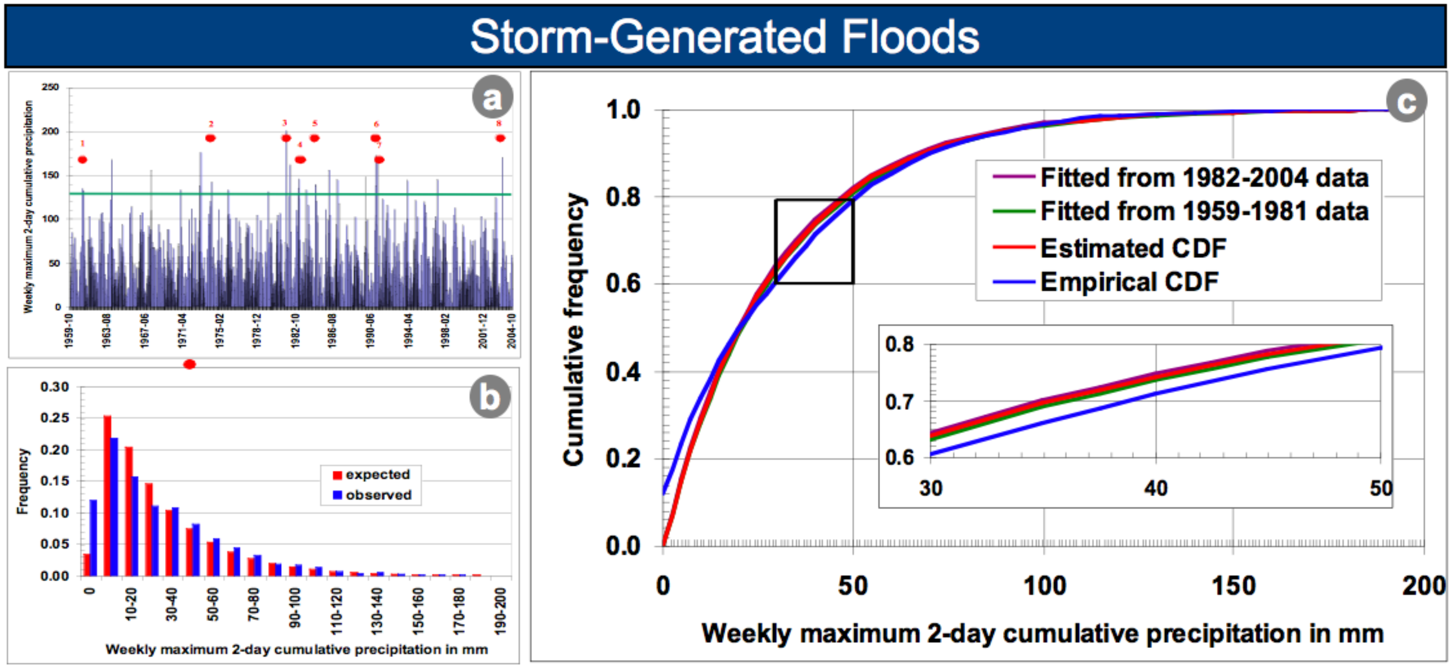


Figure 5-18: a) Empirical frequency distribution of weekly maximum 2-day precipitation values derived from historical climate records, and b) derived empirical cumulative distribution functions developed to model magnitude-frequency relationships for a given area.

observed during the October flood of 2003 provide an important baseline, and underscore the need to maintain more detailed records of inundation levels to help calibrate prediction models for future flood events.

5.5.2.2 Physical Vulnerability

Vulnerability assessment capabilities of the HAZUS flood model were based on an extensive library of more than 900 depth-damage functions that have been developed, calibrated and validated over the years for key elements of the built environment (Scawthorn *et al.*, 2006c). Vulnerability functions for general building stock, essential facilities, and utility systems were derived from forensic studies carried out by the US Federal Insurance Administration and the US Army Corps of Engineers on well-documented flood events throughout the lower 48 states. Key model inputs include the occupancy classification and first floor height of structures, the depth of flooding at a specific location, and a weighted average depth for the area in which a group of structures are located. The occupancy classification was used to select an appropriate vulnerability function from the HAZUS library, while ground floor elevation and flood depth data were used to estimate expected levels of inundation. Estimated depths of flooding were then matched with appropriate vulnerability functions to estimate damage potential as a percentage of replacement cost for a given building or aggregate group of buildings. The HAZUS flood model is optimized for the assessment of aggregate buildings, but also provides a capability to assess damages to individual structures such as schools, health care facilities, emergency operation centres, and other assets that are considered essential during response operations and subsequent phases of recovery. To provide a sufficient level of detail for our analysis, we assessed flood damages at the parcel level. Results of our analyses for 1/00-year and 1/200-year flood scenarios are summarized in Figure 5-19.

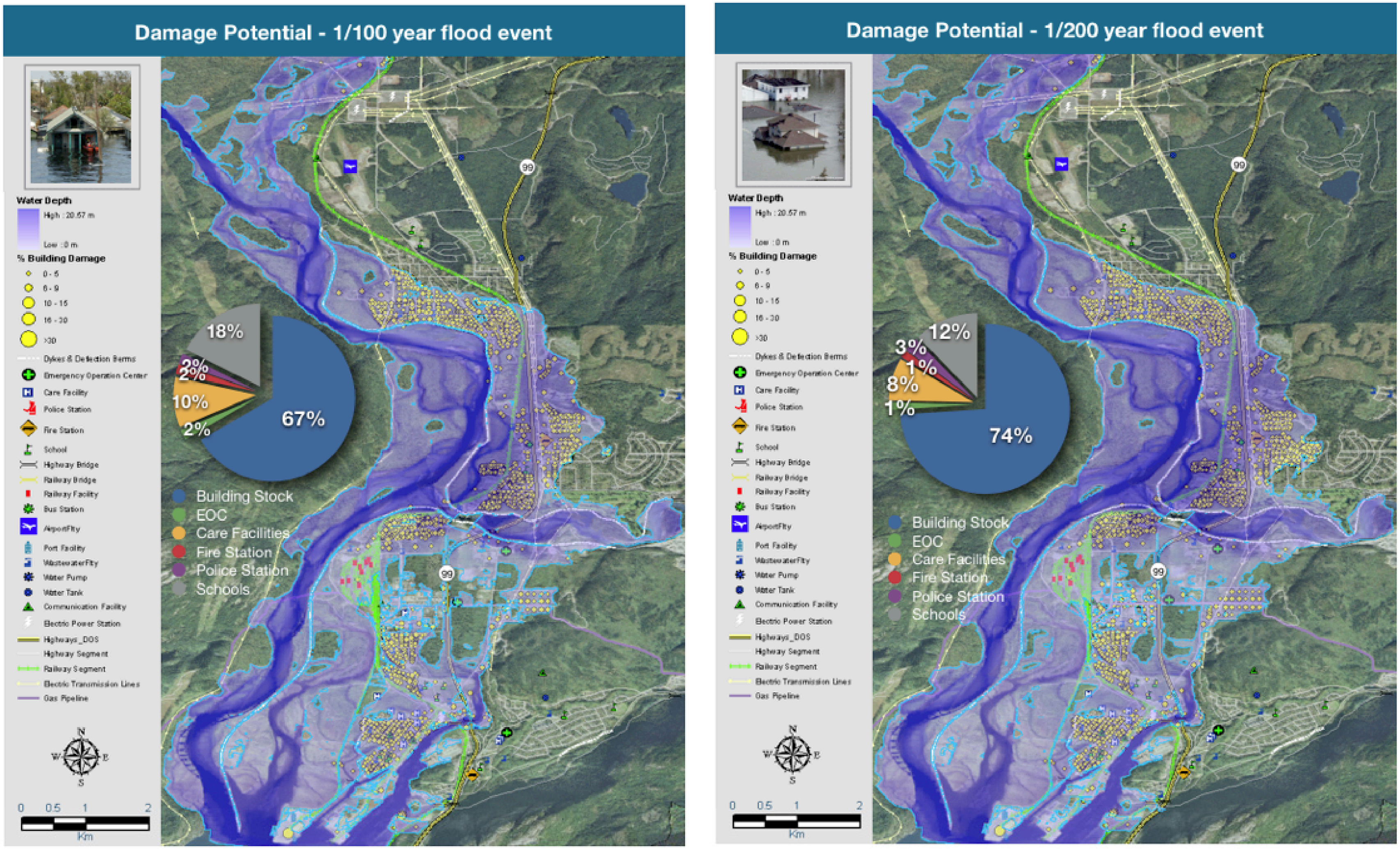


Figure 5-19: Damage potential for a 1/100-year and 1/200-year riparian flood scenarios for the Squamish Valley. Estimates were generated using HAZUS and are based on depth grids generated as part of the hazard assessment process (see Figure 5-16) and details of building occupancy and base floor elevations derived from high-resolution surface elevation models.

For the 1/100-year scenario, it was estimated that nearly half of the existing building stock in Squamish (~2,480 structures) would be exposed to potential flood damage. Approximately 770 of the flooded buildings would be exposed to water depths of less than 0.3m, while an additional 1,280 would be exposed to water depths of between 0.3-1m feet with a potential for minor damage (~10%). The remaining 423 buildings would be inundated by floodwater in excess of 1m deep with ~50 of these structures likely to sustain moderate levels of damage (30–50%) and an additional 8 structures likely to sustain substantial levels of damage (50%) that would not be repairable. In the 1/200-year flood scenario, approximately 2,750 buildings would be inundated with higher levels of overall damage. A smaller number of buildings (~600 structures) would be exposed to water depths of less than 0.3m, while more than ~1,400 buildings would be exposed to water depths of between 0.3-1m with a potential for minor damage (~10%). The remaining ~725 buildings would be inundated by floodwater in excess of 1m deep with ~73 of these structures likely to sustain moderate levels of damage (30–50%) and an additional 14 structures likely to sustain substantial levels of damage (50%) that would require replacement.

In addition to assessing direct physical damage, HAZUS provides a capability to estimate indirect impacts of flooding, including shelter requirements and the amount of debris that will need to be removed during response and recovery phases of the disaster event. Shelter requirements are assessed on the basis of the number of households that are likely to be displaced in areas of flood inundation and the corresponding number of individuals who are likely to seek emergency assistance. Demographic characteristics that influence the calculation of shelter requirements include income level, age and family structure. For the 1/100-year flood scenario, the HAZUS flood model estimated that 3,167 households would be displaced with ~3,750 individuals seeking emergency shelter. The numbers are proportionally higher for the 1/200-year flood scenario with an estimated 3,455 displaced households and 4,113 individuals in need of short-term shelter.

The assessment of disaster debris is based on a component analysis of damage state, occupancy type, and floor area. Debris that is generated as a result of flooding typically includes a mix of building contents (furniture, appliances, and personal belongings) and finishing materials such as carpeting, flooring, and drywall. The HAZUS flood model estimated that ~3,000 tons of debris material would be generated for the 1/100-year flood scenario and ~4,225 tons of material for the 1/200-year flood scenario. The estimated volume of debris would add additional costs and disruption during response operations and would likely overwhelm local capacities for solid waste management during the recovery process.

5.5.2.3 Anticipated Losses

The HAZUS flood model provides a capability to assess direct capital stock losses associated with building repair and replacement costs for structural and non-structural damage, and time-dependent income-related losses associated with relocation, loss of wages, and lost revenue (including rental income). In accordance with standard loss estimation methods, the HAZUS flood model assumes that the hazard event will almost certainly occur within any given year and computes the expected loss for an average annual probability value of ~1.0 (P_{AA} = 0.99999). Capital and income losses are calculated on the basis of depth-related damage ratios using standard methods of quantitative loss estimation (Federal Emergency Management Agency, 2006a; Scawthorn *et al.*, 2006b; Scawthorn *et al.*, 2006c). If the expected level of damage exceeds 50%, it is assumed that the building will be demolished and rebuilt. Income-related losses are calculated indirectly on the basis of cost-area estimates and of loss of functionality.

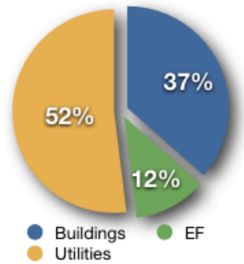
Results of loss estimation modelling for 1/100-year and 1/200-year flood scenarios in the Squamish Valley are summarized in Table 5-7. Losses are reported for capital stock, general building stock, essential facilities and utility systems (potable water and waste water facilities). We did not have sufficient technical information about bridge construction to assess damage and losses to major transportation infrastructure. Also not included in our analysis is an estimation of damages and associated losses to energy-related utilities (oil, natural gas and electrical facilities), vehicles, or agricultural assets.

Capital stock losses for the 1/100-year flood scenario are estimated to be ~$50.2 million, with 52% of the losses ($26.1 million) attributed to repair or replacement of major water and waste water facilities situated in low-lying areas of the valley. Losses associated with building contents and inventory make up the balance ($24.1 million) with residential and non-residential buildings comprising 37% of the building loss ($18.3 million) and essential facilities comprising the remaining 12% ($5.6 million). Although repair costs are relatively small for essential facilities, replacement costs for schools inundated by floodwaters is in excess of $5.0 million. Capital stock losses for the 1/200-year flood scenario are estimated to be $69.0 million with a cost distribution similar to that of

Damage & Losses for 1/100 Year Flood (FIT)

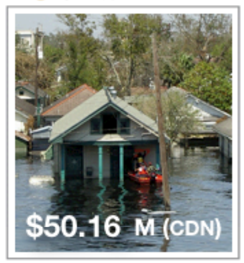
Buildings & Essential Facilities	Physical Vulnerability (# of buildings)			Economic Losses (thousands of dollars -CDN)		
	Moderate Damage	Substantial Damage	Days to Restore Service	Building Loss	Content Loss	Total Loss
‣ Building Stock	34	8	-	$11,181	$7,132	$18,313
‣ EOC	1	-	480	$20	$35	$56
‣ Care Facilities	5	-	-	-	-	-
‣ Fire Station	1	-	480	$115	$450	$565
‣ Police Station	1	-	480	$32	$55	$87
‣ Schools	9	-	480	$750	$4,338	$5,088
Totals:	**51**	**8**	**480**	**$12,098**	**$12,010**	**$24,108**

Critical Infrastructure	Physical Vulnerability			Economic Losses
	# of Facilities	Average Damage %	Non-Functional Facilities	Total Loss
‣ Potable Water Facilities	359	31.1%	209	$16,758
‣ Wastewater Facilities	22	29.9%	12	$9,298
Totals:	**381**	**30.5%**	**221**	**$26,056**



Societal Impacts	Physical Vulnerability	
	Displaced Households	# of People Requiring Shelter
‣ Vulnerable People	3,167	3,748

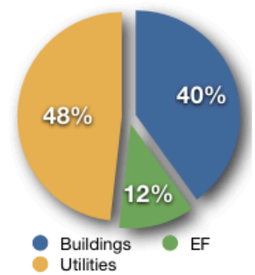
Induced Damages	Physical Vulnerability (tons of material)			
	Finishes	Structures	Foundations	Total
‣ Debris Generated	2,757	76	186	**3,019**



Damage & Losses for 1/200 Year Flood (FIT)

Buildings & Essential Facilities	Physical Vulnerability (# of buildings)			Economic Losses (thousands of dollars -CDN)		
	Moderate Damage	Substantial Damage	Days to Restore Service	Building Loss	Content Loss	Total Loss
‣ Building Stock	54	14	-	$16,808	$10,839	$27,647
‣ EOC	1	-	480	$73	$130	$203
‣ Care Facilities	6	-	-	-	-	-
‣ Fire Station	1	-	480	$122	$647	$769
‣ Police Station	2	-	480	$111	$190	$301
‣ Schools	9	-	480	$974	$5,849	$6,822
Totals:	**73**	**14**	**480**	**$18,087**	**$17,655**	**$35,742**

Critical Infrastructure	Physical Vulnerability			Economic Losses
	# of Facilities	Average Damage %	Non-Functional Facilities	Total Loss
‣ Potable Water Facilities	395	35.2%	276	$20,842
‣ Wastewater Facilities	22	35.2%	14	$12,441
Totals:	**417**	**35.2%**	**290**	**$33,283**



Societal Impacts	Physical Vulnerability	
	Displaced Households	# of People Requiring Shelter
‣ Vulnerable People	3,455	4,113

Induced Damages	Physical Vulnerability (tons of material)			
	Finishes	Structures	Foundations	Total
‣ Debris Generated	3,901	95	229	**4,225**

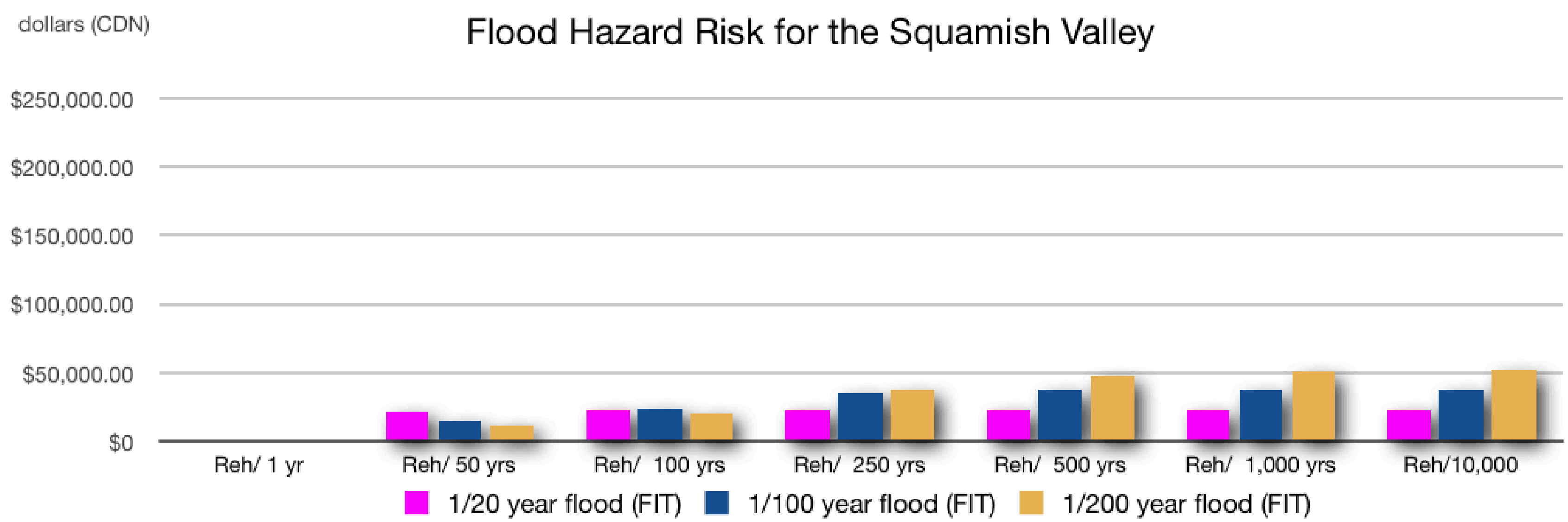
Table 5-7: Results of loss estimation modelling for 1/100-year and 1/200-year flood scenarios in the Squamish Valley. The assessment is based on standard loss estimation methods using inherent capabilities of HAZUS to model direct capital stock and income loss, shelter requirements, and debris generation as a function of damage state.

the 1/100-year event. Nearly half of the losses (48%; $33.3 million) are attributed to repair or replacement of major water and waste water infrastructure. Losses to essential facilities are equivalent in proportion to the 1/100-year scenario (12%), with replacement costs of ~$8.1 million.

5.5.2.4 Hazard risk

Our assessment of hazard risk builds on outputs of the HAZUS loss estimation model for floods and is focussed on the profile of anticipated socio-economic losses over time. The HAZUS flood model assumes there would be no serious injuries or fatalities providing there is sufficient advanced warning of severe weather events that have a potential to cause river and coastal flooding. The analysis assumes that underlying earth system processes are uniform over this period of time and does not factor in the likely effects of a changing climate on the frequency or intensity of weather-generated flood hazards.

As with debris flow and debris flood hazards, the analysis of hazard risk



$$\text{Hazard Risk } (R_{\epsilon,h}) = \sum\left[\left(L_{md} V_{\epsilon,h}\right) P_{AAh} \times \left(1 - R_{em}\right)\right],$$

Model Variables	Value
L_{mcl}: Replacement costs for buildings, contents, inventory & CI	See Table 5-7 & 5-8
V_{eh}: Physical vulnerability, measured as a function of hazard intensity	See Table 5-7 & 5-9
R_{em}: % loss avoided through emergency management measures)	25.00%

Probable Maximum Loss (PML)								
Hazard Event (of specified intensity)	Capital Loss $P_{AA}=1$	R_{eh}/ 1 yr	R_{eh}/ 50 yrs	R_{eh}/ 100 yrs	R_{eh}/ 250 yrs	R_{eh}/ 500 yrs	R_{eh}/ 1,000 yrs	R_{eh}/ 10,000 yrs
1/20 year flood (FIT)	$30,909.19	$1,159.09	$21,398.16	$23,044.64	$23,181.83	$23,181.89	$23,181.89	$23,181.89
1/100 year flood (FIT)	$50,164.25	$376.23	$14,860.92	$23,851.87	$34,573.50	$37,375.98	$37,621.56	$37,623.19
1/200 year flood (FIT)	$69,025.03	$258.84	$11,476.48	$20,408.76	$36,983.18	$47,545.89	$51,424.30	$51,768.77

Average Annual Probability (P_{AA})									
Hazard Event (of specified intensity)	$P_{CE\,h}$	T_R	P_{AA}/ 1 yr	P_{AA}/ 50 yrs	P_{AA}/ 100 yrs	P_{AA}/ 250 yrs	P_{AA}/ 500 yrs	P_{AA}/ 1,000 yrs	P_{AA}/ 10,000 yrs
1/20 year flood (FIT)	.999999	20	0.05000	0.92305	0.99408	1.00000	1.00000	1.00000	1.00000
1/100 year flood (FIT)	.999999	100	0.01000	0.39499	0.63397	0.91894	0.99343	0.99996	1.00000
1/200 year flood (FIT)	.999999	200	0.00500	0.22169	0.39423	0.71439	0.91843	0.99335	1.00000

Table 5-8: Hazard risk for 1/100-year and 1/200-year river flood events in the Squamish Valley, evaluated using methods described in Section 4.4.2 of this study (Ayyub et al., 2007; McGill et al., 2007). Estimates of financial risk are based on probable economic losses and are measured in thousands of dollars (see bar graph).

for floods incorporates a loss reduction rate that reflects the expected capability for emergency response and recovery. For floods that are triggered by extreme weather events, we have used a loss reduction ratio of ~25%, which corresponds with a forecast lead time of 18–24 hours (USACE; 1984; Scawthorn et al., 2006c). Factors that will influence the effectiveness of emergency response operations to reduce physical impacts and associated levels of risk include: the effectiveness of the forecast warning in conveying the state of knowledge about the current situation and how this situation is likely to change in the foreseeable future; how the situation is likely to impact areas of human settlement; what can be done to mitigate anticipated impacts of the hazard prior to the event happening; how individuals and groups are likely to respond to a forecast warning for a given their perceptions of risk, belief structures, and prior experience (Descurieux, 2010; personal communication).

As illustrated in Table 5-8, hazard risk trends for riparian floods in the Squamish Valley are dominated by impacts and consequences of the 1/20-year scenario for time intervals of up to 50 years, and by 1/100-year and 1/200-year scenarios for time intervals of 100 years and greater. The average annual loss for the 1/20-year scenario is $1.16 million and increases to a probable maximum loss of ~$23 million for time intervals of 100 years and greater. By comparison, the average annual loss for the 1/200-year scenario is ~$26 million and increases to a probable maximum loss of ~$48 million for time intervals of 500 years and greater. Although the risk profile does not change substantially beyond time intervals of 500 years, we have extended our assessment of flood risk for time intervals of up to 10,000 years to allow comparison with threats posed by lower-probability/higher-consequence landslide and earthquake hazards in the study area.

5.5.3 Earthquake Risk

The Geological Survey of Canada (GSC) assesses earthquake ground motion hazards using probabilistic methods that make use of frequency-magnitude relationships and scientific models of underlying plate dynamics to determine the likelihood of exceeding minimum thresholds of ground-shaking at any given location for standard recurrence intervals (Adams and Atkinson, 2003; Adams and Halchuk, 2003; Halchuk and Adams, 2008). Corresponding ground motion intensities (peak ground acceleration; PGA in units of g) and spectral acceleration values (Sa0.2, Sa0.5, Sa1.0 and Sz2.0) used for engineering design purposes are computed for a constant shear wave velocity (360–750 m/sec; Soil Class C) using standard peer-reviewed methods of assessing seismic attenuation for different earthquake source zones in Canada.

Hazard potential is reported for return intervals of 1/100, 1/476, 1/1000, and 1/2475 years. The 1/476 and 1/2475 earthquake scenarios are used as reference standards and are typically reported in terms of ground shaking intensities (PGA) for event probabilities of 10% in 50 years (1/476) and 2% in 50 years (1/2475). The Canadian National Committee on Earthquake Engineering (CANCEE) uses outputs of these assessments to develop guidelines for seismic loading and the design of engineered structures that inform the National Building Code for Canada (DeVall, 2003).

Our analysis of earthquake risk in the Squamish Valley is built on results of the GSC national seismic hazard assessment and includes estimates of hazard potential, physical vulnerability, and anticipated losses associated with earthquake scenarios referenced in the fourth generation seismic hazard maps and the 2005 National Building Code of Canada (NBCC; Adams and Halchuk, 2003; Halchuk and Adams, 2008). For purposes of reporting, we limit our discussion to results obtained using probabilistic and deterministic modelling capabilities of the HAZUS earthquake module for ground motions that exceed 10% in 50-year and 2% in 50-year probability thresholds for design earthquake scenarios referenced by the NBCC. The scope of analysis includes a consideration of site-specific amplification of ground shaking hazards caused by variations in near-surface shear wave velocity profiles, and permanent ground deformation caused by liquefaction and seismically triggered landslides. The analysis of seismic risk encompasses an assessment of physical vulnerability and damage potential for key elements of the built environment, an assessment of anticipated socio-economic losses, and an analysis of hazard risk profiles for time intervals of interest.

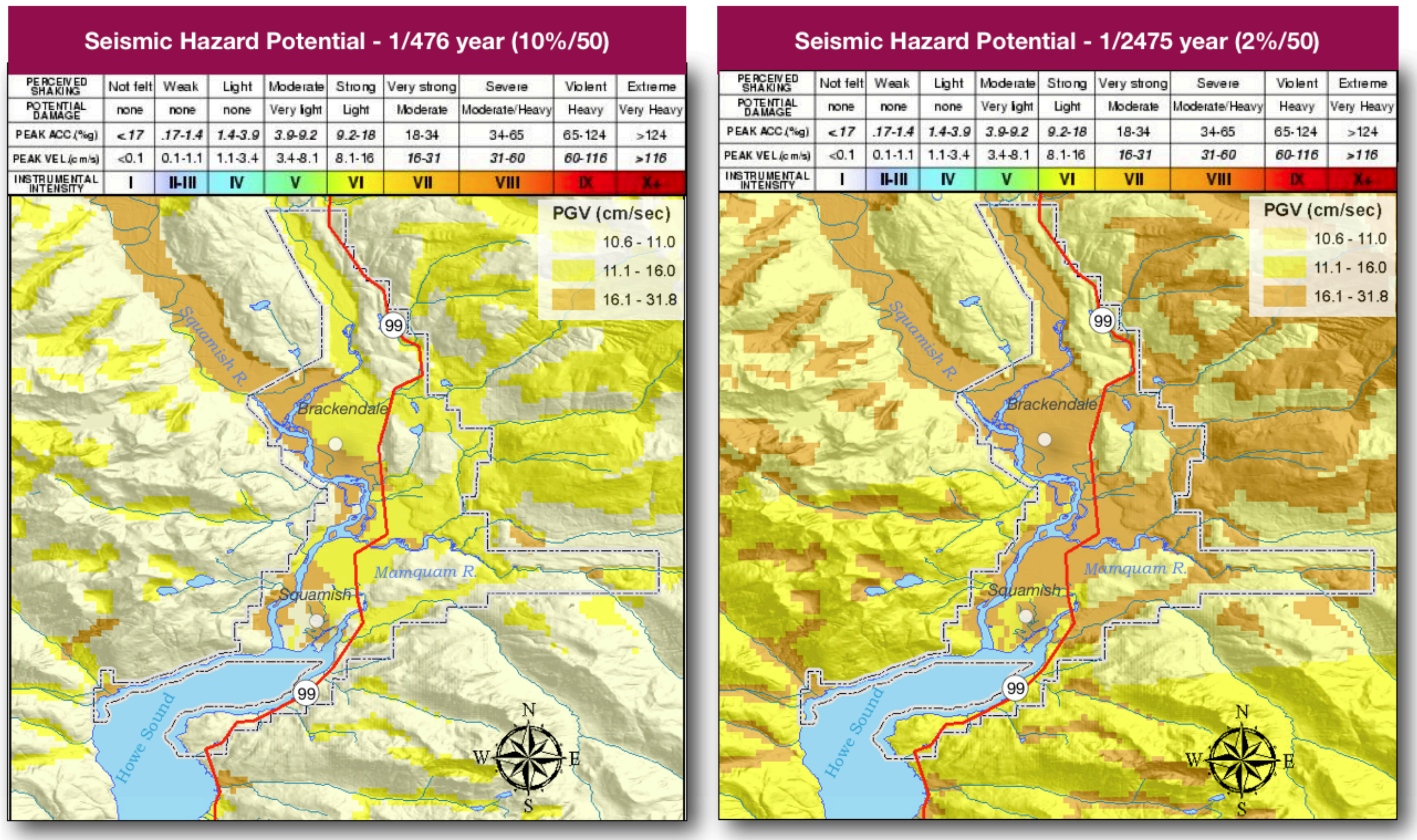


Figure 5-20: Seismic hazard potential for ground motions that exceed 10% in 50-year and 2% in 50-year probability thresholds for earthquake scenarios in the southern Sea-to-Sky region of southwest British Columbia. Ground shaking intensities were assessed using seismic parameters from the national earthquake database (Adams and Halchuk, 2003; Halchuk and Adams, 2008), and modelling capabilities of the HAZUS earthquake module (Federal Emergency Management Agency, 2006b; Kircher et al., 2006)

5.5.3.1 Hazard Potential

Seismic hazard potential for earthquake ground motions that exceed 10% in 50-year and 2% in 50-year probability thresholds in the southern Sea-to-Sky corridor area are summarized in Figure 5-20. Peak ground acceleration (PGA) and peak ground velocity (PGV) vary as a function of distance from source zones and are influenced by soil conditions and other geological factors that have a potential to amplify both the intensity and duration of ground shaking felt at the surface. Large magnitude earthquakes (~M7.3) along the Juan de Fuca oceanic plate boundary as it sinks beneath North America deep beneath the southern Strait of Georgia, and giant "megathrust" earthquakes (>M8) along the Cascadia subduction zone in offshore regions of the Pacific Northwest are the primary influences for a 10% in 50-year scenario in the southern Sea-to-Sky region. At least two events of this type are known to have occurred in the last ~300 years, including a devastating M9 earthquake that was triggered along the Cascadia subduction zone west of Vancouver Island in 1700 (Lamontagne et al., 2007). However, because the distance away from potential source zones for these types of earthquakes is large (150–250 km), associated levels of ground shaking in the Squamish Valley are likely to be dampened with expected peak ground velocities of ~11 cm/sec over regions dominated by exposed bedrock (NEHRP Soil Class B). Weakly consolidated volcanic rock and glacial sediments along the flanks of Mt. Garibaldi (NEHRP Classes C) and thick deposits of fluvial sands and silts along the valley bottom (NHERP Class D) are expected to locally amplify the level of ground shaking with peak ground velocities of up to ~30 cm/sec in these areas.

Shallow earthquakes situated along active faults in the southern and central Coast Belt region are primary influences for a 2% in 50-year scenario in the Sea-to-Sky corridor. These are low-probability but potentially high-consequence events with the capability of triggering a ~M7 or greater earthquake anywhere in the region. At least three earthquakes of this type are known to have occurred in the last ~150 years; a M6.9 in 1918 and a M7.3 in 1946, both on Vancouver Island (Lamontagne et al., 2007). A M6.8–7.3 event in 1872 is believed to have occurred in north-central Washington State near Entiat, likely on a relatively shallow blind fault accommodating active deformation in the Cascade Mountains and/or adjacent parts of the Columbia Plateau (Bakun *et al*., 2002). Although there is no direct evidence of active faulting in the southwest Coast Mountains of British Columbia, recent studies by the US Geological Survey have documented Holocene displacements on several surface fault structures along the Canada-US border, and confirmed the potential for large magnitude (>M7) shallow crustal earthquakes in the region (Johnson *et al*., 2007).

Peak ground velocities associated with a shallow crustal earthquake in the southern Coast Mountain (a 2% in 50-year event) are estimated to be 11–16 cm/sec in the northern Howe Sound region, and 10–11 cm/sec for exposed bedrock regions north of Squamish (NHERP Class B). Peak ground velocity is expected to be locally amplified to 31 cm/sec in areas underlain by recent volcanic and glacial-fluvial sediments on the west flank of Mt. Garibaldi and along all major river basins leading into the Squamish Valley (NHERP Classes C & D). In addition to a regional analysis of earthquake ground motion hazards, we have also modelled the effects of local site amplification and the potential for earthquake-triggered landslides and liquefaction in the Squamish area using results of a regional landslide susceptibility analysis by GeoReference Online Ltd. (Smyth and Poole, 2004) and a detailed microzonation study by Monahan (2005). Site amplification and liquefaction potential were assessed using available subsurface geological information from geophysical boreholes and micro-tremor surveys. The information was compiled and used to evaluate the effects of variations in the thickness, type and physical properties of marine and river sediments that fill the lower Squamish Valley. Analysis of associated seismic hazard potential was modelled in HAZUS for all regional earthquake scenarios using shear wave velocities (Vs30) corresponding to standard NEHRP site classes. Results of these site-specific studies are summarized in Figure 5-21.

The assessment of earthquake-triggered landslide potential is based on a probability ranking method known as HazardMatch, which uses advanced knowledge representation, analytic reasoning and similarity ranking to model the spatial probability of landslide hazards (Smyth and Poole, 2004; Smyth, 2007). The model compares expert understanding of the physical parameters and processes that trigger landslide events (ontological models) with available geospatial information describing the location and physical attributes of these parameters (surface morphology, aspect, surficial and bedrock geology, rainfall, etc.) to assess the likelihood of ground failure. Unlike standard approaches to landslide susceptibility mapping which use spatial queries (topological relationships) and Boolean logic to identify hazard prone areas on a map, HazardMatch is based on fuzzy logic reasoning and probabilistic

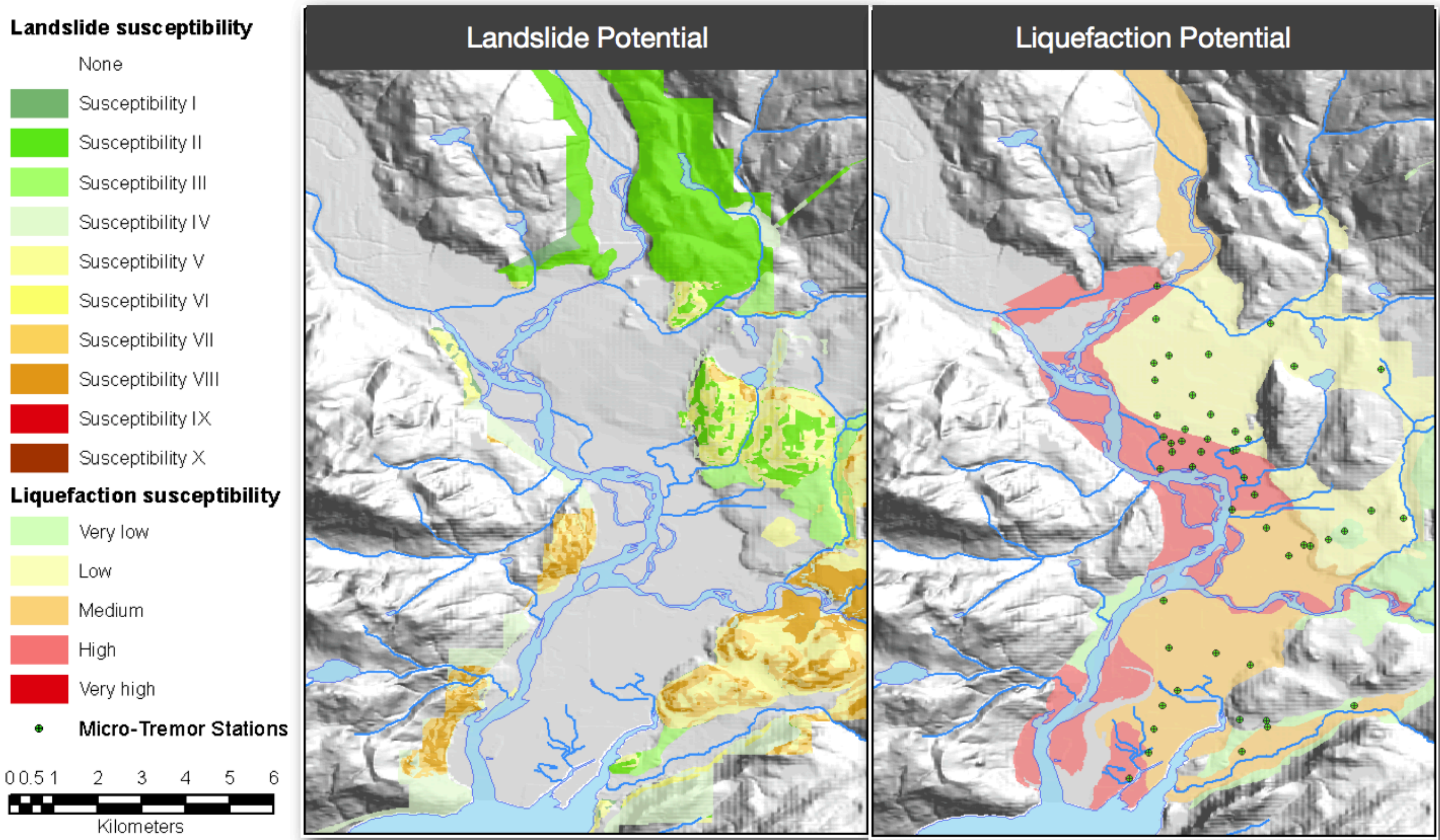


Figure 5-21: Maps showing the permanent ground deformation potential for earthquake-triggered landslides and liquefaction in the District Municipality of Squamish. The potential for seismically generated ground failure is assessed using results of a regional study of landslide probability (Smythe, 2007). The assessment of liquefaction potential is based on results of a microzonation study by Monahan (2005) using guidelines provided as part of the HAZUS earthquake module (Federal Emergency Management Agency, 2006b).

matching of semantic networks that are spatially explicit and linked to specific polygon, line, and point features. Outputs of the analysis include maps showing source areas for potential landslide events, a formal ranking of landslide probability, and full documentation of the logic used to evaluate hazard prone areas (see Figure 5-21). Results of the landslide susceptibility analysis for the Squamish area have been independently validated using a combination of geological maps, detailed air photos, and expert judgement (Jackson *et al.*, 2008).

Assessment of liquefaction potential is based on in situ measurements of internal soil cohesion and depth to the water table (Monahan, 2005). Results are summarized in Figure 5-21. Areas exposed to moderate liquefaction potential are located primarily in middle and southern reaches of the Squamish River valley, and central and eastern reaches of the Mamquam River valley, areas that underlain by fine-grained alluvial sediments and shallow groundwater aquifers. More than ~800 homes are exposed to potential liquefaction hazards (~15% of building stock), mostly in Brackendale and in isolated areas along the Cheakamus and Mamquam rivers. Except for the Squamish Elementary School in the downtown area, essential facilities are not exposed to a significant threat of liquefaction. Critical infrastructure and lifeline services of concern include port facilities and related structures along the Howe Sound waterfront, rail lines crossing the Squamish Estuary and eastern portions of Brackendale, and major rail and highway bridges crossing the Mamquam River and the Mamquam Blind Channel (Monahan, 2005).

5.5.3.2 Physical Vulnerability

The HAZUS methodology provides a capability to assess physical vulnerabilities associated with the impacts of a defined earthquake scenario in terms of the probability of reaching or exceeding discrete states of damage for a given level of ground shaking or permanent ground deformation (Kircher *et al.*, 2006). At the heart of the methodology is a robust set of damage functions that are used to assess the capacities of engineered structures to withstand the impacts of ground shaking (building capacity curves), and the probabilities of damage associated with expected ground shaking intensities and associated spectral displacements (fragility curves).

Building capacity curves are based on parameters that describe the expected response to ground shaking and ground deformation in terms of yield and ultimate strength for 36 different buildings types and other classes of engineered structures. For each building type, the capacity parameters are used to characterize a level of seismic design and an expected level of seismic performance. Fragility curves assess the probability of reaching or exceeding discrete states of damage to buildings and engineered structures, non-structural building components that are sensitive to drift, and non-structural components such as contents and inventory that are sensitive to acceleration. For a given level of building response, fragility curves are used to assess exceedance probabilities of four defined damage states; slight, moderate, extensive, and complete (Federal Emergency Management Agency, 2006b; Kircher *et al.*, 2006).

The assessment of physical vulnerability for residential and non-residential buildings is based on a portfolio of structures that are typically aggregated at the scale of census tracts. In addition, HAZUS provides capabilities to assess default damage states for essential facilities and user-defined structures, and to assess building-specific damage characteristics through an Advanced Engineering Building Module in which building response and fragility curves can be modified on a case-by-case basis. For purposes of our study, we aggregated building portfolios at the scale of individual neighbourhoods (census dissemination areas) to match the overall resolution of available information on expected ground shaking intensity and probability of ground deformation. Results of our analysis of earthquake damage potential for ground motions that exceed probability thresholds for 10% in 50-year and 2% in 50-year design events are presented in Figures 5-22.

The perceived level of ground shaking for much of the settled area in the District is expected to be moderate to strong for both earthquake scenarios, with levels of structural damage that would be comparable in magnitude to an MMI value of V to VII. For the 10% in 50-year earthquake scenario, it is estimated that 840 buildings would reach or exceed the HAZUS probability threshold for moderate damage, with an additional 22 buildings reaching or exceeding a substantial state of damage. Single- and multi-family residential buildings make up the majority of damaged structures (68% and 23%, respectively) with the balance comprising an equal mix (~3% each) of commercial, industrial, and other building classes.

At least 16 essential facilities are expected to sustain moderate levels of damage, including all three police and fire stations, two of the three emergency operation centres, five of the 20 school buildings and six of the nine health care facilities. While the susceptibility of essential

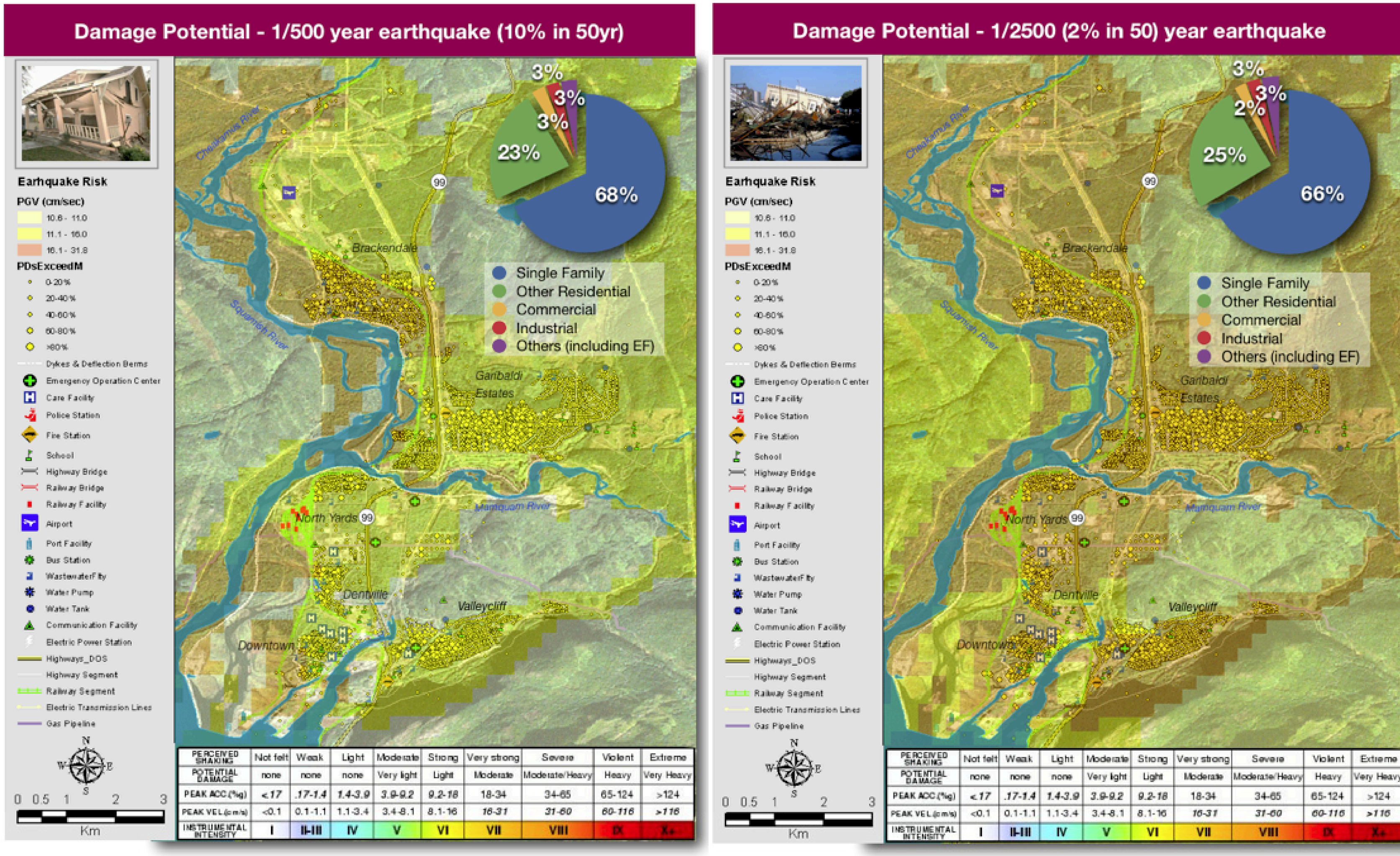


Figure 5-22: Damage potential for 10% in 50-year and 2% in 50-year earthquake scenarios in the District of Squamish. The level of ground shaking is equivalent to a Modified Mercali Intensity (MMI) of V to VII.

facilities to ground shaking and permanent ground deformation hazards is relatively high in the District, none of these structures are expected to sustain substantial levels of structural damage. Out of a total of ~25 beds at the regional hospital in Squamish, it is estimated that only one (5% of total capacity) would remain functional and available to those injured by the earthquake. As functional services are restored, bed capacity would increase to 30% by the end of the first week, and would likely reach 67% of normal service levels after 30 days.

Major transportation and utility systems are susceptible to moderate levels of shaking and localized ground deformation hazards, but are not expected to reach or exceed moderate levels of probable damage.

Utility systems (water, electricity, and communications) are particularly vulnerable to impacts of the earthquake. At least 2,500 households and businesses would be without power immediately after the earthquake, with all but 141 connections restored after 7 days. Nearly all of the other critical lifeline services are expected to have at least 50% functionality within the first week of the initial tremor.

Secondary hazards triggered by the earthquake include at least one major fire following the earthquake (~23 hectares of area burned), and the generation of over 10,000 tons of debris material that would likely impede response and recovery efforts and pose significant additional threats to the environment and to public safety. Brick, wood, and other material are expected to comprise the majority of disaster debris (78%) with concrete and steel making up the balance. Removing this amount of debris would require heavy equipment and more than 400 truckloads of material that would almost certainly overwhelm the capacity of existing solid waste management systems in the region.

For the 2% in 50-year earthquake scenario (see Figure 5-22), it is estimated that ~2,250 buildings would reach or exceed the HAZUS probability threshold for moderate damage (~10–30%), with an additional 261 buildings reaching or exceeding levels of extensive damage (~30–50%) and 34 buildings damaged beyond repair or destroyed. Single- and multi-family residential buildings make up the majority of damaged structures, with the balance comprising an equal mix of commercial, industrial, and other building classes. Although the location of these buildings with respect to ground shaking and liquefaction hazards are important factors influencing the expected level of physical damage, the pattern of damage is influenced primarily by the proportion of older wood frame structures in low-lying areas of the valley that were constructed prior to the introduction of modern building codes and seismic design guidelines in the mid-1970s (compare Figure 5-22 and Figure 5-7.

It is expected that all essential facilities would reach or exceed moderate levels of structural damage, thereby compromising response and recovery capabilities of local emergency management operations. One of the three emergency operation centres is expected to sustain extensive damage (30-50%), as would three of the nine health care facilities. Out of a total of ~25 beds at the regional hospital in Squamish, it is estimated that none would remain functional after the earthquake and available for those with serious injuries. Bed capacity is expected to increase to 4% by the end of the first week, and to reach only 36% of normal service levels after 30 days.

Major transportation and utility systems are susceptible to moderate levels of shaking and localized ground deformation hazards, and it is expected that at least three of the 19 highway bridges would reach or exceed moderate levels of damage. Fourteen of these bridges would have at least 50% functionality immediately after the earthquake, and it is expected that all would achieve comparable levels of functionality by the end of the first week. Rail bridges are expected to have at least 50% functionality by the end of the first week.

Utility systems are particularly vulnerable to impacts of the earthquake. Nearly 66% of the households and businesses in Squamish (~3,900 buildings) would be without power immediately after the earthquake, with all but 611 connections restored after 7 days. Ground shaking and permanent ground deformation are expected to result in the rupture of potable water distribution lines in at least 12 locations, and leakage in 6 more. The extent of damage is such that access to municipal water services would not likely be restored for a minimum of three months. At least one of the five communication facilities in the community would be destroyed, but all other critical lifeline services are expected to have at least 50% functionality within the first week after the initial tremor.

Secondary hazards triggered by the earthquake include at least one major fire following the earthquake (~15 hectares of area burned), and the generation of ~33,000 tons of debris material that would almost certainly impede response and recovery efforts and pose significant additional threats to the environment and to public safety. Brick, wood, and other material are expected to comprise the majority of disaster debris (67%) with concrete and steel making up the balance. The volume of material generated in the District of Squamish for this one event alone is equivalent to the estimated solid waste generation stream that is disposed of in landfills for the Squamish-Lillooet Regional District (population of ~54,250) over an entire year (Gartner Lee Ltd., 2007). Based on a study of disaster debris management trends worldwide, the direct economic costs of waste management, collection, treatment, and disposal for an event of this magnitude are estimated to be $14.2–19 million (Brown *et al.*, 2010).

Societal impacts resulting from the earthquake are estimated in terms of shelter requirements and expected levels of injury, both of which are calculated on the basis of damage states for individual buildings in the portfolio. For the lower magnitude earthquake scenario, the numbers of displaced households is small (<10). Assuming that the earthquake occurs at 5 pm in the afternoon, it is estimated that ~6 people would

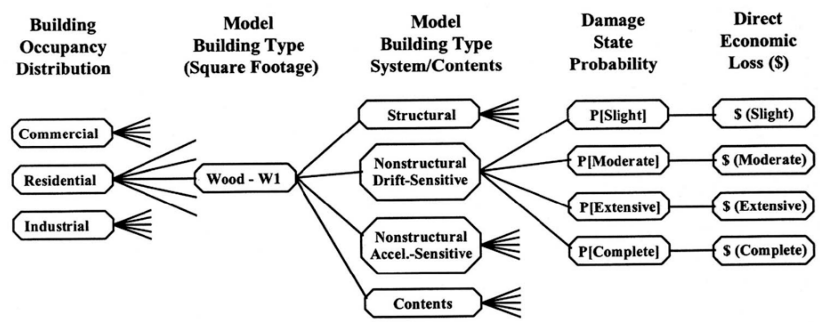


Figure 5-23: Logic tree summarizing the process of calculating direct economic losses used in the HAZUS earthquake model. Reproduced from Kircher et al. (2006; Figure 7).

sustain injuries requiring medical attention with no fatalities. For the larger magnitude scenario (2% in 50-year), the numbers of casualties is expected to be closer to 20, with one fatality. Of the 20 people injured as a result of physical damage to buildings, 15 people would require medical attention and an additional 5 would be hospitalized with serious or life-threatening injuries.

5.5.3.3 Anticipated Losses

As with the flood model, HAZUS provides a capability to assess both direct and indirect socio-economic losses resulting from the physical impacts of an earthquake. Loss functions are used to transform expected levels of damage into financial costs based on the physical damage state that is most significant and appropriate for each of the 28 building occupancy classes and additional classes of critical infrastructure that provide lifeline services to the community (Kircher et al., 2006). The overall process for calculating direct economic losses to buildings is summarized in Figure 5-23.

Capital stock losses, which include repair and replacement costs for buildings, contents and inventory are estimated by combining the probable losses for all states of structural and non-structural damage. Income-related losses, which include wage loss, relocation costs and lost revenue from commercial and rental transactions, are estimated on the basis of floor area and primary use (occupancy class; residential, commercial, industrial, retail, etc.). Default repair and replacement costs are derived from national means data for specific parts of the country, and are used to calculate anticipated losses based on levels of damage to primary structural systems and to non-structural components that are susceptible to drift and acceleration-related damages. The costs are estimated on the basis of damage state and represent a proportion of the full replacement costs for each structure in the portfolio (Federal Emergency Management Agency, 2006b)

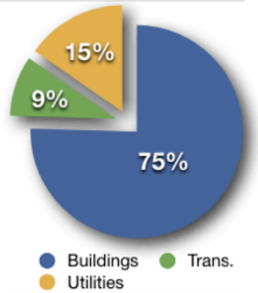
Results of our loss estimates for credible earthquake scenarios in the Squamish Valley are presented in Table 5-9. These are anticipated losses caused by damages attributed to ground motions associated with 10% in 50-year and 2% in 50-year design events. Capital stock and income-related losses are reported for aggregate buildings in each of the five general occupancy classes, which include single- and multi-family residential, commercial, industrial and others (essential facilities, government buildings, churches, and schools). Capital stock losses are reported for major transportation systems (road, rail, airport, and marine port facilities), and for each of the primary utility systems including potable water, waste water, electrical and communication facilities.

We did not have sufficient technical information to assess damage and associated losses to specific highway and rail line segments, or to vehicles that may be impacted by falling debris. Also not included in our

Anticipated Damages & Losses- 1/500 year earthquake (10% in 50yr)

Buildings & Essential Facilities	Physical Vulnerability (# of buildings)		Economic Losses (thousands of dollars -CDN)		
	Moderate Damage	Substantial Damage	Capital Losses	Income Losses	Total Loss
‣ Single Family	572	15	$33,380	$4,610	$37,990
‣ Other Residential	194	5	$13,510	$1,610	$15,120
‣ Commercial	23	1	$7,340	$2,750	$10,090
‣ Industrial	23	1	$6,000	$550	$6,550
‣ Others (including EF)	28	-	$11,960	$2,160	$14,120
Totals:	**840**	**22**	**$72,190**	**$11,680**	**$83,870**

Transportation Systems	Physical Vulnerability		Economic Losses
	With at least Moderate Damage	With > 50% Functionality after Day 7	Total Loss (x $1,000)
‣ Highway	-	19	$1,900
‣ Railway	-	6	$5,800
‣ Other	-	9	$2,500
Totals:	**0**	**25**	**$10,200**

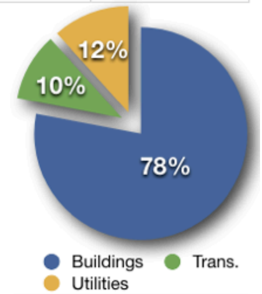


Utility Systems	Physical Vulnerability		Economic Losses
	With at least Moderate Damage	With > 50% Functionality after Day 7	Total Loss (x $1,000)
‣ Potable Water	-	8	$180
‣ Waste Water	1	1	$11,210
‣ Electrical	-	5	$4,260
‣ Communication	1	5	$1,420
Totals:	**1**	**9**	**$17,070**

Anticipated Damages & Losses- 1/2500 year earthquake (2% in 50yr)

Buildings & Essential Facilities	Physical Vulnerability (# of buildings)		Economic Losses (thousands of dollars -CDN)		
	Moderate Damage	Substantial Damage	Capital Losses	Income Losses	Total Loss
‣ Single Family	1,498	193	$76,880	$14,190	$91,070
‣ Other Residential	568	73	$31,170	$5,430	$36,600
‣ Commercial	53	9	$14,660	$8,390	$23,050
‣ Industrial	59	11	$12,210	$1,770	$13,980
‣ Others (including EF)	78	18	$26,790	$6,420	$33,210
Totals:	**2,256**	**304**	**$161,710**	**$36,200**	**$197,910**

Transportation Systems	Physical Vulnerability		Economic Losses
	With at least Moderate Damage	With > 50% Functionality after Day 7	Total Loss (x $1,000)
‣ Highway	3	19	$8,800
‣ Railway	-	6	$12,800
‣ Other	-	9	$4,600
Totals:	**3**	**25**	**$26,200**



Utility Systems	Physical Vulnerability		Economic Losses
	With at least Moderate Damage	With > 50% Functionality after Day 7	Total Loss (x $1,000)
‣ Potable Water	8	8	$1,890
‣ Waste Water	1	1	$13,620
‣ Electrical	5	5	$10,300
‣ Communication	5	4	$3,820
Totals:	**9**	**9**	**$29,630**

Table 5-9: Anticipated socio-economic losses associated with damages in the Squamish Valley caused by earthquake ground motions that exceed the probability threshold of 10% in 50 years and 2% in 50 years. Estimates are derived from outputs of the HAZUS earthquake model, and are based on an assessment of probable damage states caused by the impacts of ground shaking and liquefaction hazards, and physical descriptions of buildings and other elements of the built environment obtained from the CDMS asset inventory.

analysis of socio-economic loss is an estimate of indirect economic impacts to the community and the broader Sea-to-Sky region. Such impacts include upstream and downstream disruptions to commercial and industrial operations that would be indirectly impacted by physical damages to transportation and utility systems (roads, bridges, water, energy, etc.) causing loss of functional capacity and associated business income; damages to community assets of historical or religious significance; damages to sensitive environmental features and related ecosystem services caused by direct and induced hazard threats (hazardous material spills, fire following earthquake, etc); emotional and psychological suffering caused by the initial earthquake event and related aftershocks; and major disruptions to social and government services that would likely linger in the community for years.

Anticipated losses associated with a 10% in 50-year design earthquake in the Squamish Valley are estimated to be $111.14 million with combined capital stock and income-related losses to general building stock comprising 75% of the total risk profile ($83.9 million). Damages to single- and multi-family residential structures are responsible for

$53.11 million in losses, with commercial and other occupancy classes (including essential facilities) sustaining $10.1 million and $14.1 million in losses, respectively. Damages to industrial facilities would result in losses of $6.6 million. Losses to transportation infrastructure and utility systems are expected to be $10.2 million (transportation) and ~$17 million (utility).

Socio-economic losses associated with the higher magnitude 2% in 50-year earthquake scenario are estimated to be $253.74 million. As with the lower magnitude event, the combined losses to general building stock represent over 75% of the total risk profile ($197.9 million). Damages to single- and multi-family residential structures are responsible for $127.7 million in capital stock and income-related losses. Commercial and other building classes (including essential facilities) would sustain losses of $23.1 million and $33.2 million, respectively. Losses to transportation infrastructure and utility systems would be $10.2 million (transportation) and $29.6 million (utility).

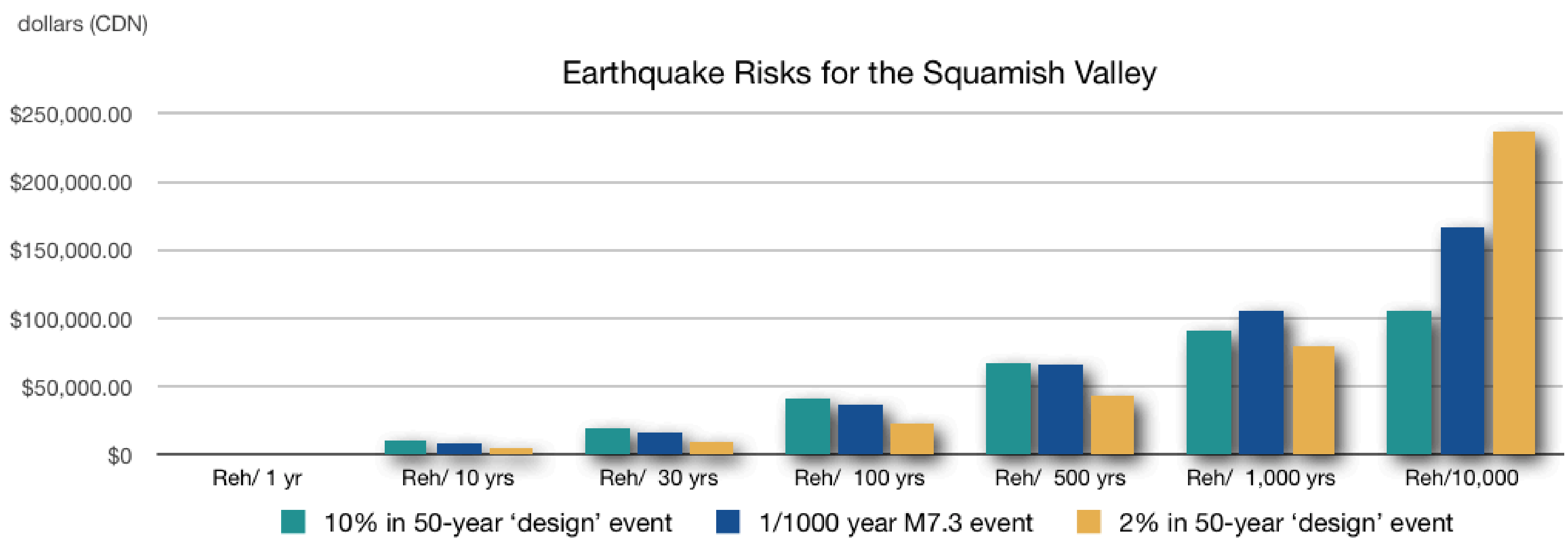
5.5.3.4 Hazard risk

Our assessment of earthquake risk in the Squamish Valley extended existing analytical capabilities of the HAZUS model by estimating probable maximum losses of credible earthquake scenarios over a range of time intervals that are relevant for strategic land use planning. Model outputs provided a basis for comparison with other low-probability/high-consequence hazards (e.g. Cheekye Fan debris flow) that are triggered by geological processes spanning much longer time frames of 500-10,000 years. Given that an earthquake event would likely occur without any prior warning, we have assumed a relatively low loss reduction ratio of 5% to reflect modest efficiencies gained in emergency response and recovery capabilities through education and pre-event scenario planning and table-top exercises. While these efforts are known to have a significant effect in promoting public safety, they would not likely have any bearing on direct physical impacts and related socio-economic losses apart from voluntary seismic upgrading by individuals and by those required to comply with local development permitting processes.

As illustrated in Table 5-10, hazard risk trends for earthquakes in the Squamish region are dominated by impacts and consequences of the higher-frequency/lower-consequence 10% in 50-year earthquake scenario for time intervals of up to 500 years, and by lower-frequency/higher-consequence earthquake scenarios for time intervals greater than 500 years. The average annual loss for the lower intensity 10% in 50-year scenario is $211,000 for any given year, and increases exponentially from probable maximum losses of ~$19.2 million to ~$66.8 million for time intervals of 100 years and 500 years, respectively. By comparison, the average annual loss for the 1/200-year scenario is ~$96,000, and increases to a probable maximum loss of ~$43.7 million for time intervals of up to 500 years. For time intervals greater than 500 years, the profile of probable maximum losses is dominated by low-frequency/high-consequence events with a maximum probable loss of $236.6 million. The combination of anticipated loss, which assumes the event could occur anytime in the future, and probable maximum loss, which accounts for the probability of the event occurring over future time horizons, provides the context for evaluating disaster mitigation scenarios in terms of effectiveness and efficiency. Missing from this analysis is any consideration of who in society bears the risk at any given point in time, and how this risk is transferred from generation to generation.

5.5.4 Social Vulnerability and Community Resilience

The history of settlement in agricultural lands and transportation corridors along the valley bottom, as well as land use decisions made by the District during periods of rapid growth in the 1970s and 1980s, has increased hazard risk in the community and will likely influence underlying patterns of vulnerability for decades to come. The densification of neighbourhoods located in areas exposed to natural hazards and the financial investment in supporting infrastructure to service these areas mean that fundamental patterns of human settlement and associated vulnerability are likely to be sustained and possibly even reinforced with time. In this section, we turn our attention to the question of who is most vulnerable to natural hazard risks in Squamish, how patterns of physical vulnerability may be amplified by social disadvantage, and the implications of these patterns with respect to overall disaster resilience of the community.



$$\text{Hazard Risk } \left(R_{\epsilon,h}\right) = \sum\left[\left(L_{md} V_{\epsilon,h}\right) P_{AAh} \times \left(1 - R_{em}\right)\right],$$

Model Variables	Value
L_{md}: Replacement costs for buildings, contents, inventory & CI	See Table 5-10 & 5-11
V_{eh}: Physical vulnerability, measured as a function of hazard intensity	See Table 5-10 & 5-12
R_{em} (losses avoided through emergency management measures)	5.00%

Hazard Event (of specified intensity)	Probable Maximum Loss (PML)							
	Anticipated Loss P_{AA}=1	R_{eh}/ 1 yr	R_{eh}/ 50 yrs	R_{eh}/ 100 yrs	R_{eh}/ 250 yrs	R_{eh}/ 500 yrs	R_{eh}/ 1,000 yrs	R_{eh}/ 10,000 yrs
10% in 50-year 'design' event	$111,140.00	$211.17	$10,057.12	$19,156.26	$41,575.73	$66,780.06	$91,322.48	$105,583.00
1/1000 year M7.3 event	$175,490.00	$166.72	$8,134.77	$15,872.61	$36,893.55	$65,622.68	$105,414.91	$166,707.97
2% in 50-year 'design' event	$253,740.00	$96.42	$4,774.11	$9,453.68	$22,943.59	$43,703.39	$79,483.27	$236,641.49

Hazard Event (of specified intensity)	Average Annual Probability (P_{AA})								
	$P_{CE\,h}$	T_R	P_{AA}/ 1 yr	P_{AA}/ 50 yrs	P_{AA}/ 100 yrs	P_{AA}/ 250 yrs	P_{AA}/ 500 yrs	P_{AA}/ 1,000 yrs	P_{AA}/ 10,000 yrs
10% in 50-year 'design' event	.10	50	0.00200	0.09525	0.18143	0.39377	0.63249	0.86494	1.00000
1/1000 year M7.3 event	.999999	1000	0.00100	0.04879	0.09521	0.22130	0.39362	0.63230	0.99995
2% in 50-year 'design' event	.02	50	0.00040	0.01981	0.03922	0.09518	0.18130	0.32973	0.98170

Table 5-10: Hazard risk for direct socio-economic losses caused by physical damages associated with earthquake ground motions that exceed reference probability thresholds of 10% in 50 years and 2% in 50 years used by the National Building Code of Canada (annual probabilities of 0.002 and 0.00404, respectively). We have also included results for a 1/1000-year M7.3 event for comparison purposes. Estimates of financial risk are based on probable economic loss using analytical methods described in Section 4.3.5.3 of this study (Ayyub et al., 2007; McGill et al., 2007) for time horizons that range from 1-10,000 years. Probable maximum loss is measured in thousands of dollars (see bar graph).

We used available best practice methods to assess dimensions of social vulnerability that incorporate elements of the well-known Social Vulnerability Index (Cutter *et al.*, 2000; Cutter, 2001; Cannon *et al.*, 2003; Masuda and Garvin, 2006; Wisner, 2006; Burton and Cutter, 2008) and revisions to this method that make refined analytical techniques to improve overall coherence and internal consistency (Hebb and Mortsch, 2007; Jones and Andrey, 2007; Andrey and Jones, 2008). Results of these previous studies have shown that causal structures, spatial patterns, and underlying dynamics of social vulnerability can change rapidly over the course of a few decades in response to growth pressures and urban development, and that these patterns can not necessarily be assumed on the basis of prevailing theories of social disadvantage and behavioural change (Andrey and Jones, 2008).

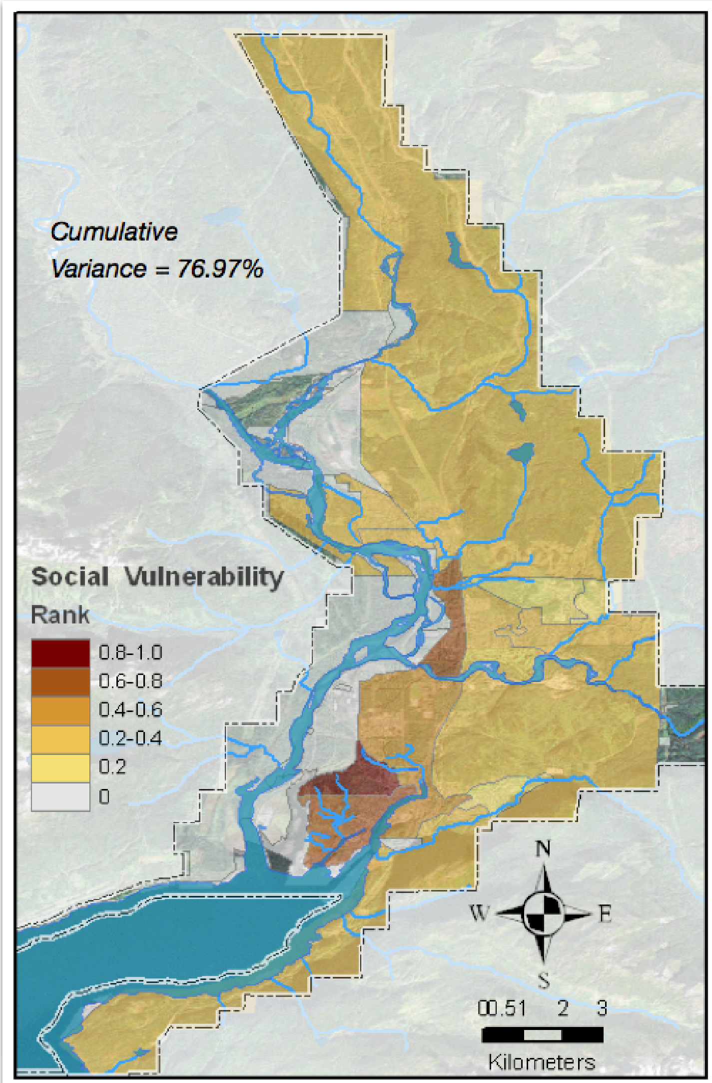
Our assessment of social vulnerability for the District of Squamish was based on an analysis of 42 population and demographic variables from the 2001 national long-form census (Statistics Canada, 2003b), and 10 additional variables describing situational exposure and susceptibility to physical damages associated with landslides, floods, and earthquakes in the region. Population and demographic variables were selected on the basis of their capacity to describe patterns of social disadvantage at a local scale (Cutter *et al.*, 2003; Andrey and Jones, 2008) and to be assessed at the neighbourhood level (census dissemination areas). Sparsely populated neighbourhoods were excluded from the analysis, as Statistics Canada does not distribute community profile data for dissemination areas in which there are fewer than 40 people to ensure individual privacy rights.

Variables selected as proxies for social agency include income, race, ethnicity, and mobility (Hewitt and Burton, 1971; Burton *et al.*, 1993; Blaikie *et al.*, 1994; Mileti, 1999; Morrow, 1999). Variables selected as proxies for coping capacity include age, family structure, gender, language, and education (Blaikie *et al.*, 1994; Hewitt, 1997; Morrow, 1999; Cutter *et al.*, 2000). All variables were transformed to a common frame of reference using linear scaling and standardization methods to ensure internal coherence of the overall dataset (Yoe, 2002; Jones and Andrey, 2007).

Principal component analysis (PCA) and Varimax rotation were then used to identify correlation patterns and to minimize issues of colinearity and double counting (Brooks, 2003; Boruff *et al.*, 2005; Cox *et al.*, 2006; Jones and Andrey, 2007; Meyers, 2007; Andrey and Jones, 2008). As part of the PCA analysis, multi-dimensional variables were clustered into a series of principal components that collectively describe core patterns of variability in the larger data set. Varimax rotation is then used to assess variance and the strength of correlation (loading) of variables within each of the principal components. The strength of correlation among variables provides a measure of relevance and an indication of underlying factors that may collectively influence conditions of social vulnerability in a particular area.

Results of our assessment are summarized in Table 5-11. Five principal component clusters (with eigen values >4.0) were identified that together explain ~77% of the statistical variance in the data set. Components are characterized by dominant variables that are known to influence social agency, coping capacity, and situational exposure. In order of decreasing influence they include: i) seniors and individuals living alone, ii) family caregivers with limited discretionary income, iii) visible minorities with language barriers, iv) exposure of essential care facilities providing social and public health services, and v) exposure of industrial sector and supporting social structures.

Spatial patterns of social vulnerability were determined by aggregating standardized values corresponding to variables with the highest loading for each of the five principal components. We used a linear un-weighted method of aggregation to minimize the influence of different numbers of variables for each principal component. Variables for each of the five principal components were grouped into one of three dimensions of vulnerability (agency, coping capacity, and exposure), and then aggregated to assess spatial patterns of vulnerability across the study area. Each of the five principal components defines a core pattern of social disadvantage; aggregation of these core factors provides a synoptic view of social vulnerability in the community. As illustrated in Table 5-11, those who are exposed to the highest levels of natural hazard threat are also the most vulnerable to negative impacts and consequences in terms of both social agency and coping capacity.



PCA-1

Eigenvalue = 17.58

% Variance = 33.82%

Variable	Description	Loading
P_SEN_ALON	% senior population living alone	-0.261
P_MIG_E	% population that has migrated from elsewhere in Canada	-0.241
P_POP_ALON	% population living alone	-0.23
DU_MH_GT5	% dwelling units exposed to multi-hazrd threats	-0.223
IN_NO_VEH	% population without access to a vehicle	-0.214
P_AGE_GT_65	% population 65 years and older	-0.199
P_MOB_LT1	% population that has moved within the last year	-0.198
P_MOB_LT5	% population that has moved within the last 5 years	-0.19
P_LFP	% lone female parent households	-0.19
P_ABORIG	% aboriginal community	-0.186
P_L_INC_F	% low-income families	-0.179

PCA-2

Eigenvalue = 7.77

% Variance = 14.94%

Variable	Description	Loading
P_SEN_GT10	% families spending > 10 hours of unpaid care to seniors	0.324
P_S_PARNT	% lone parent households	0.324
P_SEN_GT10	% families spending > 10 hours of unpaid care to seniors	0.324
MHP_BASIC	damage potential of buildings providing basic services	0.308
DU_MH_GT5	% dwelling units exposed to multi-hazrd threats	0.278
P_TEN_GT30	% tenant-occupied households spending >30% on shelter	0.264
P_OWN_GT30	% owner-occupied households spending >30% on shelter	0.237
A_RENT_TEN	average rent of tenant-occupied housing units	0.214

PCA-3

Eigenvalue = 5.47

% Variance = 10.52%

Variable	Description	Loading
P_VIZ_MIN	% visible minority	-0.383
P_LANG_N	% population without knowledge of official language	-0.338
P_BSER_OCC	% employees in basic service industries	-0.304
P_IMMIGRNT	% recent immigrants (within last 5 years)	-0.286
P_PSEC_N	% population with no post-secondary degree	-0.222
P_SOC_OC_N	% population not participating in social service occupations	-0.214
P_SERVICE	% employed in service industries	-0.198

PCA-4

Eigenvalue = 4.95

% Variance = 9.52%

Variable	Description	Loading
MHP_SOC	damage potential to social service facilities	0.336
MHP_HEALTH	damage potential of buildings providing health care services	0.308
P_AGE_LT5	% population under 5 years of age	0.308
P_PARTIC_N	% population not participating in labour force	0.296
P_TRANS	% employed in transportation, communication & public utilities	0.29
P_CHD_GT30	% families spending > 30 hours of unpaid childcare	0.215
P_DU_MAJOR	% housing units in need of major repairs	0.191

PCA-5

Eigenvalue = 4.25

% Variance = 8.17%

Variable	Description	Loading
DU_SIG_DAM	% dwelling units exposed to potential of significant damage	0.438
MHP_COMM	damage potential to commercial/industrial service centres	0.325
P_IND_OCC	% employees working in industrial sector	0.269
P_CON_LT85	% housing units constructed before 1985	0.229
P_SOC_OC_N	% population not participating in social service occupations	0.2
P_RESOURCE	% employed in primary resource extraction industries	0.198
P_DU_MAJOR	% housing units in need of major repairs	0.184

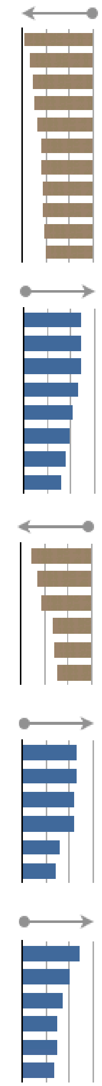


Table 5-11: Summary of PCA results and corresponding variables used in evaluating dimensions of social vulnerability for Squamish, BC.

5.5.4.1 PCA-1: Seniors and Individuals Living Alone

The first principal component (PCA-1) explains nearly 34% of the variance for the entire dataset, and is characterized by seniors (65 years and older), individuals living alone, and those who have recently moved into the community from elsewhere in Canada. Other variables that appear to be significant (high correlation values) include limited access to a vehicle, lone–female-parent households, individuals of aboriginal origin, and low-income families.

Areas of concern include an east-west tract encompassing northern parts of the downtown and southwest Dentville, and a tract encompassing the Blind Channel area and extending northward along the boundary between Loggers Lane and the industrial park into southern Garibaldi Estates. These are some of the older neighbourhoods in the community, and they are characterized by higher proportions of retired and elderly people living in homes that were constructed prior to 1975 susceptible to physical damages caused by flooding, ground shaking, and liquefaction.

5.5.4.2 PCA-2: Family Caregivers with Limited Discretionary Income

The second principal component explains ~15% of the variance and is characterized by family caregivers and single-parent households with limited discretionary income. Areas of highest concern include the south Brackendale and Squamish River/Westbank neighbourhoods. The northern half of Brackendale and portions of Garibaldi Estates situated east of Highway 99 also show high levels of correlation, as do northeastern parts of Valleycliffe and the area that encompasses Dentville and Downtown Squamish.

5.5.4.3 PCA-3: Visible Minorities with Language Barriers

The third principal component explains 10.5% of the variance and is characterized by visible minorities without knowledge of an official language, those who have recently immigrated to Canada within the last five years, and those who are reliant on employment in basic service industries. Individuals of South Asian origin make up more than 70% of all visible minorities in the community, and almost 12% of the total population. The size, internal cohesion and social norms of the community are such that groups of individuals would likely respond well to negative impacts of a disaster event. However, characteristics of individuals within these groups suggest there may be specific points of vulnerability. Areas of particular concern are localized in the downtown area and in the neighbourhood of Valleycliffe.

5.5.4.4 PCA-4: Susceptibility of Health Care and Social Services

The fourth principal component explains 9.5% of the variance in the dataset and is characterized by the susceptibility of essential facilities that provide health care and social services. Individuals that appear to be most vulnerable to loss of services in these areas include very young children under the age of 5, and individuals providing more than 30 hours a week of unpaid childcare who are not participating in the labour force. Other variables that are relevant include employment in transportation, communication, and public utility operations that would likely be disrupted in the event of a disaster, housing units that are in need of significant repair, and relatively high proportions of individuals without a high school diploma. Areas of particular concern include the boundary zone between Dentville and Downtown, and those parts of Garibaldi Estates on the east side of Highway 99.

5.5.4.5 PCA-5: Susceptibility of Industrial Sector & Supporting Social Structures

The final component of the analysis explains 8% of the variance in the dataset and is characterized by the susceptibility of homes and facilities situated in core industrial areas. Other relevant variables include individuals who are reliant on a few core industries for their livelihood, and who live in some of the older neighbourhoods in Squamish. For the most part, these are neighbourhoods characterized by homes built prior to the enforcement of modern building safety standards in the 1980s. The potential loss of commercial and industrial services and related employment following a disaster may impede short-term and long-term recovery in terms of economic vitality and shared infrastructure, and would likely have indirect consequences on the regional economy as well. Areas of particular concern include older neighbourhoods in northern Brackendale, the border zone between Loggers Lane and the industrial park, and industrial facilities located on the Cheekye Fan.

5.6 Risk Evaluation

This final component of our study provides a synthesis of information and knowledge gained about the current risk environment in the District of Squamish through the semi-quantitative appraisal of hazard threats and concerns in the community (Section 5.4), and the quantitative analysis of hazard risk for debris flow, flood, and earthquake scenarios (Section 5.5). With this as a foundation, we used methods of integrated assessment and scenario modelling to explore how underlying conditions of vulnerability are likely to evolve with future growth and development in the community, and the strengths and weaknesses of various risk reduction strategies including conventional structural mitigation measures and risk avoidance achieved through comprehensive land use planning.

Target indicators identified by the community working group at the beginning of this process were used to characterize the existing disaster risk profile, to evaluate anticipated future disaster risk trends, and to measure the performance of proposed disaster mitigation strategies in terms of public safety, socio-economic security, resource efficiency, and social equity. The indicators provide an internally coherent set of risk metrics that can be used by emergency managers and planners to make informed decisions about mitigation choices and their likely consequences. The indicators also provide an integrated framework for assessing thresholds of risk tolerance that are consistent with policy goals and objectives of the Official Community Plan, and that promote longer-term goals of disaster resilience and sustainable development.

5.6.1 Multi-Hazard Potential

In practice, risk reduction planning is often focused on individual hazard threats (landslides, floods, earthquakes, etc.) and whether a proposed land use is considered safe for the use intended, what mitigation strategies might be considered to reduce risks to tolerable thresholds, and the associated costs of these mitigation measures. In this context, hazard potential and physical vulnerability maps, similar to the ones described in preceding sections, are sufficient in communicating the anticipated extent, intensity and probability of damage for a specific hazard threat. However, a consideration of multi-hazard threats over variable time horizons is required in a broader comprehensive land use planning process that includes managing risks associated with growth and development.

There are a variety of index-based methods that have been developed to generate synthetic multi-hazard potential maps for this purpose (Pelling, 2004; Birkmann, 2006; Greiving, 2006; Tyagunov *et al.*, 2006; Birkmann, 2007). Most of these methods involve the transformation of hazard intensities (water depth, flow velocity, ground motions, etc.) into a common numeric scale of measurement (1–5) to allow comparison of severity from one hazard type to the next at a regional scale. Another approach is to compare hazard magnitude in terms of anticipated damage (Middelmann and Granger, 2000; Bell and King, 2006; Grünthal *et al.*, 2006). This method is appropriate for detailed analysis of multi-hazard risk, but does not account for independent variations in hazard severity as a function of time, nor does it provide a capacity for assessing multi-hazard threat in a futures context.

Insights gained as part of our study suggest that land use planners need a capability to objectively measure intrinsic hazard potential of single- or multi-hazard event scenarios in terms of cumulative extent, magnitude, and probability. A physical description of intrinsic hazard potential may help promote an awareness and understanding of relative severity across different hazard types for a given time horizon, and in predicting the combined effects of these hazard events over variable planning scenarios in which details of the social fabric (and associated vulnerability) may change with time.

To this end, we have developed a grid-based method for measuring multi-hazard potential using the probability of damage for a single-storey wood frame building as a common point of reference. In effect, this allows direct comparison of hazard potential in terms of magnitude (intrinsic damage potential) at any point on the landscape, and over time horizons that are of interest to the planning process. Results are independent of the actual physical state of the built environment and can be used to assess any combination of hazard threats for existing and future conditions of development. The method is similar to that used in computing probabilistic seismic hazard threat for specific recurrence intervals, and assumes that hazard events are independent of one another and that underlying earth system processes are uniform for any given time horizon. Results of our multi-hazard potential assessment for the District of Squamish are presented in Figure 5-24.

Hazard scenarios selected for the analysis include an unmitigated debris

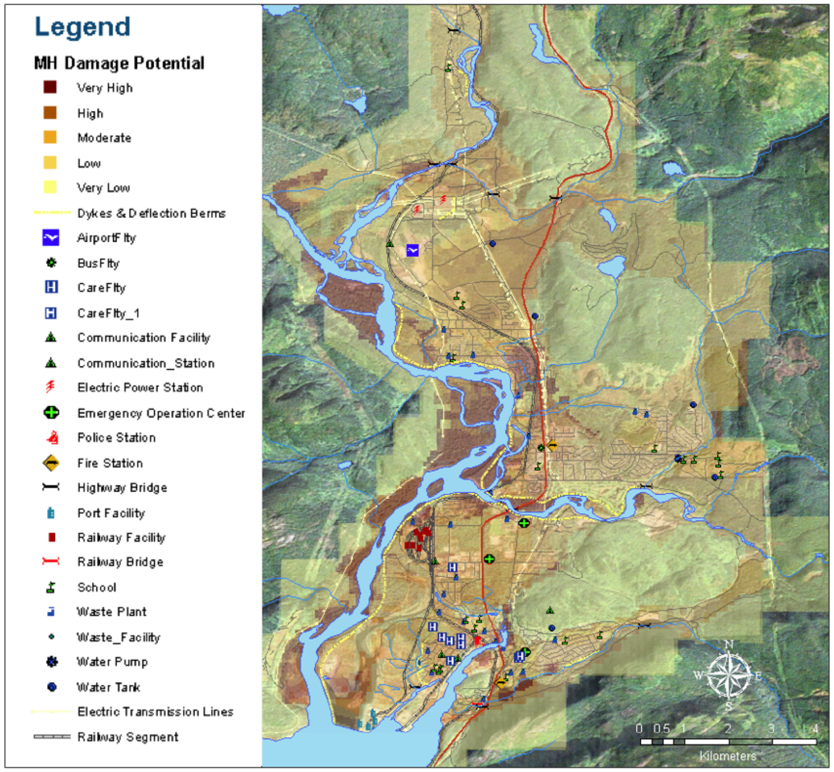


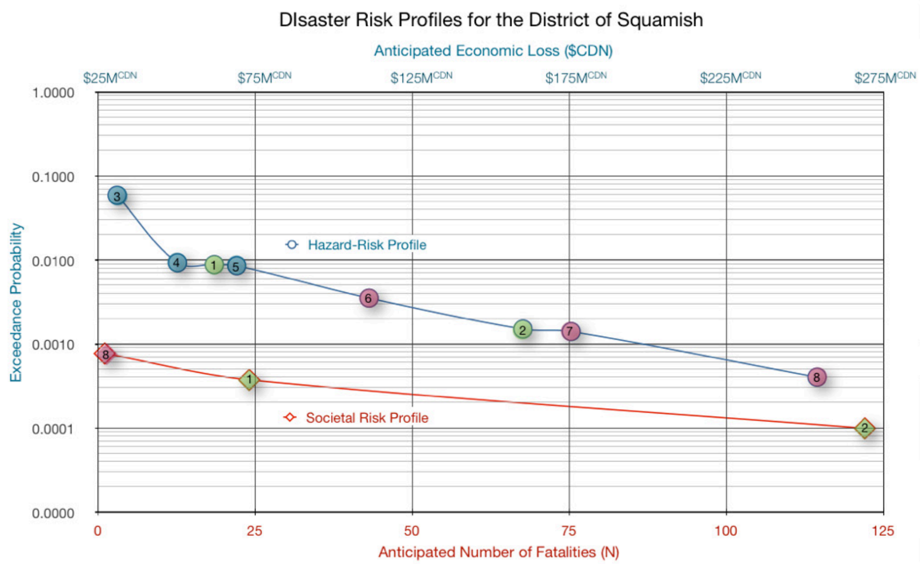
Figure 5-24: Multi-hazard potential for the District of Squamish. Assessment is based on methods described in Section 4.4.2 for maximum credible hazard threat scenarios for debris flows on the Cheekye Fan (5.4 Mm^3 scenario), riparian floods in the Squamish Valley (1/200-year scenario), and earthquakes used as a reference standard for the 2005 National Building Code of Canada (NBCC: 2% in 50-year scenario).

flow on the Cheekye Fan, a major riparian flood in the Squamish Valley, and an earthquake with ground motion intensities corresponding with the 2005 NBCC reference standard of 2% in 50 years. A reference time interval of 500 years was chosen to represent multi-hazard potential for the District as it reflects the combined influences of high-probability/low-consequence riparian flood hazards, and the impacts of lower-probability/higher-consequence debris flow and earthquake hazards in the region. The resulting map reflects best available information and knowledge about the risk environment and provides a common frame of reference for both emergency management and long-range comprehensive land use planning. For emergency managers, the map provides an overview of the combined threats posed by natural hazards in the District, and can be used to identify areas of primary concern for pre-event planning and the assessment of overall capabilities for response and recovery. For land use planners, the map provides a high-level screening tool to support the review of development permit proposals, and can be used to inform long-range growth management strategies that increase disaster resilience through risk avoidance.

5.6.2 Disaster Risk Profiles

Disaster risk profiles provide a comprehensive view of anticipated future patterns of loss associated with a portfolio of hazard threats over a range of occurrence probabilities. They are used as a decision support tool in enterprise risk management to assist businesses and governments in establishing tolerable thresholds of financial risk for a given region or community, and in developing risk management strategies that optimize expected rates of return on mitigation investments. Results are used to inform decisions about how best to transfer residual risk through disaster relief funds and/or financial markets managed by the insurance and re-insurance industry (Grossi *et al.*, 2005). In addition, they can be used to evaluate the sensitivity of our assumptions about the risk environment and to evaluate the effects of underlying causal factors (population growth, densification, etc.) that will influence changing patterns of vulnerability and risk over time. Most importantly, they help inform ongoing deliberations and judgments about how best to invest limited resources and public funds in disaster mitigation, and what levels of risk are considered tolerable in order to achieve desired outcomes as part of a strategic planning process.

Disaster risk profiles for the District of Squamish were assessed using methods described in Section 4.4.2. We analysed a portfolio of eight natural hazard scenarios that collectively describe the risk environment for higher-probability/lower-consequence riparian floods, and for lower-probability/higher-consequence debris flows and earthquakes in the region. Results of our disaster risk assessment for existing conditions are summarized in Table 5-12.



Disaster Risk - Socioeconomic Security						
	Hazard Event (Ei)	Annual probability of occurrence (Pi)	Anticipated loss (Li) in millions of dollars CDN	Probability of exceeding loss [EP(Li)]	Average Annual Loss (E[L]=(p*Li) in millions of dollars CDN
8	2%/50-year earthquake	0.00040	$253.740	0.00040	$0.101
7	5%/50-year earthquake	0.00100	$175.490	0.00140	$0.175
2	5Mm3 Debris Flow	0.00010	$160.118	0.00150	$0.016
6	10%/50-year earthquake	0.00200	$111.140	0.00350	$0.222
5	1/200-year flood	0.00500	$69.025	0.00848	$0.345
1	3Mm3 Debris Flow	0.00028	$61.876	0.00875	$0.017
4	1/100-year flood	0.00045	$50.164	0.00920	$0.023
3	1/20-year flood	0.05000	$30.909	0.05874	$1.545
	Combined Average Annual Loss for Hazard Portfolio				**$2.446**

Disaster Risk - Public Safety					
	Hazard Event (Ei)	Annual probability of occurrence (Pi)	Probable Loss of Life (N) within a group of individuals	Probability of exceeding loss [EP(Li)]	Average Annual Loss N=(p*Li) within a group of individuals
2	5Mm3 debris flow	0.00010	122	0.00010	0.012
1	3Mm3 debris flow	0.00028	24	0.00038	0.007
8	2%/50-year earthquake	0.00040	1	0.00078	0.000
	Combined Average Annual Loss for Hazard Portfolio				**0.019**

Table 5-12: Disaster risk profiles for the District of Squamish. Risks for the combined portfolio of hazard threats are described in terms of the probability of exceeding a maximum credible loss in terms of both financial resources and numbers of anticipated fatalities.

The risk profile summarizes the probability of reaching or exceeding a threshold of maximum credible loss. Events with lower probabilities of exceedance are less frequent, but have the potential for greater economic losses. These include ground motions associated with 1/2475 and 1/1000 earthquake scenarios, and a large magnitude (5.4 Mm^3) debris flow event on the Cheekye Fan. More frequent events have a higher probability of exceeding a specified level of loss, but are likely to result in lower levels of damage and economic consequence. These include all three riparian flood scenarios in the Squamish Valley (1/100 and 1/200), and the smaller magnitude (2.8 Mm^3) debris flow event. From the perspective of community wealth and socio-economic security, the spread of potential losses from any combination of hazard events in the portfolio ranges from a minimum of $30.9 million for a 1/20-year flood to a maximum of $253.7 million for ground motion intensities that exceed the 2% in 50-year threshold referenced by the 2005 NBCC guideline. Probable maximum losses associated with a 10% in 50-year (1/476) earthquake ground motion scenario represent a median value for the risk portfolio. Risk to life, as measured by the expected number of fatalities for groups of individuals, ranges from a minimum of 1 for a near-source earthquake event (>2% in 50-year ground motion intensities) to a maximum of 122 fatalities for an unmitigated debris flow event on the Cheekye Fan.

5.6.3 Disaster Risk Trends

Though framed by earth system processes that are operating at geographic and geologic time scales beyond human control, the disaster risk profile for Squamish is governed by incremental choices that have been made over the past century of settlement in the valley, and by choices that are being considered today about how to manage future growth and development of the community. In this section, we focus on the implications of existing and proposed land use policies with respect to evolving patterns of vulnerability and disaster risk in the community.

We begin with an exploration of disaster risk trends associated with two paths forward—one that is based on the existing Land Use Bylaw for the District of Squamish, (LUB 1342; District Municipality of Squamish, 2007a), and another based on growth management policies and associated land use guidelines adopted as part of the recently updated Official Community Plan (OCP 2100; District Municipality of Squamish, 2010). Each has important implications with respect to changing patterns of vulnerability and disaster risk.

The Land Use Bylaw (LUB) governs policies that guide ongoing development in accordance with provincial and federal regulatory guidelines. Decisions made as part of the development review process have a direct bearing on the physical location, form and character, type of construction, and permitted uses of land and buildings at the parcel and neighbourhood scales. The Official Community Plan (OCP) expresses a vision, guiding principles, and a statement of intent with respect to longer-term policy objectives and directions on a variety of strategic planning issues related to growth and future development of the community. Decisions made as part of the strategic planning process guide future patterns of settlement and associated infrastructure development at local and regional scales.

We evaluated the implications of existing LUB and proposed OCP land use guidelines by creating hypothetical buildout scenarios that represent the intent of both policy frameworks in terms of general massing and density of residential development. Using analytical methods outlined in previous sections, we then assessed each of these buildout scenarios in terms of changing patterns of vulnerability. Estimates of probable maximum loss for both buildout scenarios were then compared with existing conditions to evaluate how the risk environment is likely to change with time, the effectiveness of proposed mitigation strategies in terms of future growth and development, and the implications of these findings with respect to overall disaster resilience.

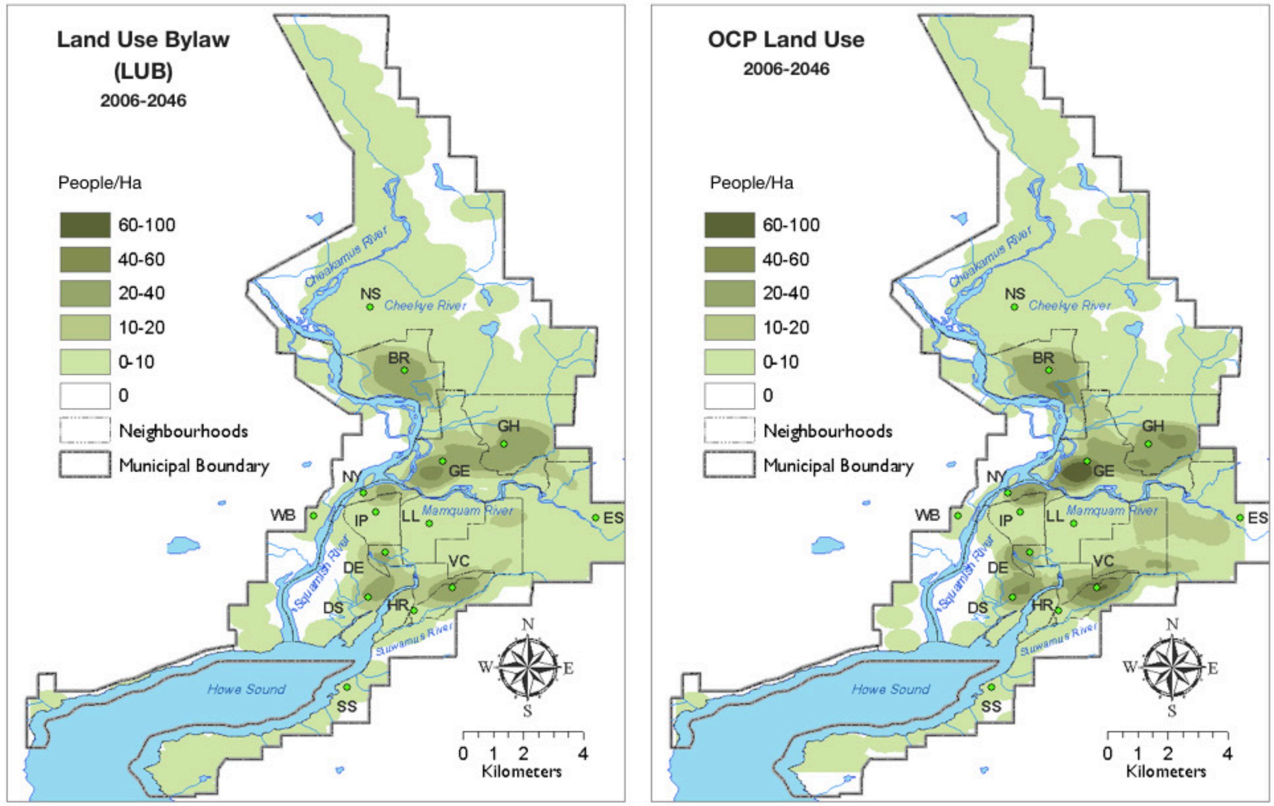
5.6.3.1 Growth Management

Existing LUB policies and proposed OCP land use guidelines make provision for anticipated demands for residential housing, commercial and industrial floor space, and infrastructure servicing requirements to accommodate an anticipated buildout population of ~33,000 people by the year 2030. Though similar in their capability to accommodate anticipated growth demands, they differ in terms of strategic direction and land use planning policies. As illustrated in Figure 5-25, these differences have important implications with respect to the location and density of new residential and commercial development in the community.

The existing LUB reflects a vision and policy direction established by the 1998 Official Community Plan during a period of economic uncertainty and slow to moderate growth. Land use policies direct the allocation of residential development toward the infilling of existing neighbourhoods with moderate density single- and multi-family housing (20–40 people per hectare (pph)), and the expansion of single-family housing into new neighbourhood developments with densities of up to 20 pph.

The updated 2009 OCP for the District of Squamish (District Municipality of Squamish, 2010; see page 27) adopts a forward-looking view (from 2006 to 2031) of Smart Growth and sustainable development that is focused on the following objectives:

- Make efficient use of the limited land base
- Create a complete community with unique, vibrant and mixed-use neighbourhoods
- Encourage economic development and the creation of local employment opportunities
- Ensure adequate inventories of suitable land and resources for future settlement and employment
- Manage long-term stewardship of the natural resource base
- Minimize municipal infrastructure costs for servicing growth and development
- Preserve natural habitat and sensitive environmental areas
- Develop a vibrant downtown core
- Manage and promote the connections between land and marine activities



Neighbourhoods: Brackendale (**BR**), Dentville (**DE**), Downtown Core (**DC**), East Squamish (**ES**), Garibaldi Estates (**GE**), Garibaldi Highlands (**GH**), Hospital Hill/Northridge (**HH**), Industrial Park (**IP**), Loggers Lane (**LL**), North Squamish (**NS**), South Squamish (**SS**), Valleycliffe (**VC**) and West Bank (**WB**)

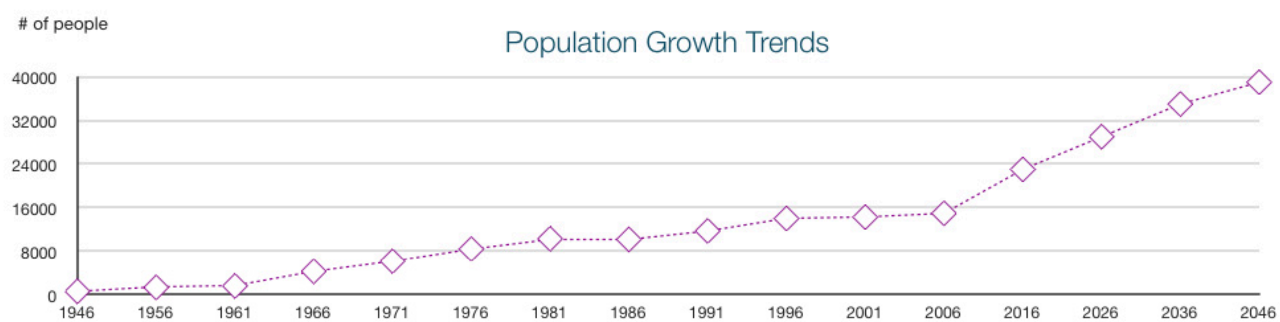


Figure 5-25: A comparative analysis of buildout densities associated with the existing Land Use Bylaw (No. 1324; 2007), and the newly adopted 2009 Official Community Plan (No. 2100; 2010).

- Promote local food production and agricultural opportunities
- Undertake area planning

As illustrated in Figure 5-25, the overall pattern of settlement in established neighbourhood nodes remains the same as the LUB buildout scenario. However, the form and character of residential and mixed-use development within these existing neighbourhood nodes is transformed into a more compact urban form with densities that range from 40–60 pph in the downtown core, Valleycliffe, and Garibaldi Estates. In addition, there is a fundamental shift in the pattern of connectivity between existing neighbourhood nodes that improves overall performance with respect to environmental stewardship, natural resource management, local economic resilience, community liveability, and the provision of infrastructure servicing.

One of the primary challenges in managing anticipated future growth in the context of the existing LUB and updated OCP land use designations is the availability of private lands to accommodate both residential and commercial development. Less than 27% of the District is currently developable due to a combination of physical and regulatory constraints (Urbanics Consultants *et al.*, 2005). As illustrated in Figure 5-26, development constraints include areas exposed to extreme flood and landslide hazards, steep slopes, ecologically sensitive habitat, and areas that are currently protected as parks or reserves (shown in shades of red). Unsettled areas outside the downtown core and existing neighbourhood nodes are further constrained by the costs of building and maintaining municipal infrastructure to service new residential and business development.

Areas currently identified as being most desirable for existing and future residential development are shown in Figure 5-26 with shades of blue. These are areas in which there are no known physical or legislative constraints, and in which natural hazard risks are considered "acceptable" based on existing information and knowledge. Areas identified as negotiable for development are shown in shades of yellow in Figure 5-26. These are areas in which there are physical or environmental constraints to development and where the risks posed by natural hazard threats may exceed thresholds of acceptability by the

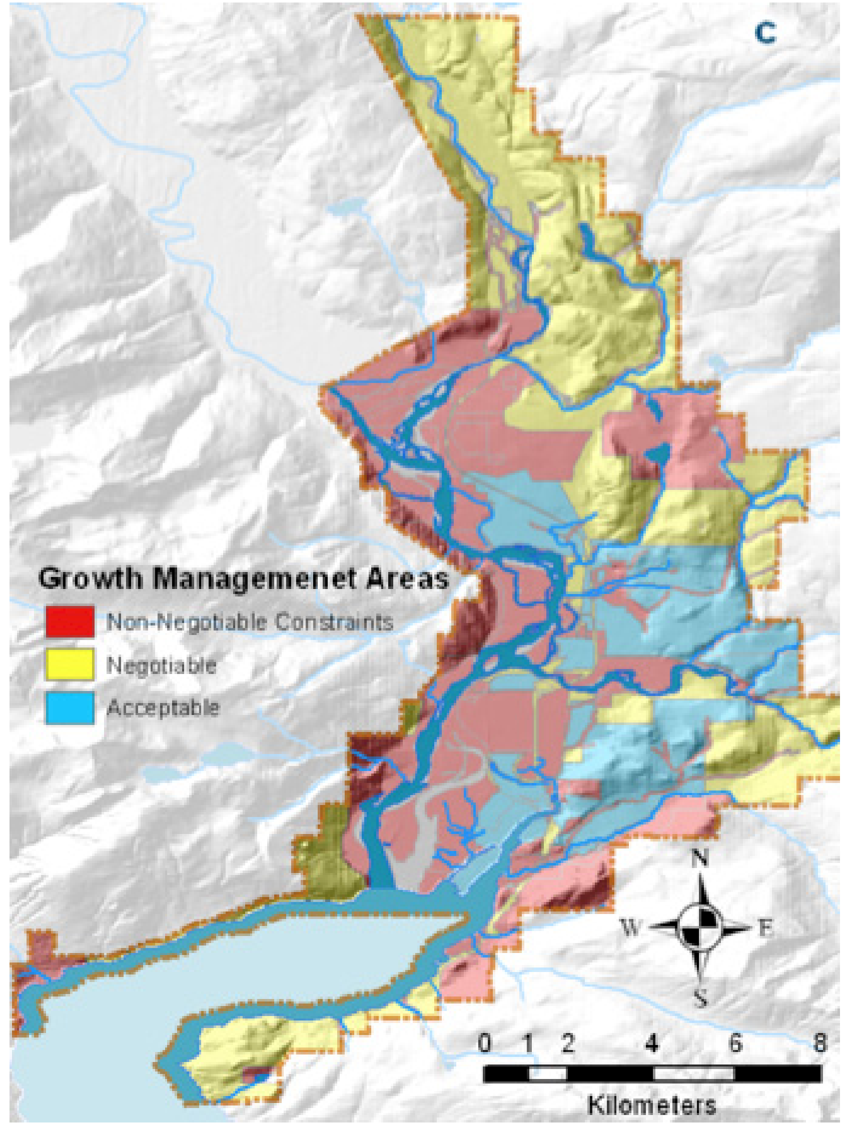


Figure 5-26: Existing constraints and opportunities for managing the demands for residential and commercial/industrial development associated with a projected trend of rapid population growth that is expected to double from current levels of ~16,000 to over 33,000 in the next 25–30 years.

community.

The scarcity of available lands to accommodate anticipated demands for residential growth also implies that areas with development potential would likely need to be re-zoned to accommodate anticipated growth demands in Squamish. It is recognized that many of the areas that could accommodate future growth are exposed to a variety of natural hazard threats. For those areas that can accommodate future growth, the motivating questions are: how safe is safe enough in terms of physical damages and societal risk (public safety), and who bears the social and economic burdens of risks assumed through future growth and development should a disaster event occur?

5.6.3.2 Landslide Risk

Existing land use zoning bylaws and OCP policies for the management of growth and development on hazardous lands acknowledge the Cheekye Fan as a Special Study Area in which any proposed development is reviewed by a qualified professional to ensure that it is safe for the use intended and does not exceed tolerable thresholds of risk as defined by the community. Tolerable risk is defined in terms of what the 1993 Thurber-Golder study considered a 1/10,000 probability threshold for loss of life, consistent with national and international safety guidelines for residential development in areas exposed to natural hazard threats (APEGBC; 2010). The Special Study Area guidelines restrict residential development in areas that exceed the 1/10,000 tolerability threshold for societal risk (Zones 1–2), and further require that any proposed residential development in Zones 3–4 comply with recommendations of a Debris Flow Management Plan developed by a qualified professional, and incorporate appropriate mitigation measures to protect life and limb. The implications of these risk management guidelines are evident in buildout scenarios for both the existing Land Use Bylaw and the OCP (see Figure 5-27).

Hazard zones 1 and 2 are based on results of the Thurber-Golder study (1993) and are meant to correspond with areas in which the depth and velocity of debris flow materials associated with a catastrophic 2.8 Mm^3 event are likely to exceed 4m and 4 m/sec. However, current modelling of the likely run-out zone for a 2.8 Mm^3 debris flow event by Kerr Wood Leidal (2003) depict run-out zones with a different spatial pattern. As a result, there is significant ambiguity with respect to areas in which residential development might be permitted with appropriate mitigation measures.

The build-out scenario based on the existing LUB results in the allocation of residential buildings in areas that the Kerr Wood Leidal study designate as being exposed to hazard threats exceeding the accepted safety threshold. In this scenario, 19 buildings would sustain moderate damage, while seven would likely be destroyed. Anticipated loss associated with this scenario would be an additional ~$6.19 million above existing conditions, which represents 9% of the total potential loss profile of $68.13 million.

The OCP buildout scenario results in a higher-density allocation of residential and non-residential buildings in northern Brackendale, and is of concern for the lower-frequency/higher-magnitude 5.4 Mm^3 event. However, for the 2.8 Mm^3 debris flow scenario, only 14 buildings are exposed to significant hazard threat. Of these, 12 would sustain moderate levels of damage, while two would likely be destroyed by the impact of debris flow materials. Anticipated loss associated with this scenario would be an additional ~$3.42 million above existing conditions, which represents 5% of the total potential loss profile of $65.37 million.

5.6.3.3 Riparian Flood Risk

As part of its legislated mandate to direct growth and development in ways that reduce the potential impacts of riparian and coastal flooding, the District collaborates with affected property owners and provincial agencies to maintain flood protection standards that meet or exceed minimum inundation levels associated with a 1/200-year event. This work includes ongoing maintenance and upgrades to existing dyke and floodwater pumps that protect existing community assets within the municipal boundary, and review of development permit applications to ensure that building elevations comply with designated Flood Construction Levels (FCL) and site-level grading guidelines. The District is also developing a Special Study Area designation and bylaw to reflect current knowledge about flood risks in the valley.

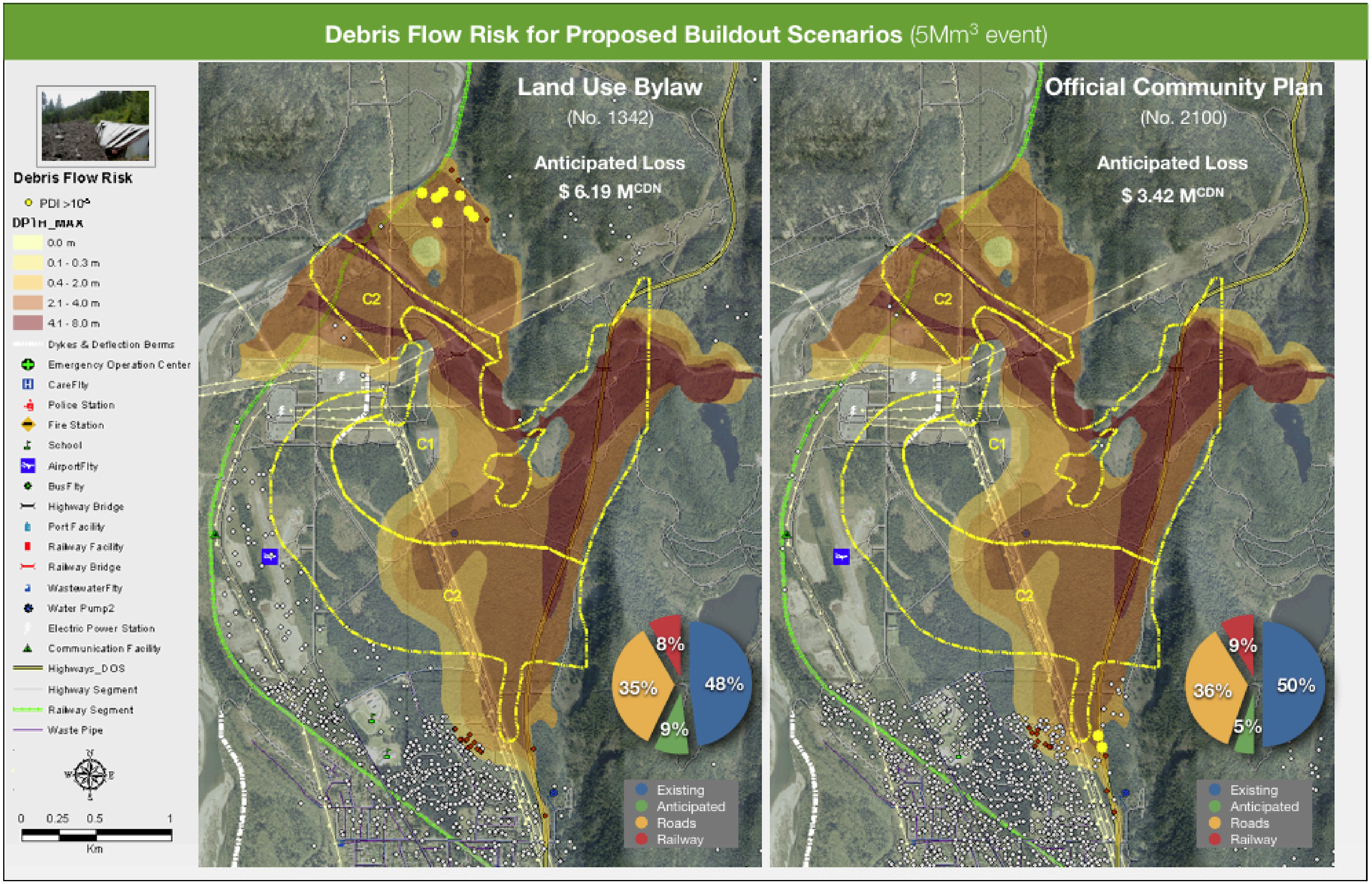


Figure 5-27: Debris flow risk for hypothetical buildout scenarios that reflect policies of the existing Land Use Bylaw (LUB No. 1342), and the Official Community Plan (OCP No. 2100).). See Section 5.5.2 for details of analytical methods used to assess damage potential and anticipated loss.

Specific areas of concern are identified in the LUB and updated OCP policy framework, including historic streetscape and commercial buildings in the downtown core and community assets along the corridor between Highway 99, the Mamquam Blind Channel, and Loggers Lane. However, there are not as yet any specific guidelines or land use policies within either the LUB or OCP that reflect

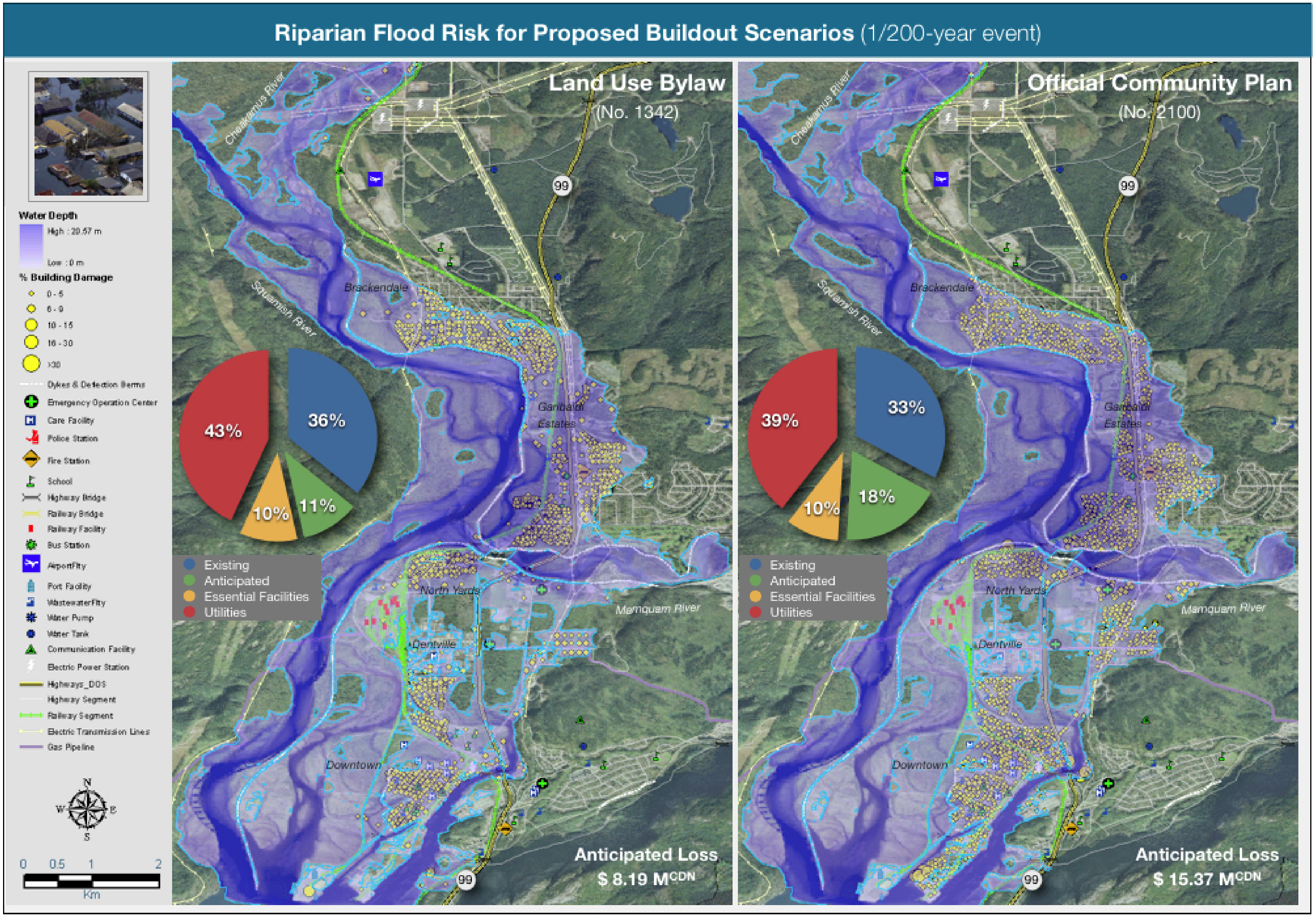


Figure 5-28: Riparian flood risk for hypothetical buildout scenarios that reflect policies of the existing Land Use Bylaw (LUB No. 1342), and the Official Community Plan (OCP No. 2100). See Section 5.5.2 for details of analytical methods used to assess damage potential and anticipated loss.

recommendations stemming from the 1994 Klohn-Leonoff-Farstad flood hazard management plan. As a result, there is significant potential for increased vulnerability and flood risk with future growth and development throughout the valley.

We constructed hypothetical buildout scenarios to model potential flood risks associated with existing LUB and OCP land use guidelines for future development. Results of our assessment are presented in Figure 5-28. Residential and non-residential buildings that are exposed to flooding associated with a 1/200-year event are shown as yellow dots that are scaled according to expected damage potential. We utilized capabilities of the HAZUS flood model to analyze user defined buildings and based our classification of occupancy type on outputs of a CommunityViz buildout analysis using LUB and OCP land use allocation rules .

The land use allocation scenario for existing LUB polices indicates that more than 700 new residential and non-residential buildings could be built on private lands that are exposed to potential damages and losses associated with a catastrophic flood event in which existing dyke systems are over-topped or structurally fail due to scouring and piping. A significant number of these buildings would be located in particularly vulnerable areas of the downtown core, Dentville, North Yards, Garibaldi Estates, and southern Brackendale. Capital stock losses loss associated with this scenario would increase existing levels of hazard risk by \$8.2M^{CDN}, which represents 11% of the total potential loss profile of \$77.2M^{CDN}.

Significantly higher levels of residential density and mixed-use development in existing neighbourhood nodes are associated with the OCP growth management plan. While the land use allocation policies are intended to promote principles of Smart Growth and sustainable development, an unintended consequence is that more than 2,300 residential and commercial buildings could potentially be located in areas exposed to damages associated with a 1/200-year flood. Of these, more than 450 buildings would be situated in areas where flood depths are expected to be 1m or more. Capital stock losses loss associated with this scenario would increase existing levels of hazard risk by ~$15.37 million, which represents 18% of the total potential loss profile of $77.21 million.

5.6.3.4 Earthquake Risk

The 2005 National Building Code of Canada (NBCC) establishes recommended safety thresholds and provides design guidelines for seismic loading to reduce physical vulnerabilities of new buildings constructed in seismically active areas. The code is based on the best scientific and engineering information available on earthquake hazard potential (extent, magnitude, and probability) and susceptibility to structural damage. The guidelines are updated on a regular basis through input provided by the Earth Sciences Sector of Natural Resources Canada (Adams and Atkinson, 2003) and the Canadian National Committee on Earthquake Engineering (Heidebrecht, 2003). Under terms of the Constitution Act, regulation of buildings in Canada is the responsibility of provincial and territorial governments who delegate authority for implementation and enforcement of National Building Code guidelines to local municipal governments and their staff. The recommended safety threshold for engineered structures is defined by ground shaking intensities that reach or exceed a 2% in 50-year probability of occurrence (1/2475 years).

We used the 2005 NBCC intensity thresholds to model anticipated damage and loss associated with buildout scenarios for both the existing LUB and the OCP growth management plan. Results of our analysis are presented in Figure 5-29. The dots correspond with hypothetical residential dwelling units exposed to earthquake ground motion hazards, scaled by the level of expected damage.

The LUB buildout scenario allocates nearly 6,000 new residential dwelling units in the District over the next 20–30 years. The pattern of settlement is more dispersed and less dense than OCP buildout scenario. As a result, the exposure of new building stock to ground shaking hazards is higher than it is for the OCP scenario. Anticipated capital stock losses associated with a 2% in 50-year earthquake scenario are estimated to be $179.5 million. This represents 41% of the total expected loss at buildout of $433.3 million and is comparable in proportion to levels of hazard risk for existing buildings in the District

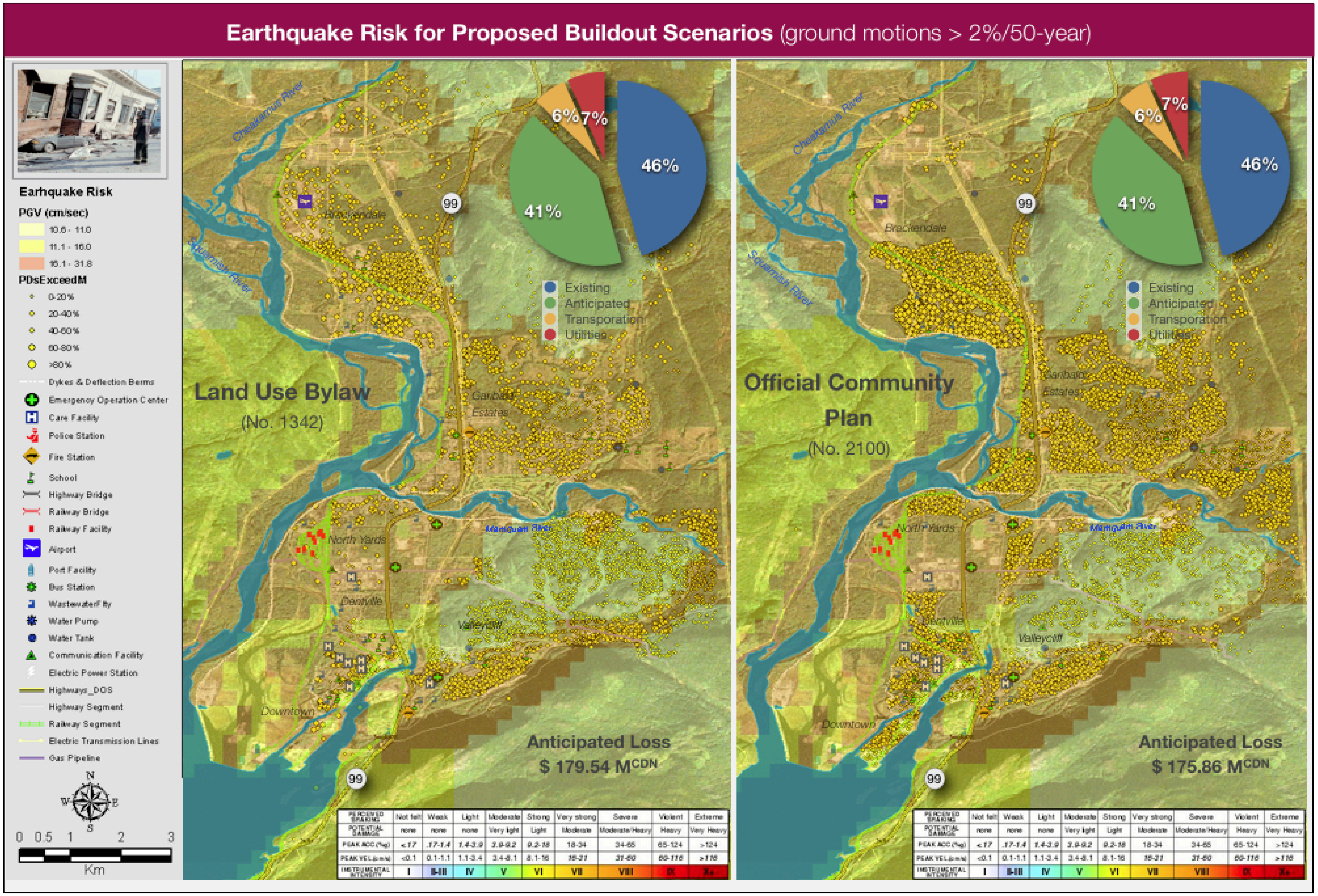


Figure 5-29: Earthquake risk for hypothetical buildout scenarios that reflect policies of the existing Land Use Bylaw (LUB No. 1342), and the Official Community Plan (OCP No. 2100). See Section 5.5.3 for details of analytical methods used to assess damage potential and anticipated loss.

(46%).

The OCP growth management scenario results in a significantly higher number of residential dwelling units. However, the overall levels of anticipated loss are comparable suggesting that overall patterns of settlement are more favourable with respect to potential ground shaking hazards. Anticipated losses associated with a 2% in 50-year earthquake scenario are estimated to be $175.9 million. As with the LUB scenario, the additional levels of risk represents 41% of the total expected loss at buildout of $429.6 million and is comparable in proportion to levels of hazard risk for existing buildings in the District (46%).

5.6.3.5 Comparative Disaster Risk Profiles

Scenario-based risk modelling provides a capability to assess changing patterns of vulnerability associated with anticipated growth and development in Squamish. We compiled results of our analysis to generate risk profiles that reflect anticipated trends in disaster risk over a 20–30 year time interval that matches the strategic planning framework for the Official Community Plan (see Figure 5-30).

As outlined in preceding sections, there are important differences between the two disaster risk profiles in terms of spatial patterns of physical vulnerability and losses sustained as a result of specific hazard events. However, the overall trend is remarkably similar for both land use allocation scenarios. Probable losses associated with the LUB buildout range from $35.6 million for a 1/20-year riparian flood scenario to $433.3 million for ground motion intensities corresponding to the 2% in 50-year design earthquake referenced in the 2005 National Building Code. The combined average annual loss for the portfolio of eight hazard scenarios is $3.06 million. Probable losses associated with the OCP buildout range from $40.9 million for high-probability/low-consequence flood events to $429.6 million for a catastrophic near-source earthquake. Average annual loss for the OCP risk profile is $3.37 million.

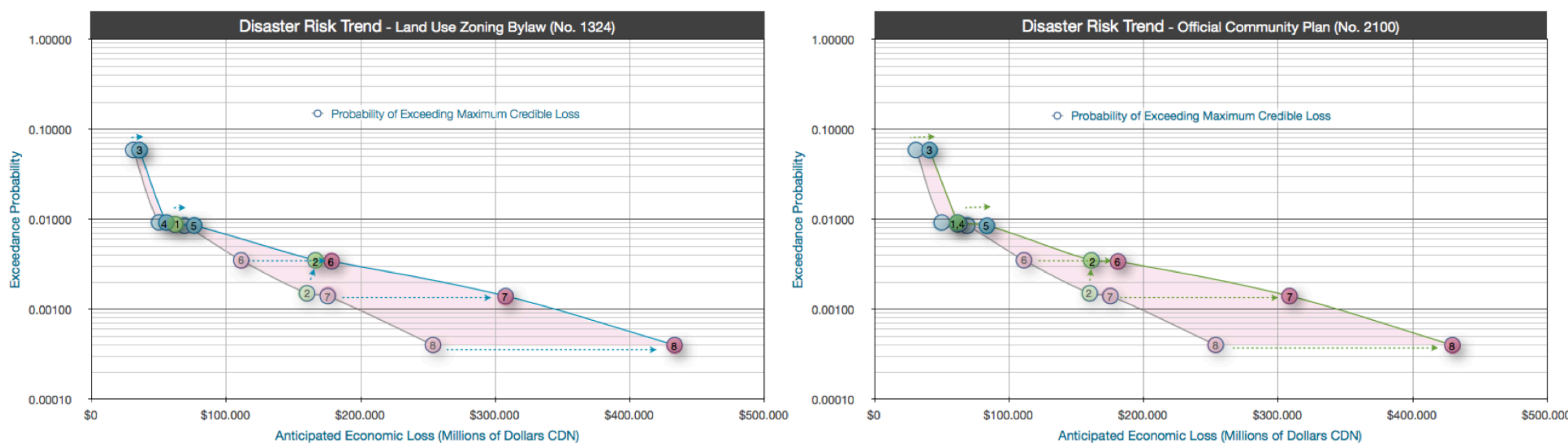


Figure 5-30: Comparative disaster risk profiles reflecting anticipated losses associated with existing conditions and projected future patterns of growth and development outlined by the existing Land Use Bylaw (LUB) and the updated Official Community Plan (OCP) for the District of Squamish. Profiles were developed using methods described in Section 4.3.5.3 for a portfolio of eight natural hazard event scenarios that characterize the risk environment for the region. Risks for the combined portfolio of hazard threats are described in terms of the probability of exceeding a maximum credible loss in terms of financial resources.

5.6.4 Mitigation Alternatives and Disaster Risk Reduction

Disaster risk management for the District of Squamish is a process of balancing the potential opportunities that come with growth and development with the uncertain negative consequences of living in an active mountain setting. Over the past several decades, the community has been proactive in managing natural hazard risk by investing significant time and resources in establishing structural mitigation strategies that focus on the reduction of physical vulnerability and consequent risk.

In this section, we review the potential benefits gained from a blend of four types of mitigation strategies. They include: i) protective barriers to deflect catastrophic debris flow materials away from buildings and critical lifeline infrastructure on the Cheekye Fan, ii) flood-proofing measures for residential and non-residential buildings exposed to inundation in the event that existing dyke structures are compromised by overtopping or structural failure, iii) seismic retrofitting of older single-family wood frame buildings that were constructed prior to the introduction of modern building codes in 1975, and iv) risk avoidance through proactive land use planning.

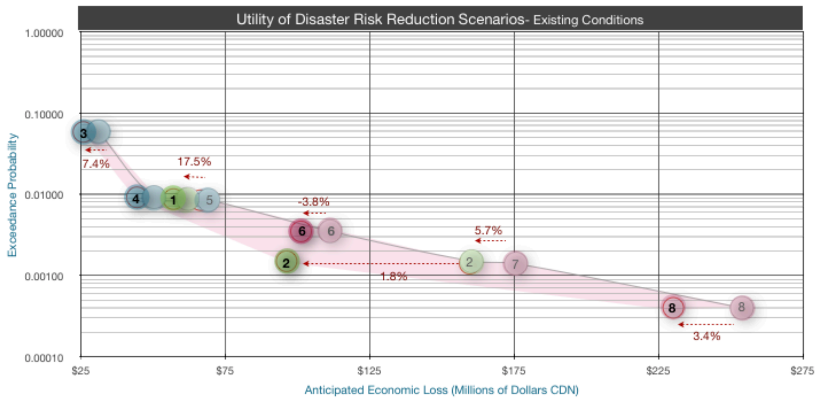
The strengths and weaknesses of mitigation scenarios are assessed in terms of reductions in physical vulnerability, losses avoided (effectiveness), and the expected annualized rate of return on investment (resource efficiency). It is acknowledged that a probabilistic analysis of expected rate of return over variable-year time horizons would likely yield a more realistic assessment of resource efficiency for the proposed mitigation scenarios. For purposes of this discussion, we compare the expected average annual rate of financial return over a 50-year time interval. For comparison, the expected annual return on investment for mutual fund investments in moderate risk portfolios over a 10-year period typically ranges between 5% and 10%. Results of our assessment are presented in Figure 5-31.

5.6.4.1 Landslide Deflection Berm

The Kerr Wood Leidal study (2003) of debris flow hazards on the Cheekye Fan included a feasibility assessment for construction of a series of deflection berms to protect community assets exposed to potential impacts and consequences of a catastrophic landslide event. In order to prevent overtopping for a design event with an expected volume of >5.4 Mm^3, the resulting deflection berm segments would need to have a height of 3–7 m. The proposed mitigation measures include a primary east-northeast-trending berm to protect residential neighbourhoods of northern Brackendale, and a series of smaller berm segments to protect critical infrastructure and residential neighbourhoods in the central and northern portions of the fan. Siting and design criteria considered a range of issues, including environmental impacts, potential transfer of risk, construction costs and implementation. The study concluded that the proposed deflection berm scheme would be effective in protecting community assets in the Brackendale area with no significant transfer of risk. The anticipated costs of mitigation range from $13.6 million to $22.71 million depending on the availability of local fill materials to construct the deflection berms and the size of the design event used to establish minimum height requirements.

We examined the overall effectiveness of the proposed deflection berm strategy in terms of reduced levels of physical vulnerability and benefits gained for current conditions (see Figure 5-31). In this context, benefits gained are represented as losses avoided by implementing the proposed deflection berms and are measured as a financial return on investment. For a design event of 5.4 Mm^3, the deflection berm strategy would provide structural protection for ~278 buildings with a total asset value of $171.7 million. Losses avoided as a result of mitigation are assessed at $64.05 million, representing a 52% reduction in hazard risk. For a design event of 2.8 Mm^3, the deflection berms would provide structural protection for ~2 buildings with an estimated reduction in anticipated losses of $4.9 million.

Overall efficiencies of the deflection berm strategy were assessed in terms of an expected financial return on investment using methods describe in Section 4.4.2. The rate of return is defined as the ratio of the benefits gained as a result of investing in the mitigation measure and the associated costs incurred. An average mitigation cost of $18.2 million was used to represent combined capital expenditures of constructing the deflection berms and the indirect economic costs of implementation and ongoing maintenance. For a design event of 5.4 Mm^3, the expected rate of return on investment over a 50-year time interval is estimated to be 1.8%. The equivalent rate of return on investment for the smaller 2.8 Mm^3 event is 0.4%.



	Hazard Event (Ei)	Annual probability of occurrence (Pi)	Anticipated loss (Li) in millions of dollars M^{CDN}	Anticipated loss (Li) with mitigation M^{CDN}	Probability of exceeding loss [EP(Li)]	Average Annual Loss (E[L]=(p*Li) in millions of dollars M^{CDN}	Average Annual Mitigated Loss (E[L]=(p*Li) in millions of dollars M^{CDN}
8	2%/50-year earthquake: existing	0.00040	$253.740	$229.991	0.00040	$0.101	$0.092
7	5%/50-year M7.3 earthquake: existing	0.00100	$175.490	$159.475	0.00140	$0.175	$0.159
2	5Mm3 Debris Flow: existing	0.00010	$160.118	$96.067	0.00150	$0.016	$0.010
6	10%/50-year earthquake: existing	0.00200	$111.140	$101.076	0.00350	$0.222	$0.202
5	1/200-year flood : existing	0.00500	$69.025	$66.285	0.00848	$0.345	$0.331
1	3Mm3 Debris Flow: existing	0.00028	$61.876	$56.907	0.00875	$0.017	$0.016
4	1/100-year flood : existing	0.00045	$50.164	$44.250	0.00920	$0.023	$0.020
3	1/20-year flood : existing	0.05000	$30.909	$25.696	0.05874	$1.545	$1.285
	Combined Average Annual Loss for the Hazard Portfolio					**$2.446**	**$2.115**
	Combined Average Return on Investment over a 50-year period					**7.16**	

Hazard Event (Ei) for P^{AA} = 1 year	Anticipated Building Loss loss (Li) in millions of dollars^{CDN}	# Buildings Mitigated	Total Asset Value of Mitigated Building Stock	MItigation Costs	Effectiveness	Losses with Mitigation in Place for P^{AA}=1	Anticipated Losses Avoided (benefits)	Expected Averge Annual Rate of Return on Investment
2%/50-year earthquake: existing	$197.910	2007	$457.273	$13.72	12.00%	$174.16	$23.75	173.12
5%/50-year M7.3 earthquake: existing	$133.460	2007	$457.273	$13.72	12.00%	$117.44	$16.02	116.75
5Mm3 Debris Flow: existing	$123.017	278	$171.673	$18.16	52.07%	$58.97	$64.05	352.78
10%/50-year earthquake: existing	$83.870	2007	$457.273	$183.55	12.00%	$73.81	$10.06	5.48
1/200-year flood : existing	$17.758	87	$96.936	$15.97	15.43%	$15.02	$2.74	17.16
3Mm3 Debris Flow: existing	$32.688	2	$4.969	$18.16	15.20%	$27.72	$4.97	27.37
1/100-year flood : existing	$15.063	78	$88.632	$14.57	39.26%	$9.15	$5.91	40.58
1/20-year flood : existing	$12.168	74	$85.791	$14.10	42.84%	$6.96	$5.21	36.98
Hazard Event (Ei) for P^{AA} = 50 year	**Anticipated Building Loss loss (Li) in millions of dollars^{CDN}**	**# Buildings Mitigated**	**Total Asset Value of Mitigated Building Stock**	**MItigation Costs**	**Effectiveness**	**Losses with Mitigation in Place for P^{AA}=50**	**Anticipated Losses Avoided (benefits)**	**Expected Averge Annual Rate of Return on Investment**
2%/50-year earthquake: existing	$3.920	2007	$457.273	$13.72	12.00%	$3.45	$0.47	3.43
5%/50-year M7.3 earthquake: existing	$6.512	2007	$457.273	$13.72	12.00%	$5.73	$0.78	5.70
5Mm3 Debris Flow: existing	$0.614	278	$171.673	$18.16	52.07%	$0.29	$0.32	1.76
10%/50-year earthquake: existing	$6.512	2007	$457.273	$13.72	-7.96%	$7.03	-$0.52	-3.78
1/200-year flood : existing	$6.129	87	$96.936	$15.97	45.68%	$3.33	$2.80	17.53
3Mm3 Debris Flow: existing	$0.451	2	$4.969	$18.16	15.20%	$0.38	$0.07	0.38
1/100-year flood : existing	$7.234	78	$88.632	$14.57	50.04%	$3.61	$3.62	24.84
1/20-year flood : existing	$7.469	74	$85.791	$14.10	14.05%	$6.42	$1.05	7.45

Figure 5-31: An assessment of disaster risk reduction scenarios for a portfolio of debris flow, riparian flood, and earthquake hazards in the Squamish Valley. Mitigation strategies are assessed in terms of reducing physical vulnerability and associated hazard risk (effectiveness) and expected financial returns on mitigation investments (efficiency).

5.6.4.2 Flood Protection

Strategies to reduce risks associated with flooding in settled areas generally involve the construction of dykes, levees and pumping facilities designed to protect community assets up to a minimum threshold of safety, and additional site-level floodproofing measures designed to protect individual homeowners and businesses in the event that community-wide dyke systems fail to perform as expected. Design guidelines in British Columbia are based on the spatial extent and expected flood levels associated with an event frequency of 1/200 years. Spatial extent is defined by a floodplain boundary that is intended to limit future growth and development in areas that are susceptible to flood inundation, and by flood construction levels (FCL) that establish a minimum threshold of safety (elevation above flood line) for engineered structures in the floodplain.

The District of Squamish maintains an extensive network of dykes and related structural floodproofing measures that are designed to accommodate river flows triggered by extreme weather events with an expected return period of up to 1/200 years. The probability of such an event occurring over a 50-year time period is ~22%. The intent of the dyke system is to keep floodwaters contained within established river floodways, and away from community assets. To this end, the District and provincial agencies have invested millions of dollars over the years to upgrade and maintain this critical threshold of safety. In the past two years alone, the District has invested in geotechnical assessment studies, extensions of the sea dyke to protect from storm surge, replacement of aging pumps to increase flow capacities, drainage works to improve storm water management, and the acquisition of portable pumps and generators to increase capability for just-in-time mitigation during an event. Although essential, these measures do not alter the fundamental design characteristics of the dyke system, which include height above grade and physical resistance to floodwaters associated with a 1/200-year flood event.

Peak flows on the Cheakamus and Squamish rivers during the 2003 flood were equivalent in magnitude to an event with an expected return interval of 1/100 years, yet nearly overtopped the dyke system. Seepage and piping of floodwaters beneath berm structures has been observed in several locations during recent events, and poses a significant threat to the structural integrity of the dykes during high water events (Thurber Engineering LTD, 2008; Baumann, 2010; Ghuman, 2010). There is no question that raising freeboard height and increasing structural resistance of the dyke system would increase the level of protection against river floods and reduce the risks associated with future events. However, structural protection alone does not rule out the potential of unexpected failure or address the underlying physical vulnerability of living on an active floodplain.

The flood scenarios considered as part of this study are based on the premise that the dykes are fallible and could be compromised by overtopping or catastrophic collapse (Klohn Leonoff LTD & Graham Farstad, 1994). We therefore focus our attention on site-level mitigation measures of dry and wet floodproofing. Dry floodproofing is a site-level mitigation strategy designed to ensure the entire building is resistant to inundation by raising the foundation and first floor elevation of the structure above expected levels of flooding. Wet floodproofing allows lower levels of a building to be inundated while keeping habitable portions of the structure above the flood line.

We assessed the benefits of site-level mitigation by modelling reductions in physical vulnerability and losses avoided as a result of investing in floodproofing measures. The effects of mitigation were analyzed by adjusting first floor heights of those buildings exposed to extreme flood hazards (>20% damage potential), then re-running the HAZUS flood model to assess changes in damage state and anticipated loss. For a 1/200-year flood event, site-level mitigation would provide protection for 87 buildings with a combined asset value of ~$97 million. Losses avoided as a result of mitigation are estimated to be ~$2.7 million, representing a 15% reduction in overall hazard risk. The effectiveness of floodproofing for smaller magnitude events is even greater (39–42%) with losses avoided that range from $5.9 million for a 1/100-year event to $5.2 million for a 1/20-year event.

The expected rate of return for investing in site-level flood mitigation varies as a function of hazard intensity. Mitigation costs were assessed on the basis of building type and area using guidelines established by FEMA (2001). For a 1/200-year flood event, the mitigation costs are $16 million with an expected rate of return over 50 years of 17.5%. Mitigation costs for a 1/100-year flood event are $14.6 million with an expected rate of return over fifty years of 25%. The cost-effectiveness of investing in floodproofing measures is diminished for higher-probability/lower-consequence events with an expected rate of return of 7.5% for a 1/20-year flood.

An independent analysis of flood mitigation alternatives for Squamish (Wein *et al.*, 2007) suggests that capital investment in community-wide dyke systems would likely yield positive returns for a 1/200-year design event, but is not an efficient choice for managing more frequent, smaller events. Study results suggest that site-level mitigation through floodproofing and/or relocation of existing structures offers a more efficient choice for managing high-probability/low-consequence events in the near term, and has the potential to yield equivalent or higher rates of return for future growth and development.

5.6.4.3 Seismic Retrofit

While implementation of 2005 NBCC guidelines will likely reduce the physical vulnerability of new buildings exposed to threats of moderate to strong earthquakes (Swan, 1999), the measures are not retroactive and do not remove the potential for significant structural damage (residual risk) in areas susceptible to extreme local ground shaking. The decision to proactively screen and retrofit buildings constructed prior to 1975 and increase the seismic resilience of operational and functional components of buildings situated in earthquake prone urban centres rests with local municipal and regional jurisdictions acting on behalf of provincial and territorial government mandates. It is at this level of decision making that hidden vulnerabilities and risks associated with continued growth and development in hazard-prone areas are ultimately negotiated and decided. The District has not yet developed policy recommendations for mitigating seismic threats to older buildings that do not meet current NBCC safety thresholds.

The effectiveness of mitigating earthquake hazards through a program of seismic retrofitting was evaluated by upgrading design levels for older building stock to a level of safety consistent with the 2005 NBCC guidelines, then re-running the HAZUS earthquake model to assess changes in damage state and anticipated loss. Although suitable for high-level assessment, this approach is not appropriate for evaluating the costs and benefits of mitigation at a site level (FEMA, 2010). A detailed analysis of the benefits and costs of investing in seismic retrofitting of individual structures would involve simulating changes to building response by adjusting capacity parameters (design strength, elastic period, etc.) and comparing the performance of pre- and post-retrofit states. This level of analysis requires the judgment of a qualified engineer to modify building capacity parameters on a site-by-site basis and was beyond the scope of this study.

As documented in our assessment of earthquake risk, the pattern of damage is influenced primarily by the proportion of older wood frame structures situated in low-lying areas of the valley that were constructed prior to the introduction of modern building codes and seismic design guidelines in the mid-1970s. For a 2% in 50-year design earthquake, seismic retrofitting would provide structural protection for ~2000 buildings, with an estimated asset value of $457.3 million. Losses avoided as a result of mitigation are estimated to be $23.8 million, representing a 12% reduction in hazard risk from pre- to post-retrofit states. Risk reduction levels for smaller-magnitude earthquake scenarios are comparable. Losses avoided as a result of mitigation range from $10.1 million for a 2% in 50-year event to $16 million for the 5% in 50-year event.

Overall efficiencies for upgrading older building stock to current safety thresholds (2005 NBCC) were evaluated on the basis of an expected financial return on investment over a 50-year period for earthquake scenarios of varying intensity. The cost of mitigation for standard wood frame buildings is estimated to be 2–3% of the total replacement value (Porter *et al.*, 2006), which works out to an overall investment of $13.7 million for the full portfolio of mitigated buildings. The expected return on investment for a 2% in 50-year design earthquake is estimated to be 3.4%. For smaller-intensity earthquakes, the expected return on investment ranges from a high of 5.7% for a 5% in 50-year event to a low of -3.8% for a 10% in 50-year event. Although rates of return are relatively small, they are comparable with results of an empirical study in California that indicates low cost-effectiveness for seismic retrofit investments for older wood frame buildings (Porter *et al.*, 2006).

5.6.4.3 Risk Avoidance Through Land Use

The principle of risk avoidance through land use is to reduce underlying physical vulnerabilities and associated socio-economic losses by relocating exiting structures situated in areas of extreme hazard threat, and by guiding new development into areas that are considered out of harm's way. Relocation involves the acquisition of properties in areas that are considered safe for the use intended, physical transportation of salvageable structures and/or the construction of new buildings, and restoration of the old site. Reducing risks associated with future growth and development involves the adoption and implementation of land use policies that govern the location, density, and intended use of buildings and supporting infrastructure. Regulatory bylaws, such as development permit areas, are incorporated into local zoning ordinances to guide the location, form and function of proposed development. Longer-range strategic land use planning guidelines can encourage future growth and development in areas where risks are considered tolerable through a blend of density transfer and infrastructure servicing policies (Burby, 1998; Burby *et al.*, 2000; Berke *et al.*, 2007). Both approaches are effective in reducing intrinsic patterns of physical vulnerability and associated socio-economic loss in a community, and have the potential to increase overall disaster resilience over time.

We evaluated the effectiveness of land use planning as a risk reduction strategy in Squamish by comparing the risks associated with hypothetical buildouts of the current Land Use Bylaw and the Official Community Plan (see Section 5.6.3). Land use guidelines that restrict new residential development in hazard-prone areas of the Cheekye Fan are effective in reducing potential future losses for both a catastrophic 5.4 Mm^3 debris flow event, and the smaller 2.8 Mm^3 event.

Efficiencies gained for earthquake risk are minimal for both the existing LUB and the updated OCP land use policies. However, the increased densities of the OCP have a negative effect on flood hazard risk by increasing anticipated losses in the designated 1/200-year floodplain by as much as $14.8 million. Although the cumulative impacts of LUB and OCP land use policies are comparable in terms of respective risk profiles (see Figure 5-31), the effect on spatial patterns of risk within the District are profound. Preliminary results of our study suggest that land use policies that are guided by knowledge of potential impacts and consequences have the potential to alter fundamental patterns of vulnerability in the District. The benefits gained by encouraging future growth and development in areas that meet or exceed tolerable thresholds of risk are significantly greater than the benefits gained through conventional structural mitigation. Though we were not able to assess the cost-effectiveness of refining existing land use policies, it is likely to be significant and worth the investment in terms of planning and implementation.

5.6.5 A Framework for Negotiating Thresholds of Risk Tolerance

The process of determining thresholds of risk tolerance through integrated assessment and multi-criteria analysis lies at the nexus of disaster mitigation planning and governance. It is an iterative and ongoing process of appraisal, analysis and evaluation whereby policy objectives (targets) and available knowledge about the risk environment (indicators) are used to guide the adjustment of boundaries between what is considered intolerable tolerable, and acceptable. It defines the realm of planning and policy development and is the trail of reasoning and deliberation that connects knowledge with action.

As defined by the International Risk Governance Council (2008), risks that are considered intolerable are those in which the potential consequences are extreme and there is either a lack of knowledge to constrain complexities and uncertainties in the system, or there is ambiguity about the effectiveness, efficiency or equity of proposed mitigation measures. Tolerable risks reflect the willingness to invest in risk-treatment measures and balance trade-offs between competing management objectives to pursue a particular course of action for the benefit it may carry. Finally, acceptable risks are those in which anticipated benefits of a proposed course of action outweigh any

CHARACTERIZATION OF RISK TOLERANCE THRESHOLDS			
THRESHOLD	RISK PROFILE	RISK TREATMENT	RESPONSIBILITY
Acceptable	The potential for negative consequences of a risk scenario exists, but is within negotiated thresholds of acceptability and is balanced by potential opportunities that promote social, economic and environmental vitality.	Manage risk through transfer of liability via financial insurance markets, disaster relief funding and/or by measures that increase community resilience.	Managed on a voluntary basis by private and public sector organizations, and by individuals.
Tolerable	The potential for negative consequences of a given risk scenario exceeds thresholds negotiated through the risk management process, but can be reduced as low as resonably practicable (ALARP) with available resources using best practices.	Reduce vulnerability by increasing technical, organizational,social and economic resilience through a blend of structural mitigation, early warning systems, land use and development guidelines, emergency preparedness and planning, and risk transfer via financial insurance markets and/or disaster relief funds.	Pubic Sector regulatory agencies, emergency preparedness and community planning agencies at Provincial, regional and Municipal levels; Private sector corporate risk managers
Intolerable	The potential for negative consequences of a given risk scenario exceeds thresholds of disaster resilience negotiated through the risk management process, and can not be effectively reduced with available resources.	Reduce vulnerability by minimizing and/or restricting exposure to natural hazard threats through: limited access, land use zoning, and/or re-location of people and community assets	Public sector: regulatory agencies at Provincial, regional and/or Munucipal levels

Table 5-13: A characterization of risk tolerance thresholds that reflect recommendations of the International Risk Governance Council.

potential negative consequences. They are characterized by common knowledge and understanding of cause-effect relationships in the system, low uncertainty, and agreement on policy goals and anticipated outcomes. With acceptable risks, the management of hazard threat is considered routine, subject to due diligence and bounded by standard protocols. Table 5-13 summarizes the criteria used to establish thresholds of risk tolerance.

In accordance with international guidelines, the Pathways framework adopts the ALARP principle (As Low as Reasonably Practicable) to help guide users in making decisions about what may constitute a tolerable threshold of risk for a given region or community. (Bouder *et al.*, 2007; International Risk Governance Council, 2008). Simply defined, the ALARP principle is about weighing measured or perceived risk against the sacrifice needed to further reduce it to levels that are considered tolerable by those who bear the consequence. The decision to reduce target thresholds of risk through investment in disaster mitigation is weighted in favour of public health and safety. If it can be shown that risks to life assumed in pursuing a proposed course of action are "grossly disproportionate" to potential benefits gained, then the onus is on the responsible party to reduce the potential for injury or loss of life through mitigation (UK Health and Safety Commission, 2001). Judgment of what may constitute a tolerable and practicable threshold of risk is informed by knowledge about potential impacts and consequences and available resources for mitigation, but is ultimately governed by local values that will determine who and what are considered most vulnerable and in need of safeguarding. Our assessment of disaster risk in the District of Squamish provides a characterization of potential impacts and consequences for a portfolio of natural hazard threats that are of concern to the community. It serves as a basis for informing choices about key risk decisions in the community and for navigating a path forward.

Target criteria and indicators identified by community working group members were used to measure the performance of proposed disaster mitigation strategies with respect to desired levels of hazard protection, public safety, socio-economic security, resource efficiency, and social equity. They provide an internally coherent set of risk metrics that can be used by emergency managers and land use planners to make informed decisions about mitigation choices and their likely consequences. They also provide a framework for planners to assess thresholds of risk tolerance that are consistent with policy goals and objectives of the Official Community Plan, and that promote longer-term goals of disaster resilience and sustainable development.

5.6.5.1 Levels of Hazard Protection

Level of protection refers to the structural robustness and effectiveness of mitigation measures to ensure minimum thresholds of safety and security for a community or region. From a policy perspective, structural mitigation seeks to reduce the physical impacts and associated risks of a hazard threat through protective measures that limit exposure or increase structural resistance of the built environment.

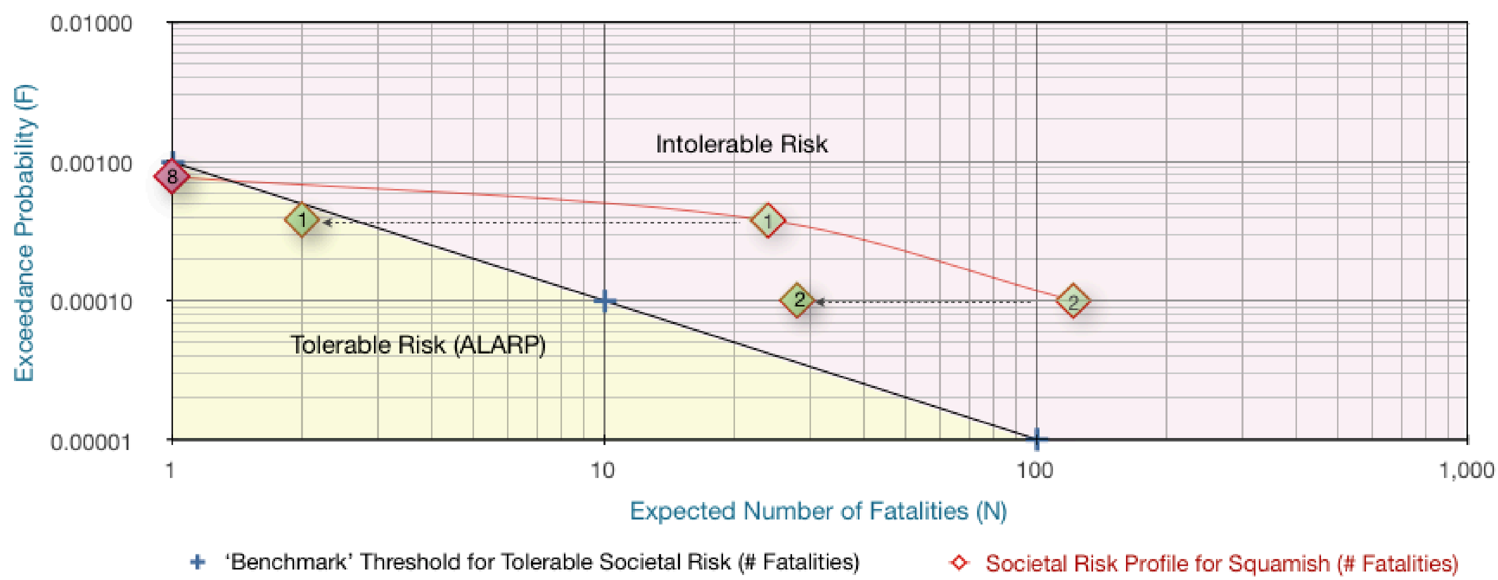
The construction of proposed deflection berms on the Cheekye Fan and the implementation of additional floodproofing and seismic retrofitting measures have the potential to significantly increase current levels of structural protection for community assets. The relative effectiveness of these strategies can be measured as the ratio of benefits gained with mitigation divided by the anticipated capital losses that would have been sustained without mitigation. Benchmark values range from a minimum of 12% for seismic retrofitting of older wood frame buildings that are susceptible to damage from ground shaking associated with a design earthquake, to a maximum of 52% for construction of a deflection berm to protect against the impacts of a catastrophic 5.4 Mm^3 debris flow event on the Cheekye Fan. The effectiveness of floodproofing increases as a function of inundation level, ranging from 15% for lower-probability/higher-consequence events (1/200-year flood), to 43% for higher-probability/lower-consequence events (1/20-year flood).

Establishing a threshold of risk tolerance for future levels of protection will involve a consideration of overall feasibility and the practicality of implementing each of the proposed mitigation strategies. Choices made about hazard-specific mitigation targets (effectiveness) will have implications for public safety and the long-term security of community assets but will need to be balanced against the costs of implementation and ongoing maintenance (efficiency), which are likely to exceed available levels of public funding.

5.6.5.2 Public Safety

As a policy objective, public safety reflects intent to increase the capability of people and systems to withstand and respond to the impacts of a hazard event. Management objectives and performance targets are expressed in terms of indicators that track the extent and severity of injury (probability of injury and fatality), anticipated levels of assistance or intervention required during or immediately after the impact of a hazard event (shelter requirements), and the requirement to provide basic and essential services through emergency management operations.

Thresholds of societal risk are established on the basis of the probability of exceeding a minimum number of fatalities over a range of event frequencies. As illustrated in Figure 5-32, national and international benchmarks for tolerable risk using the ALARP principle are defined by the probabilities of exceeding 1 fatality for higher probability events (1/1,000) , 10 fatalities for events with a probability of 1/10,000, and 100 fatalities for rare but catastrophic events with a probability of 1/100,000 (APEGBC, Australian Geomechanics Society, 2000; 2010).



	Hazard Event (Ei)	Annual probability of occurrence (Pi)	Probable Loss of Life (N) within a group of individuals	Probability of exceeding loss [EP(Li)]	Average Annual Loss N=(p*Li) within a group of individuals
2	5Mm3 debris flow (un-mitigated)	0.00010	122	0.00010	0.012
1	3Mm3 debris flow (un-mitigated)	0.00028	24	0.00038	0.007
8	2%/50-year earthquake	0.00040	1	0.00078	0.000
	Combined Average Annual Loss for Hazard Portfolio				**0.019**
	Hazard Event (Ei)	Annual probability of occurrence (Pi)	Probable Loss of Life (N) within a group of individuals	Probability of exceeding loss [EP(Li)]	Average Annual Loss N=(p*Li) within a group of individuals
2	5Mm3 debris flow (mitigated)	0.00010	28	0.00010	0.003
1	3Mm3 debris flow (mitigated)	0.00028	2	0.00038	0.001
8	2%/50-year earthquake (mitigated)	0.00040	1	0.00078	0.000

Figure 5-32: Thresholds of tolerable risk for Public Safety. The red line represents the disaster risk profile for existing conditions in Squamish and is defined by the expected number of fatalities associated with earthquake and debris flow events over a range of event probabilities. The black line represents national and international guidelines for what constitutes a tolerable threshold of societal risk (AGS, 2001). The dashed arrows represent the amount of risk that could be reduced by investing in proposed mitigation measures.

Societal risks associated with a 2% in 50-year design earthquake are within the established threshold of tolerable risk for loss of life. However, debris flow risks associated with residential development on the Cheekye Fan for both a 2.8 Mm^3 and 5.4 Mm^3 event exceed tolerable thresholds of risk for existing conditions and warrant consideration for mitigation. The proposed deflection berm strategy would be effective in reducing risks associated with the 2.8 Mm^3 debris flow scenario to within tolerable thresholds, but not for the lower-probability/higher-consequence 5.4 Mm^3 event. Establishing a target that reduces societal risk would require an investment in additional structural protection and/or changes to existing land use policy; both of which would need to be considered in light of what is feasible and considered practicable with available mitigation resources.

5.6.5.3 Socio-economic Security

Socio-economic security reflects intent to increase the integrity and vitality of socio-economic systems following a hazard event. Management objectives and performance levels are expressed in terms of indicators that track direct and indirect losses. Direct losses include anticipated financial consequences and capital costs of repairing or replacing damaged buildings and contents, relocation expenses, and losses to rental and business income incurred as a result of the hazard event. Indirect losses include impacts on quality of life and anticipated upstream and downstream disruptions to employment and income in regional economic sectors. Figure 5-33 illustrates a hypothetical example of how the cumulative risk profile of probable maximum losses might be used to establish thresholds of risk tolerance for Squamish.

Suppose, for example, that the District of Squamish determined that $50 million was a tolerable threshold of risk for managing hazard threats with a frequency of 1/100 years. In order to meet this target, the community could: 1) invest in mitigation measures to address financial consequences of natural hazard threats that exceed the $50 million threshold, thereby assuming risks for a larger portion of the overall portfolio, and/or: ii) transfer residual risk (>$50 million) for higher-consequence flood, landslide, and earthquake events to higher levels through insurance/re-insurance markets and disaster relief funding from higher levels of government.

If $50 million were taken to be a tolerable threshold of loss for the community, then the next phase of negotiation would be to determine how much residual risk to apportion to higher levels of government. Suppose, that the Province of British Columbia determined that it could cover up to $100 million in disaster relief funding for the risk portfolio. This would then determine the level of risk (through disaster relief funding) assumed by the federal government in the event that a major disaster exceeds the capabilities of the Province. In our hypothetical example, the District of Squamish would cover 50 million through local equity markets, with the remaining $200 million covered through some combination of private and public sector investment.

The information gathered as part of this negotiation process is used to inform long-range financial planning at local and regional levels, and provides a means of determining specific levels of tolerable risk that would be born by all stakeholders. Local decisions on tolerable thresholds of risk for individual and community assets will determine capabilities to increase levels of protection and public safety through mitigation investments. However, there are limits to available public funds and the capabilities of higher levels of government to ensure socio-economic security on an ongoing basis. Both require careful consideration of the benefits gained, and the overall efficiencies of longer-term mitigation investments.

5.6.5.4 Resource Efficiency

Resource efficiency reflects the intent to maintain or increase community wealth through investment in risk treatment measures that promote pubic safety and socio-economic security. Management objectives and performance targets are expressed in terms of overall return on investment (ROI) that can be assessed over variable time horizons.

For purposes of this study, we assessed thresholds of financial risk in terms of an expected rate of return over a 50-year time interval. All but one of the proposed mitigation scenarios yield small but positive returns with average ROI values that range from 0.4% for investments in

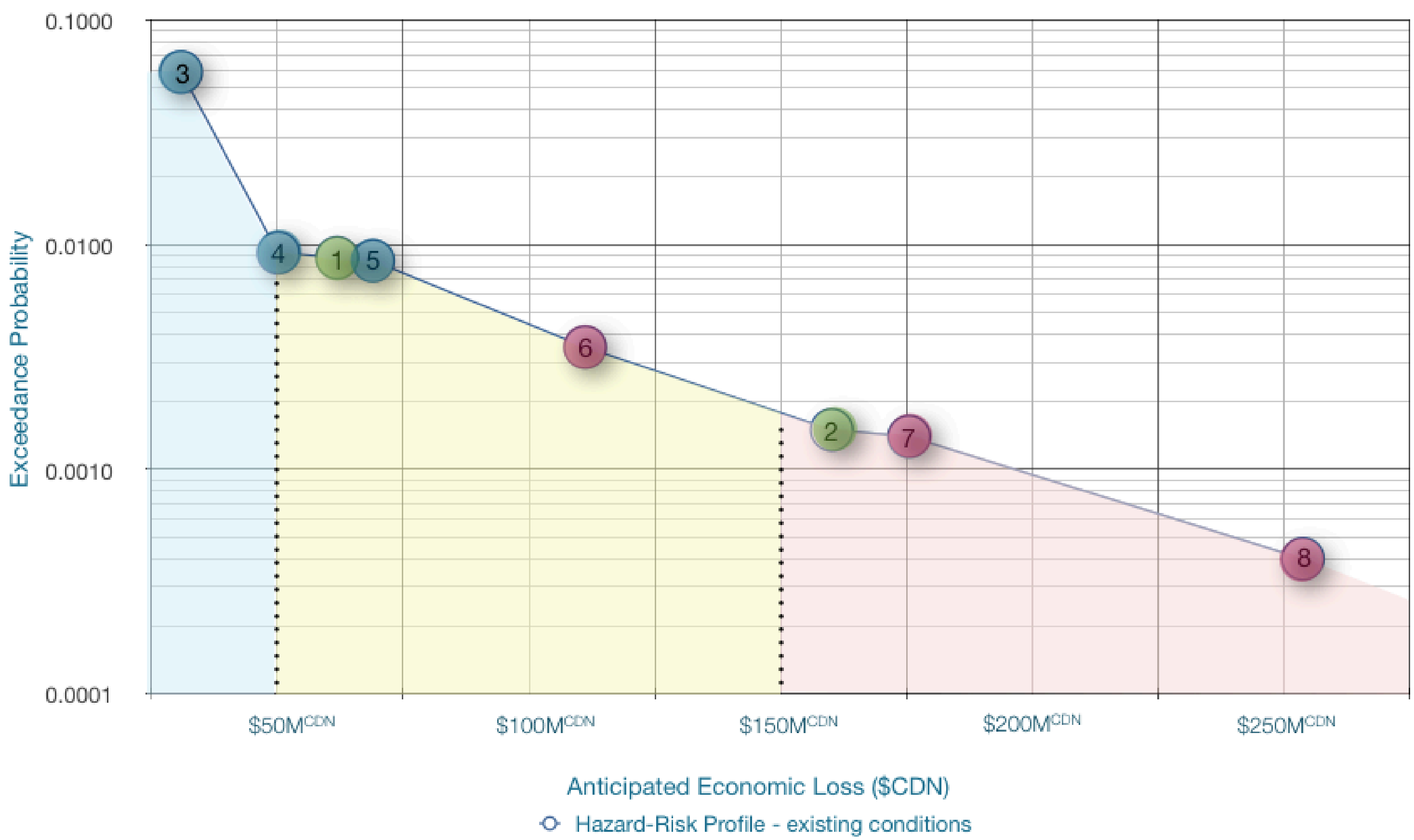


Figure 5-33: Hypothetical thresholds of tolerable risk for the security of socio-economic assets. The area of the disaster risk profile that is shown in blue represents a tolerable threshold of risk for that level of government responsible for community assets on the ground. Areas in shades of yellow and red represent portions of the risk profile that are transferred to higher levels of government through a combination of investments in insurance and re-insurance markets and disaster relief funding.

deflection berms to mitigate the impacts of a 2.8 Mm^3 debris flow event, to 25% for investments in site-level floodproofing measures to mitigate the impacts of high-intensity floods that exceed a 1/100-year design event. These rates are comparable to those determined for proposed seismic retrofit programs in the State of California, and for mitigation strategies that have been proposed to address disaster risks in developing countries. For comparison, recall that the expected annual ROI for mutual fund investments in moderate risk portfolios over a 10-year period typically range between 5–10%.

Judgements about tolerable thresholds of financial risk typically involve a balance of trade-offs between competing policy objectives of utility and equity. If the priority is to optimize the performance of public funds invested in disaster mitigation, then decisions will likely favour those proposals that optimize expected returns on mitigation investment. These tend to be proposals that address hazard risks that are well-defined in terms of cause-effect relationships (low level of uncertainty) and in which safety thresholds are clearly defined by regulatory standards or best practice guidelines. If the priority is to reduce levels of societal risk (fatalities) and to ensure the security of private or public assets within the community at large, then local governments might be willing to accept a lower rate of return on mitigation investments to ensure a balanced performance between social, economic, and environmental imperatives. The decision-making process ultimately involves a balance of trade-offs between performance-based targets of effectiveness and efficiency, and value-based targets that address quality of life and issues of social justice (Bouder *et al.*, 2007).

5.6.5.4 Social Equity

As a public policy objective, equity reflects the intent to establish and maintain a balance in the distribution of risk across all sectors and demographic elements of a community, including individuals and groups of an existing population and those of future generations. Management objectives and performance targets are expressed in terms of physical exposure to hazard threats and proximity to emergency services, the agency or capacity of individuals and groups to make decisions that will directly influence their own well-being, and the ability of these individuals and groups to cope with the impacts and consequences of a disaster event.

Results of our social vulnerability analysis (see Section 5.5.4) make evident existing patterns of social disadvantage in the District of Squamish, and offer a baseline for assessing trade-offs between policies that focus on performance-based targets of effectiveness and efficiency. Patterns of social disadvantage are known to be dynamic and likely to change over periods of 5–10 years (Andrey and Jones, 2008). Levels of social disruption can be influenced by abrupt changes in regional and global financial markets, by political instability, and by physical changes in settlement patterns that are driven by migration, growth, and development (Wisner, 2003; Wisner, 2004; Masuda and Garvin, 2006; Meyers, 2007). Local decisions about tolerable thresholds of social equity involve an ongoing assessment of how the community is changing, and the implications of these changes in terms of overall disaster resilience for both existing populations and future generations that will ultimately bear the consequences of incremental risk decisions.

5.6.6 Risk Management Strategy: Next Steps

Results of this study have been presented and discussed with land use planners and the emergency program coordinator for the District of Squamish, and have been formally submitted to municipal council for review and consideration. Although council did provide direction for planning staff to incorporate outputs of the risk assessment study into their final review and update of the Official Community Plan, no decisions have yet been made with respect to moving forward with a review of existing risk management policies.

There are several ways in which the outputs of this study might support further development and refinement of risk management policies for the District of Squamish. The first step in this process would be to transfer available knowledge about the risk environment (hazards, vulnerabilities, and risks) into a form that can be used by District staff to support both operational and longer-term strategic planning functions. This might include access to information on hazard potential to support the review of development permit applications and the capability of using risk scenarios to explore mitigation alternatives for larger comprehensive land use and infrastructure development projects. These same risk scenarios would provide the necessary foundation for pre-event emergency planning, the refinement of existing emergency response and recovery operations, and the development of a comprehensive business continuity plan for the community.

Bridging the gap between knowledge about the risk environment and actionable mitigation strategies is an ongoing challenge that will require further exploration and negotiation of risk tolerance thresholds by the community, and the development of formal policy recommendations for review and consideration by council. Recommendations by District staff could include minor revisions to the existing Land Use Bylaw to limit exposure to and the potential impacts of known hazard threats, the development of formal guidelines and modifications of existing land use policies to reduce vulnerabilities associated with future growth and development, and the development of an integrated risk management strategy that establishes a formal set of policy recommendations for moving forward with mitigation alternatives that will promote longer-term disaster resilience for the community. It could also include further investment in structural mitigation to reduce the potential impacts and associated consequences of known hazard threats.

There is no question that pressures to accommodate existing and anticipated demands for growth and development in the Squamish Valley have the potential to substantially increase the vulnerability and associated risk profile of the community for years to come. At the same time, knowledge gained as part of this study provides a means of anticipating what could happen in the event of a disaster, and the capability to navigate an alternate path forward—one that is informed by scientific insights about potential impacts and consequences and that is governed by what the community considers to be vulnerable and in need of safeguarding. While the people of Squamish continue to work toward principles of sustainability that balance economic, social, and environmental imperatives, it is the landscape itself and the dynamic interactions between human and natural systems that will ultimately determine thresholds of disaster resilience for the community and the region.

5.7 Key Findings and Reflections

A key premise of our work is that case-based research in high-fidelity planning environments will ultimately lead to a better understanding of methods and tools that are required to support risk-based planning at local and regional levels in Canada. Our partnership with the District of Squamish has provided valuable insights on the challenges of risk-based planning in a fast-growing community that is exposed to a wide variety of natural hazard threats. In this section, we summarize key findings and reflections on the case study process and lessons learned.

5.7.1 Establishing Context and Setting Priorities

The degree of correlation between perceived and measured levels of hazard risk in the Squamish Valley reflects a high level of tacit knowledge and expertise among community members that likely comes with the accumulated experience and clear memory of past disaster events. It also reflects understanding about the challenges of living in a dynamic mountain environment that is subject to change without notice. Fundamental patterns of vulnerability in the community were identified early in the risk identification process, as were clear statements of intent with respect to strategies to reduce the impacts and consequences of potential threats through a mix of structural and non-structural mitigation strategies.

Disaster risk management objectives suggested by the working group were considered viable in terms of minimizing potential negative impacts of natural hazard threats. However, it was acknowledged that available financial resources would likely limit choices about any of these policy alternatives. It was also acknowledged that utilizing available private lands to accommodate existing demands and anticipated pressures of continued growth and development would have short-term economic benefits that would likely have political support by local government. Although frustrating to the group, these findings are consistent with other case studies involving the management of societal risks that are characterized by high levels of system complexity, scientific uncertainty, and ethical ambiguity (Renn and Walker, 2008).

5.7.2 Maintaining Balance between Analysis and Deliberation

Most case study projects reported in the literature focus on either the analytic or deliberative aspects of risk-based planning. A significant finding of this project is that failure to integrate these two dimensions of risk can introduce a significant bias in problem framing that has a potential to compromise the evaluation of risk management strategies.

By focusing only on linear cause-effect relationships between natural hazard processes and their expected consequences, there is a danger that outputs of the risk assessment process may overemphasize the hazard threats and direct the evaluation and decision-making process toward issues of utility and the costs and benefits of structural mitigation or risk transfer strategies. By focusing only on social values and preferences, there is a danger that the assessment process may direct the evaluation of mitigation alternatives toward issues of equity without full consideration of physical impacts and their likely consequences to the community overall.

The choice of focus between analysis and deliberation will ultimately be determined by requirements of the planning process, and need not be limited by technical capabilities. While this may seem self-evident from the perspective of an emergency manager or community planner, there is potential for the risk analysis to filter and direct the evaluation of choices and their consequences, thereby undermining the rigor and credibility of the decision-making process.

In exploring a navigable pathway toward disaster resilience, there is also a need to better understand the operational requirements and key risk decisions for both emergency managers and land use planners in reporting results of quantitative risk assessment. This is particularly relevant in the way spatial outputs of a quantitative risk assessment are presented and used by planners and decision makers. Findings of the EU ARMONIA project suggest that hazard potential information is most relevant and useful when presented as separate map layers that depict intensity variations (flood depth, ground shaking, etc.), or as discrete zones that are rated by experts in terms of anticipated damage potential (Greiving *et al.*, 2006a; Greiving *et al.*, 2006b; Margottini *et al.*, 2008). Though we have adopted the guidelines recommended by the ARMONIA project for the representation and mapping of risk, we have not as yet been able to evaluate how this information might be interpreted and used outside the context of this project.

Disaster risk profiles represent a best practice in the insurance industry, but are not widely used in the fields of emergency management or land use planning. Our findings suggest that there is great potential for using disaster risk profiles as a way of framing the risk evaluation process. They provide an accessible and reasonably intuitive method of assessing how current conditions of vulnerability and risk are likely to change over time, and the comparative strengths and weaknesses of mitigation alternatives in the context of a complex multi-hazard risk environment and limited resources. Most importantly, they provide a means of negotiating thresholds of risk tolerance that are transparent, and that can be supported with risk metrics that make evident the linkage between choice and consequence.

5.7.3 Limits of Knowledge

Though we were able to refine existing estimates of flood and earthquake hazard potential, our regional assessment using a HAZUS Level 2 analysis, the results may still not be detailed enough to address specific issues of concern to the District. Detailed geotechnical studies are underway to refine assessments of safety thresholds on existing levee structures in the District. Specific structural weaknesses in existing dyke structures could be used to model failure scenarios and their implications with respect to vulnerability and risk in adjacent low-lying areas.

There is a need to better understand flood hazard potential caused by run-off associated with extreme weather events that appear to be getting more intense and more frequent. We have compiled frequency-magnitude relationships for severe storm events that have resulted in flood events in Squamish, but have yet to establish correlations with corresponding flood depths in the valley to assess corresponding hazard potential.

5.7.4 Risk Assessment as a Strategic Planning Process

Results of our study have validated the importance of integrated assessment modelling and structured decision making processes in negotiating thresholds of tolerable risk and in evaluating strategies of risk reduction. Pathways provides a suitable framework of indicators for evaluating high-level policy goals embedded in the National Disaster Mitigation Strategy for Canada and more specific management objectives established by local and regional governments. The use of synoptic disaster risk indicators is critical in establishing a common understanding of hazard risk and vulnerability.

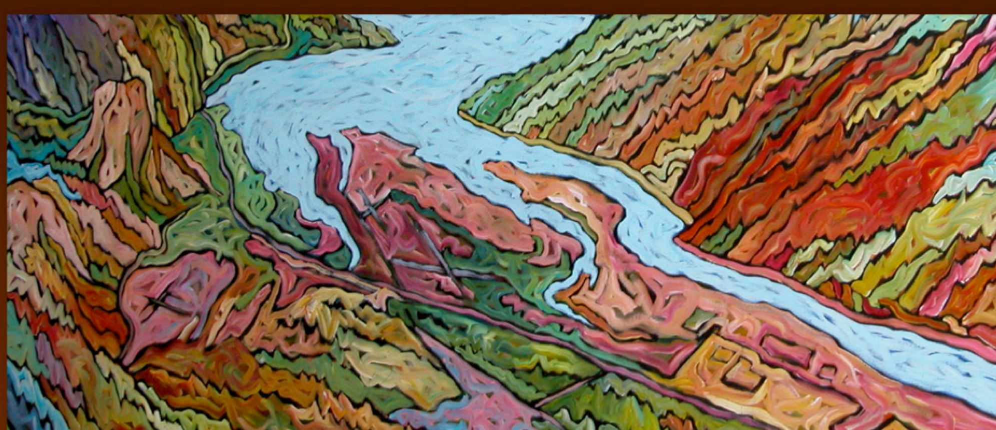
Finally, we have demonstrated the importance of incorporating simple land use modelling techniques into the overall process of risk analysis. The ability to see and explore linkages between land use choices and their consequences in terms of physical and social vulnerability provides the necessary foundation for understanding the dynamics of risk in a community. These models and tools are becoming more accessible for land use planning at local and regional scales. They can be used as part of the routine planning process to examine the implications of past land use policy decisions on current conditions of vulnerability and risk in a community, to establish baseline projections of how existing land use policies may influence future conditions of risk, and to evaluate strategies for managing risk through a blend of mitigation measures that promote disaster resilience and sustainable land use.

pathways

Chapter Six:

Summary

Understanding the risk environment and making decisions to reduce or mitigate risk requires the integration of scientific knowledge, values and community preferences across a diverse group of stakeholders—each with a different perspective and often with a different set of expectations for managing risk. In this context, decision making involves three primary activities: alerting society to potential challenges and problems that lie ahead (diagnosis); defining and assisting in structuring complex problems to facilitate the exploration and negotiation of desirable policy alternatives through analysis and deliberation (decision support); and utilizing scientific knowledge and understanding to help guide action before and after political consensus is attained (assessment).



6. Summary

This final chapter summarizes key outputs of the Pathways study. It reviews the challenges of risk-based planning, the assumptions and expectations that underlie the Pathways framework, and provides an overview of the processes, methods and tools that have been developed to implement the framework in support of local and regional planning.

6.1 The Landscape of Disaster Risk Reduction: Challenges and Opportunities

Risk-based planning is about developing a vision and common understanding of a place in order to anticipate the actions required to achieve a desired set of outcomes—while also minimizing vulnerabilities and potential losses through targeted mitigation efforts that promote longer-term disaster resilience and sustainability. Though straightforward in concept, the path toward disaster resilience can be difficult to navigate in practice.

6.1 1. Paradigms and Paradoxes

The ultimate goals of disaster risk reduction are to save lives, protect property, promote socio-economic security, and preserve the environment. These are among the most important responsibilities of government agencies at all jurisdictional levels. Though concepts of resilience and sustainability are increasingly embedded in policy mandates at all levels of government, the task of navigating a path toward these overarching goals is often left up to individual planners and emergency managers to negotiate on a case-by-case basis.

While it is clear that land use planners and emergency managers each have the potential to influence decisions that will reduce disaster losses and increase the resilience of communities living with risk, there is very little guidance to assist them in working together toward a common set of goals and solutions. In many cases, current practices in land use planning and emergency management can lead to scenarios that inadvertently increase the vulnerabilities of people and critical assets.

6.1 1..1 Safe Development

Although structural mitigation measures are effective in meeting design standards to protect against anticipated levels of hazard threat, they do not provide complete protection from low-frequency/high-consequence disaster events that are relevant in the context of longer-term comprehensive land use planning. As a result, they promote a false sense of security that can lead to circumstances where levels of risk are actually increased as a result of ongoing mitigation investment. The paradox of safe development is that in trying to make hazardous areas safer, governments have substantially increased the potential for catastrophic property damages and economic loss, (Burby, 1998; 2006).

6.1 1..2 Smart Growth and Sustainable Development

Smart Growth principles of increased density and compact development are effective in mitigating the negative impacts of urban sprawl, and in lessening our ecological footprint through the efficient use of land and supporting infrastructure. However, without considering the broader geographic context in which hazard events may occur, there is a danger that emerging new practices of land use planning may inadvertently increase the vulnerability of people and critical assets. The paradox of smart growth and sustainable development is that by focusing attention on the form and function of individual neighbourhoods and buildings, there is a potential to loose sight of broader earth system processes that can trigger unexpected disasters that undermine the sustainability of communities and regions for years to come (Berke, 2002).

6.1 1..3 Risk Governance

If risks and disaster losses associated with development in hazard-prone areas are borne principally at the community level by home and business owners, it follows that mitigation strategies to reduce risk and promote the safety and security of citizens ought to be a high priority for municipal and regional governments. The paradox of local government is that while citizens bear the brunt of human suffering and financial loss when disasters occur, local governments give insufficient attention to threats posed by hazards when they allow intensive development of hazardous areas (Burby, 1998; 2006).

Understanding the relationship between vulnerability and risk is critical for the identification and implementation of mitigation strategies that will promote longer-term disaster resilience and sustainability. Strategies that explicitly aim to reduce vulnerability and increase system resilience (prevention and avoidance) will inevitably lead to reduced levels of outcome risk. However, strategies that are focused only on reducing outcome risk (protection through structural mitigation) will not necessarily reduce levels of system vulnerability or ensure base levels of disaster resilience. Similarly, if time frames for measuring trade-offs between policy alternatives are set too short, solutions that reduce outcome risk will tend to be favoured over longer-term solutions that address underlying causal structures of vulnerability. By not addressing intrinsic patterns of vulnerability, levels of risk will continue to be magnified with growth and development, resulting in escalating disaster trends that outstrip the capabilities of conventional risk reduction practices.

6.1 2. The Geography of Risk

The risk environment of a community or region can be characterized in terms of four overlapping domains that encompass increasingly broader dimensions of the human-natural system, more complex geographic settings, and longer planning horizons that are relevant in the context of comprehensive planning and sustainable development. *Hazard potential* describes the geographic extent and severity of physical processes that have a potential to trigger a disaster event and the likelihood of these events occurring at some point in the future. *Hazard risk* describes the probable impacts and consequences of these events in terms of damages, injuries, and anticipated socio-economic losses. *Vulnerability* describes the intrinsic characteristics of people and the physical environment in terms of their exposure and susceptibility to potential negative impacts of a hazard event. *Resilience* describes the capabilities of human-natural systems to withstand, respond to and recover from the impacts of a hazard event and to adapt to changing conditions of risk over time. The goal is to find a vantage point from which these different perspectives come into focus and can be fully articulated and explored through the interweaving of scientific understanding (objective measures) and judgment (subjective measures).

6.1 2..1 The Importance of Place

Place provides the necessary context and focus for understanding risk and informing decisions. Characteristics of geographic setting and underlying earth system processes will determine the likelihood and magnitude of natural hazards occurring in a given area (hazard threat), and the levels of protection that may be needed to ensure safety and security. Patterns of human settlement will determine the exposure of people and critical assets, and the probable extent of damages, injuries, and losses that can be expected if a hazard event were to occur at some point in the future (hazard risk). However, it is the heart and soul of a community that will ultimately determine who and what are most in need of safeguarding (vulnerability) and the capabilities that are needed to withstand and adapt to changing conditions of risk over time (disaster resilience).

6.1 2..2 The Physical Dimensions of Risk

From the perspective of physical systems, risk encompasses a functional understanding of cause-effect relationships between underlying processes that have a potential to trigger hazard events (extent, magnitude, and probability); the expected impacts of these events on people and the environment (injuries and damages); and the likely consequences of these events in terms of direct and indirect socio-economic losses. The physical dimensions of risk are characterized through a combination of observations, measurements, and predictions that objectively describe system conditions for existing or future conditions. While it is clear that objective measures of risk provide an understanding of the impacts and likely consequences of a hazard threat, they may have little meaning if separated from the social and behavioural context in which mitigation alternatives are considered and decisions are made (Stern and Fineberg, 1996; Sarewitz, 2000; Barnes, 2002; Renn, 2006a).

6.1 2..3 The Human Dimensions of Risk

From the perspective of human systems, risk is framed and assessed in terms of subjective measures and normative judgments that express what people consider of value and worth protecting. The assessment of risk is based on underlying ethical perspectives and beliefs of what constitutes value and danger, and how best to manage change in an uncertain world. While subjective measures of risk reflect value-based judgments of who and what are considered most vulnerable and why, they can be marginalized in situations where a community may be threatened by unforeseen or emerging hazards that can only be anticipated through expert understanding of system processes (Barnes, 2002; Stefanovic, 2003).

6.1 2..4 Risk as a Measure of Change

Human and natural systems are in a constant state of flux. As communities continue to grow and develop in areas exposed to natural hazard threats, so too do underlying conditions of vulnerability and risk. The fundamental characteristics of vulnerability and risk can, therefore, be understood only in the context of a time continuum that encompasses conditions of the past, the present, and the future. In this context, natural hazard risk is an emergent property of change that is influenced by earth systems processes and human choices that interact over time.

As the process of planning and characteristics of the built environment vary from region to region, so too will the relationships between hazard intensity and damage potential. By not accounting for changing norms and physical characteristics of a particular place, there is potential for static models to either underestimate or overestimate the likely consequences of a hazard threat. In addition to physical variability, the socio-economic characteristics of a landscape will also vary from place to place as a function of historical patterns of human settlement and resulting cultural norms. These variations, although subtle, can have a significant influence on the way in which hazards of comparable intensity manifest themselves over the landscape and are framed for the purposes of risk assessment and planning. Individuals and communities that have the experience of living through the impacts of hazard events are more likely to be aware of potential impacts and consequences and take proactive measures that reduce their vulnerability to these events in the future.

Effective and accountable decision making thus requires a common understanding of the risk environment and how it evolves over time, and a clear expression of what constitutes a tolerable threshold of risk for any given community or region. From this perspective, risk is not simply a measure of system conditions, but rather the outcome of a comprehensive planning process through which mitigation alternatives are evaluated and decisions are made based on available knowledge and societal preferences.

6.1 3. Finding Common Ground

Understanding the risk environment and making decisions to reduce or mitigate risk requires the integration of scientific knowledge, values and community preferences across a diverse group of stakeholders—each with a different perspective and often with a different set of expectations for managing risk. In this context, decision making involves three primary activities: alerting society to potential challenges and problems that lie ahead (diagnosis); defining and assisting in structuring complex problems to facilitate the exploration and negotiation of desirable policy alternatives through analysis and deliberation (decision support); and utilizing scientific knowledge and understanding to help guide action before and after political consensus is attained (assessment).

6.1 3..1 Diagnosis: An Evidence-Based Approach

A full characterization of the risk environment requires an integrated approach incorporating both science-based and values-based approaches. Scientific enquiry emphasizes the generation of new knowledge for the purpose of refining or expanding insight on human-natural systems and how they work. It is focused on objective measures of risk that describe cause-effect relationships. Knowledge claims are based on observations and information that are assumed to be true. The corresponding proposition is that scientific knowledge and understanding of human-natural systems (epistemology) ought to provide the necessary foundation for informed decisions of how best to manage risk on behalf of society. This might be referred to as the predictive or "science-based" approach to risk management (Sarewitz and Pielke Jr, 2001). While scientific analysis provides an objective measure of risk, it does not necessarily address the question of who or what ought to be safeguarded, or how to balance the potential costs and benefits of mitigation measures.

For individuals and groups in society who must bear the consequences of uncertain hazard events, risk is framed in terms of values—subjective measures and normative judgments that express what people consider to be vulnerable and in need of safeguarding. Knowledge claims are based on perceived hazard threats, levels of concern, potential for injury, damages and economic losses, and the capacity to respond and recover from the impacts of these events in order to achieve an outcome that minimizes negative effects while promoting overall management objectives. The corresponding proposition is that clear articulation of what humans consider of value will provide the necessary context, rationale and focus for policy development and collective decision making. This might be referred to as the deliberative or 'value-based' model of risk management (Gregory and Slovic, 1997; McDaniels et al., 2004; Gregory et al., 2005). Though subjective measures of risk reflect community values and preferences, it can be challenging to reconcile individual and collective views of what might constitute a desirable set of outcomes in terms of both costs and benefits.

From the perspective of place-based planning and policy analysis, risk is more often framed in terms of choices and consequences (opportunities and liabilities). In this context, risk is an emergent property of a decision making process that seeks to balance scientific knowledge and understanding with social values and preferences. It is a forward-looking process whereby choices and their consequences are analyzed and evaluated for the purpose of determining the most appropriate course of action. The result of integrating the above science-based and values-based models is the proposition that land use planning and emergency management ought to be informed by available scientific knowledge about the risk environment, and governed through judgments of what constitutes acceptable or tolerable thresholds of potential loss by those impacted by the decision making process. This might be referred to as the integrative or "evidence-based" approach to planning (Pahl-Wostl et al., 2000; Rotmans and Van Asselt, 2000; Sarewitz and Pielke Jr, 2001; van der Sluijs, 2002; Engels, 2005).

6.1 3..2 Decision Support and Assessment: Rational Analysis, Integrated Assessment, and Scenario Modelling

Though founded on principles of rationality and democratic choice, the practice of risk-based planning usually charts a course somewhere in-between. The conventional approach to risk-based planning involves a process of rational analysis that is informed by scientific insights and predictive modelling of cause-effect relationships, and governed by choices that optimize system performance in terms of effectiveness or efficiency. Rational analysis is used widely in the fields of emergency management and community planning to support a science-based approach to decision making. In contrast, integrated assessment involves a process of adaptive planning that relies on scientific analysis and scenario-based modelling of decision alternatives to identify patterns that make evident the link between policy choices and their likely consequences. Integrated assessment supports an evidence-based approach to decision making that is informed by available scientific understanding and governed by value-based decisions that balance trade-offs between system performance (effectiveness and efficiency), environmental integrity, and social justice. Although distinct in terms of approach and methods, rational planning and integrated assessment both have a role in the evolving field of risk-based planning and disaster mitigation. In different ways, they represent structured forms of decision making that encompass the analysis of complex systems and the evaluation of policy alternatives for the purpose of assisting decision makers in selecting a future course of action—one that moves an organization or community toward a desired set of policy goals while minimizing potential negative impacts and consequences.

There are, however, limits to the capacity of scientists to understand and model the complex network of interactions that characterize human and natural systems, their patterns of evolution, and the implications of uncertainty in assessing the dimensions of vulnerability and risk.

Similarly, there are limits to the abilities of planners and emergency managers to solicit input that will reflect the full range of values and preferences for a community. Rather than relying on scientific models as predictive tools to provide an answer, the emphasis should be on using scenario models to develop a common understanding of the risk environment that reflects available knowledge and community-based thresholds of risk tolerance.

For those working in the field of land use planning, there is a need for decision support systems that make evident how the dynamics of vulnerability and risk are likely to change in the future, and that facilitate the evaluation of risk tolerance thresholds and the implementation of corresponding actions required to promote longer-range policy goals of community resilience and sustainable development (Mileti and Gailus, 2005). For those working in the field of emergency management, there is a need for decision support systems that help prioritize actions that are required to ensure public safety and socio-economic security for a community, and a capability to respond to and recover from known or emerging hazard threats within the limits of available resources.

A central thesis of this study is that existing conceptual frameworks and methods of risk management need to be extended to encompass principles of disaster resilience and sustainable land use planning. This requires a systems-based approach that builds on existing best practices to develop a comprehensive framework for risk-based planning using integrated assessment and scenario planning. To this end, we have critiqued more than 20 existing risk assessment frameworks that are used in support of disaster risk reduction efforts worldwide. Each of the frameworks evaluated represents a best practice with respect to the context and purpose for which it was designed. However, they offer only partial solutions in terms of the needs and operational requirements that have been identified in this study for risk-based planning. Rather than develop new methods of assessment to address these limitations, we have focused our efforts on the adaptation of existing best practices that are standards-based, and that can be combined into a comprehensive framework for risk-based planning that builds on the strengths of rational analysis, integrated assessment and scenario-based modelling.

6.2 Disaster Resilience by Design: The Pathways Framework

The process of integrated risk assessment requires focused and sustained methods of deliberation that engage relevant actors at appropriate stages of the planning and policy development cycle; that facilitate the discovery and transformation of knowledge and understanding; and that provide overall structure for the decision-making process. The Pathways framework builds on the theoretical foundations of rational planning and integrated assessment, and adopts an earth systems approach that is place-based and that acknowledges the need to integrate scientific analysis and the evaluation of policy alternatives as part of the decision-making process. It is designed to support the needs and operational requirements for risk-based planning in areas that are exposed to natural hazard threats by combining analytic and deliberative methods in ways that account for the many and varied interactions between natural and human systems (complexity), the limits of scientific knowledge (uncertainty), and the challenges of balancing diverse and often competing policy objectives (ambiguity).

Deliberative components of the Pathways framework extend existing standards and protocols for risk assessment (CAN/CSA-Q850; AS/NZ 4360; ISO 31000) to include emerging practices of risk governance and place-based planning (Burby *et al.*, 2000; Swart *et al.*, 2004; Renn, 2006a; Robinson *et al.*, 2006; IRGC, 2008). The conformance to established and emerging best practices in the fields of risk assessment and comprehensive planning helps build a bridge between conventional modes of emergency management and community development. The process of risk-based planning developed as part of the Pathways framework is designed to bring together an interdisciplinary team of planners, emergency managers, domain experts, policy analysts, and members of the community—each contributing in different ways to a common understanding of the risk environment and the actions required to promote disaster resilience on the ground.

Analytic components of the Pathways integrated assessment model are built around an internally coherent system of target indicators that are aligned with national and international policies for disaster risk reduction and also provide overall structure and capability for assessing natural hazard risks at local and regional scales. When combined with methods of interactive scenario modelling and decision analysis, the Pathways model offers an effective means of transforming knowledge about the risk environment into actionable mitigation strategies that are informed by science and governed by community values and preferences. Scenario models provide a means of exploring changing patterns of vulnerability and risk through time, and help to establish overall context and focus for the decision-making process. Implementation of the Pathways framework is facilitated through the use of best practice methods and tools that have been adapted for use in a Canadian context.

6.2 1. A Process for Risk-Based Planning

The Pathways process is a four-stage comprehensive planning cycle that builds on key elements of the ISO standard for risk assessment and the IRGC guideline for risk governance. Each stage of the framework is comprised of a sequence of smaller steps that provide guidance to practitioners through a set of suggested tasks and related activities that can be modified to reflect the needs and requirements of the local planning process. In some instances, this may involve minor revisions to allow integration with existing land use planning and emergency management functions. In other instances, it may require modification of the framework to accommodate available knowledge and resources, or to address a wider spectrum of natural and anthropogenic hazards that are relevant to a particular community or region.

6.2 1..1 Stage 1: Establishing Context

Establishing overall context and focus for the planning process involves the identification of existing and emerging societal risks for a study region of interest, a diagnosis of system conditions and driving forces that are likely to influence the risk environment, the assessment of opportunities and liabilities for moving forward with a proposed set of policy goals and objectives, and the definition of assessment criteria and decision protocols that will be used to guide the planning and policy development process.

6.2 1..2 Stage 2: Risk Analysis

Risk analysis provides insights and knowledge about the impacts and consequences of hazard threats based on direct observation and experience of past events, and/or indirect measurement and modelling of potential cause-effect relationships. Semi-quantitative risk appraisal utilizes input from community members and domain experts to generate knowledge about perceived hazard threats, levels of concern, and adaptive capacity. Quantitative risk analysis utilizes synthetic information based on theory and experiment to generate knowledge about hazard potential, probabilities of damages, anticipated socio-economic losses, system vulnerability and resilience. Both methods offer the means of objectively measuring the dimensions of vulnerability and risk to inform the evaluation of mitigation alternatives. The level of analysis will vary as a function of complexity, uncertainty, and ambiguity of the risk problem, and requirements of the planning process.

6.2 1..3 Stage 3: Risk Evaluation

Risk evaluation is the process of reconciling knowledge claims about the risk environment with value-based judgments about mitigation alternatives. Judgments about empirical uncertainty involve synthesizing relevant analytic measures in order to explore the sensitivities of model assumptions with respect to anticipated system behaviour. Judgments about societal values and preferences involve an assessment of costs and benefits and the overall performance of mitigation alternatives with respect to policy targets and negotiated thresholds of risk tolerance.

Scenario models provide a capability to evaluate baseline conditions of risk for a given community or region and to help make evident spatial interactions between natural and human processes that influence changing patterns of vulnerability in a futures context. They also provide a common framework of understanding to explore and develop mitigation strategies that are evaluated in terms of target criteria and indicators, which in turn measure compliance with thresholds of risk tolerance that are either prescribed by legislative or regulatory standards for public health and safety, or defined locally on the basis of community values and preferences. Formulation and testing of mitigation scenarios is an iterative process of analysis and evaluation that relies on effective collaboration and ongoing dialogue between scientists, planners, and community members to ensure that resulting policy recommendations are evidence-based and aligned with community values and preferences.

6.2 1..4 Stage 4: Risk Treatment

In the Pathways process, the risk treatment stage is limited to final deliberation, approval, and implementation of mitigation strategies that have been formulated and tested through an iterative process of analysis and evaluation. It marks the transition between knowledge generated through the risk assessment phase of the process, and actions that are taken on the ground to approve and implement mitigation measures.

The Pathways framework does not explicitly address functions of risk treatment or implementation, as these will be determined by policy mandates and the specific legislative and institutional context in which the risk assessment is undertaken. However, it does offer a framework of target criteria and performance measures that can be used to support decision making and to monitor progress toward or away from policy goals and objectives during the final approval and implementation phases of the risk management process.

6.2 2. A Model for Integrated Risk Assessment and Scenario Modelling

The Pathways framework introduces a model for integrated assessment and scenario planning that is defined by an internally coherent system of indicators and target criteria. Indicators reflect available information and knowledge about system conditions, and can be assessed using a combination of semi-quantitative and quantitative methods. Target criteria express intent with respect to a desired set of outcomes and help to establish thresholds of risk tolerance that will guide the planning and decision-making process.

When formulated with a desired future state in mind, target criteria and associated indicators offer members of the planning team a forward-looking perspective for analyzing available information and knowledge about the risk environment, characterizing thresholds of tolerability based on community values, and evaluating the efficacy of mitigation alternatives through the lens of local preferences or established policy guidelines. When incorporated into the full cycle of risk-based planning, target criteria offer decision makers a structured, transparent, and evidence-based framework for evaluating mitigation alternatives and choosing a path forward that advances overall policy objectives while minimizing any potential negative impacts on people and critical assets.

6.2 2..1 Community Profile

Community profile indicators provide a snapshot of existing system conditions for a community or region. They describe patterns of human settlement and physical characteristics of the built environment, and are used to increase situational awareness in support of strategic land use planning and emergency management operations. Patterns of human settlement are described in terms of population densities and demographic characteristics that define a community or region. The built environment is described in terms of the form and function of buildings and critical infrastructure and the distribution of other critical assets in the community. Collectively, these indicators are used to identify individuals and groups that may be vulnerable to a hazard event; building stock, critical infrastructure and related lifeline services, and additional features that are considered significant in terms of their socio-economic, cultural, or environmental value.

6.2 2..2 Hazard Threat

Indicators of hazard threat provide insights on the likelihood, intensity, and probable impacts of natural hazards, and their potential to cause damage to the built environment. Information characterizing the severity and magnitude of a potential threat is referenced with respect to the probability of occurrence and spatial extent of a specific hazard event scenario. Indicators describing damage potential are used to provide a common understanding of intrinsic physical vulnerabilities of the built environment, and to assess the effectiveness and efficiencies of existing mitigation measures in providing overall protection to people and critical assets. The goal is to reduce the vulnerabilities of physical assets by developing mitigation strategies that minimize the extent or intensity of the hazard itself (e.g. by building protective dykes and deflection berms), or that maximize the capability to withstand the anticipated impacts of these hazard events over time.

6.2 2..3 *Public Safety*

Indicators of public safety provide insights on the anticipated human or societal impacts of a hazard event. Societal impacts are measured in terms of the probability of injury or death caused by physical impacts of a hazard event, and the anticipated level of emergency assistance that may be required to ensure the health and safety of individuals and groups who are likely to be displaced from their homes or who do not have the capacity to provide for themselves. Management objectives and performance targets are expressed in terms of the expected severity of injuries and fatalities, anticipated levels of assistance or intervention required during or immediately after the impact of a hazard event (shelter requirements), and the requirement to provide basic and essential services through emergency management operations.

6.2 2..4 *Socio-economic Security*

Socio-economic security is a measure of community wealth and the integrity of social, economic, and environmental assets that may be exposed to hazard threats. Indicators track anticipated losses if the disaster event were to occur at some point in the future, the probable economic consequences of this same event over a specified planning horizon, and the relative costs and benefits of investing in mitigation measures over time. As a policy objective, the goal is to maximize the security of community wealth through strategic investments in mitigation measures that protect what is considered of value and that will yield a positive rate of return over time horizons of interest.

6.2 2..5 *System Functionality*

Target criteria are expressed in terms of indicators that track dimensions of resistance, debris generation, recovery time, and adaptive capacity. As a policy objective, system functionality is used in the Pathways model to assess the capability of complex human-natural systems to absorb the sudden shocks of hazard events that threaten structural coherence and functional integrity, and the capability of these systems to evolve and adapt to changing conditions of vulnerability over time. The goals are to increase the resistance of system components to potential hazard impacts, and to reduce the amount of time required to restore essential functions and lifeline services to pre-disaster levels.

6.2 2..6 *Social Equity*

Equity reflects intent to establish and maintain a balance in the distribution of risk across all sectors and demographic elements of a community, including individuals and groups of an existing population and those of future generations. Target criteria and indicators are expressed in terms of hazard susceptibility, the agency of individuals and groups to make decisions that will directly influence their own well-being, and the ability of these individuals and groups to cope with the impacts and consequences of a disaster event.

6.2 3. A Planning Support System for Disaster Mitigation

The Pathways model has been successfully implemented as spatial decision support system using a constellation of quantitative and semi-quantitative methods and tools. The selection of methods and tools was based on current uptake and use in the domains of land use planning and emergency management, and the capacity of the system to facilitate the full cycle of analysis and evaluation. While the selected applications provide an operational proof-of-concept for implementing the Pathways framework, they are not prescriptive. The standards-based architecture and modular design allows the substitution of equivalent applications that may already be used in local planning contexts, and the ongoing refinement of methods and tools as best practices continue to evolve and are made available in the public domain. Choices about implementation methodology will be driven by severity of the hazard threat, requirements for legally defensible assessments of impacts and consequences, the availability of scientific knowledge, and the level of technical expertise on hand to support the planning process.

Most planning support systems are focused on either the deliberative or analytic elements of the assessment process. An important innovation of the Pathways framework is the coupling of design-based (deliberative) methods with model-based (analytic) ones. Design-based methods capture social values and intent with respect to a desired future state of disaster resilience and model-based methods provide a capability to analyze and explore the risk environment and to evaluate the likely consequences of policy choices over time. The integration of deliberative and analytical dimensions of the planning process is facilitated through the use of risk scenarios that are developed using CommunityViz®; an interactive modelling and scenario planning tool developed by the Orton Family Foundation to assist communities in assessing and visualizing the consequences of land use decisions (Walker and Daniels, 2011).

6.2 3..1 Design-Based Methods and Tools

Participatory planning is the process through which decision pathways are identified and navigated. It is a structured process of dialogue and negotiation that involves the exchange of information and perspectives amongst domain experts, planners, elected officials, and those who may be impacted by the decision-making process. The process of participatory planning is supported in the Pathways framework through the design of workshops that incorporate best practices for group visioning, deliberative dialogue, expert solicitation, and community mapping. The risk appraisal component of the planning process utilizes Delphi-based methods that are consistent with emerging national guidelines for capability-based planning that are part of the broader Canadian All-Hazard Risk Assessment Framework (Goudreau, 2009; Hales and Race, 2010; Public Safety Canada, 2010).

6.2 3..2 Model-Based Methods and Tools

Quantitative methods of risk assessment provide a capability to analyze, model, and predict the outcomes of complex system interactions and to evaluate the strengths and weaknesses of mitigation alternatives within the limits of available information, knowledge, and resources. Quantitative risk assessment methods used to implement the Pathways model include public domain software applications for information management and structuring of asset inventory data (Beyond 20/20® and CDMS); FEMA's standardized damage and loss estimation methodology for assessing the impacts and consequences of floods, earthquakes, hurricanes, and related hazard threats (HAZUS); and commercial methods of multivariate statistical analysis for assessing dimensions of social vulnerability (SoVI). Although focused on natural hazards, the Pathways framework is designed so that additional analytic models can be incorporated into the system to assess other hazard threats that may be relevant to the planning process (fire, hazardous spills, etc.). Outputs of these models are used to evaluate indicators of hazard potential, physical vulnerability, system resilience, and anticipated loss. Financial risk and expected returns on mitigation investments can be modelled using a variety of benefit-cost models including the USGS Land Use Portfolio Model (LUPM) and FEMA's Benefit-Cost Analysis Tool (BCA).

6.3 Navigating a Path Forward

Testing and validation of the Pathways framework was carried out in the context of a collaborative case study with the District Municipality of Squamish and the US Geological Survey (Journeay *et al.*, 2007a; Journeay *et al.*, 2007b; Talwar *et al.*, 2007; Wein *et al.*, 2007). The study was undertaken in support of a revision to the District's Official Community Plan (District Municipality of Squamish, 2007b). Results were used by District planning staff to inform policies on disaster mitigation and sustainable land use planning in the community, and by the Pathways development team to help guide ongoing refinements of methods and tools. Insights and lessons learned through the case study evaluation indicate that the Pathways framework offers a viable platform for hazard mitigation and disaster resilience planning at local and regional scales of governance.

In November of 2010, Canada formally launched its national platform for disaster risk reduction—a consortia of public, private, and academic sector partners that have come together to support policy mandates set out as part of the International Hyogo Framework for Action (United Nations, 2005). The Hyogo framework outlines a series of high-level principles, goals and objectives for reducing the risks posed by natural hazards worldwide, and for promoting disaster resilience through a coordinated program of emergency management and community-based planning.

Through leadership and coordination provided by the Centre for

Security Science, Public Safety Canada (PSC) and Defence Research and Development Canada (DRDC) have jointly initiated a multi-year program that supports a national platform for disaster risk reduction. The program contains operational guidelines for emergency management developed to align with ISO standards for disaster risk management and business continuity planning (PSC, 2010), and also contains a framework for all-hazard risk assessment that is based on principles of systems thinking and scenario planning (Goudreau, 2009; Hales and Race, 2010).

Outputs of the Pathways study are aligned with and have contributed to these broader national efforts by establishing a framework for risk-based planning at local and regional scales that is standards-based and that builds on existing best practice methods and tools for the assessment of natural hazard threats in Canada. While the Pathways framework has proven effective in addressing the challenges of managing risks associated with growth and development in areas exposed to natural hazards, much more work is needed in order to develop an operational capability to address goals and objectives that are set out in the Hyogo Framework for Action. Through ongoing research and development efforts of the ESS Public Safety Geoscience Program (2009–2014), we look forward to working with others in addressing the challenges of disaster risk reduction and working toward solutions that will help build disaster resilience and sustainability for communities and regions across Canada.

v. BIBLIOGRAPHY

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Appendices

Appendix I: A Glossary of Concepts & Terminology

Appendix II: A Critique of Best Practices for Risk Assessment

Appendix III: Natural Hazard Events for the Community of Squamish, BC

vi. APPENDIX I: A Glossary of Concepts & Terminology

Acceptable Risk: the potential for negative consequences of a risk scenario exists but is below target thresholds determined by decision criteria, is counterbalanced by potential gains and/or can be treated through routine investment in risk-treatment options.

Analytical-Deliberative Methods: the assumptions, parameters and techniques used in observing and measuring both the empirical and normative dimensions of vulnerability and risk.

Anticipated Consequences: expected losses caused by a potential hazard event, assessed in terms of potential injuries; physical damage; direct and indirect losses to social, economic, and environmental assets; and/or disruptions to human-natural systems and the services they provide for existing and/or future conditions.

Asset Inventory: a spatial inventory of people and their assets, physical elements of the built and natural environment and human-ecological systems that are considered of value and vulnerable to the impacts of potential events.

Base Case Scenario: risk scenario(s) for current and short-term future conditions based on impact assessment of proposed risk-treatment options (predictive forecast modelling), using decision criteria and negotiated thresholds of tolerability as points of reference.

Built Environment: the spatial distribution of existing landscape features and land-use functions including the density, type and function of residential and nonresidential buildings, essential facilities and critical infrastructure, and the allocation of people, homes, jobs and businesses.

Capacity: the ability of an organization or community to withstand and respond to the impacts of potential hazard events, to recover from the consequences of these events over time, and to realize potential net benefits.

Concern Assessment: an appraisal of overall concern that stakeholders, individuals, groups or different cultures may associate with a hazard or cause of hazard based on perceptions of potential consequences (losses), capacities for response and anticipated benefits.

Criteria: the operational objectives that will be used to address priorities and determine thresholds of risk tolerance, including available benchmarks and targets.

Current State: a characterization of potential consequences to key elements at risk (social, economic, environmental) for baseline conditions, including the elements currently in existence and those anticipated to come into existence within the mandate(s) of existing organizational plans and/or legislative bylaws.

Decision Criteria: the overarching management priorities and associated operational objectives that will be used to negotiate thresholds of risk tolerance, including available benchmarks and targets.

Direct Loss: anticipated financial consequences of a hazard event, including capital costs of repairing or replacing structural and nonstructural elements of the built environment, relocation expenses, and losses to rental and business income.

Economic Capacity: available economic resources to implement risk-treatment measures through dedicated organizational budgets and/or mitigation/capital improvement loans and to respond to anticipated consequences of potential hazard events through risk-transfer mechanisms including financial insurance/re-insurance markets and disaster-relief funds.

Establish Context: the issue(s) of concern that will frame the problem for a given area and planning horizon, the external and internal factors that are considered to influence the extent and level of risk and the overall objectives, methods and criteria that will guide the process of appraisal, analysis and evaluation.

External Context: the external environment in which the organization seeks to achieve its objectives, including driving forces, legislative and regulatory structures, political agency, socioeconomic conditions and cultural norms that may influence societal perspectives on risk.

Frequency-Loss Relationships: a graphical representation of perceived and/or measured relationships between the likelihood of a hazard event of known intensity occurring within a given area over a specified time frame and the consequences of this event in terms of anticipated loss (damage, injury, system disruption, etc).

Future Land-Use Scenario: a geospatial model of land-use features and functions over variable time scopes as determined by current and/or proposed growth management policies, including the distribution, density, type and function of residential and nonresidential buildings, essential facilities and critical infrastructure, and the allocation of people, homes, jobs and businesses.

Future Trends: a characterization of potential consequences to existing and anticipated future elements at risk (social, economic, environmental) based on projections of current trends in population growth and associated demand and/or on alternate public and private-sector growth-management strategies that define potential future conditions and policy pathways for achieving desired outcomes.

Hazard Extent: a measure of the presence or absence of a particular hazard threat at any given geographic location on the landscape.

Hazard Frequency: the number of events that are considered likely to occur within a given time frame based on experience, and/or available information and knowledge of causal factors and associated recurrence intervals

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Hazard Intensity: the physical severity of a hazard event measured in absolute physical terms (ground-shaking, depth, velocity, etc.).

Hazard Magnitude: the anticipated severity of a hazard event based on past experience and/or available information and knowledge about cause-effect relationships between hazard intensity (ground-shaking, depth of water, wind speed, etc.) and potential for injury/damage.

Hazard Potential: the specific threat posed by a hazard, measured as a function of geographic extent, physical intensity and the probability that an event of equivalent intensity could occur in a given area over a specified time interval.

Hazard Probability: a statistical measure of the likelihood that a hazard event of a given intensity will occur in a particular geographic area over a specified time interval.

Hazard Threats: a perception of threat(s) posed by specific hazards based on past experience, available information and knowledge about hazard events and underlying causal factors for a given region.

Hazard Type(s): may include any combination of natural forces, (geological, meteorological, climatological), anthropogenic activities (physical-chemical-biological agents, acts of violence or terrorism) or resulting induced hazards (fire, inundation, etc.).

Human Assets: the population and demographic profile of a particular area or region, including patterns of human settlement (density, housing type, etc.), characteristics of the social fabric (income, age, gender, ethnicity, etc.) and both individual and collective assets (social, cultural and economic) that are considered vulnerable to the impacts of potential hazard events.

Human Impact: the number and severity of injuries as a result of direct and/or indirect physical impacts of a hazard event and the number of displaced individuals and those requiring short-term shelter due to loss of habitation.

Implementation: the realization of risk-treatment measures in accordance with relevant operational and/or legislative guidelines, regulations and governance structures.

Indicators: performance measures that track progress toward and/or away from operational risk-management objectives.

Indirect Loss: ancillary consequences to socioeconomic networks and systems that do not sustain direct damage but are nonetheless impacted by shocks associated with a hazard event.

Internal Context: the internal environment in which the organization seeks to achieve its objectives, including linkages and interdependencies with other (often competing) policy mandates, organizational norms for decision-making, including stakeholder representation, liabilities, and prevailing value-belief structures that may influence local perspectives on risk.

Intolerable Risk: the potential for negative consequences for a given risk scenario exceeds perceived benefits and thresholds determined by decision criteria and cannot be effectively or efficiently reduced with available resources.

Land-Use Allocation: a physical description of the human-natural system for existing conditions based on empirical observations and legal descriptions of the urban and rural landscape and/or a model of anticipated future land use based on projections of current or proposed land-use and growth-management strategies.

Loss Estimation: the anticipated consequences of a potential hazard event, measured in terms of public health and safety, direct costs for repair and replacement of damaged buildings and lifeline system components, business costs associated with loss of function, and indirect impacts on income, employment, economic security and social vitality.

Losses Avoided: benefits gained by investing in risk treatment measured as the difference between anticipated losses resulting from a hazard event under current conditions, and the anticipated losses resulting from the same hazard event with risk-treatment measures in place.

Management Objectives: the specific priorities, criteria and metrics that will be used to guide the decision-making process, including anticipated outputs and outcomes.

Mitigation Costs: investment costs of implementing risk-treatment measures, including structural mitigation, early warning, emergency preparedness, land-use planning and risk-transfer mechanisms through insurance and re-insurance markets.

Monitoring and Review: an ongoing assessment of risk levels that remain after implementation of risk-treatment measures using decision criteria, performance measures and negotiated thresholds of tolerability established as part of the risk-management plan.

Natural Assets: physical and biological elements and/or services of an ecosystem that are considered vulnerable to the impacts of potential hazard events, including sensitive habitat features and associated plants and animals.

Objectives: specific operational objectives or anticipated outcomes of the risk-management process, expressed as relative and/or absolute targets with respect to referenced performance levels.

Organizational Capacity: public and private-sector capabilities to undertake appropriate levels of emergency preparedness and strategic planning including proactive measures to limit exposure to hazard threats (regulation, land-use zoning) and warn of impending threats (early warning systems), as well as reactive measures of response and recovery.

Physical Assets: physical elements of the built environment, associated systems and/or services that are considered vulnerable to the impacts of potential hazard events, including buildings and their associated contents, essential facilities and critical infrastructure.

Physical Vulnerability: the likelihood of damage to physical features in the built environment for existing and future conditions based on a statistical assessment of cause-effect relationships between hazard intensity and structural fragility.

Priorities: the underlying goals for the risk-management process (social, economic, environmental), as determined by normative assessment of problem scope and context.

Problem Framing and Diagnosis: defines the overall context and focus for the risk-management process for an organization in terms of objectives, perceived threats and opportunities, root causes and local conditions that may predetermine the state of vulnerability and capacity to achieve objectives.

Process Design: the specific approach, process elements and methods that will be used address risk-management objectives based on an organizational mandate and institutional capacity.

Public Safety: level of concern for the safety, well-being and inequity of individuals and/or groups who may be exposed to the impacts of potential hazard events including the very young, the elderly, people living with disabilities, economically disadvantaged, ethnic minorities and others.

Resilience: the extent to which natural and human systems are able to withstand, recover and adapt to changes without loosing internal coherence and baseline levels of functionality.

Return on Investment: the balance of costs incurred and benefits gained by investing in risk-treatment measures.

Risk: an expression of uncertainty about threats posed by natural and/or anthropogenic events, their impacts on human-natural systems, and the likely consequences of these events (negative and positive) on people and the things they value.

Risk Analysis: a quantitative measure of hazard potential and associated impacts to people and the built environment for existing and future conditions, the probable consequences of these events in terms of direct and indirect losses, and the financial liabilities and potential benefits of investing in risk-treatment measures.

Risk Appraisal: a qualitative and/or semi-quantitative assessment of risk scenarios including where, when, why and how hazard event(s) could occur, the potential consequences of these scenarios in terms of preventing, degrading, delaying or enhancing the achievement of objectives for an organization, and strategies for risk treatment.

Risk Approval: the decision-making process and associated protocols through which elected officials judge the proposed risk-management plan and grant authority for implementation on behalf of the constituents they represent.

Risk Avoidance: anticipated losses are intolerable and managed by public-sector regulatory agencies through avoidance measures, including minimizing and/or restricting exposure to hazard threats through limited access, land-use zoning and/or relocation of people and critical assets.

Risk Characterization: a judgment of acceptable, tolerable and intolerable levels of risk based on a synthesis of information and knowledge gained through appraisal and analysis of potential impacts and consequences, and by evaluation of decision criteria.

Risk Evaluation: a comparison of estimated risk levels (normative and empirical) against pre-established decision criteria and a systematic assessment of policy alternatives in terms of both potential benefits and negative consequences.

Risk Governance: refers to the broader institutional structures and partnerships through which risk-management policies and processes are implemented, authority is exercised, collective decisions are made and measures are taken to reduce risk and promote resilience within and across jurisdictional entities.

Risk Index: performance measures that indicate baseline conditions for the existing state of the system and progress toward or away from operational objectives (targets) for alternate future states.

Risk Management Plan: a document that specifies the process, protocols, procedures and resources required to implement a preferred course of action and achieve objectives of a risk-management policy in the context of a particular place and governance structure.

Risk Management: an expression of intent based on an integrated set of principles and objectives that collectively establish a course of action for managing societal risk that is selected from among alternatives, and that guides present and future decisions through ongoing analysis and deliberation.

Risk-Management Process: the systematic application of management policies, procedures and practices for the purpose of evolving a shared understanding of societal risk (normative and empirical), evaluating policy alternatives and their consequences, and implementing a course of action that promotes resilience while reducing potential negative impacts of uncertain hazard events.

Risk Policy Recommendation: a document outlining core issues identified through the process of decision analysis, a recommended course of action and supporting rationale, and an accounting of alternate policy choices and their consequences with respect to decision criteria and negotiated thresholds of tolerability.

Risk Profiles: a synthesis of available information and knowledge derived from normative appraisal and/or empirical measurement of risk for selected scenarios that may influence system behaviour over time.

Risk Reduction: Actions taken that reduce underlying system vulnerability and/or that minimize potential impacts and consequences of hazard events on people and critical assets

Risk Scenario(s): A narrative and/or model-based description of the risk environment over planning horizons of interest, including past present and desired future conditions.

Roles and Responsibilities: identification of key actors in the risk-management process, their contributions to specific activities and tasks, and assignment of responsibility to ensure effective collaboration in meeting milestones and addressing anticipated outputs and outcomes.

Scenario Analysis: integrated assessment modelling of risk scenarios with and without treatment measures in place to evaluate their effectiveness and/or efficiency in balancing trade-offs between organizational objectives using decision criteria and negotiated thresholds of tolerability as points of reference.

Scope: delineates the specific risk factors that will be considered as part of the management process, the area(s) of potential impact and the planning horizon over which associated risks will be analyzed and evaluated to determine appropriate risk-treatment measures.

Social Capacity: the integrity, cohesiveness and robustness of social networks as evidenced by levels of communication and consultation, risk awareness and understanding, and by participation (volunteerism) in personal and community preparedness.

Social Vulnerability: the likelihood that individuals and groups may be exposed to the negative impacts of a hazard event based on a statistical assessment of underlying causal factors that may predispose them to displacement, injury and/or loss as a result of their physical exposure and capacity for response and recovery.

Socioeconomic Security: level of concern for the robustness and resilience of homes and businesses that may be exposed to the impacts of potential hazard events, including mitigation and replacement costs and anticipated benefits.

Standards: reference documents that will be used to frame the management process, including terminology, process guidelines and relevant organizational protocols for communication, consultation, decision making and reporting of results.

System Dynamics: direct and/or indirect assessment of underlying causal factors and their influence on system behaviour through deterministic and/or stochastic modelling of assumptions and associated uncertainties.

Technical Capacity: the capability of structural systems (and their components) to withstand immediate and induced physical impacts of a hazard threat in accordance with accepted/desired levels of performance and efficiency.

Tolerable Risk: the potential for negative consequences of a given risk scenario exists and exceeds thresholds determined by decision criteria but can be reduced as low as reasonably possible (ALARP) with available resources to achieve organizational objectives and realize potential gains.

Uncertainty Assessment: an evaluation of the sources and types of uncertainty embodied in the risk-assessment process (appraisal and analysis), including the capacity for precise and accurate measurement (stochastic), system complexity and variability (aleatory) and lack of knowledge or understanding and resulting ambiguity in the interpretation of results (epistemic).

Vulnerability: the extent to which people and socioeconomic and biophysical assets are exposed to the impacts of potential hazard events, measured statistically in terms of intrinsic social and/or physical characteristics of human settlement that predispose a population or area to the likelihood of injury and/or damage.

What-if Scenario(s): risk scenario(s) and risk-treatment measures to determine preferred future state(s) of disaster resilience and the corresponding policy choices that will achieve desired long-term outcomes while balancing trade-offs between management objectives (exploratory backcast modelling), using decision criteria and negotiated thresholds of tolerability as points of reference.

A core mandate of this study is the evaluation of existing risk-assessment methods that may be suitable for use in a Canadian context to support the implementation of the National Disaster Mitigation Strategy (NDMS). To establish a basis for this evaluation, a review and cross-sectional survey of selected methods was undertaken. The survey focuses on methodological frameworks at all scales of operation with the intent of identifying best practices for both risk analysis and evaluation.

Detailed descriptions and evaluations of more than twenty separate methods for risk assessment are summarized below. Some of the methods are generic. Others provide analytical methods intended for use by those who manage risk in the context of a specific geographic setting and planning horizon. They include both qualitative and quantitative approaches that range in scope from conventional methods of analyzing hazard risk and vulnerability to more holistic methods of analyzing the resilience of coupled human-natural systems. The survey is informed by and contributes to a number of comparative risk-assessment studies reported in the literature (Pelling, 2004; Pelling *et al.*, 2004; Birkmann, 2006; Birkmann, 2007). However, it intentionally emphasizes pre-event–planning stages of disaster mitigation, as defined in the Emergency Management Framework for Canada (2007). It does not consider risk-assessment methods developed in fields of human and ecological health, environmental degradation or corporate enterprise.

Global Stage

Risk assessment methods developed for use on a global stage focus on disaster risk management of existing hazard threats at a sub-national and national scale, and on emerging threats related to changing socioeconomic structures and related international service networks for the transportation of goods, energy and related commerce. Analytic methods are geared toward measuring the vulnerability of people and assets, and on quantitative loss estimation through robust hazard-risk models. Outputs are used to evaluate strategies for risk transfer through insurance and financial markets. Methods that focus on governance are geared toward providing a synoptic view of global risk and generating knowledge that can be used to support development of international policy on disaster risk reduction in both developed and developing nations.

1. Catastrophe Models for Risk Appraisal (CAT)

This category includes a collection of leading-edge proprietary hazard-risk models developed by the insurance and re-insurance industry to assist national governments and corporate enterprises in analyzing financial risk (return on investment), evaluating the probability of loss for complex worldwide portfolios, pricing risk-transfer strategies and providing estimates of economic loss to assist in response efforts and recovery planning (Grossi *et al.*, 2005). Hazard-risk models are based on analytical methods that have been subjected to rigorous peer review by the scientific and engineering communities. They typically include capacities for both regional and site-specific assessment of hazard threat, physical vulnerability and anticipated loss. Examples include RMS (risk-management solutions), EQECAT (ABS consulting) and AIR. These and other industry-based methods have set the standard for hazard-risk models used at a variety of scales in the public domain, several of which are reviewed below. Collectively, these methods offer a wide array of quantitative stochastic techniques and tools for analyzing hazard potential, physical vulnerability and expected economic loss.

CAT models assess hazard potential using probabilistic measures of extent and intensity. Estimates of geographic extent, magnitude and probability of occurrence are calibrated using global databases documenting physical characteristics of ~800 000 severe storm and cyclone events and ~2.5 million earthquake and related geohazard events. Assessment of damage potential is based on extensive exposure databases and a combination of both engineering performance and stochastic models calibrated with forensic information from actual disaster events. Model outputs are used to analyze and evaluate expected economic loss and return on investment for maximum credible event scenarios. Catastrophe models for risk analysis generally conform to recommended standards and guidelines for enterprise risk management but are typically focused on analytical and evaluation stages to inform investment in risk-treatment measures.

2. The Natural Disaster Hotspot Analysis (NDH)

NDH is an index-based method of vulnerability assessment for assessing global patterns of multihazard risk in terms of mortality and economic loss. The method is administered by the Center for Hazard and Risk Research at Columbia University under the umbrella of the World Bank and the ProVention Consortium. Model outputs are used by international aid and development organizations in "*providing a rational basis for prioritizing risk reduction efforts and to highlight areas where risk management is most needed*," (Dilley *et al.*, 2005b). NDH conforms to the UN/ISDR protocol for vulnerability assessment. It is a deductive analytical methodology for assessing multihazard potential and global trends in disaster risk (mortality and economic loss). Hazard potential (extent, magnitude, probability) is analyzed using peer-reviewed global models for earthquakes, volcanoes, landslides, floods, droughts and cyclones. Intrinsic vulnerability is deduced through spatial statistical analysis of synthetic population density, gross domestic product (GDP), agricultural value and the extent of transportation and infrastructure systems.

Risk is analyzed as a function of hazard probability, exposure and vulnerability. The method is appropriate for risk assessment at sub-national scales (~55 km^2 or greater), where population density permits. The NDH is limited in scope to risk assessment elements of the risk-management process (analysis and evaluation). However, the evaluation component is focused primarily on comparative assessment of disaster risk and does not have a capacity to evaluate system dynamics, sources of uncertainty or policy alternatives. There is no direct coupling between the risk index and policy guidelines or management objectives, though outputs are intended to inform policy analysis and decision-making.

3. The Disaster Risk Index (DRI)

DRI is an index-based vulnerability method for assessing and comparing national-level patterns of multi-hazard exposure, susceptibility and disaster risk potential for earthquakes, tropical cyclones and floods. It is administered by the Bureau of Crisis Prevention and Recovery; a branch of the United Nations Development Program (UNDP). Outputs of the analyses are used by international aid and development organizations in "*providing quantitative evidence to advocate for the reorientation of development policy and planning in a way that contributes to the management and reduction of disaster risk*," (Pelling, 2004; Pelling *et al.*, 2004).

The DRI method is based on the premise that disaster risk is historically constructed through human activities and processes that can be quantitatively modelled using information on hazard extent and patterns of human settlement. It uses inductive methods of analysis and statistical regression to determine patterns of hazard exposure and vulnerability. Hazard exposure is calculated on the basis of the average number of people exposed to a hazard event in a given year. Vulnerability is measured using a suite of economic, social, technical and environmental indicators that collectively represent the capacity of population centres to absorb the impacts and recover from a hazard event. Risk is evaluated as a function of hazard exposure and the number of people actually killed by each hazard type. Vulnerability at a national scale is calculated by dividing the number of people killed by the number exposed. Outputs of the assessment include a national ranking of vulnerability and risk.

Results of the DRI assessment are used as a guideline by international development organizations to evaluate disaster risk reduction and sustainable-development strategies. DRI assessments are focused primarily on the analysis of vulnerability and do not address other dimensions of the risk-management cycle or underlying system dynamics. There is no direct coupling between the risk index and policy guidelines or management objectives, though outputs are intended to inform policy analysis and decision-making.

1. Catastrophe Modeling for Insurance Re-Insurance Sectors (CAT)

Criteria	Attributes	Rank
Context & Focus		
• Conceptual Framing	Hazard-Risk model	3
• Spatial Extent	local, regional, national, global	5
• Temporal Horizon	historical profile, current conditions	4
• Hazard Type(s)	earthquake; flood; landslide; volcano; meteorological; other	5
• Vulnerability	physical vulnerability	3
• Risk	injuries; direct loss; indirect loss; resource efficiency	4
Risk Assessment		
• Analytic methods	qualitative, quantitative, deterministic, probabilistic	5
• Deliberative methods	developed primarily for private sector	1
• System Design	proprietary	1
Risk Management		
• Establish Context	problem framing & diagnosis, decision criteria, process design	4
• Appraisal	NA	1
• Analysis	vulnerability; socio-economic risk; costs& benefits	5
• Evaluation	risk profile, characterization, risk treatment alternatives	5
• Treatment	policy recommendations, implementation, monitor & review	5
Suitability Scale: *1= Weak 2= Fair 3= Moderate 4=Strong 5=Very Strong*		**72.86** Score: (0-100%)

Source: *MunichRe, Risk Management Solutions (RMS), ABS Consulting Group, AIR Consulting Gorup*

Reference Documents: *Grossi, P. and H. Kunreuther, Eds. Catastrophe modeling: a new approach to managing risk. Risk, Insurance, and Economic Security. New York, Springer*

Relevant Websites: *http://www.rms.com/Catastrophe/ ;http://www.eqecat.com/index.cfm ;http://www.air-worldwide.com/_public/index.asp*

2. Natural Disaster Hotspots (NDH)

Criteria	Attributes	Rank
Context & Focus		
• Conceptual Framing	Hazard-Risk model	3
• Spatial Extent	global, sub-national (~55 km2 grid cells)	2
• Temporal Horizon	historical profile	1
• Hazard Type(s)	earthquake, volcano, landslide, flood, cyclone, drought	5
• Vulnerability	intrinsic vulnerability	2
• Risk	injuries (mortality) & direct loss	3
Risk Assessment		
• Analytic methods	quantitative assessment based on historical stochastic data	4
• Deliberative methods	communication, learning	1
• System Design	accessible, interoperable	4
Risk Management		
• Establish Context	problem framing, driving forces	1
• Appraisal	risk identification	1
• Analysis	multi-hazard potential, exposure, risk	5
• Evaluation	risk comparison (spatial)	3
• Treatment	support for policy guidelines	3
Suitability Scale: *1= Weak 2= Fair 3= Moderate 4=Strong 5=Very Strong*		**54.29** Score: (0-100%)

Source: *Center for Hazards & Risk Research, Columbia University; World Bank, ProVention Consortium*

Reference Documents: *Dilley, M., R. S. Chen, et al. (2005). Natural Disaster Hotspots: A Global Risk Analysis, Final Report. Disaster Risk Management.*

Relevant Websites: *http://www.ldeo.columbia.edu/chrr/research/hotspots/ ;http://geohotspots.worldbank.org/hotspot/hotspots/disaster.jsp*

3. Disaster Risk Index (DRI)

Criteria	Attributes	Rank
Context & Focus		
• Conceptual Framing	Hazard-Risk model	2
• Spatial Extent	global coverage	1
• Temporal Horizon	historical profile	1
• Hazard Type(s)	earthquake, flood, cyclone	3
• Vulnerability	exposure, susceptibility	2
• Risk	mortality	1
Risk Assessment		
• Analytic methods	quantitative assessment based on historical stochastic data	3
• Deliberative methods	communication, learning	1
• System Design	accessible	2
Risk Management		
• Establish Context	problem framing, driving forces	1
• Appraisal	NA	1
• Analysis	hazard exposure, mortality	4
• Evaluation	risk comparison (non-spatial)	1
• Treatment	support for policy guidelines	2
Suitability Scale: *1= Weak 2= Fair 3= Moderate 4=Strong 5=Very Strong*		**35.71** Score: (0-100%)

Source: *United Nations Development Program*

Reference Documents: *Pelling, M., Maskrey, A., Ruiz, P., and Hall, L., eds., 2004, Reducing Disaster Risk; A challenge for development: New York, United Nations Development Program, Bureau for Crisis Prevention and Recovery, 161 p.*

Relevant Websites: *http://www.undp.org/cpr/disred/english/wedo/rrt/dri.htm; http://gridca.grid.unep.ch/undp/*

4. Participatory Disaster Risk Assessment (PDRA)

Criteria	Attributes	Rank
Context & Focus		
• Conceptual Framing	Pressure-Release model	4
• Spatial Extent	local	2
• Temporal Horizon	historical profile, current conditions	3
• Hazard Type(s)	multi-hazard	5
• Vulnerability	human susceptibility, adaptive capacity	3
• Risk	NA	0
Risk Assessment		
• Analytic methods	qualitative methods include surveys, community mapping, etc.	3
• Deliberative methods	communication,learning, mediation, judgement, decision making	5
• System Design	accessible, transferrable, flexible	4
Risk Management		
• Establish Context	problem framing & diagnosis, objectives	5
• Appraisal	threats, assets, consequences, capacities, concerns	4
• Analysis	NA	1
• Evaluation	NA	3
• Treatment	policy recommendations, implementation, monitor & review	2
Suitability Scale: *1= Weak 2= Fair 3= Moderate 4=Strong 5=Very Strong*		**62.86** Score: (0-100%)

Source: *International Federation of Red Cross and Red Crescent Societies IIFRC); Disaster Mitigation for Sustainable Livelihood Program (DiMP) at the University of Cape Town, South Africa.*

Reference Documents: *International Federation of Red Cross and Red Crescent Societies (IFRC), 2007, CVA toolbox 2007, 182p; Disaster Mitigation for Sustainable Livelihoods Programme, 2008, Weathering the Storm:, 201 p*

Relevant Websites: *http://www.ifrc.org/what/disasters/preparing/preparedness-tools/vca.asp; http://www.egs.uct.ac.za/dimp/*

4. Participatory Disaster Risk Assessment (PDRA)

PDA is a qualitative vulnerability assessment method for use at the level of regions and communities. The method is the result of sustained research and development co-ordinated by the International Federation of Red Cross and Red Crescent Societies and its partners to "*promote resilience at a community level by proactively implementing risk reduction measures at a community level to minimize potential for loss of life and disruption, while improving local, regional and international capacities for response and recovery to natural disasters*" (International Federation of Red Cross and Red Crescent Societies, 1999; 2006a). The Disaster Mitigation for Sustainable Livelihood program (DiMP) at the University of Cape Town uses a modified version of the PDRA method for managing risks associated with growth and development of informal settlements in South Africa (Holloway *et al.*, 2008).

PDRA has developed a robust suite of qualitative assessment methods for evaluating vulnerabilities and risks to people caused by potential hazard threats, and the capacities of these same people to cope with, respond to and recover from the impacts of future disaster events. Information and local knowledge on hazard threats and potential impacts is collected and systematized through workshops and focus-group sessions using a broad range of participatory planning techniques, including surveys, community-based mapping and problem-tree analysis. The PDRA method encompasses normative aspects of the risk-management process with a focus on problem framing, diagnosis, appraisal and risk treatment. There is no formal analysis or evaluation, though results of the assessment are used to guide strategy development and community decision-making.

European Union

The development and refinement of risk-assessment methods in Europe has taken place against the backdrop of a multinational governance framework that emphasizes evidence-based approaches to managing existing and emerging societal threats for member countries (Funtowicz *et al.*, 2000; Walker, 2000; Engels, 2005). Research and development is coordinated through various directives for risk management and is administered through large-scale programs involving collaborations between major academic institutions and public-sector agencies throughout Europe. Relevant EU directives include the Environmental Assessment Directive (2001/42/EC) and the Assessment and Management of Flood Risks Directive (2007/60/EC).

Research and development of risk-assessment methods in support of these policy directives is geared toward integrated assessment of multi-hazard vulnerability and risk. Two representative examples are profiled below. The first is a summary of work on analytical methods for national-scale multi-hazard vulnerability and risk assessment undertaken by the European Spatial Planning Observation Network (EPSON: 2002–2005). The second profiles work recently completed by the European Commission 6th Framework Program for Global Change and Ecosystems to establish a framework for harmonizing methods of multi-hazard risk assessment for use by sectors responsible for disaster risk management at regional and local levels across the European Union (ARMONIA).

5. European Spatial Planning Observation Network (ESPON)

The EPSON method integrates conventional hazard-risk and vulnerability assessment models for the purpose of analyzing spatial patterns and territorial trends in societal risk at a national scale across the European Union. The objective of the research was "*to harmonize results of international hazards research with innovative new methods to analyse, map and compare information on vulnerability and risk in a common framework for the European Union and associated countries.*" (Thome, 2006)

In implementing this method, natural hazard risks are first characterized and ranked using assessment criteria established by the German Advisory Council on Global Change (Klinke and Renn, 2002), then filtered on the basis of spatial relevance with respect to human settlement. Index-based methods are used for analyzing, aggregating and mapping dimensions of multi-hazard potential and vulnerability. Standardized hazard-intensity scales are used to rank and uniformly measure relative hazard magnitude across different types of natural and human-induced hazards (floods, droughts, earthquakes, etc.).

Multi-hazard potential is assessed and mapped by aggregating index

5. European Spatial Planning Observation Network (ESPON)

Criteria	Attributes	Rank
Context & Focus		
• Conceptual Framing	Hazard-Risk, & Vulnerability models	4
• Spatial Extent	regional, sub-national, national	5
• Temporal Horizon	current conditions	3
• Hazard Type(s)	earthquake, landslide, cyclone, human-induced hazards	5
• Vulnerability	physical vulnerability	2
• Risk	hazard x vulnerability	3
Risk Assessment		
• Analytic methods	qualitative, quantitative, deterministic	4
• Deliberative methods	communication,learning, mediation	4
• System Design	accessible; transferrable	3
Risk Management		
• Establish Context	problem framing & diagnosis	2
• Appraisal	threats, assets, consequences, capacities, concerns	5
• Analysis	vulnerability,socio-economic risk	3
• Evaluation	risk treatment alternatives	2
• Treatment	policy recommendations, implementation	2
Suitability Scale: *1= Weak 2= Fair 3= Moderate 4=Strong 5=Very Strong*		**67.14** Score: (0-100%)

Source: *the European Observation Network for Territorial Development and Cohesion, as adopted by the European Commission on 7 November 2007*

Reference Documents: *Becker, J., W. Saunders, et al. (2008). Pre-event recovery planning for land use in New Zealand: An Updated Methodology. Science Report. Geoscience New Zealand: 39; King, A. and R. Bell (2006). Riskscape New Zealand- A Multi-Hazard Loss Modelling Tool, NZSEE Conference Proceedings*

Relevant Websites: *http://www.gns.cri.nz/services/hazardsplanning/index.html; http://www.niwa.cri.nz/pubs/wa/ma/15-3/tool;*

6. Applied Multi-Risk Mapping of Natural Hazards for Impact Assessment (Armonia)

Criteria	Attributes	Rank
Context & Focus		
• Conceptual Framing	Hazard-Risk model	3
• Spatial Extent	local, regional, national	5
• Temporal Horizon	historical profile, current conditions	3
• Hazard Type(s)	earthquake; flood; landslide; volcano; meteorological; other	5
• Vulnerability	physical vulnerability	3
• Risk	injuries, direct loss,	3
Risk Assessment		
• Analytic methods	qualitative, quantitative, deterministic	4
• Deliberative methods	communication	3
• System Design	accessible	3
Risk Management		
• Establish Context	problem framing & diagnosis	3
• Appraisal	NA	5
• Analysis	vulnerability, socio-economic risk	3
• Evaluation	risk profile	4
• Treatment	policy recommendations, implementation	4
Suitability Scale: *1= Weak 2= Fair 3= Moderate 4=Strong 5=Very Strong*		**72.86** Score: (0-100%)

Source: *European Union 6th Directive on Sustainable Development, Global Change and Ecosystems*

Reference Documents: *Greiving, S. (2007). Multi-risk assessment of Europe's regions. Measuring Vulnerability to Natural Hazards. ed., J. Birkman: 210-226 ; Margottini, C., S. Menoni, et al. (2008). Land Use Planning and Management in Hazardous Areas: Findings and Perspectives for the Future Proposed by the Armonia Project. Contract No 511208*

Relevant Websites: *http://www.eu-medin.org/projectPage.php?acronym=ARMONIA*

scores for relative intensity across hazard types. Vulnerability is assessed on the basis of damage potential and coping capacity, consistent with the UN/ISDR definition, and with the 'Hazards of Place' model of Cutter and others (Cutter *et al.*, 2000; Cutter, 2001; Cutter *et al.*, 2003). A suite of indicators is used to measure the dimensions of damage potential and coping capacity, then weighted and aggregated into an overall assessment of vulnerability at the scale of individual territories.

The EPSON method interprets risk as the product of hazard potential and vulnerability and uses an aggregate index for each territory to assess overall risk potential for single and multiple hazards. The weighting of component indicators is based on the overall characterization of risk using a Delphi-based approach that synthesizes expert knowledge and understanding. Model outputs are presented as single and multiple hazard-risk maps at the territory level. They are intended to provide a science-based framework to inform future policy on disaster risk management in the European Union.

6. Applied Risk Mapping of Natural Hazards for Impact Assessment (ARMONIA)

The ARMONIA method builds on results of the EPSON project and a number of related research initiatives across Europe. It combines methods of vulnerability assessment used at the regional scale with hazard-risk models used at the regional/local scale. It is geared toward integrating disaster risk management and standardizing land-use planning activities and practices across the European Union. The overall objective of ARMONIA is "*to provide the European Commission with a set of harmonized methods for producing integrated risk maps that can be used to achieve more informed and effective spatial planning procedures in areas prone to natural disasters in Europe*," (Greiving, 2006; Greiving *et al.*, 2006a; Greiving *et al.*, 2006b; Greiving, 2007). Outputs of the research and development program include an extensive set of technical guidelines and methods for multi-hazard risk assessment. Regional models are based on the UN/ISDR protocols for vulnerability assessment and are implemented using heuristics and synthetic indicators of relative hazard potential and anticipated consequences developed partly through the EPSON project.

Risk assessment at the regional/local scale is based on conventional hazard-risk models and implemented using methods of both deterministic and probabilistic analysis. Hazard potential is evaluated for each hazard type based on parameters of extent, intensity and likelihood of occurrence. Physical vulnerability is evaluated on the basis of engineering performance models that relate hazard intensity to the probability and severity of expected damage for specific elements of the built environment. Risk is evaluated for individual hazard types using standard methods of quantitative loss estimation and is only aggregated at regional scales for the purpose of comparison.

Methods developed by ARMONIA are consistent with the ISO and comparable standards for risk assessment, and with guidelines introduced as part of the IRGC framework. They are situated in the context of a spatial decision support system (DSS) that is intended to assist emergency preparedness and land-use planning agencies in harmonizing their collective approach to disaster risk management.

Australia and New Zealand

The 2002 report to the Council of Australian Governments advocates a shift from traditional roles of emergency preparedness, response and recovery to proactive disaster mitigation and pre-event planning (Council of Australian Governments, 2002). On the strength of recommendations put forward in the 2002 report, Australia has since established a National Risk Assessment Framework for Sudden Onset Natural Hazards (The Australian Government Department of Transport and Regional Services, 2004).

The framework provides co-ordination for the development and refinement of risk-assessment methods across the various agencies involved in the broader context of disaster risk management. Natural hazards of particular concern include bushfires, earthquakes, floods, storms, cyclones, storm surges, landslides, tsunamis, meteorite strikes and tornadoes. An equivalent framework exists in New Zealand to co-ordinate research and development of risk-assessment methods in support of the Resource Management Act (RMA) and the Civil Defense Management Act (CDEM, 2002).

7. Geoscience Australia: Risk and Impact Analysis Program (GA)

Methods developed by Geoscience Australia contribute to core mandates of the Australian National Risk Assessment Framework (NRAAG) through research and development of analytical techniques to assess disaster risk in terms of hazard potential, vulnerability and socioeconomic consequence (Granger and Hayne, 2000; Middelmann and Granger, 2000; Granger and Michael-Leiba, 2001; Dwyer *et al.*, 2004; Middelmann, 2007). Resulting methods and tools are used by Geoscience Australia and partner agencies responsible for national disaster risk management to develop "*a systematic and widespread national process of disaster risk assessment and, most importantly, a paradigm shift in focus towards cost effective, evidence-based disaster mitigation*," (The Australian Government Department of Transport and Regional Services, 2004).

Geoscience Australia has developed a robust suite of analytical methods and tools for quantitative assessment of hazard potential, intrinsic vulnerability and risk for multiple natural hazard types. These include tropical cyclones, floods, severe storms, bushfires, landslides, earthquakes and tsunamis. Hazard potential is assessed at a national scale in terms of extent, intensity and likelihood of occurrence. Intrinsic social vulnerability is assessed at local and regional scales using quantitative methods of spatial statistics and decision-tree analysis. Risk is assessed using standard hazard-risk models for quantitative loss estimation and disaster potential. The analytical methods are incorporated into proprietary modelling systems used by Geoscience Australia and its partners for the assessment of risk to specific sectors (transportation, infrastructure, etc.) at all jurisdictional levels. The methods and tools address the risk analysis component of the Australian–New Zealand standard for risk management (AS/NZ 4360, 2004).

8. Australian Geomechanics Society (AGS)

Methods developed by the Australian Geomechanics Society contribute to core mandates of the Australian National Risk Assessment Framework (NRAAG) through the development of analytical techniques and professional guidelines to assess, evaluate and treat landslide risk. Outputs are used by geotechnical practitioners and regulators in Australia and abroad to provide "*professional guidelines on terminology, procedures for landslide risk management, methods which should be used to carry out a rigorous and defensible risk analysis and information to assist in determining acceptable and tolerable risks for loss of life,*" (Australian Geomechanics Society, 2000).

The guidelines establish a robust suite of analytical methods and tools for quantitative assessment of landslide hazard potential, physical vulnerability and risk. Hazard potential is assessed at a local and site-specific scale in terms of extent, intensity and likelihood of occurrence. Physical vulnerability is assessed using a semi-quantitative method that relates hazard-intensity categories to anticipated proportions of damage to property and injury to people. Risk is assessed using quantitative methods of loss estimation that take into account probabilities of occurrence and likelihood of asset exposure. The analytical methods are incorporated into proprietary modelling systems used by professional engineers for site-specific risk assessment, evaluation and design of treatment options.

The AGS guidelines conform to principles and procedural elements of the Australian–New Zealand standards for risk management (AS/NZ 4360, 2004) and are focused primarily on elements of risk analysis, evaluation and treatment. They provide a standard method for comparing landslide risks and establishing thresholds of tolerable risk for design standards. However, they do not include formal methods for evaluation or decision analysis.

9. Emergency Management Australia (EMA)

Emergency Management Australia provides a comprehensive suite of procedural manuals and guidelines that cover all aspects of the disaster risk management cycle. They are used by emergency-response professionals and by agencies responsible for implementation of a national risk-assessment framework as directed by the Council of Australian Governments (COAG). The objective is to increase capacities "*to deal with the wide variety and scale of hazards that may affect Australian communities, whether these originate from natural, technological, biological or social agents or result from an interaction between agents in any of these fields,*" (Emergency Management Australia, 2001; 2002).

The EMA guidelines document a wide range of methods and tools for semi-quantitative and quantitative assessment of multi-hazard risk. Methods are tailored to available information, knowledge and expertise at the community level. The averaging approach uses methods for estimating loss per impacted dwelling, with average values for business premises based on the area of the structure. The synthetic approach uses engineering performance models to calculate damage probabilities for a variety of representative structures. The survey approach uses post-event forensics to determine losses sustained from an event. Proprietary software applications are used to evaluate anticipated consequences for both averaging and synthetic approaches.

The EMA guidelines conform to principles and procedural elements of the Australian–New Zealand standards for risk management (AS/NZ 4360, 2004) and address all elements of the disaster risk management cycle. The methods and guidelines are designed for practitioners and take full advantage of best practices for quantitative risk analysis. Methods for risk evaluation and decision analysis are limited in scope to risk-risk comparisons and cost-benefit analysis.

10. Geoscience New Zealand Hazards and Society Program (GNS)

Geoscience New Zealand contributes to the national mandates of the Resource Management Act (RMA) and the Civil Defense Management Act (CDEM, 2006) through research and development of methods, tools and guidelines for risk assessment and risk-reduction planning (Paton *et al.*, 2001; Kerr *et al.*, 2002; Finnis, 2004; Becker *et al.*, 2005; Martin *et al.*, 2005; Seville and Metcalfe, 2005; Saunders and Glassey, 2007; Becker *et al.*, 2008). (Bell and King, 2006)Outputs include procedural guideline documents and quantitative assessment methods

7. Geoscience Australia: Risk and Impact Analysis Program (GA)

Criteria	Attributes	Rank
Context & Focus		
• Conceptual Framing	Hazard-Risk model, Pressure-Release model	4
• Spatial Extent	local, regional, national	4
• Temporal Horizon	current conditions	2
• Hazard Type(s)	cyclone, storm, flood, bushfire, landslide, earthquake, tsunami	5
• Vulnerability	intrinsic vulnerability, susceptibility	5
• Risk	injuries, direct loss, indirect loss	4
Risk Assessment		
• Analytic methods	quantitative, deterministic, probabilistic	5
• Deliberative methods	communication, translation,	2
• System Design	accessible, robust	4
Risk Management		
• Establish Context	NA	0
• Appraisal	NA	0
• Analysis	vulnerability,socio-economic risk, costs& benefits	5
• Evaluation	risk profile, risk characterization	2
• Treatment	policy recommendations	4
Suitability Scale: *1= Weak 2= Fair 3= Moderate 4=Strong 5=Very Strong*	**65.71**	Score: (0-100%)

Source: *Geoscience Australia, Dept. of Transport & Regional Services, Council of Australian Governments*
Reference Documents: *Geoscience Australia: Middelmann, M. H. (2007). Natural Hazards in Australia, Identifying Risk Analysis Requirements.; Dwyer, A., C. Zoppou, et al. (2004). Quantifying Social Vulnerability Granger K. and M. Hayne (2000). Natural Hazards & the Risks they Pose to South-East Queensland.*
Relevant Websites: *http://www.ga.gov.au/hazards/risk/*

8. Australian Geomechanics Society (AGS)

Criteria	Attributes	Rank
Context & Focus		
• Conceptual Framing	Hazard-Risk model	3
• Spatial Extent	local	2
• Temporal Horizon	current conditions	2
• Hazard Type(s)	landslide	1
• Vulnerability	physical vulnerability	3
• Risk	injuries, direct loss	3
Risk Assessment		
• Analytic methods	quantitative, deterministic, probabilistic	5
• Deliberative methods	communication	2
• System Design	accessible	2
Risk Management		
• Establish Context	NA	1
• Appraisal	NA	1
• Analysis	vulnerability,socio-economic risk, costs& benefits	5
• Evaluation	risk profile, risk characterization	3
• Treatment	development guidelines	4
Suitability Scale: *1= Weak 2= Fair 3= Moderate 4=Strong 5=Very Strong*	**52.86**	Score: (0-100%)

Source: *Geoscience Australia, Dept. of Transport & Regional Services, Council of Australian Governments*
Reference Documents: *Australian Geomechanics Society: Landslide Risk Management Concepts and Guidelines (2000); Guideline for Landslide Susceptibility, Hazard and Risk Zoning for Land Use Planning (2007).*
Relevant Websites: *http://www.australiangeomechanics.org*

9. Emergency Management Australia (EMA)

Criteria	Attributes	Rank
Context & Focus		
• Conceptual Framing	Hazard-Risk model	3
• Spatial Extent	local, regional, national	5
• Temporal Horizon	current conditions, historical conditions	3
• Hazard Type(s)	all hazards	5
• Vulnerability	physical vulnerability	3
• Risk	injuries, direct loss	3
Risk Assessment		
• Analytic methods	quantitative, semi-quantitative, deterministic	4
• Deliberative methods	communication, translation	4
• System Design	accessible, transferrable, robust	4
Risk Management		
• Establish Context	NA	3
• Appraisal	NA	4
• Analysis	vulnerability,socio-economic risk, costs& benefits	4
• Evaluation	risk profile	2
• Treatment	emergency preparedness guidelines and policy	5
Suitability Scale: *1= Weak 2= Fair 3= Moderate 4=Strong 5=Very Strong*	**74.29**	Score: (0-100%)

Source: *Emergency Management Australia*
Reference Documents: *Emergency Management Australia: (2007): Concepts and Practice, Manual 1; Emergency Risk Management Applications Guideline, Manual 5; Disaster Loss Assessment Guidelines, Manual 27;*
Relevant Websites: *http://www.ema.gov.au/*

10. Geoscience New Zealand Hazards and Society Program (GNS)

Criteria	Attributes	Rank
Context & Focus		
• Conceptual Framing	Hazard-Risk model	3
• Spatial Extent	local, regional, national	5
• Temporal Horizon	current conditions	3
• Hazard Type(s)	earthquake, landslide, cyclone, volcano, tsunami	5
• Vulnerability	physical vulnerability	2
• Risk	injuries, direct loss	3
Risk Assessment		
• Analytic methods	qualitative, quantitative, deterministic	3
• Deliberative methods	communication,learning, mediation	3
• System Design	accessible; transferrable	3
Risk Management		
• Establish Context	problem framing & diagnosis	3
• Appraisal	threats, assets, consequences, capacities, concerns	3
• Analysis	vulnerability,socio-economic risk	4
• Evaluation	risk treatment alternatives	3
• Treatment	policy recommendations, implementation	4
Suitability Scale: *1= Weak 2= Fair 3= Moderate 4=Strong 5=Very Strong*	**67.14**	Score: (0-100%)

Source: *Geoscience New Zealand*
Reference Documents: *Becker, J., W. Saunders, et al. (2008). Pre-event recovery planning for land use in New Zealand: An Updated Methodology. Science Report. Geoscience New Zealand: 39; King, A. and R. Bell (2006). Riskscape New Zealand- A Multi-Hazard Loss Modelling Tool, NZSEE Conference Proceedings*
Relevant Websites: *http://www.gns.cri.nz/services/hazardsplanning/index.html; http://www.niwa.cri.nz/pubs/wa/ma/15-3/tool;*

and tools. Both are used by public and private-sector agencies responsible for national disaster risk management to "*build resilience to natural hazards through effective land-use risk reduction and recovery,*" (Becker *et al.*, 2008).

The GNS develops methods for the assessment of hazard potential at a national scale, the assessment of physical vulnerability and loss estimation at local and regional scales. Hazard potential assessment uses standard hazard-risk models for evaluating extent, magnitude and frequency for earthquakes, surface rupture faults, volcanoes, landslides and tsunamis. Risk analysis is based on quantitative synthetic methods for assessing damage probability and consequent loss. The analytical methods are incorporated into a risk-assessment tool known as Riskscape New Zealand, which is intended for use by agencies responsible for disaster risk management at all jurisdictional levels (Bell and King, 2006). The scope of assessment is currently limited to the analysis of damages and anticipated losses to building stock.

The GNS guidelines conform to principles and procedural elements of the Australian–New Zealand standards for risk management (AS/NZ 4360, 2004) and are focused primarily on risk analysis, evaluation and treatment stages. Guideline documents for integrating disaster risk management with land-use planning have been developed for landslide and earthquake-generated fault rupture (Kerr *et al.*, 2002; Saunders and Glassey, 2007). Additional guidelines are in progress. Guideline documents are also available for pre-event recovery planning (Becker *et al.*, 2008).

Latin America

Research and development of risk-assessment methods in Latin America is co-ordinated in part through national and international efforts of the Inter-American Development Bank and the UN Development Program. The work is largely undertaken through research institutes in South America and in collaboration with international research and development efforts centred in Europe. The emphasis is on developing standardized methods for hazard-risk modelling of major urban centres and for subnational and national-level vulnerability assessment. As with the EPSON project in Europe, the intent is to provide a synoptic overview of societal risk at national and subnational scales for countries in Latin America and the Caribbean. The methods are aligned with policy mandates of the Hyogo Framework for Action and conform to assessment guidelines of the UN ISDR for hazard-risk modelling and the UNDP for vulnerability assessment.

11. Urban Seismic Risk Index (USRi)

The Urban Seismic Risk index is an index-based method for evaluating losses associated with earthquake events in major urban centres in the Americas. It uses statistical methods for transforming quantitative measures of physical and intrinsic social vulnerability into an integrated measure of total risk (Carreño *et al.*, 2007b). The methods were developed by the Institute of Environmental Studies (IDEA) at the University of Colombia and are incorporated into the MEGA-Index, developed by Earthquakes and Megacities Initiative (EMI). The index is intended for use by disaster risk management agencies working at the municipal level to "*promote risk communication among different stakeholders to assist policy decision making and monitoring of different risk reduction practices implemented at the local level.*"(Carreño *et al.*, 2007a).

The USRi method uses deterministic seismic-hazard models and statistical methods for assessing 'physical risk' and 'social fragility.' Physical risk is assessed by aggregating estimates of exposure and physical susceptibility into a composite ordinal measure of physical damage (injuries, fatalities and impacts on selected infrastructure elements). Social fragility is evaluated using selected demographic variables such as population density, mortality rate and indirect measures of social disparity and capacity for response and recovery. Vulnerability parameters are transformed into fragility functions (impact factors) using an analytical hierarchy process (AHP) to evaluate relative contributions to intrinsic vulnerability and capacity for response and recovery. Subindices are then normalized and aggregated into a composite measure of risk. There is no direct coupling between the USRi index and policy guidelines or management objectives, though outputs are intended to inform policy analysis and decision-making.

12. Disaster Risk and Management Indicators for the Americas (IDEA)

IDEA is an index-based method for assessing and benchmarking patterns of multihazard risk and the socioeconomic factors that contribute to the configuration of risk at a national scale in South and Central America The method reflects research and development by the Institute of Environmental Studies (IDEA in Spanish) at the University of Columbia and the Inter-American Development Bank (IDB). It is intended for use by national-level disaster risk management agencies and the IDB "*to inform decision-makers on priority areas for action and resource allocation, and to complement more detailed risk assessments and profiles as a basis for planning at the national and sub-national levels*." (Cardona *et al.*, 2005).

The IDEA indicator framework is based on the UNDP definition of vulnerability and uses inductive analytical methods for assessing and benchmarking patterns of multi-hazard risk at a national scale. The disaster deficit index (DDI) measures the potential for a country to respond to catastrophic disaster events in terms of macroeconomic and financial capacity. The local disaster index (LDI) assesses social and environmental risks associated with the impacts of natural hazards on local population centres. It is used in conjunction with more detailed assessments of total risk in urban centres (Carreño *et al.*, 2007a). The prevalent vulnerability index (PVI) characterizes prevailing conditions of vulnerability in terms of exposure, susceptibility, socioeconomic fragility and social resilience. The risk management index (RMI) measures organizational and institutional capacities for disaster risk reduction. There is no direct coupling between the IDEA risk indices and policy guidelines or management objectives, though outputs are intended to inform policy analysis and decision-making.

13. UN Economic Commission for Latin America and the Caribbean (ECLAC)

The UN Economic Commission for Latin America and the Caribbean framework (ECLAC) is an index-based method for assessing the consequences of disaster events in countries of Latin America and the Caribbean in terms of the environment and financial impacts on social and economic structures. It is used by international organizations and by member countries to assist in the development of disaster mitigation strategies and pre-event planning. The methods comprise a set of guidelines "*to identify the most affected social, economic and environmental sectors and geographic regions, and therefore those that require priority attention in reconstruction following a disaster event*," (UN Economic Commission for Latin America and the Caribbean, 2003).

The ECLAC guidelines focus on methods for assessing damage caused by a disaster event including direct economic losses to capital stocks, indirect losses caused by interruptions to the production flows of goods and services, and macroeconomic performance. Assessment of direct damage includes an accounting of total or partial destruction of physical infrastructure, buildings, machinery, equipment and destruction of agricultural assets. Indirect losses are assessed on the basis of increased operational costs due to the loss of physical infrastructure and inventories, diminished production capacity and/or service provision and impacts on income and employment. Assessment of macroeconomic impacts provides a measure of reduced sector-based economic performance and is based on estimates of how these sectors might have performed had the disaster not occurred. Assessments account for impacts to gross domestic product, gross investment, balance of payments, public finances and employment. The ECLAC guidelines assess post-event disaster consequences and do not explicitly reference broader guidelines or standards for disaster risk management.

14. Deutsche Gesellschaft fur Technische Zusammenbareit (GTZ)

GTZ is an index-based method for identifying and measuring the dimensions of risk at the community level. Developed by Germany's Federal Ministry for Economic Co-operation and Development (GTZ), the method has been used to support community-based disaster risk management efforts in Latin America, Africa and Asia and is intended to *"enhance the importance and priority of disaster prevention and preparedness and make them more effective, as a way of reducing damage and losses from extreme natural disasters, thereby reducing the need for emergency aid,"* (Kohler *et al.*, 2004).

11. Urban Seismic Risk Index (USRi)

Criteria	Attributes	Rank
Context & Focus		
• Conceptual Framing	Hazard-Risk model, Pressure-Release model	4
• Spatial Extent	local	3
• Temporal Horizon	current conditions	2
• Hazard Type(s)	earthquake	2
• Vulnerability	physical vulnerability, intrinsic vulnerability	3
• Risk	indirect measures	2
Risk Assessment		
• Analytic methods	inductive, quantitative	4
• Deliberative methods	NA	1
• System Design	accessible	2
Risk Management		
• Establish Context	NA	1
• Appraisal	NA	1
• Analysis	vulnerability, risk	3
• Evaluation	risk profile	2
• Treatment	policy recommendations	3
Suitability Scale: *1= Weak 2= Fair 3= Moderate 4=Strong 5=Very Strong*		**47.14** Score: (0-100%)

Source: *The Institute of Environmental Studies (IDEA) at the University of Colombia; Earthquake and Megacities Initiative (EMI)*
Reference Documents: *Carreno, M.-L., Cardona, O., D., and Barbat, A.H., 2007, Urban Seismic Risk Evaluation: A Holistic Approach: Natural Hazards, v. 40, p. 137-172.*
Relevant Websites: *http://www.emi-megacities.org*

12. Disaster Risk and Management Indicators for the Americas (IDEA)

Criteria	Attributes	Rank
Context & Focus		
• Conceptual Framing	Pressure-Release model	2
• Spatial Extent	regional, national	4
• Temporal Horizon	current conditions	2
• Hazard Type(s)	multi-hazard	3
• Vulnerability	exposure, susceptibility, intrinsic vulnerability	3
• Risk	direct loss, injuries	3
Risk Assessment		
• Analytic methods	quantitative	4
• Deliberative methods	communication	1
• System Design	accessible	1
Risk Management		
• Establish Context	problem framing & diagnosis	2
• Appraisal	NA	0
• Analysis	vulnerability, socio-economic risk	4
• Evaluation	risk profile	2
• Treatment	policy recommendations	2
Suitability Scale: *1= Weak 2= Fair 3= Moderate 4=Strong 5=Very Strong*		**47.14** Score: (0-100%)

Source: *The Institute of Environmental Studies (IDEA) at the University of Colombia; Inter-American Development Bank*
Reference Documents: *Cardona, O., D., J. Hurtado, E., et al. (2007). Indicators of disaster risk and risk management; Summary Report Updated 2007; Carreno, M.-L., O. Cardona, D., et al. (2007). "Urban Seismic Risk Evaluation: A Holistic Approach." Natural Hazards 40: 137-172.*
Relevant Websites: *http://idea.unalmzl.edu.co*

13. Economic Commission for Latin America and the Caribbean (ECLAC)

Criteria	Attributes	Rank
Context & Focus		
• Conceptual Framing	Hazard-Risk model	3
• Spatial Extent	national	4
• Temporal Horizon	current conditions	2
• Hazard Type(s)	multi-hazard	3
• Vulnerability	physical vulnerability	1
• Risk	direct loss, injuries, indirect loss	4
Risk Assessment		
• Analytic methods	forensic assessment	2
• Deliberative methods	communication	1
• System Design	accessible	1
Risk Management		
• Establish Context	NA	0
• Appraisal	NA	0
• Analysis	vulnerability, socio-economic risk	4
• Evaluation	NA	0
• Treatment	policy recommendations	2
Suitability Scale: *1= Weak 2= Fair 3= Moderate 4=Strong 5=Very Strong*		**38.57** Score: (0-100%)

Source: *United Nations Economic Commission for Latin America and the Caribbean*
Reference Documents: *ECLAC, 2003, Handbook for Estimating the Socio-economic and Environmental Effects of Disasters: UN Economic Commission for Latin America and the Caribbean, 357 p*
Relevant Websites: *http://www.cepal.cl/default.asp?idioma=IN*

14. Deutsche Gesellschaft fur Technische Zusammenbareit (GTZ)

Criteria	Attributes	Rank
Context & Focus		
• Conceptual Framing	Hazard-Risk model	2
• Spatial Extent	local, regional	2
• Temporal Horizon	current conditions	3
• Hazard Type(s)	non-specific	2
• Vulnerability	physical vulnerability, capacity	3
• Risk	impacts	2
Risk Assessment		
• Analytic methods	semi-quantitative normative assessment	3
• Deliberative methods	communication	3
• System Design	accessible	3
Risk Management		
• Establish Context	problem framing & diagnosis	3
• Appraisal	hazard threat, vulnerability, impact	3
• Analysis	NA	0
• Evaluation	NA	0
• Treatment	policy recommendations, implementation	3
Suitability Scale: *1= Weak 2= Fair 3= Moderate 4=Strong 5=Very Strong*		**45.71** Score: (0-100%)

Source: *Germany's Federal Ministry for Economic Cooperation and Development*
Reference Documents: *Kobler, Julich and Bloemertz, 2004. Risk Analysis- A Basis for Disaster Risk Management. Guidelines Document*
Relevant Websites *http://www.gtz.de/en/themen/uebergreifende-themen/krisenpraevention/21272.htm*

GTZ use an index-based framework to identify and measure the dimensions of risk at the community level in terms of hazard, exposure, vulnerability and capacity. Hazard threats are assessed on the basis of frequency and severity using overlay methods to determine the extent of exposure for various elements of the built environment. Vulnerability and capacity are assessed using a modified Delphi approach to rank damage potential to community assets in the natural and built environment, potential impacts on people and the local economy, and capabilities to respond and recover from a hazard event. Indicators are weighted according to perceived importance and aggregated into one of the four major indices.

Scores for each of the four indices are normalized and aggregated into an overall measure of disaster risk. The method provides a means of identifying patterns of risk in any given community and a metric for comparing overall levels of risk across communities in a given region. The GTZ guidelines and methods encompass normative aspects of the risk-management process with a focus on problem framing, diagnosis and risk appraisal. There is no formal analysis or evaluation, though semi-quantitative indicators are used to guide strategy development and community decision-making.

North America

Public-domain risk-assessment methods in the United States and Canada have evolved in the context of a regulatory governance framework that, until recently, has been aimed at structural mitigation, emergency preparedness, response and recovery. With a shift toward more proactive modes of disaster mitigation and pre-event planning, there has also been a corresponding refinement of risk-assessment methods. Methods and tools encompass the full gamut from quantitative hazard-risk models for loss estimation at local and regional scales to regional and national-scale assessments of social vulnerability to an innovative new suite of disaster-resilience models for analyzing patterns of existing and emerging risk in coupled human-natural systems.

In the United States, much of this work is co-ordinated through the Federal Emergency Management Agency (FEMA), the Institute for Building and Housing Safety (IBHS) and the American Planning Association (APA). Together, these organizations have worked to heighten awareness and understanding of disaster mitigation among professional planners, and to strengthen the political will of decision-makers to adopt proactive hazard mitigation and risk-reduction policies across jurisdictional levels (Deyle *et al.*, 1998; FEMA, 2000; American Planning Association, 2005b; Institute for Business & Home Safety, 2005). Their work reflects a shared concern that *"traditional mitigation efforts have focused largely on improving building codes, strengthening code enforcement, and testing new building techniques and materials. That focus certainly addresses the question of how we build, but land-use planning brings into focus the equally important question of where we build*," (Institute for Business & Home Safety, 2005)

While it is acknowledged that land-use planning is governed by local and regional jurisdictions, these groups and organizations advocate a role for the federal government in providing a 'supportive climate and statutory context' for risk-based comprehensive planning and development. These and other advocacy efforts have led to establishment of:

- The US Disaster Mitigation Act of 2000 (Disaster Mitigation Act, 2000), which requires state, tribal and local governments to develop a formal risk assessment and mitigation plan to be eligible for enhanced levels of disaster relief through the Hazard Mitigation Grant program and
- The Safe Communities Act of 2005 (H.R. 3524), which authorizes the Secretary of Homeland Security to make grants encouraging community safety by incorporating disaster mitigation and emergency preparedness into comprehensive plans or land-use statutes.

Equivalent efforts in Canada are mandated by the 2007 Emergency Management Act and coordinated through Public Safety Canada and Defence Research and Development Canada.

15. FEMA Multi-Hazard Loss Estimation Methodology (HAZUS)

HAZUS is a hazard-risk assessment framework for analyzing and evaluating consequences of natural hazard events in terms of direct and indirect economic losses and impacts on people (National Institute of Building Sciences, 2002; FEMA, 2004; Kircher *et al.*, 2006; Scawthorn *et al.*, 2006a; Scawthorn *et al.*, 2006c; Schneider and Schauer, 2006; Bostrom *et al.*, 2008). It encompasses an integrated suite of analytical models, spatial decision support tools and procedural guidelines for disaster risk management. Methods are developed and maintained by the US Federal Emergency Management Agency (FEMA) and by the National Institute of Building Sciences (NIBS). The framework supports US national policy objectives of the Disaster Management Act (Disaster Management Act, 2000), and is intended for use by decision-makers at all jurisdictional levels in "*identifying the most effective policies and actions to decrease risk and the potential for future losses in the community,*" (FEMA, 2004).

HAZUS includes a wide array of quantitative stochastic methods and tools for analyzing damages to the built environment and associated economic impacts caused by earthquakes, floods and hurricanes (Kircher *et al.*, 2006; Scawthorn *et al.*, 2006a; Scawthorn *et al.*, 2006c). Hazard potential is modelled using a mix of deterministic and probabilistic methods to analyze the spatial extent and severity of an event scenario for specific recurrence intervals. These event scenarios provide inputs for calculating probabilities of structural and nonstructural damage using calibrated engineering performance models to assess the fragility of buildings, essential facilities, critical infrastructure and lifeline services. Direct and indirect impacts are calculated for single and multiple hazard event scenarios in terms of injuries, loss of shelter, replacement costs and related impacts on employment and income.

The HAZUS methods, procedural guidelines and comprehensive technical manuals support all aspects of the disaster risk management process and are consistent with ISO guidelines and standards (National Institute of Building Sciences, 2002; FEMA, 2004). The method has undergone extensive peer review and represents a standard for local and regional-scale risk assessment in the context of disaster-mitigation policy development in the US (Scawthorn *et al.*, 2006a; Scawthorn *et al.*, 2006c; Schneider and Schauer, 2006; Gall *et al.*, 2007; Burton and Cutter, 2008; Ding *et al.*, 2008).

16. USGS Land-Use Portfolio Model (LUPM)

LUPM is a method for analyzing and evaluating financial risks associated with investment in hazard-mitigation measures. It is used to complement standard loss-estimation methods and provides a capacity for analyzing costs, benefits and efficiencies of proposed investment strategies. The methods and supporting software applications were developed by the US Geological Survey to *"assist public agencies and communities in evaluating economic liability (rate of return on investment), and in optimizing risk reduction strategies that seek to balance trade-offs between economic efficiency and community well being."* (Bernkopf *et al.*, 2001).

LUPM is adapted from financial-portfolio theory, a method for evaluating financial risks of investment scenarios based on probability distributions of expected economic loss (consequent risk) and return on investment. Losses avoided by investing in mitigation strategies are evaluated by modelling portfolios of community assets with and without mitigation measures in place. Loss estimations are based on standard protocols for catastrophe modelling. The return on investment (resource efficiency/financial risk) is evaluated by modelling the amount of community wealth that is retained as a result of implementing measures to mitigate the impacts of natural hazards (protection strategies) and/or to increase longer-term disaster resilience through land-use management (avoidance strategies).

The LUPM method has a relatively narrow but strategic focus on financial risk analysis and the evaluation of investment strategies. It does not explicitly reference ISO or comparable standards for risk management but does provide capacity and tools for cost-benefit analysis and evaluation. Outputs are intended to inform policy analysis and decision-making.

17. Emergency Management and GeoHazards (EmerGeo)

EmerGeo is an integrated suite of geospatial modelling and software tools designed to promote situational awareness and to support all aspects of incident management. Developed in Canada, EmerGeo is used internationally to assist government and emergency management industries manage multihazard risks in the fields of emergency

15. FEMA Multi-Hazard Loss Estimation Methodology (HAZUS)

Criteria	Attributes	Rank
Context & Focus		
• Conceptual Framing	Hazard-Risk model	3
• Spatial Extent	local, regional, national	5
• Temporal Horizon	current conditions	4
• Hazard Type(s)	earthquake, flood, hurricane	3
• Vulnerability	physical vulnerability	4
• Risk	injuries, direct loss, indirect loss; resilience	5
Risk Assessment		
• Analytic methods	qualitative, quantitative, deterministic, probabilistic	5
• Deliberative methods	communication,learning, mediation	3
• System Design	accessible,transferrable, flexible	5
Risk Management		
• Establish Context	problem framing & diagnosis, process design	4
• Appraisal	threats, assets, consequences, capacities, concerns	4
• Analysis	vulnerability,socio-economic risk	5
• Evaluation	risk treatment alternatives	3
• Treatment	policy recommendations, implementation, monitor & review	5
Suitability Scale: *1= Weak 2= Fair 3= Moderate 4=Strong 5=Very Strong*		82.86 Score: (0-100%)

Source: *U.S. Federal Emergency Management Agency; U.S. National Institute of Building Safety.*
Reference Documents: *FEMA,Using Hazus-MH for Risk Assessment (How-to Guide 433); NIBS, A Guide to Using Hazus for Mitigation*
Relevant Websites: *http://www.fema.gov/plan/prevent/hazus/; NIBS: http://www.nibs.org/hazusweb/overview/hazus.php*

16. USGS Land-Use Portfolio Model (LUPM)

Criteria	Attributes	Rank
Context & Focus		
• Conceptual Framing	Hazard-Risk model	3
• Spatial Extent	local, regional	5
• Temporal Horizon	dependent on capacity of catastrophe model	2
• Hazard Type(s)	dependent on capacity of catastrophe model	2
• Vulnerability	physical vulnerability	2
• Risk	financial risk	2
Risk Assessment		
• Analytic methods	quantitative, deterministic, probabilistic	5
• Deliberative methods	mediation, judgement, decision making	4
• System Design	accessible, transferrable, flexible	4
Risk Management		
• Establish Context	NA	1
• Appraisal	NA	1
• Analysis	cost-benefit, resource efficiency	4
• Evaluation	risk profile, characterization, risk treatment alternatives	4
• Treatment	policy recommendations, implementation, monitor & review	5
Suitability Scale: *1= Weak 2= Fair 3= Moderate 4=Strong 5=Very Strong*		62.86 Score: (0-100%)

Source: *U.S. Geological Survey, Western Region*
Reference Documents: *Bernkopf, R.L., et. al., 2001. A Portfolio Approach to evaluating natural hazard mitigation policies: An applicaiton to lateral-spread ground failure in coastal California: International Geology Review, p. 424-440.*
Relevant Websites: *http://geography.wr.usgs.gov/science/lupm.html*

17. Emergency Management and GeoHazards (EmerGeo)

Criteria	Attributes	Rank
Context & Focus		
• Conceptual Framing	Hazard-Risk model	3
• Spatial Extent	local, regional	3
• Temporal Horizon	current conditions	3
• Hazard Type(s)	earthquake, flood, landslide, other	5
• Vulnerability	physical vulnerability, capacity	3
• Risk	injuries, direct loss	3
Risk Assessment		
• Analytic methods	quantitative, deterministic	5
• Deliberative methods	communication,learning, decision making	4
• System Design	accessible; transferrable; flexible; interoperable	5
Risk Management		
• Establish Context	problem framing & diagnosis	1
• Appraisal	NA	0
• Analysis	physical vulnerability, risk	4
• Evaluation	characterization, risk treatment alternatives	3
• Treatment	policy recommendations, implementation, monitor & review	3
Suitability Scale: *1= Weak 2= Fair 3= Moderate 4=Strong 5=Very Strong*		64.29 Score: (0-100%)

Source: *EmerGeo Solutions*
Reference Documents: *Webb, T., 2000, Adapting the NHEMATIS Approach for use in a Raster Based Modeling Tool for Emergency Preparedness Canada: Emergency Preparedness Canada, 52 p*
Relevant Websites: *http://www.emergeo.com/*

18. NOAA Risk and Vulnerability Assessment Tool (RVAT)

Criteria	Attributes	Rank
Context & Focus		
• Conceptual Framing	Pressure-Release model	3
• Spatial Extent	local, regional	4
• Temporal Horizon	current conditions	3
• Hazard Type(s)	multi-hazard	2
• Vulnerability	physical vulnerability, intrinsic vulnerability	3
• Risk	impact	2
Risk Assessment		
• Analytic methods	qualitative, index-based overlay method	2
• Deliberative methods	communication,learning	3
• System Design	accessible, transferrable, flexible	4
Risk Management		
• Establish Context	problem framing & diagnosis	2
• Appraisal	threats, assets, consequences, capacities, concerns	4
• Analysis	NA	0
• Evaluation	NA	0
• Treatment	limited	2
Suitability Scale: *1= Weak 2= Fair 3= Moderate 4=Strong 5=Very Strong*		48.57 Score: (0-100%)

Source: *U.S. National Oceanic and Atmospheric Administration in collaboration with FEMA and New Hanover Dept. of Emergency Management*
Reference Documents: *Flax, Jackson and Stein, 2002. Community Vulnerability Assessment Tool. Natural Hazards Review, 3(4): p 163-176*
Relevant Websites: *http://www.csc.noaa.gov/rvat/; http://www.csc.noaa.gov/products/nchaz/startup.htm*

preparedness, environmental monitoring, public health and safety and security (http://www.emergeo.com/).

EmerGeo currently includes models for evaluating extent, magnitude and potential consequences of anthropogenic and natural hazard events, including hazardous-material accidents, earthquakes, floods and landslides. Science models for earthquakes and floods are refined versions of those developed as part of the NHEMATIS system (Tucker *et al.*, 2000; Webb, 2000a; b), and are very similar in design and function to those of HAZUS.

The earthquake model uses standard seismic-attenuation algorithms to generate peak ground acceleration (PGA) and Modified Mercalli Intensity index (MMI) shake maps outlining seismic-hazard potential (spatial extent and magnitude). The flood model uses a hybrid depth-velocity-loss function to assess physical vulnerability using a combination of depth-damage relations from the US Army Corps of Engineers (USCACE) and velocity-damage relationships from the UK Department of Environment, Food and Rural Affairs (DEFRA). Models for hazardous material accidents are based on standard assessment methods (ALOHA and ERG2004 plume models). EmerGeo functions as a smart client application and is most often used in conjunction with emergency service integration software (WebEOC, EmerGeo Solutions) to provide operational and strategic support for disaster response and recovery.

18. NOAA Risk and Vulnerability Assessment Tool (RVAT)

The risk and vulnerability assessment tool (RVAT) is a method developed by the Coastal Services Center of the US National Oceanic and Atmospheric Administration (NOAA) with assistance from the US Federal Emergency Management Agency (FEMA) and the New Hanover Department of Energy Management. The method is based on principles of community mapping and participatory GIS and is intended to *"assist emergency managers and planners in their efforts to reduce hazard vulnerabilities through hazard mitigation, comprehensive land use planning and development planning,"* (Flax *et al.*, 2002).

The RVAT method provides a comprehensive and systematic framework to identify and prioritize hazards and to assess vulnerabilities of critical facilities, the economy, societal elements and the environment through the use of semiquantitative index-based overlay methods. The hazard threat is appraised by ranking relative severity of anticipated hazard events using a scoring system based on frequency, the area impacted and estimates of potential damage. Physical, social and environmental impacts are evaluated on the basis of aggregate exposure to potential hazard threats. Evaluation of risk-management strategies is limited to a qualitative assessment of strengths and weaknesses and does not include formal decision analysis.

RVAT is intended primarily as a screening tool to assess relative levels of risk at a community level. It encompasses normative aspects of the risk-management process with a focus on problem framing, diagnosis, appraisal and risk treatment. There is no formal analysis or evaluation, though results of the assessment are used to guide strategy development and community decision-making.

19. Social Vulnerability Index (SoVI)

The social vulnerability index (SoVI) is a method for measuring the intrinsic social vulnerability of communities and regions in the United States. It is part of a broader Hazards of Place model developed by the Hazard and Vulnerability Research Institute at the University of South Carolina. The index is a comparative metric that highlights *"where there are uneven capacities for emergency preparedness and response, and where resources might be used most effectively to reduce pre-existing conditions of vulnerability,"* (Cutter *et al.*, 2000; Cutter, 2001; Cutter *et al.*, 2003)

SoVI is based on the UNDP 'Pressure-Release' approach to risk analysis with a focus on measuring and mapping intrinsic physical and socioeconomic characteristics that predispose a place and its people to potential negative impacts of a natural hazard event. The spatial dimensions and causal structures of vulnerability are analyzed using a combination of biophysical and socioeconomic parameters derived from hazard assessments and census data. The method relies on geostatistical analysis to determine which factors have the greatest degree of influence and strength of correlation (interdependence, co-linearity) between these factors. A national study using the SoVI method found that 11 independent variables accounted for more than 76% of the

19. Social Vulnerability Index (SoVI)

Criteria	Attributes	Rank
Context & Focus		
• Conceptual Framing	Pressure-Release model	3
• Spatial Extent	local, regional, national	5
• Temporal Horizon	existing conditions	3
• Hazard Type(s)	non-specific	2
• Vulnerability	intrinsic vulnerability	4
• Risk	non-specific	2
Risk Assessment		
• Analytic methods	quantitative, inductive	4
• Deliberative methods	communication,learning	2
• System Design	accessible, transferrable,	3
Risk Management		
• Establish Context	problem framing & diagnosis	2
• Appraisal	consequences, concerns	1
• Analysis	intrinsic vulnerability	4
• Evaluation	NA	0
• Treatment	policy recommendations	3
***Suitability Scale:* 1**= *Weak* **2**= *Fair* **3**= *Moderate* **4**=*Strong* **5**=*Very Strong*		**54.29** Score: (0-100%)

Source: *Hazard and Vulnerability Research Institute, University of South Carolina*
Reference Documents: *Cutter, S., L., Boruff, B., J., and Shirley, W.L., 2003, Social Vulnerability to Environmental Hazards: Social Science Quarterly, v. 84, no. 2, p. 243-261*
Relevant Websites: *http://webra.cas.sc.edu/hvri/*

20. Hazard-Vulnerability-Risk Assessment Model (HVRA)

Criteria	Attributes	Rank
Context & Focus		
• Conceptual Framing	Pressure-Release model	3
• Spatial Extent	local, regional	3
• Temporal Horizon	current conditions	2
• Hazard Type(s)	multi-hazard	3
• Vulnerability	physical vulnerability, social vulnerability	3
• Risk	injuries, damage, resilience	4
Risk Assessment		
• Analytic methods	qualitative, index-based	4
• Deliberative methods	communication,learning, mediation	4
• System Design	accessible, transferrable	4
Risk Management		
• Establish Context	problem framing & diagnosis, decision criteria, process design	3
• Appraisal	threats, assets, consequences, capacities, concerns	5
• Analysis	Overlay	1
• Evaluation	Comparative Risk Assessment	2
• Treatment	policy recommendations	3
***Suitability Scale:* 1**= *Weak* **2**= *Fair* **3**= *Moderate* **4**=*Strong* **5**=*Very Strong*		**62.86** Score: (0-100%)

Source: *Academic research (cited below); British Columbia Provincial Emergency Program*
Reference Documents: *Ferrier, N., and Haque, E., 2003: Natural Hazards, v. 28, no. 2-3, p. 271-290; BC Provincial Emergency Program, 2003, Hazard, Risk and Vulnerability Analysis Toolkit: Ministry of Public Safety, Provincial Emergency Emergency Program, 62 p*
Relevant Websites: *http://www.pep.bc.ca/index.html*

21. Hazard-Impact-Risk & Vulnerability Model (HIRV)

Criteria	Attributes	Rank
Context & Focus		
• Conceptual Framing	Pressure-Release model	3
• Spatial Extent	local, regional	3
• Temporal Horizon	current conditions	2
• Hazard Type(s)	multi-hazard	3
• Vulnerability	physical vulnerability, social vulnerability	3
• Risk	injuries, damage, resilience	4
Risk Assessment		
• Analytic methods	qualitative, index-based	4
• Deliberative methods	communication,learning, mediation	4
• System Design	accessible, transferrable	4
Risk Management		
• Establish Context	problem framing & diagnosis, decision criteria, process design	3
• Appraisal	threats, assets, consequences, capacities, concerns	5
• Analysis	Overlay	1
• Evaluation	Comparative Risk Assessment	2
• Treatment	policy recommendations	3
***Suitability Scale:* 1**= *Weak* **2**= *Fair* **3**= *Moderate* **4**=*Strong* **5**=*Very Strong*		**62.86** Score: (0-100%)

Source: *Academic research (cited below); British Columbia Provincial Emergency Program*
Reference Documents: *Pearce, L., 2003: Natural Hazards, v. 28, no. 2-3, p. 211-228*

22. Community Resilience Model (CRM)

Criteria	Attributes	Rank
Context & Focus		
• Conceptual Framing	Disaster Resilience model	5
• Spatial Extent	local, regional	5
• Temporal Horizon	current conditions, recovery period	5
• Hazard Type(s)	earthquake	2
• Vulnerability	physical vulnerability, intrinsic vulnerability, resilience	4
• Risk	injuries, direct loss, indirect loss, resource efficiency	5
Risk Assessment		
• Analytic methods	quantitative, deterministic, probabilistic	5
• Deliberative methods	communication,learning,decision making	3
• System Design	accessible, transferrable, flexible	3
Risk Management		
• Establish Context	management objectives, decision criteria	2
• Appraisal	NA	0
• Analysis	vulnerability, risk, resilience	5
• Evaluation	risk profile, characterization, risk treatment alternatives	4
• Treatment	policy recommendations, implementation, monitor & review	4
***Suitability Scale:* 1**= *Weak* **2**= *Fair* **3**= *Moderate* **4**=*Strong* **5**=*Very Strong*		**74.29** Score: (0-100%)

Source: *The Multidisciplinary Center for Earthquake Engineering Research (MCEER); The Hazard and Vulnerability Research Institute at the University of South Carolina (HVRI)*
Reference Documents: *Bruneau et al., 2003: Earthquake Spectra, v. 19; Chang, S.E., and Shinozuka, M., 2004: Earthquake Spectra, v. 20; Cutter et.al., 2008: Global Environmental Change, v 18.*
Relevant Websites: *http://mceer.buffalo.edu/*

spatial variance in social vulnerability across 3141 counties in the United States. In order of decreasing influence, key variables included personal wealth, age, density of the built environment, single-sector economic dependence, housing stock and tenancy, race, ethnicity, occupation and infrastructure dependence.

The SoVI method addresses analytical elements of the risk-management process. There is no formal evaluation component, though results of the assessment are used to guide strategy development and community decision-making.

20. Hazard-Vulnerability-Risk Assessment Model (HVRA)

HVRA encompasses a wide range of methods and tools developed for use in Canada, most of them rooted in a suite of participatory assessment methods for use by emergency planners in Canada (Ferrier, 2001; Ferrier and Haque, 2003). The method has been tested in several Canadian municipalities and forms the basis of the 'HRVA Toolkit' developed and implemented in the Province of British Columbia (BC Provincial Emergency Program, 2003). The assessment method includes an appraisal of natural hazards that are known to have impacted the community, or those considered by domain experts to have a potential for impact at some point in the future. It is intended for use primarily as a screening tool to assist emergency managers in prioritizing risk-reduction strategies.

HVRA uses a modified Delphi-based method for assessing hazard threats, vulnerability and risk. For each hazard scenario, community representatives rate overall hazard potential using narrative statements to assess relative frequency of occurrence and magnitude of impact on a scale of 1 to 10 or 1 to 5. Weighted mean scores for hazard potential and anticipated impact are then aggregated into an overall assessment of risk. Risk scenarios are normalized and plotted on a risk matrix to identify and prioritize event scenarios requiring immediate planning and mitigation actions. Information and local knowledge on hazard threats and potential impacts is collected and systemized through workshops and focus group sessions using a broad range of participatory planning techniques including surveys, community-based mapping, participatory GIS and problem-tree analysis.

21. Hazard-Impact-Risk & Vulnerability Model (HIRV)

HIRV includes participatory assessment methods developed by Pearce (2003). As with the HVRA model, HIRV uses a modified Delphi-based method for assessing hazard threats, vulnerability and risk. For each hazard scenario, community representatives rate overall hazard potential using narrative statements to assess relative frequency of occurrence and magnitude of impact on a scale of 1 to 10. Weighted mean scores for hazard potential and anticipated impact are then aggregated into an overall assessment of risk. Risk scenarios are then normalized and plotted in a qualitative risk matrix to identify and prioritize event scenarios requiring immediate planning and mitigation actions. Information and local knowledge on hazard threats and potential impacts is collected and systematized through workshops and focus groups sessions using a broad range of participatory planning techniques including surveys, community-based mapping and problem tree analysis.

HIRV encompasses normative aspects of the risk management process with a focus on problem framing, diagnosis, risk appraisal and risk treatment. There is no formal analysis or evaluation, though results of the assessment are used to guide strategy development and community decision making

22. Community Resilience Model (CRM)

The community resilience model encompasses a suite of analytical risk-assessment methods that focus on the dynamics of human-natural systems and their capacities to withstand, respond and recover from the impacts of natural hazard events (Bruneau *et al.*, 2003; Chang and Chamberlin, 2004; Chang and Shinozuka, 2004). The Multidisciplinary Center for Earthquake Engineering Research (MCEER) is a consortium of 16 member institutions that has developed analytical methods for assessing resilience of the built environment and lifeline systems. The Hazard and Vulnerability Research Institute (HVRI) at the University of South Carolina has recently expanded the scope of its Hazards of Place model to assess the resilience of coupled human-natural systems (Disaster Resilience of Place). Both approaches provide a measure of system robustness and the capacity of these systems to self-organize and adapt to threats posed by rapid onset hazards.

Methods of the MCEER focus on measures of robustness, redundancy, resourcefulness and rapidity. These properties are assessed for technical, organizational social and economic aspects of a system in terms of capacities to reduce failure probabilities, the consequences of these failures and the time needed to recover from their impacts. Loss-estimation models are used as a basis for analyzing system performance in terms of robustness and rapidity. Robustness is a measure of the extent to which a system can withstand the impacts of a hazard event and remain functional. Rapidity is a measure of the time required to restore system functionality to minimum thresholds of performance. Both properties can be used to analyze resilience for purposes of pre-event planing and postevent response and recovery. Methods of the CRM extend capacities of catastrophe and loss-estimation methods by including methods for risk characterization, decision analysis and coupling with policy objectives.

Meta-Analysis and Critique

Each of the risk-assessment frameworks selected for this survey reflects a best practice with respect to the policy context and specific purpose for which it was designed. Scientific and technical aspects of the frameworks are documented in the literature and many have been the focus of independent peer review. However, it is the framing of the risk problem (issues, goals, objectives, assessment criteria) and the planning context in which policy alternatives are considered (geographic-legislative landscape) that ultimately determine the constellation of methods, models and tools that are suitable and that have the greatest likelihood of supporting the process and achieving the intended outcomes in any particular geographic and/or legislative context.

The 2007 National Disaster Mitigation Strategy for Canada has identified the need to develop a standards-based framework for risk assessment that incorporates best-practice methods for both the analysis and evaluation of risks associated with growth and development in areas exposed to potential impacts of natural hazards. The intent of this meta-analysis is to determine which of these existing methods is most suitable for use in a Canadian context and the supporting rationale.

Evaluation Criteria

The frame of reference for this critique of risk assessment methods is based on relevance with respect to national-level policy guidelines, an evaluation of best practices in terms of analytical-deliberative methods, and conformance with national and international standards for risk management. Each of these characteristics is evaluated in terms of specific attributes that are measured using a system of indicators and corresponding assessment criteria. Judgment of what constitutes policy relevance is based on guidelines established by the National Disaster Mitigation Strategy (2007). The NDMS guidelines call for research, development and implementation of methods and practices that promote pre-event planning and disaster mitigation at regional and municipal levels of government. One of the core mandates is to "*apply and promote scientific and engineering best practices in order to build a knowledge base (and institutional capacity) for sustainable, cost effective mitigation decisions that contribute to community resiliency*," (Public Safety and Emergency Preparedness Canada, 2007)

The NDMS also makes explicit the policy goal and objectives that should guide risk assessment and disaster risk management activities of across Canada. The overall goal is *"to protect lives and maintain resilient, sustainable communities by fostering disaster risk reduction as a way of life."* Implementation guidelines encourage a flexible approach that is responsive to local/regional context and legislative requirements and that ensures shared ownership and accountability through partnership and collaboration. Indicators used to judge overall policy relevance include conceptual framing, geographic extent, planning horizon, the scope of hazard types considered and specific dimensions of vulnerability and risk included in the assessment.

Risk-assessment methods are judged on the basis of capacities for risk analysis (qualitative and quantitative), the characterization of what constitutes a tolerable level of risk for a given geography and planning horizon, and the evaluation of policy choices and their consequences. As directed by the Auditor General of Canada, risk-assessment methods should also be consistent across hazard type and informed by the best available scientific/economic information. They should have a capacity to analyze potential hazard threats within a specified geographic area and time frame, as well as the likely impacts and consequences of hazard events in terms of economic, environmental and social assets. They should also provide the information and knowledge necessary to proactively evaluate and manage threats, set priorities, develop plans and allocate resources to reduce negative impacts of potential hazard threats and realize benefits of growth and development (Auditor General of Canada, 2005, See 1.90-1.94).

Compliance with national and international standards for risk management is judged on the basis of alignment with the revised CSA guidelines for risk management (CSA Q850-97_R2007) and the standard for emergency management and business continuity (CSA Z1600-2008). Core elements of these standards are reflected in the *Integrated Risk Management Framework for Canada,* a document adopted by the Treasury Board Canada to advance the use of standardized risk-management practices in support of planning and decision-making in the public domain.

Results

Results of the assessment are summarized below in the form of a decision matrix that shows relative strengths and weaknesses of each method and overall suitability in terms of ordinal rank values.. Specific attributes were assessed on a suitability scale of 1 to 5, where rank values increase and associated colours get warmer with increased suitability (*see* Table 3-1). It is evident from the pattern of results that each method varies in terms of suitability for key attributes. Some are well suited in terms of policy relevance and alignment with risk-management standards but do not have well-developed analytical-deliberative methods for risk assessment. Others have robust analytical capabilities for measuring dimensions of vulnerability and risk but are not well suited in terms of their capacity for risk evaluation and policy analysis.

Methodological frameworks that scored highest in terms of overall suitability are balanced in terms of policy relevance (context and focus), robustness of risk assessment methods, and alignment with national and international standards for risk management. These include quantitative hazard-risk catastrophe models developed by the insurance industry (CAT); national-scale vulnerability assessment models developed by the European Union 6th Framework program (EPSON, ARMONIA); hazard-risk and vulnerability models developed by Canada (HIRV), Geoscience Australia; Emergency Management Australia and Geoscience New Zealand (GA, EMA and GNS) and hazard-risk and community resilience models developed by FEMA (HAZUS), the United States Geological Survey (LUPM), the Multidisciplinary Center for Earthquake Engineering (MCEER) in North America and the SUST method.

The Australian and North American frameworks are considered most suitable in terms of local and regional hazard-risk assessment while the EPSON and ARMONIA frameworks are most suitable in terms of regional and national-scale vulnerability assessment. Of these, only HAZUS, LUPM and the European Union frameworks are nonproprietary and provide a sufficient level of technical documentation to allow transfer and implementation in other geographic and/or legislative contexts. Notable exceptions include the global risk-assessment frameworks (NDH, DRI, PDRA), the Latin America indicator framework (IDEA) and the Hazards of Place model (SoVI) for North America. All are well documented in the literature and offer methods and protocols that are transferable and relevant for use in a Canadian context.

Summary

Analytic methods that address issues of disaster resilience are most closely aligned with policy guidelines for disaster risk management and the governance of an emerging societal threat. The model developed by Turner *et al.* (2002) explicitly recognizes the importance of coupled human-natural system dynamics and accounts for interactions between underlying processes that trigger hazard events, the amplification and attenuation of these events in complex socioeconomic structures and thresholds of resilience that can be achieved through adaptation planning and governance. The analytical approach has been tested and validated in several regional-scale studies in Latin America and in the Arctic. While this approach holds great promise for addressing both existing and emerging hazard threats, requirements for knowledge generation and scientific/technical expertise to configure and run the

		1a hazard-risk, vulnerability, resilience	1b spatial extent & temporal horizon	2a hazard potential, damages, losses	2b hazard threats, level of concern	3a quantitative analysis & modelling	3b design, appraisal & evaluation
1	CAT	4.0	4.5	5.0	1.0	5.0	3.3
2	NDH	3.3	1.5	4.0	1.0	5.0	1.7
3	DRI	2.0	1.0	3.0	1.0	4.0	1.0
4	PDRA	2.7	2.5	3.0	5.0	1.0	4.0
5	EPSON	3.3	4.0	4.0	4.0	3.0	3.0
6	ARMONIA	3.7	4.0	4.0	3.0	3.0	4.0
7	GA	4.7	3.0	5.0	2.0	5.0	0.7
8	AGS	2.3	2.0	5.0	2.0	5.0	1.7
9	EMA	3.7	4.0	4.0	4.0	4.0	3.0
10	GNS	3.3	4.0	3.0	3.0	4.0	3.0
11	USRi	2.3	2.5	4.0	1.0	3.0	1.3
12	IDEA	3.0	3.0	4.0	1.0	4.0	1.3
13	ECLAC	2.7	3.0	2.0	1.0	4.0	0.0
14	GTZ	2.3	2.5	3.0	3.0	0.0	2.0
15	HAZUS-MH	4.0	4.5	5.0	3.0	5.0	3.7
16	LUPM	2.0	3.5	5.0	4.0	4.0	2.0
17	RVAT	2.3	3.5	2.0	3.0	0.0	2.0
18	SoVI	2.7	4.0	4.0	2.0	4.0	1.0
19	HIRV	3.3	2.5	4.0	4.0	1.0	3.3
20	CRM	3.7	5.0	5.0	3.0	5.0	2.0
21	EmerGeo	3.7	3.0	5.0	4.0	4.0	1.3

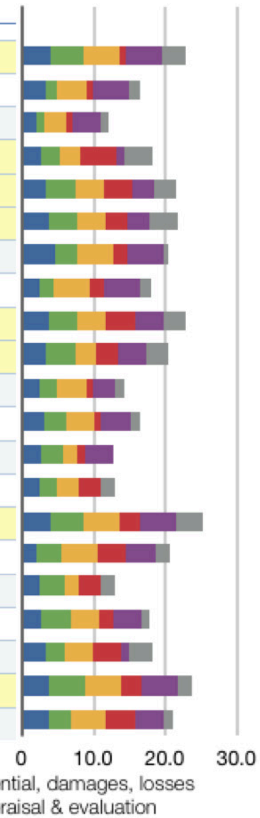

Figure A2-23: Meta-analysis of available best practice methods of risk assessment models can be significant, potentially overwhelming and beyond the capacity of routine emergency management and/or spatial planning practices.

Gaps and Opportunities

While each of the approaches and methodological frameworks reviewed in this study have their relative strengths, none offer a complete solution in terms of operational requirements for addressing risk-management objectives highlighted in the National Disaster Mitigation Strategy for Canada. There are a number of gaps that remain between what is required for analysis policy analysis and what is offered by existing methods of risk assessment.

Analyzing Complex System Behaviour

Most hazard-risk models assume linear cause-effect relationships between a hazard event and its impacts on people and the built environment. While this may be a necessary simplification to make predictions about likely consequences in terms of direct and indirect loss, there is a real danger that model outputs may overshadow or even prevent a consideration of nonlinear system dynamics (interconnectedness, feedback mechanisms, etc.). The unanticipated consequences of these complex system behaviours can in some cases be several orders of magnitude larger than single cause-effect chains that are the focus of the modelling activity.

While it may be difficult, impractical or even impossible to develop a model that takes into account all relevant factors that may influence cause-effect relationships in human-natural systems, there is a need to make these uncertainties evident and to formally incorporate them into the policy analysis and decision-making processes. Risk-assessment methods that are moving in the direction of modelling system complexity include the SUST model for vulnerability assessment (Turner *et al.*, 2003), the HAZUS model for hazard risk and loss estimation, and the Land-Use Portfolio model (LUPM) for analyzing financial risk (return on investment) using financial-portfolio theory. All of these methods incorporate quantitative techniques for analyzing and evaluating dimensions of risk in terms of probability distribution functions that are calibrated on the basis of forensic data from past disaster events and/or stochastic models.

Situating Risk in a Future Context

It is clear from even a cursory study of emerging policies for disaster risk management that approaches and methods of risk assessment need to be forward-looking. However, existing methods are based largely on static models of human-natural systems that are framed in the context of historical trends and/or current conditions. With the exception of the SUST and the Community Resilience Model (CRM), very few of these methods focus on upstream processes and underlying dynamic forces that influence conditions of vulnerability and risk. None of these methods directly model changing dynamics of societal risk in a future context. Yet, this is exactly what is needed to analyze and evaluate the longer-term consequences of disaster mitigation decisions in the context of growth management and sustainable development.

Analysis and evaluation of change and associated risks in a future context is the domain of integrated assessment, scenario-based modelling and spatial planning. Significant advances have been made in the development, implementation and refinement of both methods and practices of integrated assessment and adaptive planning, particularly in the fields of global environmental change. However, these techniques have yet to be incorporated into mainstream methods for the analysis and evaluation of risks associated with natural hazards. A capacity to model landscape change through time is needed to anticipate, consider and evaluate physical and socioeconomic changes that are likely to occur within a specific geographic setting and planning horizon, and the underlying forces that are driving existing and emerging societal risk.

Coupling of Analytical-Deliberative Methods

Existing methods tend to be optimized for either analysis or evaluation but rarely accommodate both modes of risk assessment. Risk management encompasses a wide spectrum of potential threats and must reconcile knowledge claims about likely impacts and consequences with a diversity of values, goals and belief structures that influence decisions about how to best mitigate these threats. Methods that focus on one or the other of these requirements offer only a partial solution to the problem.

Quantitative assessment of vulnerability and risk may be effective in providing an objective measure of anticipated impacts and consequences. However, if the assessments are not directly coupled with the process of evaluating choices and consequences in terms of goals and management objectives, it can be difficult for a policy analyst to determine the most appropriate course of action, even with the best available science. At the same time, methods that emphasize deliberative aspects of the risk-characterization process may provide a clear perspective of the risk-management issues in terms of goals and objectives but often lack a capacity for measurement and analysis to support the requirements of evidence-based decision-making.

It is clear that analysis and deliberation need to be coupled to address the full scope of issues involved in disaster risk management. The challenge is in finding an operational framework in which policy choices are informed by scientific analysis but framed and negotiated through deliberation (Stern and Fineberg, 1996). While there has been a shift in recent years toward more holistic approaches to science-policy integration (Klinke and Renn, 2002; Turner *et al.*, 2003), much work still needs to done to improve these linkages and to establish pathways of interaction in the fields of risk governance and sustainable development.

Decision Analysis and Risk Evaluation

Finally, none of the methods reviewed in this survey incorporate the full suite of formal decision-analysis techniques for evaluating policy alternatives. Techniques of multicriteria decision analysis are used extensively in the fields of human and ecological risk assessment, and in the management and regulation of human activities and technologies that have a capacity to pose significant societal threats (environmental degradation, critical facilities, nuclear power, etc.). However, with the notable exception of proprietary cost-benefit models used by the insurance industry, existing methods for natural-hazard risk assessment do not incorporate formal assessment criteria that can be directly coupled with policy goals and management objectives to allow a systematic analysis of choices and consequences.

This is a curious trend, given the severity of recent natural disasters in North America and Europe and the clear recognition of failure in terms of pre-event planning and systematic policy analysis in the public domain (Light, 2005; Burby, 2006; Costanza *et al.*, 2006; Federal Emergency Management Agency, 2006; US 109th Congress, 2006). Numerous studies have identified this gap and pointed to the need for methods and tools that provide a capacity for negotiating thresholds of risk tolerance for a given geographic setting and planning horizon, and for exploring choices and consequences of risk-management decisions through a blend of scenario modelling and decision analysis (Rotmans, 1998; McDaniels and Thomas, 1999; Rotmans and van Asselt, 2000; Renn, 2001; Folke *et al.*, 2002; Gregory, 2002; Gregory and Satterfield, 2002; OECD, 2003; McDaniels and Gregory, 2004; Renn and Klinke, 2004; Rotmans, 2005; Renn, 2006).

Implications for Research and Development

Addressing the scientific and technological challenges outlined above will require sustained research and development activity within the broader disaster risk management community over the coming decades. In the meantime, there are a number of research and development initiatives that could be pursued here in Canada to support implementation of the National Disaster Mitigation Strategy.

The first would be to adopt an existing method (limitations notwithstanding) that comes closest to addressing identified needs and requirements for use in a Canadian context. Results of the comparative analysis offered here might assist in this selection process (*see* Table 4-1), as would other published reviews of risk-assessment methods (Birkmann, 2006; Pelling, 2004). The danger here is that imported methods designed for use in a different policy context and with different operational requirements may not perform as expected.

It is well documented that imported solutions can and often do fail if the full spectrum of issues required for successful implementation is not addressed up front, regardless of the promise they may hold. These can include policy relevance, adaptability of methods to specific operational requirements and the availability of information and/or expertise to implement the method as intended (Gibbons *et al.*, 2000).

A more rigorous technocratic approach to address limitations of existing risk-assessment methods in Canada might be through a conventional cycle of research and development that begins with a formal scoping study (user needs and legislative/operational requirements) and progresses through formulation of prototype methods and models that are refined and updated through formal evaluation of demonstration projects. The development and ongoing refinement of HAZUS by the US Federal Emergency Management Agency and the US National Institute of Building Sciences, and similar efforts by the Coalition of Australian Governments and the European Commission (6th and 7th frameworks science-policy integration) are excellent examples of how this process can work in support of a national framework for disaster risk management.

While this approach has merit, there is an obvious danger of investing in the development of methods and tools that may already exist in other forms or fields of research. For example, methods and tools that have been developed to address issues of global environmental change lend themselves to analysis and evaluation of threats associated with choice and consequence in a future context. However, the methods are not necessarily tuned to the requirements of examining risks associated with impacts of natural hazard events.

An alternate approach, and the one advocated in this study, is one of adaptive design and development. It too is framed by relevant policy goals and management objectives, and begins with a formal scoping study to determine requirements for risk assessment. However, it does so from the bottom up; through targeted case studies that provide an opportunity to research, test and adapt existing methods on the ground, recursively, and in the context of actual planning and policy-development processes that make evident existing legislative and institutional needs and challenges.

This case-based approach involves an iterative workflow that mirrors formal standards and guidelines of the risk-management process. At each stage of the process (problem framing, analysis, evaluation and treatment), requirements are determined through formal consultations with potential users. These include experts who provide scientific information and knowledge about natural hazards and potential impacts, risk managers and practitioners who provide information and knowledge about the local landscape and the dynamics of risk, and planners and policy analysts who have practical experience using this information and knowledge in the context of public domain planning and governance.

Observations made and information gained through this design process are used to generate the elements of an integrated assessment framework (design patterns) that serves as the overarching reference model for ongoing testing and refinement.

This involves a process known as scaffolding, whereby existing best practice methods and tools for risk assessment are assembled into working prototypes that are tested, adapted and refined on an ongoing basis. The abstract part of this process involves the development of an integrated assessment model that captures key indicators and criteria needed to analyze and evaluate the dynamics of risk in a changing landscape. The concrete part of this process involves disaggregating existing methods and tools to their essential components and reassembling them as part of an integrated assessment framework in which indicators are paired with best practices for analysis and evaluation. The gaps that remain then become the focus for targeted research and development. Chapter IV of this report documents the reference model used in the design and development of this proposed framework.

viii. APPENDIX III: Natural Hazard Events for the Community of Squamish, B.C.

Event	Hazard Event	Impacts
1906-09-08	Extreme weather/ riparian flooding	164-218mm rain over 5 days resulted in significant flooding along the Cheakamus and Squamish rivers. 3.6m of flood water in the Squamish valley caused significant damage to farms and related infrastructure in the Brackendale/Garibaldi Estates areas and washed away primary bridges over the Cheakamus and other major rivers in the valley
1908-12-12	Storm surge/tidal flooding	Hurricane force winds and high tides drove sea waters over the dykes lining the Squamish River causing inland flooding 1.6 km up the valley. The flooding tide was ~1.2m above previously recorded levels, resulting in overtopping of the sea dyke and flooding of fields. Only minor damage reported.
1924-09-20	Extreme weather/ riparian flooding	183-211mm of rain over 4 days resulted in flooding in the Squamish valley and structural damage to the PGE rail line bridge crossing the Mamquam River.
1933-12-20	Storm surge/tidal flooding	118mm of rain over 5 days, combined with gale force winds resulted in a combination of storm surge and riverine flooding. Businesses and residential neighbourhoods in the Dentville and Downtown core areas were flooded to a depth of ~1.2 meters resulting in considerable damage to building stock, PGE rail infrastructure and communication facilities.
1937-10-28	Extreme weather/ riparian flooding	~140mm of rain over 3 days resulted in significant flooding on all major rivers in the Squamish valley. Low-lying areas of Brackendale, Garibaldi Estates, North Yards, Dentville and Downtown Squamish. 1.2m of floodwater were reported along the railway bridge over the Cheekye River and the bridge over the Mamquam River was washed away. The Mamquam River jumped the main channel, running down its old bed near the Squamish school.
1940-10-18	Extreme weather/ riparian flooding	~212mm of rain over 4 days with intense 1-day downpours resulted in heavy flooding along the Mamquam River and ~1.5 meters of inundation in the Dentville/Downtown areas. Flooding elsewhere in the Squamish Valley (Brackendale/Garibaldi Estates) resulted in significant damage to farms and residential properties. Nearly all livestock in the valley were drowned and 20 families were evacuated to higher ground. Rail and road infrastructure, including several bridges were severely damaged. Up to 6 meters of floodwater was trapped behind the main sea dyke and smaller river dykes upstream, several of which had to be blasted with dynamite. Flood debris floated into Howe Sound, impeding navigation by boat.
1949-11-26	Extreme weather/ riparian flooding	~180-309mm of rain over 8 days resulted in up to 2.1 meters of flooding along all major rivers in the Squamish valley. 300 homes were inundated in low-lying areas and 10-12 families were evacuated. Flooding caused significant damage to rail and road infrastructure throughout the valley. THighway and railway bridges over the Mamquam River were taken out by log-jammed floodwaters.
1950-10-07	Flooding/debris flow	~283mm of rain over 8 days resulted in flooding of the Squamish and Mamquam Rivers. Impacts included significant bank erosion along the Squamish River and up to 3 meters of flooding in low-lying areas of North Yards and Dentville. Several families were evacuated. Torrential rains triggered two separate debris flow events along the Cheakamus River valley, disrupting rail service for 4 days.

1953-01-06	Storm surge/tidal flooding	High tides and severe wind resulted in storm surge and tidal flooding in low-lying waterfront areas of Squamish causing minor damage to roads and at least one home.
1954-11-04	Riparian flooding	~92mm of rain over 2 days and melting snow resulted in minor flooding along the Squamish River. Flooding along the Mamquam River was up to but not exceeding dyke levels. No major damage reported.
1954-11-17	Riparian flooding	~276mm of rain over 8 days resulted in isolated valley flooding and loss of municipal water services as raging floodwaters along the Stawamus River caused damage to potable water systems. Damages resulted in disruptions to hospital service.
1955-10-25	Riparian flooding	~126mm of rain over 3 days resulted in up to 2.4 meters of flooding in low-lying areas of the Squamish valley. Log-jammed floodwaters took out the Mamquam highway bridge and threatened the PGE railway bridge downstream. Twelve families were evacuated and many thousands of dollars of damage reported.
1955-11-01	Riparian flooding	~165mm of rain over 3 days resulted in extensive flooding in the Squamish River valley and significant damage to sensitive fish habitat and ~90% loss of salmon stocks. Protective dykes were overtopped along the Squamish and Mamquam rivers and more than 100 people were evacuated. Floodwaters caused significant damage to building stock and to both electrical and potable water systems. Flooding was made worse by high tides that prevented drainage in the waterfront areas of Dentville and Downtown and nearly overtopped the main sea dyke.
1955-12-01	Storm surge/tidal flooding	High tides and strong winds resulted in overtopping of the sea dykes along the waterfront and breaching of other dykes along lower portions of the Squamish River. 30cm of water inundated portions of downtown Squamish and adjacent neighbourhoods.
1956-09-26	Riparian flooding/ debris flooding	Heavy rain caused the Mamquam River to rise 1.8 meters at its confluence with the Squamish River. Logs and debris carried in the floodwaters took out the PGE railway bridge.
1957-09-05	Extreme weather/ riparian flooding	~96mm of rain over 3 days resulted in extensive flooding on all major rivers in the Squamish valley. Overtopping of dykes along the Squamish River resulted in up to 4.2 metres of flooding and associate damage to residential buildings. Overtopping of a flood protection structure above a new powerhouse facility along the Cheakamus River caused significant damage.
1958-08-28	Debris flow	Following a sudden rainstorm, ~100,000 m3 of rock debris and logs rushed down the Cheekye River building a 4.5 meter temporary dam across the mouth of the Cheakamus River. The debris flow is reported to have been up to 3 meters deep and moving at a velocity of up to 8 km/hour. A debris flow event of similar intensity is reported to have occurred in the same located ~30 years earlier.
1958-10-11	Riparian flooding	~118mm of rain over 3 days resulted in flooding along the Squamish River, which overtopped protective dykes, inundating low-lying areas with up to 1.5 meters of water. Two families were evacuated and only minor damage to road infrastructure was reported.
1961-07-07	Forest Fire	465 hectares burned in the Elaho valley. Believed to have been ignited by human activity
1961-07-25	Forest Fire	625 hectares burned in the upper Mamquam River valley. Believed to have been ignited by human activity
1961-07-29	Forest Fire	989 hectares burned on the western slopes of Howe Sound. Believed to have been ignited by human activity
1963-06-14	Forest Fire	890 hectares burned in the upper Suamish valley. Believed to have been ignited by human activity

1975-11-04	Riparian flooding	~307mm of rain over 9 days combined with melting snow tidal influences caused flooding along both the Cheakamus and Squamish Rivers. Although flood depths were less than a meter in most places, residents of a mobile home park in the Garibaldi Estates area were inundated by ~1.5 meters of water. Reservoir levels on Daisey Lake threatened to overtop the dam. BCHydro was forced to open spillways into the Cheakamus River, causing significant localized flooding downstream. 25-30 people evacuated their homes.
1975-11-30	Earthquake	A M4.7 mid-crustal event at a depth of 32km within a 50 km radius
1980-12-26	Riparian flooding/ debris flooding	~212mm of rain over 5 days, combined with melting snow conditions resulted in streamflows along the Squamish, Mamquam and Stawamus Rivers that corresponded to intensities associated with flood events with a 130-190 year return interval. BC Hydro was again forced to open spillways on the Daisey Lake dam, contributing to flooding along the Cheakamus and Squamish valleys. Dykes prevented flooding in Downtown Squamish, but unprotected low-lying areas north of the Mamquam River were extensively flooded, resulting in significant damage and/or destruction of ~200 homes. 6 people were evacuated by air. Reported losses are estimated to have been $313, 670 CDN.
1981-10-30	Riparian flooding/ debris flooding	~303 mm of rain over 5 days resulted in a series of tragic debris flow events along the Sea-to-Sky highway, and significant riverine flooding in the Squamish valley. The Squamish River overtopped its bank downstream of existing dyke structures resulting in significant flooding in low-lying areas. Losses associated with damages to buildings and critical infrastructure is estimated to have been ~$290,000 CDN.
1981-11-11	Riparian flooding	~83mm of rain over 2 days resulted in flooding of the Cheakamus River, which overflowed its banks, breached existing dyke structures and inundated low-lying parts of the upper Squamish valley including paradise Valley and parts of Brackendale. 21 people from the Brackendale Elementary school were stranded by floodwaters.
1983-04-09	Earthquake	Shallow crustal M2.1 event at a depth of 7 km
1984-10-08	Riparian flooding/ debris flooding	~352mm of ran over 5 days resulted in record-level river discharge of 2,610 m3/second on the Squamish River, resulting in a significant change to the river course and extensive damage to flood protection works. As with earlier major flood events, water depths in low-lying residential areas were several meters deep, resulting in significant damages to homes and related infrastructure. The Cheakamus highway bridge was washed out during the same event. Losses associated with flood damages for the Squamish area are reported to have been ~$623,000 CDN. Total losses in the Sea-to-Sky corridor were ~$1,946,700 CDN.
1987-04-08	Earthquake	A M3.8 shallow crustal event at a depth of <5km within a 50 km radius
1987-09-16	Earthquake	A M3.0 shallow-crustal event at a depth of <5km within a 50 km radius
1987-09-18	Earthquake	A M2.3 shallow-crustal event at a depth of <5km within a 50 km radius
1990-12-07	Earthquake	A M2.9 shallow-crustal event at a depth of <5km within a 50 km radius
1991-02-19	Earthquake	A M4.3 shallow-crustal event at a depth of <5km within a 50 km radius
1991-05-01	Earthquake	A M2 shallow event at a depth of <5 km within a 20km radius
1991-07-03	Earthquake	A M3.0 shallow-crustal event at a depth of <5km within a 50 km radius
1991-12-03	Earthquake	A M2.2 shallow-crustal event at a depth of 17km within a 50 km radius

1991-08-31	Rparian flooding/debris flooding	~103mm of rain over a 1 day period resulted in high water flows in the Squamish, Cheakamus, Cheekye, Mamquam and Stwamus Rivers, causing extensive bank erosion and damage to flood protection measures. Overtopping of river banks and some dyke structures in the northern portion of the valley resulted in ~1.5 meters of flooding in the First Nation community of Cheekye causing damage to 15 homes and forcing the evacuation of residents by helicopter.
1992-01-28	Riparian flooding/ debris flooding	~332mm of rain over 12 days resulted in flooding near the confluence of the Cheekye and Cheakamus Rivers. Damage was limited as much of the floodwater was diverted from residential settlements by fill along the Paradise Valley roadbed, which acted as a temporary levee.
1992-10-23	Riparian flooding	~216mm of rain over 7 days resulted in isolated flooding (15-30cm) along the Squamish River near Brackendale.
1995-01-31	Earthquake	A M2.6 shallow-crustal event at a depth of <5km within a 50 km radius
1995-11-28	Earthquake	A M2.8 shallow-crustal event at a depth of <5km within a 50 km radius
1997-06-13	Earthquake	A M3.4 shallow-crustal event at a depth of <5km within a 50 km radius
1997-06-24	Earthquake	A M4.6 shallow-crustal event at a depth of <5km within a 50 km radius (Georgia Strait)
1999-01-21	Earthquake	A M3.0 shallow-crustal event at a depth of <5km within a 50 km radius
2002-12-11	Earthquake	A M2.1 shallow-crustal event at a depth of 15km within a 50 km radius
2003-03-24	Earthquake	A M2.7 shallow crustal event at a depth of <5km within a 50 km radius
2003-08-03	Earthquake	A M2.4 shallow crustal event at a depth of ~5km within a 50 km radius
2003-10-18	Extreme weather/ riparian flooding	~480mm of rain over a 7 day period resulted in significant flooding and debris slide events along the Sea-to-Sky corridor. All major rivers in the Squamish valley were running high, but did not overtop their banks. Bank erosion caused significant damage to flood protection measures. Storm water runoff trapped behind dyke structures in low-lying areas of the valley caused extensive flood damage to buildings. More than 360 people were forced to seek refuge with local emergency services. Losses associated with flood damages are estimated to have been ~$30,000,000CDN