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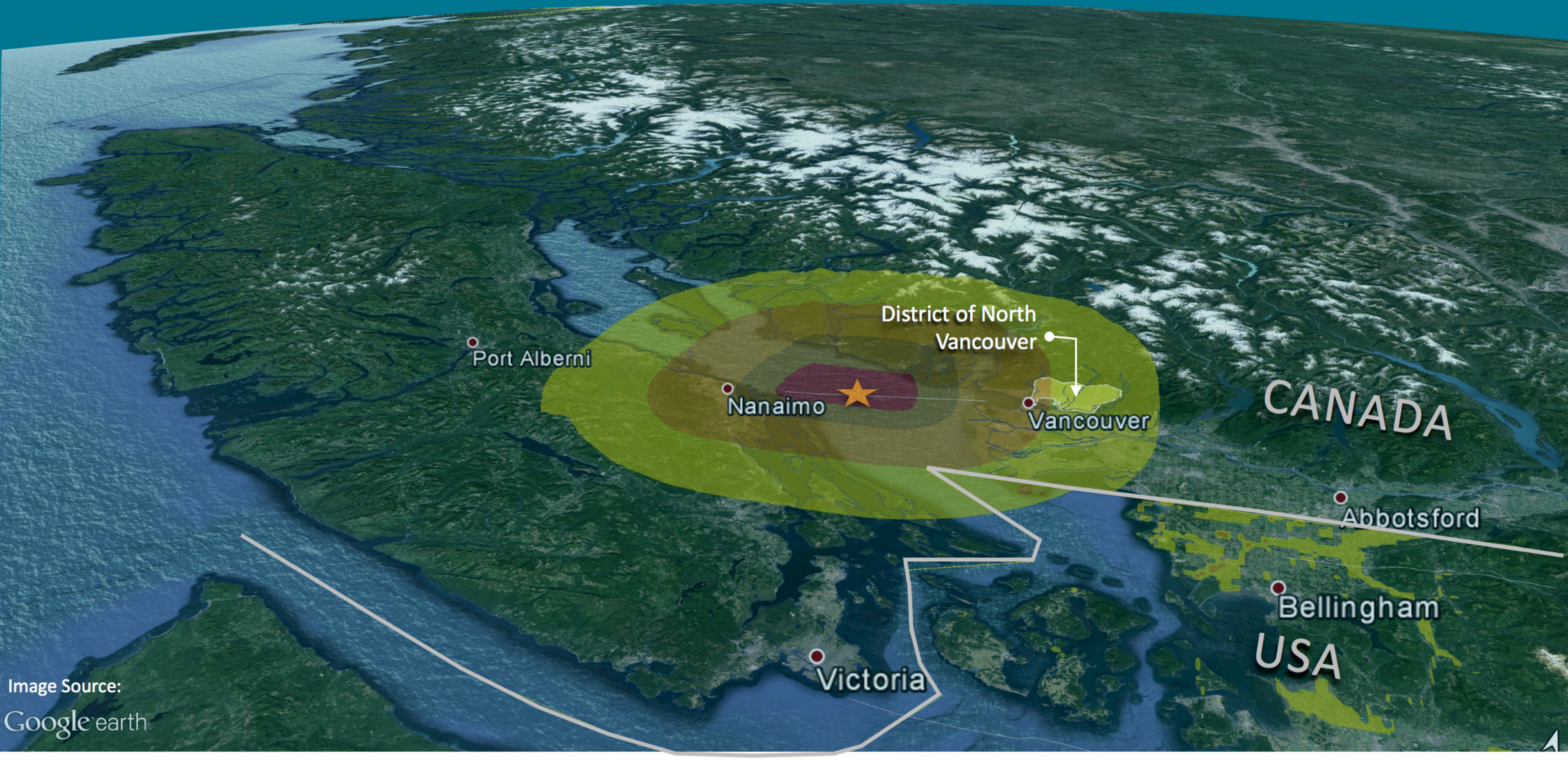

Image Source: Google earth

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Mayor Richard Walton, District of North Vancouver

On behalf of the District of North Vancouver, I am pleased to introduce this innovative and meaningful study which takes a detailed look at the earthquake risks and resiliency opportunities for our community.

It is important to fully understand the potential risks that we face as a community, and to put those risks into the context of our daily lives, before we commit resources towards risk reduction. This study provides a clear picture of what we can expect in the event of a major earthquake, and what we can do to prevent future losses and increase our resilience. It is our hope that this study, along with the associated community outreach program, will foster action in all levels of our community.

When the Ground Shakes is our plain language companion piece to the detailed technical study. It tells the story of three fictional, but typical, North Vancouverites and their experiences immediately following a major earthquake. The EQ Story Map is our interactive storytelling tool that uses images and GIS maps to highlight important components of the report.

This is a call to action for our residents, our businesses and those of us in government, to be as prepared as we can for a major earthquake or other serious emergency.

The District is taking stock of municipally owned assets, such as buildings, underground utilities and other infrastructure, and is borrowing best practices from around the world to strengthen these systems through mitigation. Seismic risk will be incorporated into our asset management program. We now know which areas of the municipality will be most severely impacted, and can plan to send our emergency response teams there first. And we can ensure that key facilities are hardened so that they will function as areas of refuge and reunification. We have been participating in exercises to practice how we work together in our Emergency Operations Centre to coordinate and prioritize response and recovery activities. Our new town centres present an opportunity to redevelop some older neighbourhoods, with structures currently quite vulnerable to earthquakes, to current standards for seismic safety.

If you are a business owner, we invite you to make use of the resources on the North Shore Emergency Management Office website aimed to increase business continuity and reduce economic losses. For some businesses, it may simply be a matter of restraining tall shelving and heavy objects, and backing up critical data off-site. For those in older, more vulnerable buildings, you may consider investing in seismic retrofits to protect your business and ensure that you can recover quickly with minimal disruption. We encourage businesses to work together with their supply chains and pool resources with neighbouring businesses to become resilient hubs.

And if you are a resident, please do educate yourself about possible hazards in your area, stock up on emergency supplies, prepare a family emergency plan and, perhaps most importantly, get to know your neighbours. You will be relying on each other for support until response agencies are able to get to you, which may take some time.

In the spirit of regional cooperation and as a United Nations Role Model City, we will openly share this study and the outcomes generated by it. We also invite the opportunity to learn from others who may have experienced a major earthquake and know first-hand what works and what doesn't. Our thanks to Natural Resources Canada and the University of British Columbia for this opportunity to partner with them on this ground-breaking work that has helped us better understand and prepare for the hazards and risks in our community.

ABSTRACT

The societal costs of natural hazards are large and steadily increasing in Canada due to increased urban development, an aging infrastructure, and limited capacities to anticipate and plan for unexpected disasters. Lessons learned from recent 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 have a potential to minimize future disaster losses and increase the resilience of communities to the dynamic and uncertain forces of change

We cannot predict or prevent earthquakes from happening. However, we do have the knowledge and capabilities to change the outcome of earthquake disasters through a combination of risk assessment and disaster resilience planning. Risk assessment is the process through which knowledge about a community and its exposure to natural hazards is used to anticipate the likely impacts and consequences of an unexpected event at some point in the future. Disaster resilience planning is focused on actions that can be taken in advance to balance policy trade offs for growth and development (opportunities) with risk reduction investments that have a potential to minimize future losses (liabilities) while increasing capabilities of a community to withstand, respond to and recover from unexpected disaster events (resilience).

This study provides a detailed assessment of earthquake risk for the District of North Vancouver – an urban municipality of approximately 83,000 people situated along the North Shore Mountains in southwestern British Columbia. It describes the probable impacts of a significant earthquake with greater clarity and detail than ever before, and develops both a methodology and target criteria to guide future risk reduction and disaster resilience planning activities through the lens of building performance, public safety, lifeline resilience and socioeconomic security. We examine cause-effect relationships and seismic risks for a plausible earthquake scenario in the Strait of Georgia (M7.3), and undertake a more general assessment of who and what are vulnerable to known earthquake hazards in the region using probabilistic ground motion models that are consistent with those used to establish seismic safety guidelines in the National Building Code of Canada (NBCC, 2010).

Study outputs offer a capacity to explore thresholds of risk tolerance and opportunities for mitigation through ongoing emergency planning and land use decision-making activities in the community. Methodologies and insights gained through this study are transferrable to other communities who may face similar challenges of managing growth and development in areas exposed to earthquake hazards. Key findings and recommendations of the study contribute to broader efforts led by the Canadian Safety and Security Program to support disaster resilience planning at a community level in Canada.

A recent M3.2 tremor in the Georgia Strait (December 2014)— a reminder that we live in earthquake country.

PROJECT TEAM

A Profile of Earthquake Risk for the District of North Vancouver is the result of a five-year research and development effort led by the Earth Sciences Sector of Natural Resources Canada (ESS/NRCan). The study explores the realm of earthquake risk reduction at a municipal scale through collaborative partnerships with practitioners responsible for managing growth and development in areas exposed to earthquake hazards, and with researchers responsible for the development of methods and tools to support earthquake risk reduction and disaster resilience planning in Canada.

Case Study Partners

The District of North Vancouver (DNV) is the lead municipal case study partner and responsible for overall context and focus for the project. Primary roles included the sharing of detailed technical information about the community and critical assets, and the identification of policy goals and target criteria that have guided all aspects of the risk assessment process. Staff members from the Engineering department (Fiona Dercole, Michelle Weston and colleagues) have worked with research partners at each step of the process and have provided important new insights on the needs and operational requirements for earthquake risk reduction and disaster resilience planning at a municipal scale in Canada. They have worked with community members of the Natural Hazards Task Force to review study results and to help transform scientific and technical knowledge about the risk environment into a form that will support both day-to-day and longer-term strategic planning activities in the community.

The North Shore Emergency Management Office (NSEMO) coordinates cross-jurisdictional planning, preparedness, and the development of core operational capacities that are required to support emergency response and recovery efforts on behalf of the District of North Vancouver, the City of North Vancouver and the District of West Vancouver. As a member of the Integrated Partnership for Regional Emergency Management in the greater Metro Vancouver area, NSEMO also acts as a liaison between local and regional governments in the development of emergency plans and the coordination of disaster response and recovery efforts. Staff members at NSEMO (Dorit Mason and colleagues) have provided technical information on essential facilities and emergency service capacities in the region, and have contributed to the development of strategies for promoting the uptake and use of earthquake risk information by local governments, the business community, and members of the general public.

Research Partners

Natural Resources Canada (NRCan: Public Safety Geoscience Program) is the lead researcher for the project and one of several federal departments with a mandate to carry out fundamental research to help reduce the economic, social, and environmental impacts from natural hazards in Canada. NRCan contributes to the public safety mandate for Canada by generating knowledge about natural hazards (earthquakes, volcanoes, landslides, etc.) and developing integrated assessment methods to support risk reduction and disaster resilience planning in the public and private sector. Researchers with the Public Safety Geoscience Program (Murray Journeay, Nicky Hastings, Jorge Prieto, and Carol Wagner) have taken a lead role in the analysis and evaluation of earthquake risks for the District of North Vancouver through collaborative partnerships with case study partners, and with academic colleagues at the University of British Columbia and Simon Fraser University.

The UBC School of Community and Regional Planning (SCARP) is one of only a few research facilities in Canada that focuses on disaster management and urban sustainability at local and regional scales. Research is focused on issues of disaster recovery and the resilience of urban infrastructure systems, and includes both empirical studies of major urban disasters and computer-based modelling and analysis of risk reduction strategies. Researchers at SCARP (Stephanie Chang and Autumn Lotze) contributed to the analysis of business disruption and related income losses that are likely to be sustained in the District as a result of earthquake damages to buildings and related critical infrastructure systems that provide essential lifeline services to the community. In addition, they have provided key insights on earthquake risks within the business sector, and strategies to increase disaster resilience through strategic investments in both mitigation and adaptation.

The UBC Department of Civil Engineering is a leader in fundamental and applied research on seismic hazards and structural engineering in Canada. Researchers at the Earthquake Engineering Research Facility (EERF; Carlos Ventura and Liam Finn) worked with members of the NRCan team to assess local-scale seismic hazards using a combination of deterministic and probabilistic ground motion models, and contributed vital information on building assets to support a site-level analysis of earthquake risks for the District of North Vancouver. In addition, they have provided important insights and recommendations on seismic retrofit strategies that may be effective in reducing the vulnerabilities of older buildings that are susceptible to severe earthquake hazards in the District.

Peer Review

We are grateful to members of the DNV Natural Hazard Task Force for their guidance on this study and critical review of the final report. Their insights have helped to ensure that study outputs are relevant and will inform disaster resilience planing and policy development in the community. We also thank NRCan research scientists Trevor Allen and Heather Crow for critical review of study outputs and thoughtful contributions to the technical content of this report. Finally, we thank Shana Johnstone for reviewing analytical results and translating study outputs into a more accessible narrative form to help promote a broader awareness and understanding of earthquake risks in the DNV.

NORTH VANCOUVER
DISTRICT

North Shore Emergency
Management Office
City of North Vancouver • District of North Vancouver • District of West Vancouver

Project Sponsors

Defence Research and Development Canada (DRDC) is the project sponsor and the lead federal agency responsible for science and technology in support of public safety and socioeconomic security in Canada. Operational funding was provided to the Public Safety Geoscience program of NRCan through the Risk Assessment and Capability Integration Program of DRDC (Risk 09/10-0001SCP; Quantitative Risk Assessment Methods Project), Outputs of this study contribute to broader efforts led by DRDC and Public Safety Canada to develop an all-hazards risk assessment framework to support policy goals and operational requirements for a National Disaster Mitigation Program.

Federal Emergency Management Agency (FEMA) provided technical assistance and logistical support for the project through a Cooperative Activity Arrangement with Defence Research and Development Canada (DRDC) and Natural Resources Canada. The primary objective of this work was to establish a standardized methodology for quantitative damage and loss estimation that extends capabilities of Hazus to assist local and regional authorities in analyzing the impacts and consequences of natural hazards (floods, earthquakes and hurricanes), and in evaluating mitigation strategies that increase the disaster resilience of communities and regions. Secondary objectives were to help build a capability for quantitative risk assessment through a coordinated program of outreach and training that addresses the needs and requirements of emergency managers and land use planners in Canada.

SCARP
School of Community
And Regional Planning

DEFENCE DÉFENSE
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EXECUTIVE SUMMARY

We live in a world where connections between natural and human systems are increasingly complex, and where decisions about how to manage societal risk are increasingly uncertain and ambiguous. As communities continue to grow and develop in areas exposed to the impacts of natural hazards, so too does the potential for increasingly severe and devastating events like the ones recently witnessed in Japan and New Zealand. Lessons learned from these and other global disasters underscore the need for a risk-based approach to community planning and emergency management — one that balances the risks of growth and development in hazardous terrain (constraints) with actions that can be taken in advance of a disaster to increase community resilience (opportunities; Figure 1).

Southwestern British Columbia is one of the most seismically active regions in Canada [Cassidy et al., 2010]. Smaller earthquakes occur daily and the region is known to have experienced some of the largest earthquakes ever recorded along the Pacific 'Ring of Fire.' Though infrequent, these larger earthquakes have the potential for catastrophic losses and pose an imminent and credible threat to settled areas in the Pacific northwest regions of British Columbia and Washington State.

A recent study commissioned by the Insurance Bureau of Canada reveals that losses associated with a major earthquake in southwestern British Columbia could exceed $75 billion [AIR Worldwide, 2013]. The Lower Mainland region of Metro Vancouver and the Fraser Valley are exposed to a wide range of seismic hazards including severe ground shaking, liquefaction, earthquake-triggered landslides and tsunami. All have the potential to cause catastrophic damage, loss of life and financial hardship. Areas at greatest risk include older neighbourhoods and commercial/industrial districts in downtown Vancouver, Richmond, Delta, Annacis Island and North Vancouver.

This study examines earthquake risks for the District of North Vancouver (DNV) — an urban municipality of approximately 83,000 people situated along the North Shore Mountains and marine waterfront areas of Burrard Inlet. It includes a detailed analysis of what to expect in terms of impacts and consequences should a major earthquake occur at some point in the near future, and provides insights on actions that might be considered to increase disaster resilience of the community over time.

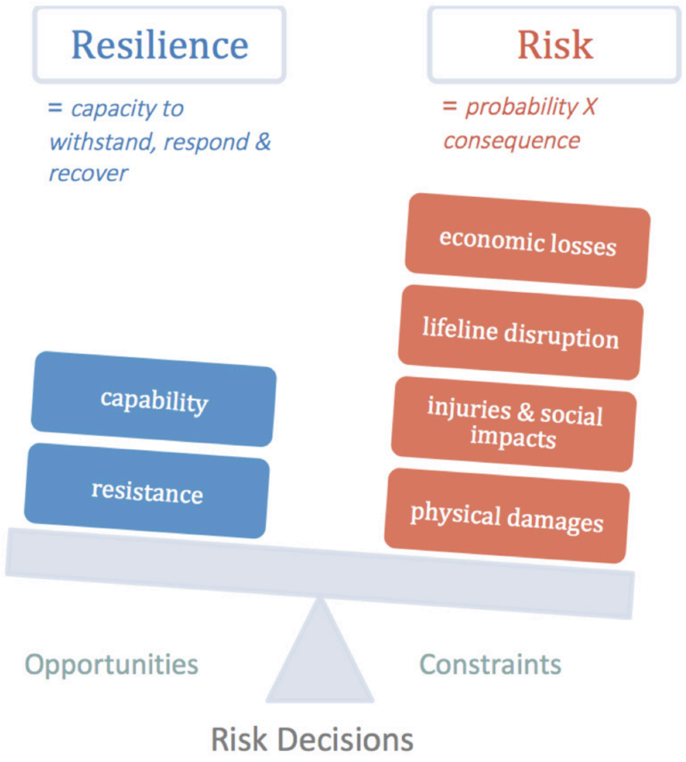


Figure 1: Balancing the risks of growth and development in hazardous terrain (constraints) with actions that can be taken in advance of a disaster to increase community resilience (opportunities)

Our Process at a Glance

Disaster resilience planning is a forward-looking process of analysis and deliberation through which knowledge about the risk environment is used to develop actionable strategies that increase the safety and security of a community and its capacity to respond and recover from hazard threats of concern.

We have adopted a framework for disaster resilience planning [J M Journeay, 2015] that utilizes methods of integrated assessment and scenario modelling to help bridge the gap between knowledge and action (Figure 2). Quantitative methods of integrated risk assessment are used to analyze cause-effect relationships and likely impacts and consequences for hazard threats of concern. Design-based methods of participatory planning and scenario modelling are used to establish decision protocols and to evaluate policy alternatives based on negotiated thresholds of risk tolerance.

The framework is aligned with national and international standards for risk management [Australia/New Zealand Standards, 2006; CAN/CSA-Z1600, 2008; ISO 31000, 2008], and incorporates best practices for risk governance and disaster resilience planning [International Risk Governance Council, 2008; Renn, 2006b]. Integrated risk assessment offers a structured and evidence-based approach to disaster resilience planning that is informed by

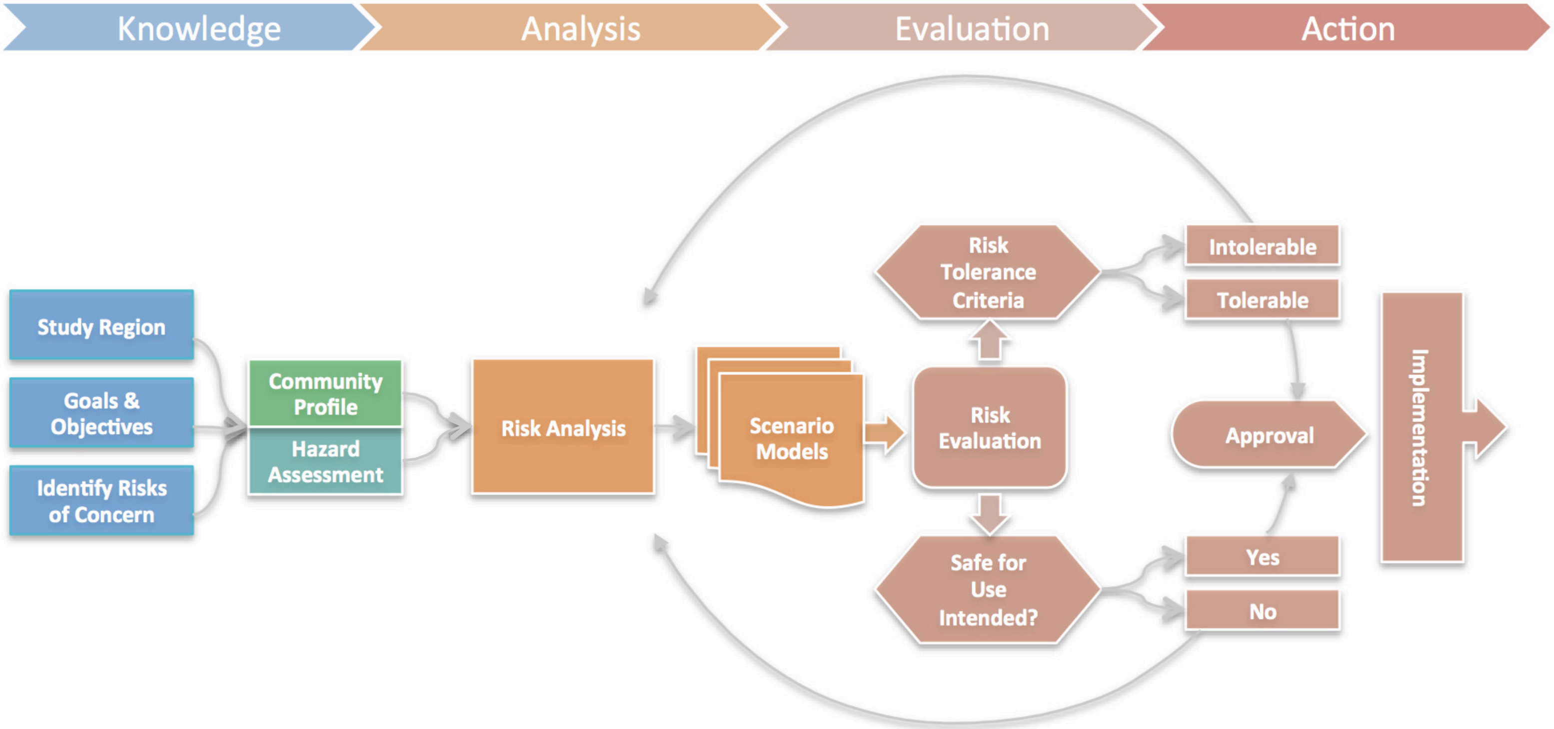


Figure 2: Elements of an integrated risk assessment framework for disaster resilience planning (Adapted from Journeay, 2015).

scientific analysis and predictive modelling, and governed by community values and preferences with respect to who and what are considered vulnerable and in need of safeguarding. Figure 3 is a summary of the process used to assess earthquake risks for the District of North Vancouver. Although described in terms of discrete steps, the process was iterative and evolved through ongoing deliberation, analysis and scenario modelling.

Deliberative components of the process are focused on subjective measures of risk, including the identification of community values and policy goals used to frame the risk assessment process (Step 1), and the establishment of target criteria used to evaluate mitigation alternatives in terms of building performance, public safety, lifeline resilience and socioeconomic security (Step 5). Deliberations were facilitated through a series of design-based workshops with planning staff from the District and North Shore Emergency Management Office (NSEMO), and with members of the Natural Hazards Task Force – a voluntary advisory group representing homeowners and the interests of commercial and industrial businesses in the community.

Analytic components of the process are focused on objective measures of risk, including factors that have contributed to the vulnerability of people and critical assets in the community (Steps 1 and 2), and what might be expected should a major earthquake strike at some point in the near future (Steps 3-5). Our assessment includes an analysis of damage potential and expected socioeconomic lesses for major earthquakes of concern, and an evaluation of risk reduction strategies based on target criteria established by the community (Step 5). Earthquake analysis and the evaluation of mitigation alternatives were facilitated using Hazus – a standardized loss estimation methodology developed for use in the public domain [FEMA, 2004; National Institute of Building Sciences, 2002].

Step 1: Establish Context

- Define study region & compile available information & knowledge assets from community and domain experts.
- Establish policy goals and assessment criteria (indicators) that will inform planning & risk reduction decisions.
- Identify risks of concern through semi-quantitative appraisal of known hazards, vulnerabilities and resilience capacity

Step 2: Community Profile

- Develop GIS exposure model describing characteristics of the community (population & demographics) and the built environment (buildings & lifeline infrastructure).
- Perform gap analysis and validate exposure model with community members to ensure completeness and accuracy

Step 3: Hazard Assessment

- Develop ground motion models for deterministic assessment of a representative scenario earthquake (~1/500 yr), and for probabilistic assessment of known sesimic hazards in region
- Analyse effects of local site amplification
- Analyse effects of permanent ground deformation (liquefaction & earthquake-triggered landslides)

Step 4: Risk Analysis

- Use Hazus loss estimation methodology to assess impacts & consequences of earthquake hazards with respect to building performance, public safety, lifeline resilience and economic security.
- Use geostatistical methods to model patterns of intrinsic social vulnerability within the community.

Step 5: Risk Evaluation

- Develop 'What-if' scenarios that model the effects of risk reduction through mitigation and adaptation
- Use indicators to assess thresolds of risk tolerance and compliance with regulatory safety guidelines

Figure 3: Synopsis of risk assessment process used in this study.

What Can We Expect?

We explore the likely impacts of a significant earthquake through a system of performance measures (indicators) that offer a comprehensive profile of risk at the community level. The framework of indicators provides a capability to assess both current conditions of earthquake risk, and the effectiveness of risk reduction strategies that might be considered to increase longer-term disaster resilience of the community. Risk metrics include:

- Seismic Hazard Potential: The intensity of shaking and potential for ground failure at any given location as a result of seismic energy generated by an earthquake event.
- Building Performance: the likelihood of damage (resistance) and the estimated time to restore functionality to homes and businesses after a major earthquake (recovery).
- Public Safety: the likelihood of injury or death from earthquake damages, and the extent of social disruption caused by loss of habitation and business interruption.
- Social Vulnerability: intrinsic characteristics of a community (population & demographics) that may contribute to unsafe conditions and have the potential to amplify the negative impacts and consequences of a disaster event.
- Lifeline Resilience: the capacity of utility and transportation systems to withstand and recover from the impacts of a major earthquake.
- Economic Security: expected capital and income-related losses resulting from a major earthquake and the benefits of investing in mitigation and/or adaptation measures.

The focus of our study is the District of North Vancouver, one of 23 large urban centres within the broader Metro Vancouver region of southwest British Columbia (Figure 4). Our analysis does not include results for the City of North Vancouver. Nor does it include a full representation of critical lifeline systems (power, communication, etc) that are owned and/or operated in the private sector. While we have made every effort to use the best available information and methods of catastrophic loss modelling to assess likely impacts and consequences of a major earthquake at the community level, there are limits in our ability to fully represent the complexity of cause-effect relationships and the full range of scientific uncertainty. For this reason, the numbers reported in this study are considered estimates only, and do not reflect the full range of possibilities.

Figure 4: Study area location in southwest British Columbia, Canada.

Seismic Hazard Potential

The Cascadia region of southwest British Columbia is one of the most seismically active regions in Canada. More than 400 felt earthquakes occur each year in a region extending from the north of Vancouver Island to Seattle. Most occur in offshore regions and do not pose an imminent threat to people or critical assets. Moderate-sized earthquakes capable of causing damage and socioeconomic losses occur every decade or so in the Cascadia region. Destructive earthquakes with a potential for catastrophic damage and losses occur on average every few hundred years and are among the World's greatest disaster threats [Cassidy et al., 2010]. With increased urbanization and expansion of global trade in the Pacific region, these rare but destructive earthquakes have the potential for socioeconomic losses and disruption that would challenge existing capacities for disaster resilience at all levels of government.

Our assessment of seismic risk for the District of North Vancouver is based on a catastrophic earthquake triggered by displacement along a shallow fault in the Strait of Georgia, ~50 kilometres west of Metro Vancouver (Figure 5). The fault is known to have ruptured in 1997, causing a M4.6 earthquake that rumbled throughout the Cascadia region causing minor damage. We use detailed ground motion models to explore what might be expected if this same fault were to rupture again at some point in the future with a displacement capable of generating a M7.3 earthquake.

The Georgia Strait scenario earthquake is similar in character to a M7.3 event that struck sparsely settled areas of eastern Vancouver Island in 1946. It is also representative of shallow crustal earthquakes of equivalent magnitude that are known to have occurred in the Georgia Basin region over the past ~500 years [Hyndman et al., 2003; Rogers, 1979]. Although credible, the Georgia Strait M7.3 event is not a prediction of what is most likely to happen, nor is it a worst-case scenario. Rather, it represents a scientifically plausible ground motion model that helps makes evident cause-effect relationships and what might be expected if a

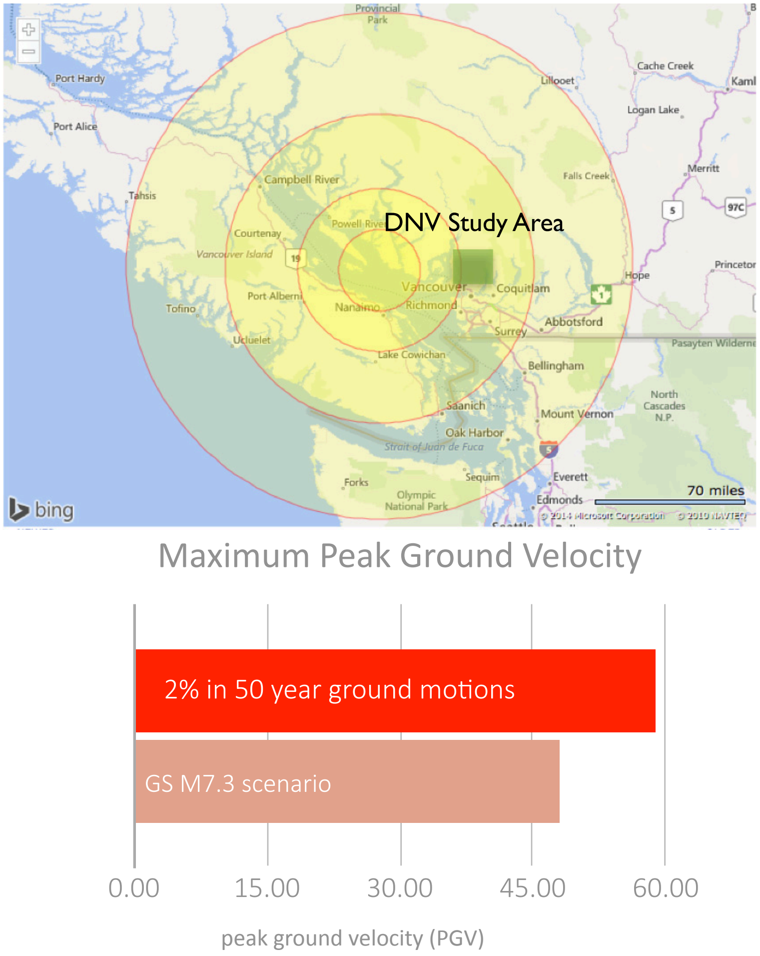


Figure 5: Comparative analysis of ground motions (PGV max) for the Georgia Strait M7.3 scenario earthquake with respect to all known seismic hazards with a return period of 2% in 50 year.

near-source catastrophic earthquake were to occur at some point in the future.

In terms of ground shaking intensity, the Georgia Strait scenario is an example of what might be expected for a cumulative portfolio of earthquake hazards with a return period of ~1/500 years (p~12% in 50 years). With respect to shaking thresholds used for seismic safety guidelines in the 2010 National Building Code of Canada (1/2475 years; p =2% in 50 years), the Georgia Strait scenario ranks ~80% in terms of maximum peak ground velocity (PGV) and ~64% in terms of maximum lateral building displacement (Figure 5).

Because the earthquake epicentre is located close to the Earth's surface, it would be felt widely throughout the Georgia Basin region with very strong and locally severe ground shaking in the Metro Vancouver region (MMI VII-VIII). The main earthquake event would likely last only 20 and 30 seconds but would be felt as a combination of rumbling pressure waves causing violent push-pull motions, and rolling surface waves that would rock buildings and make it difficult to stand or drive a vehicle.

The initial quake would be followed by lesser magnitude but significant aftershock events that could last for several months. In addition to intense shaking, the Georgia Strait scenario earthquake would also cause liquefaction in low-lying areas and seismically triggered landslides in steeper terrain along valley walls. The intensity of shaking and related ground deformation hazards would be similar to those experienced during the powerful M6.3 earthquake that struck Christchurch, New Zealand in 2011.

Predicted ground motions vary considerably across the study area as a function of distance from the earthquake epicentre, geologic setting and the effects of local site amplification. Peak ground velocity (PGV) is a measure of instantaneous shaking at the surface and is often used as reference for assessing the relative intensity of an earthquake event at any given location. PGV values for the District are expected to range from 6.4 cm/second in highland areas underlain by solid bedrock — to a maximum of 48.1 cm/second in lowland areas where seismic waves are amplified by underlying layers of relatively soft sediment (Figure 5).

Building motions measure the lateral displacement of a building envelope with respect to a fixed point on the surface. Building displacements for the Georgia Strait scenario earthquake are expected to range from less than a centimetre to as much as 15.3 cm in areas of local site amplification (Figure 6). Though within the range of what is considered safe for recently constructed buildings, lateral displacements of this magnitude are sufficient to cause structural failure and/or collapse in older masonry and concretes buildings that do not conform to current seismic safety design guidelines.

Liquefaction is expected to occur in areas underlain by water-saturated soils that would loose cohesion during intense ground shaking. Of concern are low-lying waterfront areas underlain by saturated glacial outwash sediments and/or landfill deposits

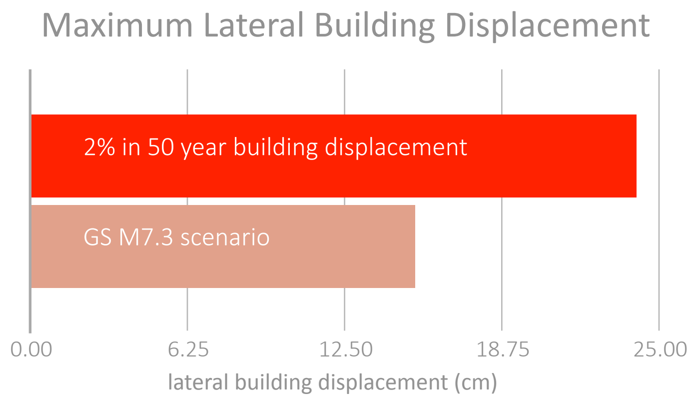


Figure 6: Comparative analysis of building displacement for the Georgia Strait M7.3 scenario earthquake with respect to all known seismic hazards with a return period of 2% in 50 years.

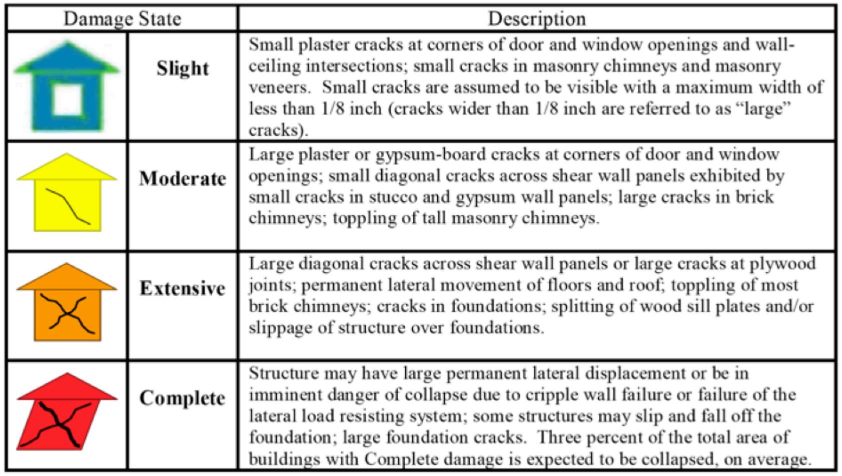
(sand, gravel, crushed rock). Lateral displacements in these areas are likely to be 60-90 cm, and in some places greater than 150 cm. Other areas of concern include delta and outwash terrace deposits of sand and gravel in the lower Capilano and Seymour valleys, where lateral displacements are likely to be 30-60 cm.

Earthquake-triggered landslides occur along steep unstable slopes where severe ground shaking results in forces that are strong enough to overwhelm the internal shear strength of surficial materials and the gravitational forces that hold them in place on the hillside. Hotspots of concern coincide with areas of previous landslides, and zones of high landslide potential identified through independent geotechnical studies commissioned by the District of North Vancouver [M Porter et al., 2007]. They include steep valley walls and preserved outwash terraces along the east shore of Capilano Reservoir, upper reaches of the Capilano River, Mackay Creek, Mosquito Creek, Lynn Creek and the Seymour River.

Building Performance

Building performance is a measure of physical vulnerability in the built environment— the capacity of a structure to withstand a wide spectrum of seismic forces that are experienced at a given site during an earthquake event. We have used the Hazus methodology to estimate damage state probabilities and corresponding levels of uncertainty for both individual structures and aggregate portfolios of buildings at the neighbourhood level [NIBS,FEMA, 2004; 2011; 2002; Schneider and Schauer, 2006].

Hazus uses fragility curves to assess the probability of exceeding minimum thresholds of damage for a given level of shaking and related ground failure. Damage probabilities are calculated for each of five states: None, Slight, Moderate, Extensive and Complete (See Figure 7). Overall building performance is reported on the basis of damage states with the highest probability of occurrence. Slight and moderate damage states describe physical impacts that exceed the yield point of a building but that do not compromise structural integrity. Extensive damage states are those in which load-bearing structural elements of a building are compromised beyond repair. Complete damage states are those in which there is a likelihood of structural failure by tilting and/or toppling with a potential for total collapse.



Damage State		Description
	Slight	Small plaster cracks at corners of door and window openings and wall-ceiling intersections; small cracks in masonry chimneys and masonry veneers. Small cracks are assumed to be visible with a maximum width of less than 1/8 inch (cracks wider than 1/8 inch are referred to as "large" cracks).
	Moderate	Large plaster or gypsum-board cracks at corners of door and window openings; small diagonal cracks across shear wall panels exhibited by small cracks in stucco and gypsum wall panels; large cracks in brick chimneys; toppling of tall masonry chimneys.
	Extensive	Large diagonal cracks across shear wall panels or large cracks at plywood joints; permanent lateral movement of floors and roof; toppling of most brick chimneys; cracks in foundations; splitting of wood sill plates and/or slippage of structure over foundations.
	Complete	Structure may have large permanent lateral displacement or be in imminent danger of collapse due to cripple wall failure or failure of the lateral load resisting system; some structures may slip and fall off the foundation; large foundation cracks. Three percent of the total area of buildings with Complete damage is expected to be collapsed, on average.

Figure 7: Building performance measured in terms of damage state probabilities. Estimates are based on Hazus loss estimation methodology.

Our analysis of building performance for the District includes an assessment of damage potential for current conditions and what might be expected if the most vulnerable buildings were seismically retrofitted according to modern seismic safety standards. Results are evaluated for the Georgia Strait scenario earthquake and for minimum thresholds of expected ground motion for all known seismic hazards over a return period of 1/2475 years (2% in 50 year design threshold). Differences between current and mitigated states provide a measure of effectiveness for investments in seismic retrofits.

General Building Stock

There are ~23,700 buildings spread across 45 neighbourhoods and commercial-industrial areas in the DNV. More than 60% of homes and businesses in the DNV were built before 1975, prior to the introduction of modern building code guidelines for seismic safety. Many of the older neighbourhoods and town centres in the District are located along the waterfront and valley escarpments—areas that have been significantly modified from their natural state to accommodate increasing demands for growth and development over the years.

The majority of buildings in the District (~92% of total) are expected to perform very well in the Georgia Strait scenario earthquake with little or no damage. These are either residential wood frame structures that are inherently resistant to ground shaking hazards, or concrete and steel frame buildings built after 1975. More than 1,000 buildings (4.4% of total) are expected to sustain slight or moderate levels of damage that would require inspection and repairs to restore full levels of functionality. These include older wood frame, concrete and masonry structures that predate modern safety codes and that are located in areas of very strong and severe shaking.

An additional ~840 buildings (3.6% of total) are expected to sustain extensive and/or complete levels of damage with varying levels of structural failure (Figure 8). These are primarily older unreinforced masonry and concrete structures in areas of severe ground shaking that are likely to be demolished and rebuilt during the recovery process. Seismic retrofits to the most vulnerable of these buildings would result in significant risk reduction with only ~20 structures expected to sustain damages that would require demolition during the recovery process.

Residential Sector

Most people in the District of North Vancouver (95%) live in single-family wood frame homes situated in well-established residential neighbourhoods. The remaining 5% live in multi-family condominium, apartment and townhouse complexes made of wood, steel, concrete and masonry that are situated in or adjacent to multi-use residential/commercial town centres.

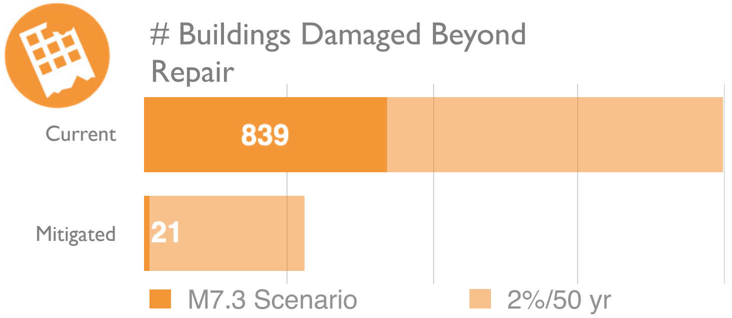


Figure 8: Estimates of building performance for ~22,700 structures in the DNV. Results are compared for the Georgia Strait M7.3 scenario earthquake and all known seismic hazards for a return period of 1/2475 years (2% in 50 years)

At least 640 pre-code wood frame houses are expected to sustain slight and moderate levels of damage from a major earthquake in low-lying areas of Norgate and in valley escarpments along the Capilano River. Concentrated pockets of extensive or complete damage are expected in the older residential neighbourhoods of Norgate, Pemberton Heights, Highlands, Edgemont, Lynnmour-South, and Riverside—areas that would be exposed to a combination of extreme shaking and ground failure during a major earthquake.

More than 215 residential buildings in these areas are likely to sustain permanent structural failure and would be in imminent danger of collapse (Figure 9). These include a mix of older wood frame single family buildings, and multi-family buildings made of concrete and/or masonry that do not conform to modern seismic safety standards. Results of our analysis indicate that nearly all of these structures could be preserved as a result of investments in seismic retrofits prior to a major earthquake.

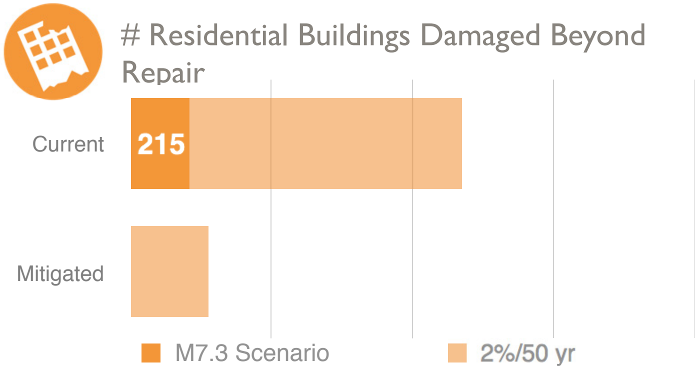


Figure 9: Comparative number of residential structures that are expected to sustain extensive and/or complete damage in the scenario earthquake.

Business Sector

Commercial and industrial businesses contribute 30% of the overall property tax revenue for the District and employ nearly 22,000 people. The majority are small home-based businesses (fewer than 50 employees) with approximately 1,300 buildings used for commercial purposes. Most of these buildings are wood-frame structures in residential neighbourhoods that are expected to sustain little or no damage in the scenario earthquake. However, at least 25 of these home-based businesses are likely to be damaged beyond repair. There are 1,200 larger commercial and industrial buildings in the District. Areas of highest business concentration (where five or more business share one building) occur along the waterfront where buildings are exposed to some of the highest levels of ground shaking and liquefaction.

At least half of all commercial and industrial buildings in the District (~600 structures) are expected to sustain extensive and/or complete levels of structural damage in the scenario earthquake (Figure 10). The most vulnerable of these are pre-code concrete and unreinforced masonry buildings located in the Lower Capilano-Marine, Edgemont, Lynnmour, and Maplewood areas.

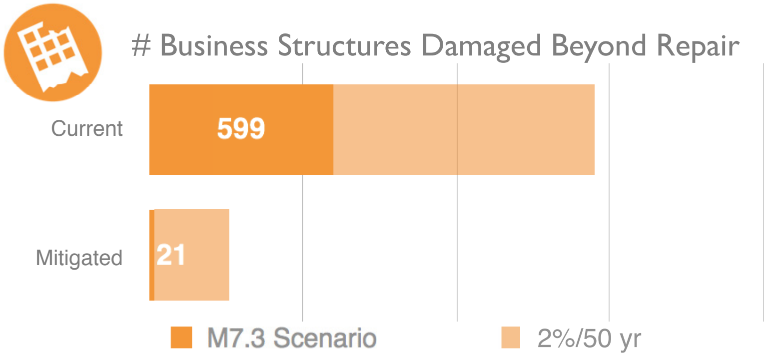


Figure 10: Comparative number of business structures that are likely to sustain extensive and/or complete damage in the scenario earthquake.

Investment in seismic retrofits prior to a major earthquake would likely preserve all but 21 of these structures.

Public Sector

There are ~350 community assets of concern in the District. These include more than 150 municipal buildings and related facilities used for government operations and essential services (police, fire), 115 school facilities owned and operated by the British Columbia Ministry of Education, and ~90 public/private care facilities for young children and the elderly. Of these, at least twenty-five structures are expected to sustain extensive and/or complete levels of damage in the scenario earthquake (Figure 11). Nearly all of these structures would survive the impacts of a major earthquake with seismic retrofit measures in place.

The majority of facilities under municipal jurisdiction (80%) are likely to perform well in the scenario earthquake with little or no significant damage. However, at least 30 buildings are expected to sustain significant levels of damage, and 20 of these are likely to be damaged beyond repair. Buildings of concern include the DNV's Operations Centre and related structures in Lower Lynn, and a variety of historic buildings and recreational facilities in Norgate, Edgemont, Delbrook, Maplewood and Dollarton.

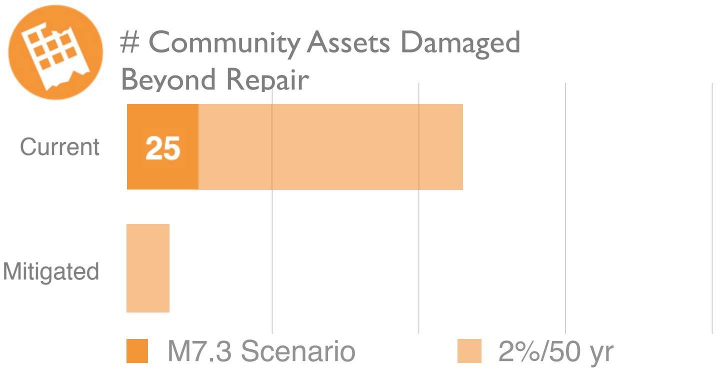


Figure 11: Comparative number of shared community assets (municipal buildings, schools, care facilities, etc) that are expected to sustain extensive and/or complete damage in the scenario earthquake.

Police services and the North Shore Emergency Management Office (NSEMO) are co-located in a newer building adjacent to the Lions Gate Hospital in the City of North Vancouver. All of these facilities are on firm ground and expected to perform well in a major earthquake. However, emergency fire and paramedic services within the DNV are likely to be impacted. Of concern are Fire Hall #2 and nearby emergency supply storage and training facilities in Lower Lynn, which are susceptible to damages caused by severe ground shaking and liquefaction. Facilities and emergency operation services in hardest hit areas are expected to be operating at less than 25% capacity in the days following a major earthquake.

The DNV has over 90 child and elder care facilities. They include a mix of public and private facilities in both commercial and residential buildings that are exposed to a wide range of seismic hazards. More than 95% of these buildings are expected to sustain little or no significant damage in the earthquake. However, a few facilities are located in older concrete and unreinforced masonry buildings located in low-lying neighbourhoods along the waterfront—areas that will experience severe ground shaking and liquefaction. Hotspots of concern include day care facilities in Lower Lynn and Norgate where at least three structures are expected to sustain extensive and/or complete damage.

There are 35 schools and a major university that collectively encompass more than 115 structures (buildings and related facilities) in the District of North Vancouver. Four elementary and secondary schools have been upgraded as part of the provincial seismic retrofit program and three more schools are in the process of being retrofitted to comply with current design guidelines for life safety. As a result of these mitigation efforts, approximately 80 of the 115 structures (70%) are expected to sustain little or no damage from the earthquake.

It is estimated that 25 structures (22%) are vulnerable to moderate levels of damage that will require extensive repairs during the recovery process. Most of these are older concrete buildings that support auxiliary functions (recreation, school operations, etc.) and temporary structures (portables) that are used as overflow classrooms. At least 9 of these structures (8%) are likely to sustain extensive and/or complete levels of damage. Only three of these are primary buildings. These rest are auxiliary buildings exposed to severe ground shaking and/or liquefaction hazards.

Public Safety and Social Disruption

Public safety is measured in terms of indicators that track the extent and severity of injuries, and levels of social disruption that may result from damaged homes and the displacement of business that sustain significant levels damage during a major earthquake. Although severe shaking and related ground deformation are expected to last for less than a minute, the impacts and consequences of a major earthquake like the Georgia Strait event would have consequences that will resonate in the community for many years.

More than 60,000 people make their way to work and school on any given day. Nearly half of those commuting from the DNV travel to jobs in downtown Vancouver and across the greater Metro Vancouver region by car, bus and ferry. The remaining population is at home or at jobs and activities within the community during the day.

Injuries

It is estimated that several thousand people would sustain injuries requiring immediate medical attention if the scenario earthquake occurred during the day. Several hundred individuals are expected to sustain life-threatening injuries that would result in hospitalization and/or death.

Areas of concern include the Lynnmour-Maplewood area where more than 1,000 people are expected to sustain injuries that would require immediate medical care, and the Norgate area where more than 650 people are expected to need paramedic services. The number of injuries requiring medical care would likely overwhelm the capacity of existing hospital resources that serve all of the north shore communities in the Vancouver Coastal Health District.

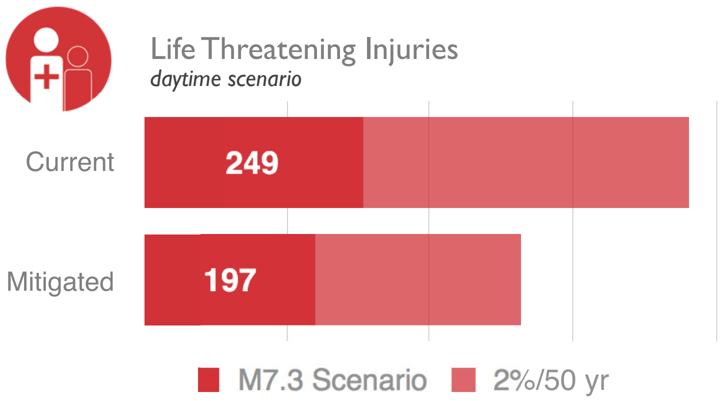


Figure 12: Comparative number of life threatening injuries that are expected for a daytime earthquake scenario.

At least ~250 people are likely to sustain life threatening injuries as a result of toppling and/or collapse of vulnerable buildings during a daytime earthquake scenario (Figure 12). Most of those with life-threatening injuries are employees working in vulnerable concrete and unreinforced masonry buildings in areas of severe ground shaking and liquefaction. By comparison, only ~30 people are expected to sustain life-threatening injures for a night-time earthquake scenario. While serious injuries are inevitable, more than 50 casualties could potentially be with avoided seismic retrofit measures in place.

Social Disruption

The majority of people in the District are likely to shelter in place following a major earthquake, but approximately 4,250 people are expected to seek shelter elsewhere as a result of damages to their homes. Most of those displaced from their homes will seek short-term shelter with family and friends while others will stay in motels or arrange rental accommodation in areas with little or no damage. Several hundred people will likely not have the means to provide for themselves and will seek public shelter and emergency services that are provided by relief organizations.

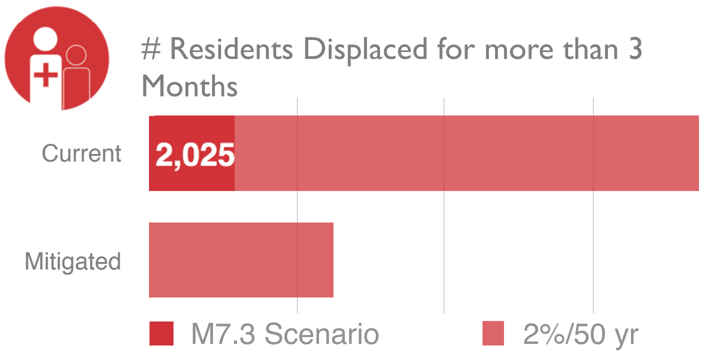


Figure 13: Estimated number of residents that are likely to be displaced from their homes for more than six months in the scenario earthquake.

Most people are expected to return home within a month after the earthquake. However, it is estimated that as many as 2,025 people will be displaced for more than three months and an additional 770 people will be displaced for up to a year, possibly longer (Figure 13). Those who have lost their homes may be forced to relocate. Investment in seismic retrofits would decrease recovery times with only a handful of residents being displaced from their homes for more than six months.

Damages to commercial and industrial businesses along the waterfront will result in a significant level of disruption to jobs and wages, the impacts of which will ripple through the community for a year or more. Hardest hit are employees in small retail and larger industrial businesses located in older buildings susceptible to higher levels of earthquake damage. Hotspots of damage are localized in business precincts along the waterfront and in the town centres of Lower Capilano-Marine, Edgemont, Lynnmour, and Maplewood areas. It is estimated that more than 17,850 employees will be displaced from their place of work for more than six months (Figure 14). The extent and concentration of damage in these areas will be significant and large parts of the business district are likely to be cordoned off for up to a year or more during the recovery and rebuilding process. The extent and level of disruption to the business sector would be similar to that experienced following the Christchurch earthquake of 2011.

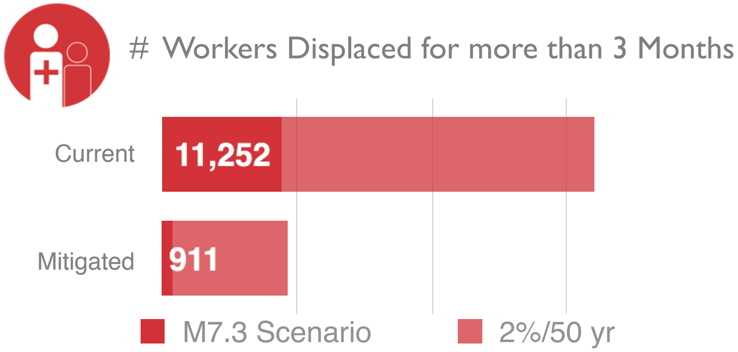


Figure 14: Estimated number of employees that are likely to be displaced from their place of work for more than six months in the scenario earthquake.

Social Vulnerability

Social vulnerability reflects the intrinsic characteristics of exposure and susceptibility that create unsafe conditions in a community, and that have the potential to amplify the negative impacts and consequences of a disaster event. Key factors include:

- Exposure: the location of homes and businesses and their susceptibility to earthquake damage;
- Agency: social and economic variables that will enable some to take actions that minimize the impacts of a major earthquake while forcing others to succumb; and
- Capacity: demographic variables that will influence capabilities to cope with and recover from the impacts of a disaster event.

Knowing who is most vulnerable and the underlying socioeconomic drivers provides insights on the types of emergency services that are likely to be needed in these areas during response and recovery operations. Our analysis of social vulnerability for the DNV is based on the well-known 'hazards of place' model, which utilizes geo-statistical methods to detect and rank patterns based on a wide range of demographic variables that reflect social and economic interactions at a neighbourhood level [Cox et al., 2006; Cutter et al., 2000; Dwyer et al., 2004].

As it turns out, the most vulnerable populations in the DNV are situated in areas exposed to some of the highest levels of shaking and ground failure during an earthquake.Areas of greatest concern include older neighbourhoods along the waterfront and isolated pockets throughout the community where the physical impacts of ground shaking and liquefaction are likely to be amplified by a more limited capacity of residents to respond and recover on their own. These are areas in which the demand for emergency social services is likely to be the greatest during and after a disaster event.

Lifeline Services

The District of North Vancouver relies on an extensive system of reservoirs, dams, pipes, pumps, roads, rails, bridges, and other engineering structures to provide essential lifeline services — failure of any one component as a result of natural and/or anthropogenic causes has the potential to disrupt water and power service to the community and the Metro Vancouver region as a whole. Lifeline systems are jointly owned and operated across several levels of government and by private sector utility companies. Critical infrastructure systems are inherently complex, interconnected and increasingly in need of upgrades to meet the needs of ongoing growth and development in the region.

Utilities

Utility systems are expected to sustain damage and loss of functionality in low-lying areas along the waterfront and in older residential neighbourhoods at higher elevations. These are areas in which there is a higher proportion of older non-ductile pipes and related facilities, and that are susceptible to damage from ground shaking and lateral displacement caused by liquefaction.

Of particular concern are water facilities adjacent to the Capilano Reservoir and pumping stations that service the neighbourhoods of Cleveland, Upper Lynn and Northlands. It is expected that nearly half of all homes and businesses in the DNV will be without access to potable water (~14,300), and as many as 3,250 buildings will be without electrical services seven days after a major earthquake (Figure 15).

Mean recovery times for areas hardest hit by the earthquake are estimated to be 30 days or more depending on the capacity of service crews to inspect and repair damages. These are considered conservative estimates as the recovery of lifeline services will likely be prioritized across the broader Metro Vancouver region depending on the extent of disruption and the criticality for emergency response and recovery operations.

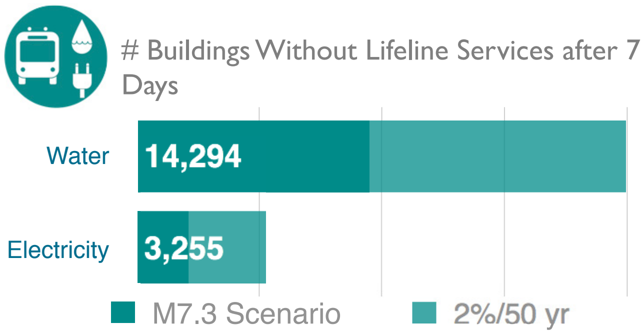


Figure 15: Estimated number of homes and businesses without access to essential lifeline services one week after the scenario earthquake.

Transportation Networks

Transportation hotspots for the scenario earthquake include designated disaster response routes along the waterfront and major east-west transportation corridors that cross the Capilano, Lynn and Seymour valleys (Figure 16). Of particular concern is the impedance of emergency response efforts and delays in the repair of water and electrical lines provided by repair service trucks and equipment.

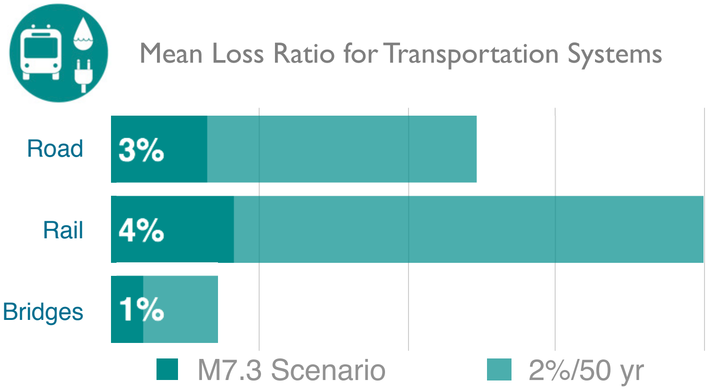


Figure 16: Mean loss ratios for transportation system components damaged as a result of the scenario earthquake.

Road and rail systems networks are vulnerable to damage from severe ground shaking, liquefaction and earthquake-triggered landslides. Second-order impacts include vehicle accidents and hazardous material spills, both of which can cause injury and loss of life. While it is expected that damages to highway and rail segments would be repaired in the days and weeks following the earthquake, loss of functionality immediately after the event would seriously compromise emergency response and recovery efforts.

Disaster Debris

Disaster debris poses a direct threat to individuals who are outside during an earthquake, and has the potential to burden recovery efforts for many months following the event. Areas with the most disaster debris will be found in higher-density town centres and in older neighbourhoods where a higher proportion of buildings are likely to sustain extensive or complete damage.

It is estimated that 280,000 tons of debris could be generated by scenario earthquake. This includes nearly 160,000 tons of steel and concrete and 120,000 tons of mixed wood, brick, glass and general building debris. The total amount of debris is equivalent to 11,200 truckloads of material that would need to be relocated either to infill sites within the community or transported to landfill sites outside the Metro Vancouver region.

Economic Security

Economic security is a measure of community wealth and the capacity of local and regional economies to withstand and recover from the consequences of a major disaster event. It is influenced by the location and exposure of monetary assets; the extent and duration of business disruption; and the degree to which any potential losses are covered by risk transfer through insurance markets.

Indicators of economic security track capital assets (stocks) and income generated by the exchange of goods and services (flows) before and after a disaster event. From a policy perspective, the goal is to maximize the security of community wealth and economic vitality through strategic investments in mitigation and/or adaptation measures that have a potential to reduce vulnerabilities and yield a positive rate of return over time horizons of interest to the planning process.

Community wealth for the District of North Vancouver is estimated to be in excess of $20.3 billion. This includes $18.4 billion of capital investments in buildings and critical infrastructure, and $1.9 billion in gross annual revenues generated by the flow of goods and services in the business sector.

Total economic losses for the scenario earthquake are estimated to be nearly $3 billion with an overall mean loss ratio of ~16.7% — comparable to that of the 2011 Christchurch earthquake [Daniell and Vervaeck, 2011]. Direct economic losses resulting from damages to buildings and contents are estimated to be $2.33 billion (~80% of total). Hardest hit are commercial and industrial businesses in major town centres along the waterfront where direct economic losses include both capital investments in buildings and contents (~$1.18 billion), and $645 million in lost revenue caused by service disruption in the weeks and months following the earthquake (Figure 17).

Capital Losses

The mean loss ratio for residential homes is ~13%, which translates into an average capital loss of ~$66,000 for a single-family residence and ~$345,000 for multi-family apartment and condominium complexes. The mean loss ratio for business assets is significantly higher with expected average capital losses of $360,000 for commercial buildings and up to $500,000 for industrial facilities. As expected the profile of loss is skewed by the vulnerability of older concrete and unreinforced masonry buildings in commercial/industrial zones along the waterfront.

Total capital losses for lifeline systems damaged in the scenario earthquake are estimated to be over $26 million (Figure 17).

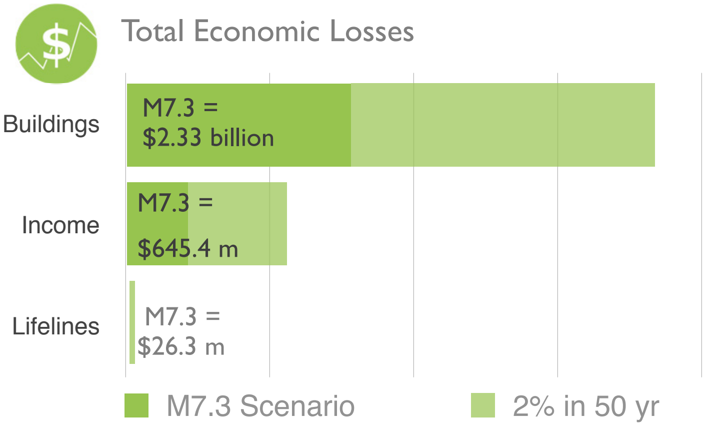


Figure 17: Estimated total economic losses from the scenario earthquake

About 78% of these losses are the costs of repairing roads damaged by ground failure. This includes $16.5 million to repair highways and secondary roads and an additional $3.2 million for rail lines and related facilities. Capital losses to water utility systems are estimated at $5 million. Losses specific to potable water systems are $2 million, with more than half of these caused by damage to treatment and pumping facilities and the balance shared between pipelines and water distribution lines. Losses specific to wastewater systems are $3 million and are evenly allocated between pipelines and distribution lines.

These are considered very conservative estimates as they do not account for losses to power and communication facilities (electricity, natural gas, telecommunications, etc.) that are privately owned and operated and for which we did not have access to information on asset vulnerability or replacement costs. Also not included in our analysis are direct economic losses to bus, ferry and port facilities in the DNV. Capital losses to port facilities are expected to be substantial as they are likely to sustain significant damage caused by severe shaking and liquefaction along the waterfront. Prolonged disruption of port operations will likely interrupt international trade and have a profound impact on both regional and national economies.

Business Disruption and Income-Related Losses

Businesses play an integral role in the functioning of a community — as revenue generators, employers, and providers of goods and service. DNV has more than 3,400 licensed businesses situated in 2,500 buildings across the District (District of North Vancouver, 2011). Commercial service providers represent more than 50% of the local business sector with the balance distributed across mining, construction and transportation industries (18%), wholesale and retail trade (15%), finance, insurance and real estate (8%), manufacturing (5%) and health services (3%). Extrapolating from provincial annual industry employment counts and gross domestic product (GDP) data, the DNV business community generates an estimated annual GDP of approximately $1.93 billion.

Income-related losses to the business sector are dependent on earthquake damage, interruptions to critical lifeline services (water & power), and the time required to restore baseline levels of functionality. Losses include reduced business revenue and the costs of relocation from areas that are cordoned off during the recovery process.

Because commercial and industrial assets are concentrated in areas of greatest vulnerability in the DNV, the business sector is expected to bear the largest burden of financial risk with a potential for up to 90% loss in gross daily revenue. This translates into nearly $645.4 million of total income-related losses for the duration of the recovery process. Prolonged business disruption at this level would have a substantial and lasting impact on the community and economic vitality in the broader Metro Vancouver region.

Financial Risk

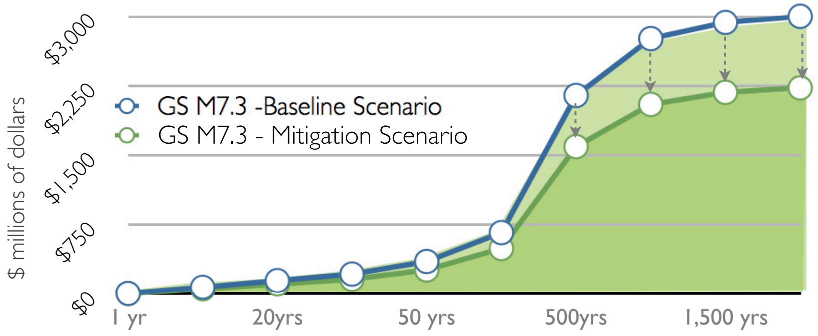
Financial risk is a function of total expected economic losses resulting from a disaster event (consequences), the likelihood of these losses occurring over a specified time horizon (probability), and the potential to reduce future losses through a combination of mitigation, business continuity planning and/or risk transfer (capacity). Since future patterns of economic risk are uncertain, investments in risk reduction measures need to be justified economically on the basis of losses that are avoided on average every year or over a specified planning horizon.

There are no specific guidelines on what constitutes a tolerable threshold of financial risk for municipal governments. However, the Canadian Office of the Superintendent for Financial Institutions (OSFI) does provide guidelines to secure collective investments in federally regulated institutions such as banks, pension plans and insurance companies that are exposed to earthquake risk (OSFI, 2013b). Minimum thresholds of economic risk are based on Probable Maximum Losses (PML) corresponding to earthquakes with a ~1/500 year likelihood of occurrence [CRESTA, 2003; Kovacs and Seweeting, 2004].

The Georgia Strait M7.3 earthquake is representative of large shallow crustal events that are known to occur in the upper plate of the Cascadia subduction region with a recurrence rate of ~1/500 years [Hyndman et al., 2003]. As such, it is a suitable scenario for exploring what might constitute a tolerable threshold of earthquake risk for the District of North Vancouver. A 30-year time horizon is often used as the financial planning context for managing individual and collective risks associated with capital investments in homes and businesses (mortgages, bank loans, etc.).

The 30-year probable maximum loss for the Georgia Strait scenario earthquake is estimated to be ~$220M for baseline conditions and ~$160M with structural mitigation measures in place (Figure 18). Probable maximum losses for longer time horizons that are relevant for strategic land use and infrastructure planning (100 years) are estimated to be ~$665M for baseline conditions and ~$490M with mitigation measures in place.

Risk Reduction Potential Through Investment in Seismic Retrofits



Probable Maximum Loss (PML) - $ millions of dollars over planning horizons of interest								
Hazard Event (of specified intensity)	**Expected Loss PAA=1**	**1 yr**	**10 yrs**	**30 yrs**	**50 yrs**	**100 yrs**	**500yrs**	**1,000 yrs**
GSM7.3 (B2)	$ 3,000.7	$7.5	$ 74.2	$217.1	$353.0	$ 664.5	$2,142.3	$ 2,755.2
GSM7.3 (M2)	$ 2,228.1	$5.6	$ 55.1	$161.2	$262.1	$ 493.4	$1,590.7	$ 2,045.7
Risk Reduction Potential	$ 772.6	$1.9	$ 19.1	$ 55.9	$ 90.9	$ 171.1	$ 551.6	$ 709.4

Figure 18: Risk profiles for the scenario earthquake without mitigation measures in place for planning horizons of interest.

From Knowledge to Action

Disaster resilience is a forward-looking process of planning through which knowledge about the risk environment is transformed into actions that have potential to reduce intrinsic vulnerabilities and increase the capacities of a community to withstand, respond to and recover from unexpected hazard events. The aim is to marshal the resources and capabilities needed to realize policy goals for growth and development (opportunities) while minimizing the potential negative impacts of hazards that can undermine the longer-term sustainability of a community or region (risks and liabilities).

Outputs of this study have been used to inform the development of an earthquake action ready plan for the District of North Vancouver (Figure 19). The plan was developed by District staff with input from the community Natural Hazard Task Force. It is aligned with risk reduction guidelines of the UN Disaster Resilience Cities Program [UNISDR, 2012], and is intended to help increase capacities of the District to reduce future losses and become more resilient to earthquake hazards through strategic investments in mitigation, emergency management and adaptation planning.

Mitigation

Mitigation is focused on measures that can be implemented before a disaster event to reduce the physical vulnerability of people and critical assets and the potential for socioeconomic losses. Structural mitigation involves retrofitting core elements of a building or engineered structure to increase physical resistance to seismic loads and lateral displacements caused by severe shaking and/or ground deformation. Non-structural mitigation includes measures that minimize the exposure of people and physical assets to known earthquake hazards through land use policies, development restrictions (permits, bylaws, etc.), early warning systems, and the physical retrofitting of non-skeletal building elements (facades, internal partitions, contents, machinery and utility systems).

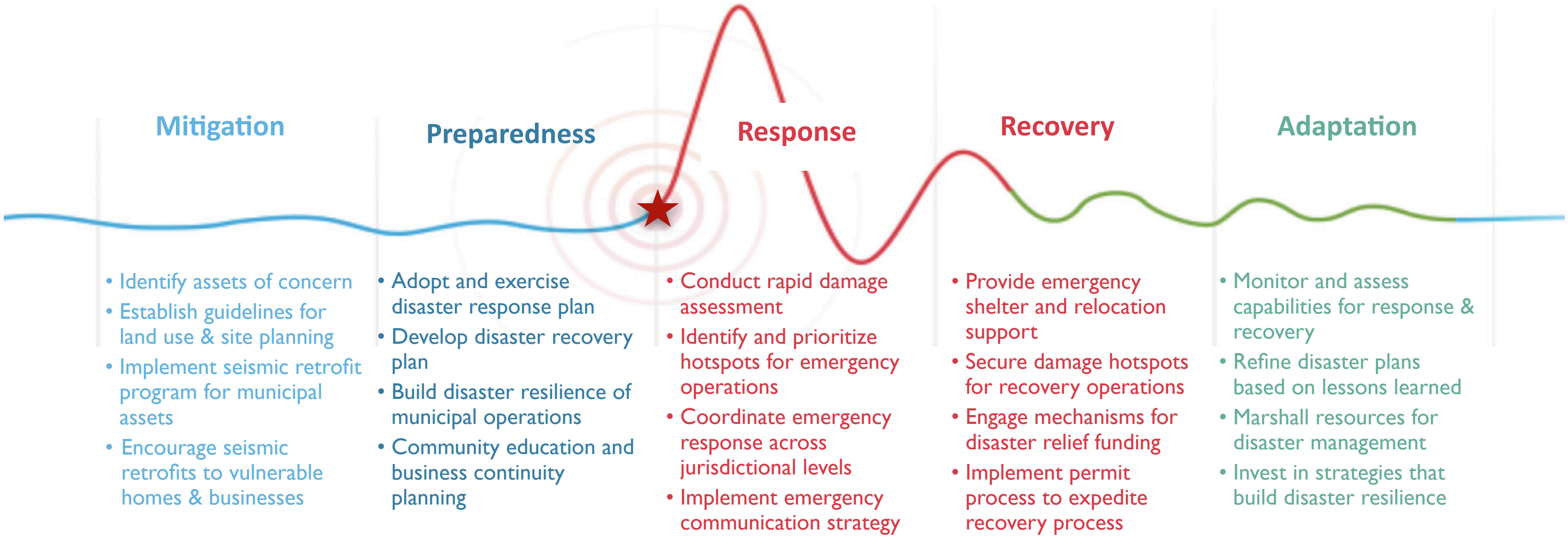
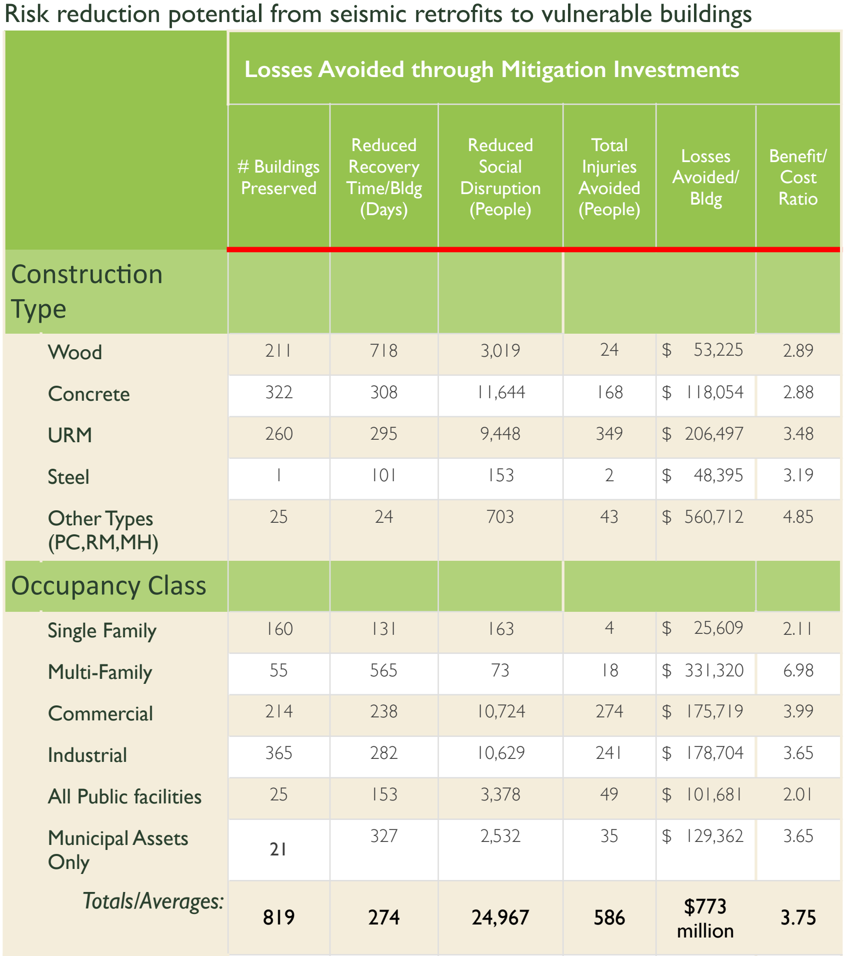


Figure 19: Elements of an earthquake action plan for the District of North Vancouver (Diagram modified from Keller and Schneider, 2014).

The DNV Earthquake Ready Action Plan includes a blend of structural and non-structural mitigation measures:

- Utilize scenario models and indicator framework to develop risk tolerance thresholds that will guide municipal planning and decision making. Risk tolerance criteria may be evaluated in terms of building performance, public safety, lifeline resilience and/or socioeconomic security.
- Establish land use policies and seismic safety guidelines to inform development in areas that exceed tolerable thresholds of earthquake risk. Investigate the feasibility of implementing development permit areas that reduce physical vulnerabilities, and encourage the establishment of professional practice guidelines to inform the work of Qualified Professionals in high-risk areas.
- Identify and prioritize municipal assets that exceed risk tolerance thresholds and develop seismic retrofit strategy that can be incorporated into the DNV asset management plan using principles of ALARP.
- Assess vulnerabilities and interdependencies of critical lifeline services (power, potable water, wastewater, etc.) in order to identify restoration priorities, and to develop an integrated recovery plan with Metro Vancouver and private owners/operators.
- Explore risk transfer strategies for municipal assets that exceed minimum thresholds, and that cannot be effectively mitigated using principles of ALARP.
- Research best practices and explore the potential of incentive programs that encourage private investment in seismic retrofits to homes and businesses in areas of high seismic risk.

We have utilized 'what-if' scenario models to evaluate the effectiveness of mitigation measures aimed at reducing the vulnerability of older buildings that are exposed to extreme seismic hazards. The analysis compares expected losses for the scenario earthquake to those of a mitigation scenario in which vulnerable buildings have been seismically retrofitted to current seismic design standards as part of the ongoing community development process (Figure 20). Mitigation costs are based on empirical data from seismic retrofit programs that have been implemented in California (Porter et al., 2006; City and County of San Francisco, 2010).



Risk reduction potential from seismic retrofits to vulnerable buildings

	Losses Avoided through Mitigation Investments					
	# Buildings Preserved	Reduced Recovery Time/Bldg (Days)	Reduced Social Disruption (People)	Total Injuries Avoided (People)	Losses Avoided/ Bldg	Benefit/ Cost Ratio
Construction Type						
Wood	211	718	3,019	24	$ 53,225	2.89
Concrete	322	308	11,644	168	$ 118,054	2.88
URM	260	295	9,448	349	$ 206,497	3.48
Steel	1	101	153	2	$ 48,395	3.19
Other Types (PC,RM,MH)	25	24	703	43	$ 560,712	4.85
Occupancy Class						
Single Family	160	131	163	4	$ 25,609	2.11
Multi-Family	55	565	73	18	$ 331,320	6.98
Commercial	214	238	10,724	274	$ 175,719	3.99
Industrial	365	282	10,629	241	$ 178,704	3.65
All Public facilities	25	153	3,378	49	$ 101,681	2.01
Municipal Assets Only	21	327	2,532	35	$ 129,362	3.65
Totals/Averages:	**819**	**274**	**24,967**	**586**	**$773 million**	**3.75**

Figure 20: A summary of risk reduction potential for the Georgia Strait M7.3 earthquake for baseline and mitigation scenarios

It is estimated that ~820 buildings would be preserved as a result of strategic investments in seismic retrofits. As expected, the most significant return on investment is for concrete and unreinforced masonry buildings in commercial/industrial centres along the waterfront, where the benefits of mitigation outweigh costs by ~4 to 1. Increased building performance through structural mitigation would also result in 585 fewer casualties (~50 fewer life-threatening injuries) and total economic savings of more than $770 million dollars. Ancillary benefits include shorter recovery times, reduced income-related losses and less social disruption — all of which translate into a higher level of disaster resilience for the community.

Emergency Management

Emergency management embraces the full spectrum of preparedness planning and operational activities that are taken both during and after a disaster to ensure the safety and security of people and critical assets. Emergency preparedness activities are designed to increase awareness, self-reliance, and response capabilities of individuals and communities. They include continuity planning for homes and businesses to minimize levels of disruption during the recovery process; risk transfer and disaster relief funding to minimize the longer-term socioeconomic consequences of a disaster; land use policies that direct the re-building and ongoing development of communities in ways that minimize exposure to earthquake hazards; and governance models that build on effective public-private partnerships to streamline the process of recovery and re-building.

Emergency preparedness recommendations developed as part of the DNV Earthquake Ready Plan include the following:

- Seek approval from municipal council to adopt and exercise the earthquake readiness action plan as part of ongoing emergency management operations in the District.
- Utilize scenario models to develop and refine post-earthquake response and recovery plans as new information becomes available.
- Build disaster resilience capacity of DNV staff through ongoing training and professional development in earthquake readiness.
- Integrate principles of earthquake readiness into sustainable community planning & DNV operations using risk tolerance criteria to help guide decision making.
- Promote an awareness and understanding of earthquake readiness through community outreach and business continuity planning.

Recommendations to increase emergency response capabilities for the District include:

- Utilize earthquake risk maps to identify and prioritize emergency response operations based on hotspots of concern (damages & casualties) and available resources.
- Increase capacity of rapid damage assessment unit to collect and catalogue earthquake impacts. Revise emergency response operations as new information and resources become available.
- Coordinate emergency response operations across all levels of government according to EMBC protocols and existing mutual assistance programs developed as part of the Integrated Partnership for Regional Emergency management in Metro Vancouver.
- Implement emergency communication strategy to ensure that information about the disaster event and evolving response/recovery operations is accessible and updated regularly.

Recommendations to increase the effectiveness of recovery operations in the District include:

- Provide short-term emergency shelter and relocation support based on initial damage assessment reports and updates from social assistance operations.
- Secure hotspots of concern for recovery operations and provide estimates for restoration of lifeline services (water, power, etc) and baseline functionality for homes and businesses that are damaged by the earthquake.
- Engage mechanisms of disaster relief funding for homes and businesses that sustain economic losses exceeding minimum thresholds established by Provincial and Federal agencies.
- Implement post-disaster permit guidelines and procedures to expedite recovery process for homes and businesses that are damaged in the earthquake.

Adaptation

Adaptation encompasses a wide range of actions that are planned in advance but implemented after a disaster event to increase the capacities of people, buildings, and engineered systems to respond and recover from the impacts and consequences of a major earthquake. Resilient systems experience relatively small levels of disruption and are likely to recover baseline levels of performance in a relatively short period of time. In some cases these systems may even increase overall performance due to adaptive design and reorganization during the recovery period. Systems characterized by low levels of resilience experience a relatively large drop in performance following a disaster, take a longer period of time to recover, and may never regain pre-event levels of functionality.

Adaptation measures identified in the DNV Earthquake Ready Action Plan are to:

- Monitor and assess capacities to withstand, respond and recover from earthquake event.
- Refine DNV guidelines and policies for disaster resilience planning based on lessons learned.
- Marshall the resources needed to meet community thresholds of risk tolerance for vulnerable populations and critical assets.
- Share lessons learned

The window of opportunity for implementing adaptation measures following a disaster event is often small and quickly crowded with diverse and often competing public policy issues. The key is to identify those actions with the greatest potential to effect change during the recovery process, and to marshal resources and capabilities that will be required to implement these measures when the time comes.

Outcomes

While we cannot predict when a devastating earthquake will strike, we do have the ability to anticipate what might happen, and 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. Outputs of this study provide a foundation for ongoing disaster resilience planning and sustainable community development in the District of North Vancouver.

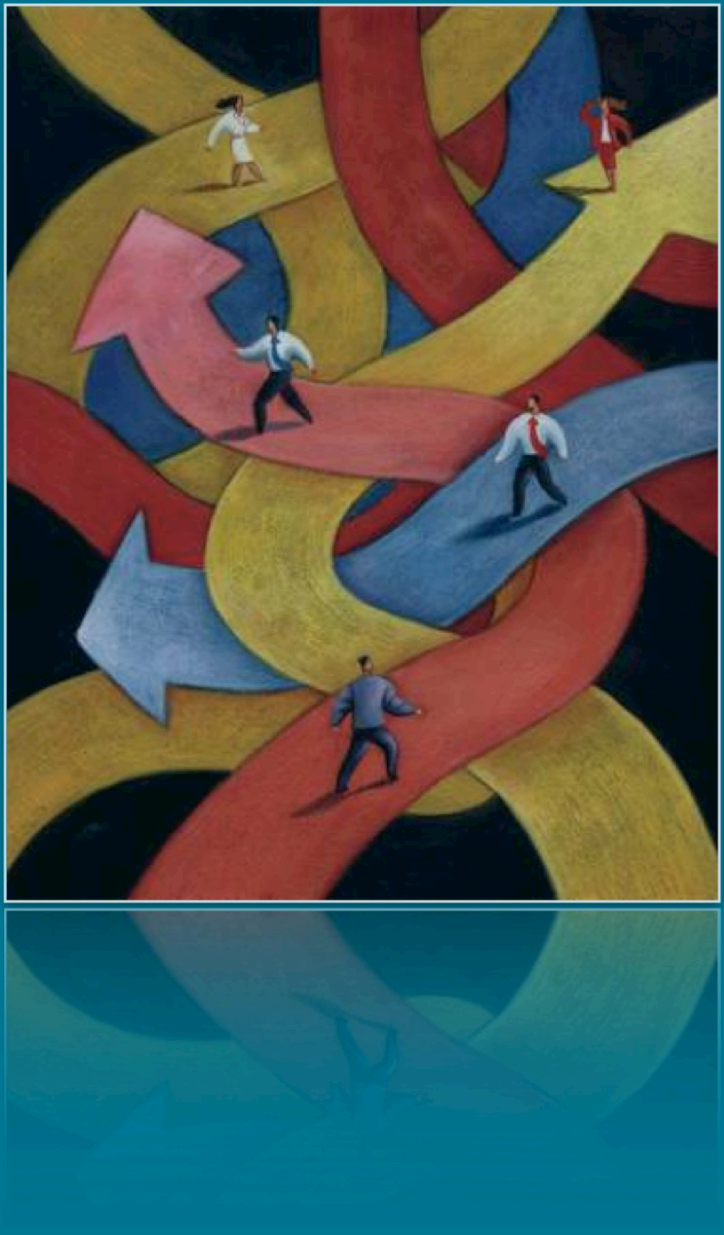
Insights and methodologies are transferrable to other communities who may face similar earthquake risks in Canada, and contribute to broader efforts by the Canadian Safety and Security Program to promote a culture of risk awareness in Canada, and to build capacities for an all-hazard approach to disaster resilience planning at a national scale.

CHAPTER 1:
INTRODUCTION

Canada does not yet have a comprehensive framework for managing risks associated with growth and development in areas exposed to earthquake hazards. National building codes incorporate seismic design guidelines to ensure public safety for new buildings (NBCC, 2010). However, the guidelines do not address safety concerns for older buildings constructed prior to the mid-1970's, or the broader range of impacts and consequences that are relevant for emergency management and land use planning at a community level . These include building damage, recovery time, injuries, level of social disruption, economic losses, and financial risk.

This study addresses the need for improved methods and capabilities for earthquake risk assessment and disaster resilience planning at the community level. We explore the realm of earthquake risk at a scale that is relevant for municipal planning and policy development, and validate a framework for integrated assessment and scenario modelling that is designed to help guide risk reduction and disaster resilience planning activities at local and regional scales. Motivating questions for our work include:

- Who and what are considered most vulnerable to known earthquake hazards and in need of safeguarding?
- What are the likely impacts and consequences of a major earthquake, and the socioeconomic drivers of risk ?
- How might this information be used to inform mitigation and adaptation planning activities that are effective in reducing future losses and building disaster resilience ?



CHAPTER 1: INTRODUCTION

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COMING TO TERMS WITH RISK

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. The assessment of earthquake risk involves four overlapping domains that encompass increasingly broader dimensions of scientific enquiry, planning and policy development (Figure 21). They include an assessment of hazard potential, exposure and vulnerability, likely impacts and consequences (risk), and capabilities for response and recovery (resilience).

Seismic hazard assessment describes the geographic extent and severity of ground motions, and the likelihood of an earthquake occurring at some point in the future. Exposure and vulnerability describe intrinsic characteristics of people and critical assets in terms of their susceptibility to injury and damage from earthquake hazards. Risk modelling measures the probable impacts and consequences of seismic events in terms of damages, injuries, and anticipated socio-economic losses. Disaster resilience represents the interface between science and policy. It is focused on transforming knowledge about the risk environment into actionable strategies that increase the capacities of a community to withstand and recover from the impacts of a major earthquake, and adapt to changing conditions of risk over time. An understanding of risk and resilience provides important insights on how to manage growth in areas exposed to natural hazards, and is an essential component of comprehensive land use planning and sustainable community development.

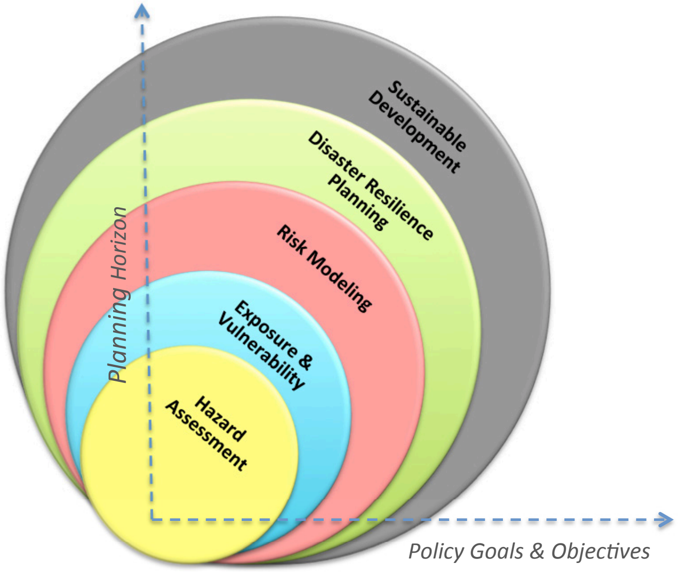


Figure 21: Overlapping domains of risk assessment and disaster resilience planning.

Earthquake Hazards

The Lower Mainland of British Columbia is exposed to a wide range of earthquake hazards including severe ground shaking, liquefaction, earthquake-triggered landslides and tsunami (Figure 22). All have the potential for significant damage and loss of life. Our assessment of earthquake hazards for the District of North Vancouver utilizes complementary methods of deterministic and probabilistic analysis. Both methods predict the likelihood and

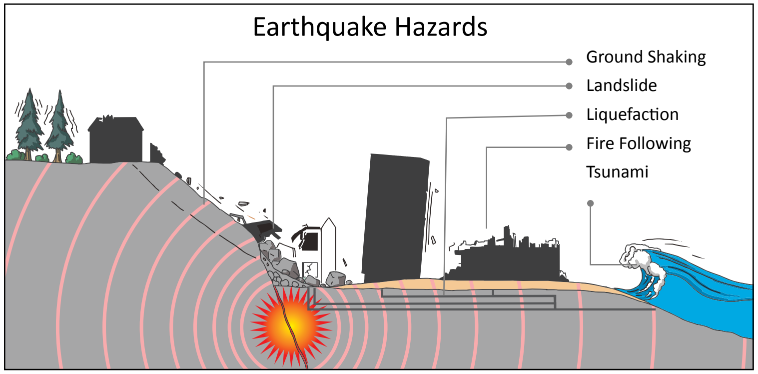
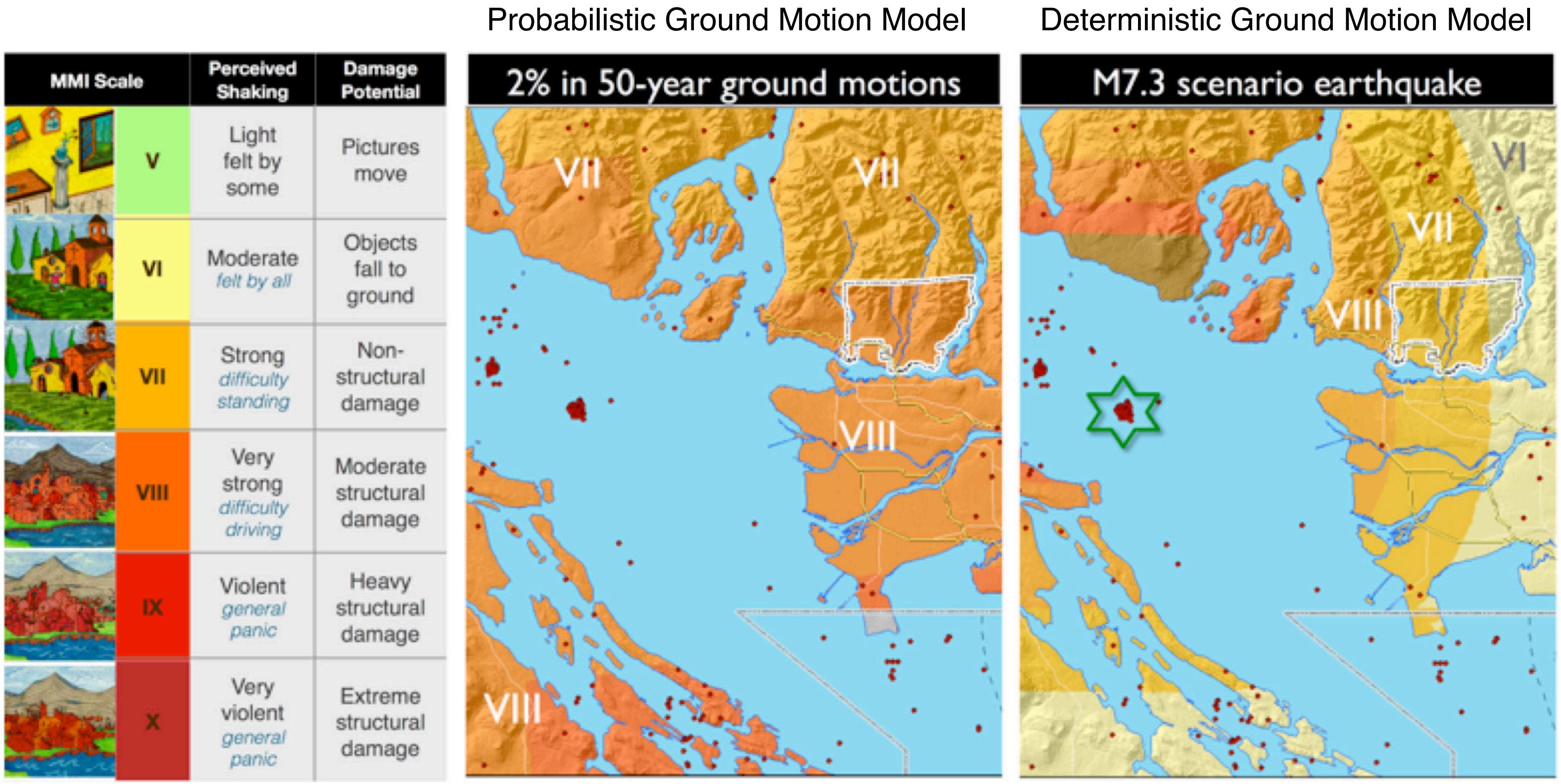


Figure 22: Schematic representation of earthquake hazards

intensity of future events, but from very different perspectives (Figure 23).

Probabilistic seismic hazard assessment (PSHA) is designed to quantify the overall likelihood of exceeding minimum thresholds of ground motion at a specific location for a portfolio of known earthquake hazards over a given time horizon. Results are used to establish safety thresholds and guidelines for seismic design of new structures, and to develop risk reduction policies for existing elements of the built environment that take into account the cumulative earthquake risk from all known seismic source zones. In accordance with NBCC guidelines, we have developed detailed



MMI Scale	Perceived Shaking	Damage Potential
V	Light felt by some	Pictures move
VI	Moderate *felt by all*	Objects fall to ground
VII	Strong *difficulty standing*	Non-structural damage
VIII	Very strong *difficulty driving*	Moderate structural damage
IX	Violent *general panic*	Heavy structural damage
X	Very violent *general panic*	Extreme structural damage

Figure 23: Probabilistic and deterministic ground motion models used to assess earthquake hazard potential for the District of North Vancouver.

probabilistic ground motion models for the District of North Vancouver that represent seismic hazards for a return period of 1/2475 years and a probability of 2% in 50 years [Prieto et al., 2012].

Scenario-based methods of hazard assessment (DSHA) are designed to quantify the intensity of ground motions for a hypothetical earthquake and the likely impacts and consequences of this event on a collection of community assets. Outputs are used to analyze linear cause-effect relationships and to evaluate the effectiveness of risk reduction strategies. We have modelled expected ground motions for a M7.3 earthquake along a zone of known seismicity in the Strait of Georgia [Prieto et al., 2012]. The scenario earthquake is representative of destructive earthquakes that are known to have occurred in the Cascadia region over the past ~500 years [Hyndman et al., 2003], and is consistent with financial risk management guidelines that recommend loss scenarios with a likelihood of ~10% in 50 years [OSFI, 2013b].

Exposure and Vulnerability

Vulnerability describes the extent to which people and critical assets are exposed to earthquake hazards and their capacity to withstand the impacts of a disaster event. (Figure 24). Physical vulnerability is a measure of hazard exposure and the extent to which buildings and critical infrastructure systems are likely to sustain damage as a result of an earthquake event. Key factors include location, age and type of construction; and the overall resistance of these structures to dynamic forces that are generated during an earthquake.

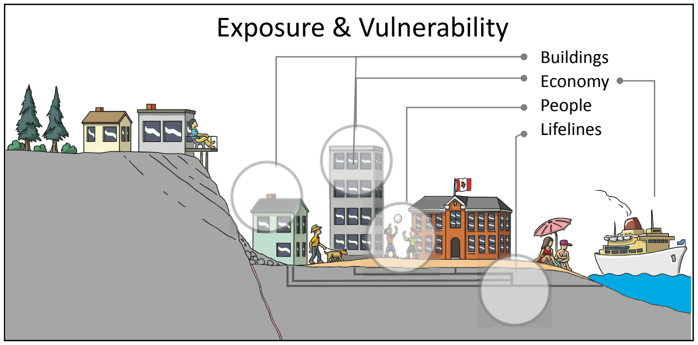


Figure 24: Schematic representation of exposure and vulnerability

Social vulnerability describes the intrinsic characteristics of a community that create unsafe conditions and that have the potential to amplify the negative impacts and consequences of a disaster event. These include hazard exposure and a range of socioeconomic variables, such as age, health and income, that influence the capabilities of an individual to withstand and recover from the impacts of a disaster event.

Our assessment of exposure and physical vulnerability for the District of North Vancouver is based on a site-level inventory of ~23,700 buildings, and a distributed network of engineered structures that provide critical lifeline services under municipal jurisdiction (utility and transportation systems). The inventory includes a description of individual buildings and structures in terms of age, occupancy class, and construction types that are common in a North American context (Figure 25).

Figure 25: General characteristics of the built environment in the District of North Vancouver.

Age and type of construction are used in conjunction with empirical models of structural fragility to assess the physical vulnerability of buildings based on compliance with regulated safety thresholds in the National Building Code [FEMA, 2011]. Building types include light wood frame and un-reinforced masonry construction used for single storey and low-rise structures, and steel braced frame and concrete construction used for multi-storey and high-rise structures. In general, older masonry and concrete buildings constructed prior to the enforcement of seismic design guidelines tend to be more susceptible to physical damage.

Occupancy class is used to characterize building function and the implications of physical damages in terms of injury, social disruption and economic loss. Occupancy classes include single and multi-family dwellings used for habitation, commercial and industrial buildings used for retail trade and fabrication, and general purpose facilities such as churches, community halls, and government buildings that are used for public gatherings.

Patterns of social vulnerability for the District are based on a neighbourhood-level analysis of demographic variables that describe general characteristics of hazard exposure, agency and coping capacity [Statistics Canada, 2006]. Exposure is a function of proximity to hazard threats of concern, the location of people at different times of day, physical susceptibility and the general level of protection offered by buildings or engineered structures. 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 personal or family income, access to financial reserves, education and literacy [Tierney, 2006]. Coping capacity is a function 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. Relevant factors include age, physical ability, access to emergency social services, and the degree of connectedness in a community [Davis et al., 2004; Kuban et al., 2001].

Earthquake Risk

Earthquake risk is a measure of the likely impacts and consequences of a seismic hazard. It is assessed in terms of physical damage, injuries, social disruption and economic losses sustained as a result of the disaster event (Figure 26). Physical damages will vary as a function of hazard intensity and the inherent capacity of a building or engineered structure to withstand the effects of ground shaking and related seismic hazards.

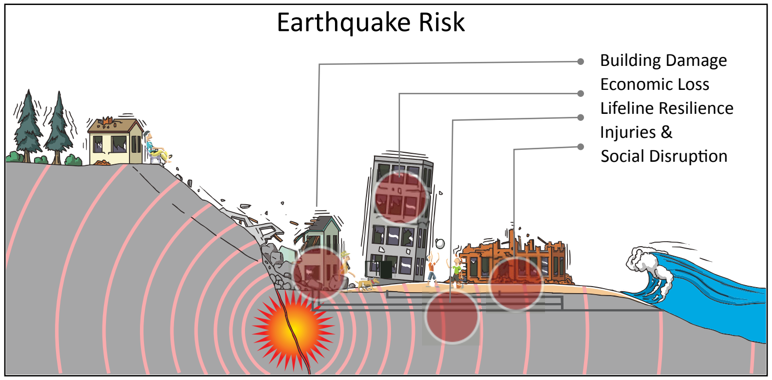


Figure 26: Schematic representation of earthquake risk in terms of damages, injuries and losses

Injuries and the extent of social disruption are dependent on the level of physical damage to buildings and engineered structures, where people are when the earthquake strikes, and their capacity to withstand the impacts caused by building failure and/or falling debris. Economic losses include the costs to repair and/or replace capital assets that are damaged during the earthquake, and income-related losses sustained as a result of business disruption and/or relocation.

Our assessment of risk for the District of North Vancouver is focused on impacts and consequences of a M7.3 scenario earthquake triggered by displacement along an active fault system in the Strait of Georgia. Risk metrics are used to develop a framework of target criteria that monitor:

- Building Performance: the likelihood of damage (resistance) and the estimated time to restore functionality to homes and businesses after a major earthquake (recovery).
- Public Safety: the likelihood of injury or death from earthquake damages, and the extent of social disruption caused by loss of habitation and business interruption.
- Lifeline Resilience: the capacity of utility and transportation systems to withstand and recover from the impacts of a major earthquake.
- Economic Security: expected capital and income-related losses resulting from a major earthquake and the benefits of investing in mitigation and/or adaptation measures.

Risk metrics are analyzed for existing baseline conditions, and for ‘what-if’ scenarios that model the benefits and costs of mitigation. When incorporated into the broader context of planning and emergency management, risk metrics and associated target criteria offer decision makers a structured, transparent, and evidence-based framework for evaluating policy alternatives and identifying development opportunities that advance overall community objectives while minimizing any potential negative impacts on people and critical assets.

Disaster Resilience

Disaster resilience encompasses the broader spatial and temporal dimensions of risk and is focused on bridging the gap between knowledge and action. It is a forward-looking process of analysis and planning that emphasizes a more holistic evaluation of mitigation and/or adaptation measures that have a potential to reduce future losses and increase the capacities of a community to withstand, respond to, and recover from unexpected disaster events over time. (Figure 27).

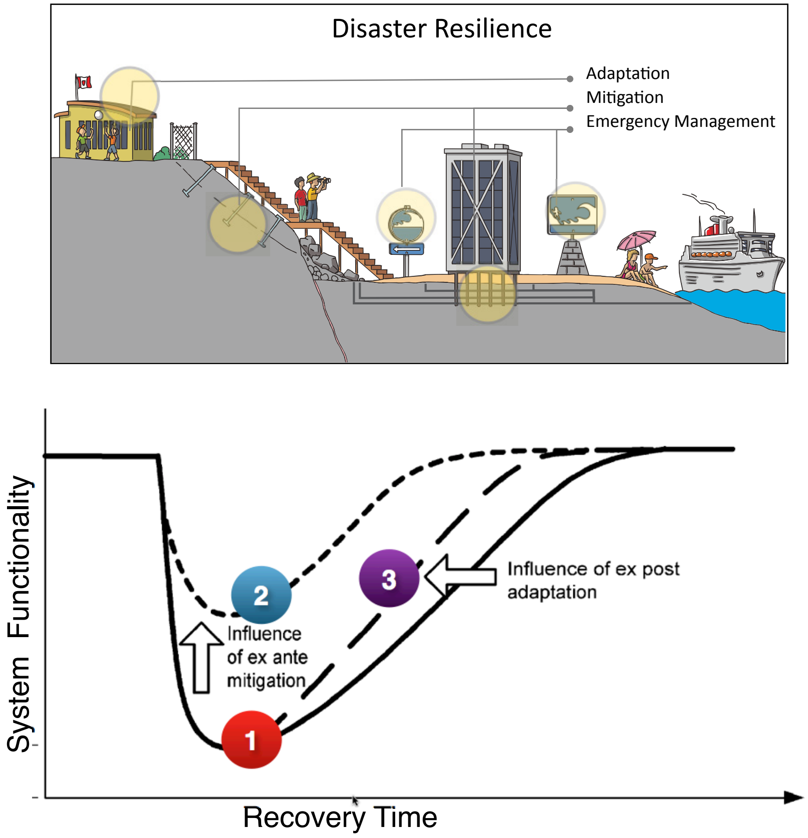


Figure 27: Schematic representation of disaster resilience in terms of mitigation, emergency management and adaptation.

Mitigation encompasses those actions that can be taken before a disaster event to reduce intrinsic vulnerabilities and increase overall resistance to disaster events through investments in structural and/or non-structural measures. Structural mitigation involves seismic retrofits to core elements of an existing building to increase physical resistance to seismic loads and lateral displacements caused by severe shaking and/or ground deformation. Non-structural mitigation is focused on measures that minimize the exposure of people and physical assets through land use policies and related development restrictions (permits, bylaws, etc.). The effectiveness of mitigation is measured by increased levels of system functionality immediately after an earthquake (compare recovery curves 1and 2 in Figure 27).

Adaptation encompasses a wide range of actions that are planned in advance but implemented after a disaster event to increase the capacities of a community to respond and recover from the impacts and consequences of a major earthquake. Actions include emergency planning and preparedness measures that are designed to increase awareness, self-reliance, and response capabilities of individuals and groups; continuity planning for homes and businesses to minimize levels of disruption during the recovery process; and land use policies that expedite the re-building process and direct ongoing development of communities in ways that minimize exposure to known earthquake hazards. The effectiveness of adaptation measures can be measured by reductions in the amount of time to restore baseline levels of system functionality and/or increases in overall service capacity (compare recovery curves 1 and 3 in Figure 27).

Our evaluation of disaster resilience for the District is focused on the effectiveness of investing in mitigation measures for vulnerable buildings in areas of highest seismic risk in the community. We model expected losses for the scenario earthquake with and without seismic retrofits in place and evaluate the effectiveness of mitigation investments in terms of benefits gained and costs incurred. Benefits are assessed using a multi-criteria analysis of building performance, reductions in the number of people injured, and economic losses avoided as a result of investing in seismic retrofits. Mitigation costs are estimated using empirical data from seismic retrofit programs that have been successfully implemented in North America [City and County of San Francisco, 2010].

Risk-Based Planning

Risk-based planning is about managing opportunities for growth and development in ways that minimize potential future losses and that promote community resilience. It requires a common understanding of the risk environment, and the development of strategies that are framed by policy goals, informed by scientific knowledge, and tempered by the need to make practical choices between diverse and often competing social values and preferences.

The conventional approach to risk assessment and emergency planning involves a process of rational assessment that is informed by predictive modelling of cause-effect relationships, and that is governed by choices that seek to optimize system performance in terms of effectiveness and/or efficiency [Davidoff and Reiner, 1962]. It is often referred to as a science-based approach to decision making through which impacts and consequences of a hazard event are analyzed, a set of policy alternatives are evaluated, and a course of action is selected based on mitigation measures that optimize the performance of specific risk reduction targets such as public safety or economic security.

The strength of a rational planning model is that it provides a structured process of reasoning though which scientific knowledge can be used to objectively evaluate policy choices that involve compliance with regulatory requirements and/or the expenditure of public funds. It is ideally suited to risk decisions that involve limited complexity and/or uncertainty. Because the underlying methods are based on facts about the world that can be validated with scientific theory or experiment, there is an expectation that policy choices will be legally defensible and will lead to the best possible decision in terms of effectiveness and efficiency. The vast body of evidence suggests that this is rarely the case [Frodeman, 2003; Sarewitz et al., 2000].

We have adopted an alternate approach that situates the analysis of natural hazard risks in the broader context of comprehensive planning and sustainable community development [Burby et al., 1999; Folke et al., 2002; Mileti, 1999; Renn, 2006b; Stern and Fineberg, 1996]. The framework is based on principles of integrated assessment — a structured process of analysis and deliberation that explicitly acknowledge issues of complexity, scientific uncertainty and political ambiguity [Jaeger, 1998; Renn, 2006b; J Rotmans, 1998; 2006; van Asselt and Rotmans, 1999].

Often referred to as an evidence-based approach to planning and decision making, integrated assessment utilizes a process of scenario modelling and community engagement to support a more comprehensive analysis of the underlying socio-political forces that drive changing conditions of vulnerability over time, and actions that can be taken in advance of a disaster to reduce future losses and build resilience in the community.

Insights gained through analysis and scenario modelling are used to evaluate policy alternatives and to select a suitable course of action based on a multi-criteria framework of indicators that seek to balance trade-offs between growth opportunities and the constraints of development in areas exposed to natural hazards. Integrated assessment and scenario modelling extend the capabilities of rational analysis by allowing a broader selection of decision criteria that more completely reflect available knowledge about the risk environment, and that make evident underlying value-based judgments that are likely to influence the decision making process.

Figure 28 summarizes key elements of the integrated risk assessment framework used in this study [J M Journeay, 2015]. The framework is aligned with national and international standards for risk management [Australia/New Zealand Standards, 2004; CAN/CSA-Z1600, 2008; ISO 31000, 2008], and incorporates best practices for risk governance and disaster resilience planning [IRGC, 2008; Renn, 2006b]. It is implemented using analytic methods and tools available in the public domain, and makes explicit roles and responsibilities of those involved in the risk assessment process.

Stage 1: Establish Context

Establishing study context and focus are vital first step in framing the risk assessment process. The goal is to identify who and what in the community are considered most vulnerable and in need of safeguarding. The process involves a diagnosis of system conditions and driving forces that are likely to influence changing conditions of risk over time, opportunities and constraints for development in areas exposed to hazards of concern, and the definition of policy goals, assessment criteria and decision protocols that will be used to guide the planning process (Figure 28).

Our study of earthquake risks is situated within the broader context of a strategic 30-year plan for sustainable development that was established independently through a community engagement process led by District staff [District of North Vancouver, 2011a]. The resulting Official Community Plan (OCP) reflects collective social values and expresses intent with respect to future growth and development through a framework policy guidelines, action plans and performance indicators. Embedded within the OCP is a formal set of risk tolerance criteria developed by the community to help guide decision making in areas exposed to natural hazards (debris flows, floods and forest fire).

We conducted a complementary suite of design workshops to explore how knowledge about earthquake risks and disaster resilience might be incorporated into the broader OCP policy framework for sustainability through development of a strategic action plan and supporting target criteria. We met with District staff to identify policy goals and establish operational requirements for the risk assessment process, and with members of the DNV Natural Hazards Task Force to review study outputs

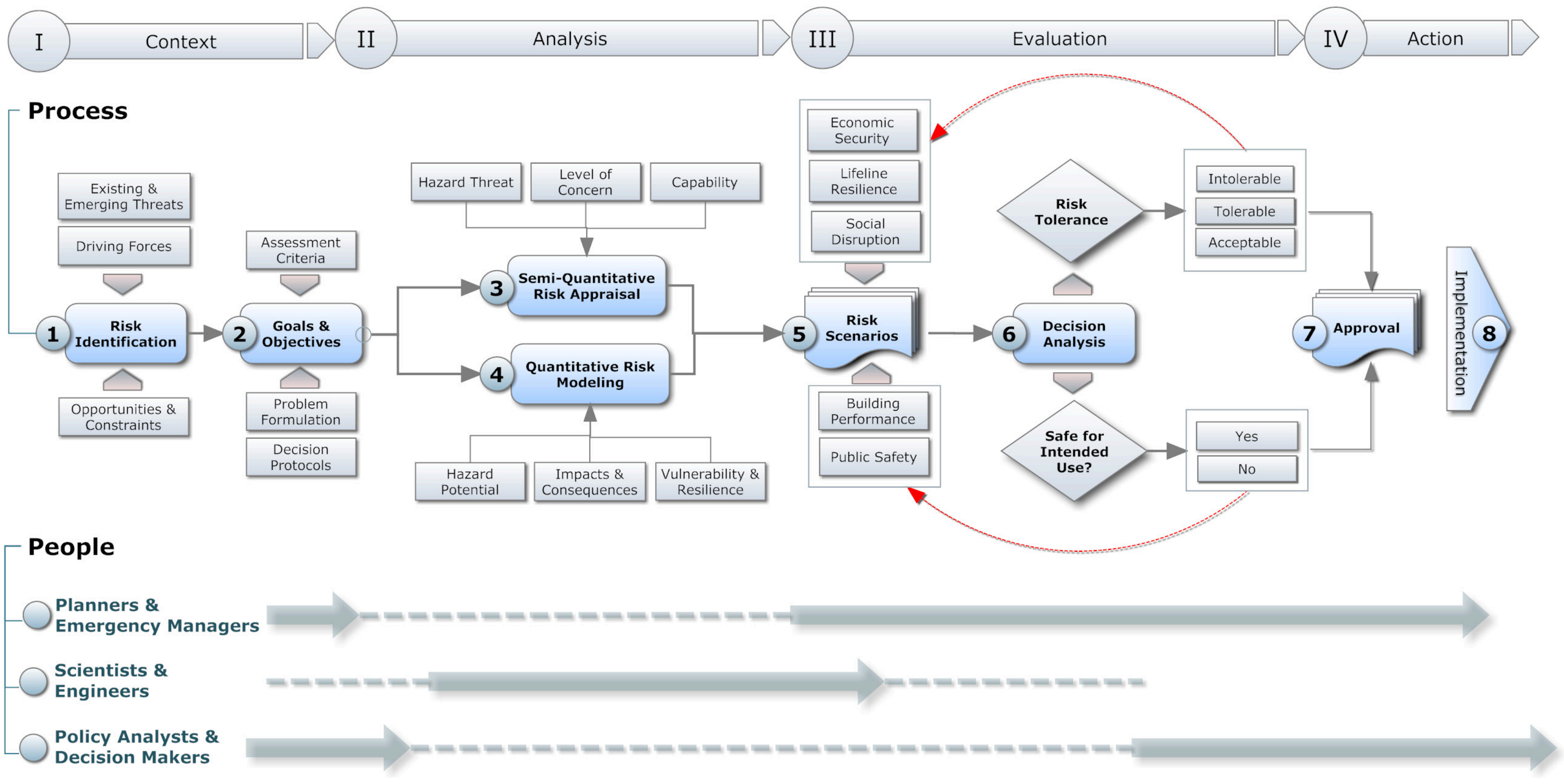


Figure 28: Framework for integrated risk assessment and scenario modelling used in this study (adapted from Journeay, 2015)

and develop a framework of assessment criteria to help guide ongoing planning and policy development in the community.

Stage 2: Risk Analysis

Risk analysis is focussed on generating knowledge about the potential impacts and consequences of a hazard threat based on direct observation and experience from past events (risk appraisal), and/or indirect measurement using quantitative modes of probabilistic and scenario-based analysis (risk modelling). We have used a combination of these methods to compare perceived and measured levels of earthquake risk in the community (Figure 28).

Risk Appraisal

Risk appraisal is a semi-quantitative method of analysis that utilizes input from community members and domain experts to rank the severity of hazard threats in terms of expected impacts and consequences, and the capabilities for response and recovery following a disaster event. We used a combination of Delphi-based survey methods and interactive mapping techniques to develop a set of indicators that subjectively measure hazards of concern for the District, and that help make evident who and what are considered most vulnerable in the community.

Community resilience was assessed in terms of technical, organizational, social, and economic capabilities. Technical capabilities measure the extent to which buildings and engineered structures provide adequate levels of protection in the event of a disaster. Organizational capabilities measure the effectiveness of existing emergency management operations and land use planning guidelines are effective in minimizing hazard exposure and the vulnerabilities of people and critical assets in the community. Social capabilities measure the effectiveness of communication and outreach activities in promoting awareness and understanding of natural hazards impacts, and the capabilities of individuals and groups in the community to work together to support emergency response and relief operations. Economic capabilities measure the effectiveness of individuals and organizations in accessing financial resources required for mitigation, their ability to transfer outstanding risks through insurance markets, and their ability to access emergency relief funds in the event of a disaster

Hotspots of greatest concern to the community are vulnerable populations exposed to a combination debris flow and wildfire hazards in remote coastal areas and valley escarpments; and critical lifeline systems (water, power & communications) exposed to the impacts of a near-source destructive earthquake (M7 or greater). The majority of those surveyed did not consider earthquake risks a primary concern for homes or businesses in the District — most believe that adoption of modern building codes have been effective in ensuring a high level of seismic safety in the community.

Risk Modelling

Risk modelling is a quantitative method of analysis that utilizes probabilistic and scenario-based methods to objectively measure hazard potential, likelihood of damage, injuries, social disruption, economic loss and system resilience. We have used an integrated suite of methods and catastrophic loss models that are available in the public domain to analyze and evaluate earthquake risks for the District of North Vancouver (Figure 29).

The analytic framework is built around Hazus — a standardized loss estimation method developed by the National Institute of Building Sciences and US Federal Emergency Management Agency to analyze the impacts and consequences of natural hazards (earthquake, floods & hurricanes) in support of emergency management and land use planning at a community level [NIBS, FEMA, 2004; 2011; 2002]. Earthquake and flood modules of the Hazus methodology have been adapted for use in Canada by the NRCan Public Safety Geoscience Program [Ulmi et al., 2014]. The Hazus earthquake module is based on state-of-the-art scientific and engineering knowledge that is used to model cause-effect relationships using industry standard methods of catastrophic loss modelling.

At the core of the Hazus methodology is a suite of analytic models that predict the likely impacts and consequences of an earthquake event based on empirical fragility curves that relate the probability of damage to the intensity of ground motion at any given location. Model inputs include site-level information describing the physical characteristics of buildings and critical infrastructure (construction type, age, etc.); and census data describing population distributions and socioeconomic characteristics of the community (income, employment, etc.). Model outputs are combined into a framework of indicators and scenarios that measure earthquake risk in terms of hazard potential, building performance, public safety, lifeline resilience and socioeconomic security (Figure 29).

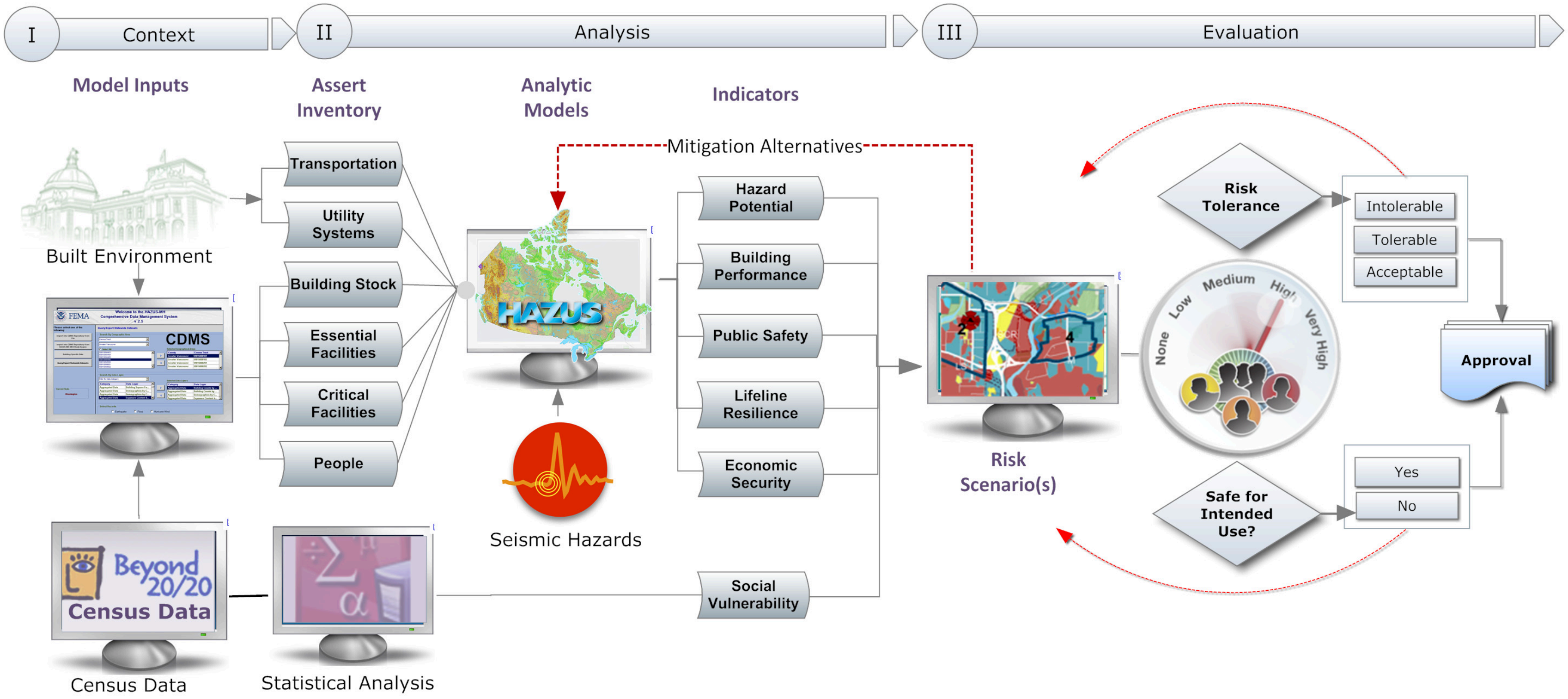


Figure 29: Methods and tools used to support integrated assessment and scenario modelling for the District of North Vancouver.

Stage 3: Risk Evaluation

Risk evaluation is the process of reconciling knowledge claims about the risk environment with value-based judgments about who and what are considered vulnerable and in need of safeguarding. Judgments about cause-effect relationships and scientific uncertainty involve a synthesis of analytic outputs in order to explore gaps in available knowledge and the sensitivities of model assumptions. Judgments about community values and preferences involve an evaluation of policy alternatives with respect to target indicators and negotiated thresholds of risk tolerance (Figure 29).

An important aspect of this process is the ongoing exchange of knowledge about the risk environment between domain experts, planners, community representatives and decision makers. Planners need timely access to analytic outputs in order to validate risk scenarios, formulate mitigation alternatives, and provide direction on policy choices that are actionable within the limits of available resources. Community members need an opportunity to assess hotspots of concern and evaluate target criteria with respect to negotiated thresholds of risk tolerance. Decision makers need a synopsis of key findings in a condensed form to help them evaluate mitigation alternatives and select a course of action that is evidence-based and aligned with broader policy goals for the community.

We have used scenario models and methods of integrated assessment to help develop a shared understanding of earthquake risk for the District of North Vancouver. Scenario models facilitate the integration of analytic, cognitive and visual capabilities to help people explore the risk environment and better understand the implications of model assumptions and scientific uncertainties [Bishop et al., 2009; Engels, 2005; Gahegan and Brodaric, 2002; Sheppard, 2006]. They help people think critically about the strengths and weaknesses of mitigation alternatives through a framework of performance indicators that track progress toward and away from policy targets.

Target indicators used for integrated assessment provide a means of structuring the decision-making process and a capability to incorporate both objective and value-based measures of risk in evaluating policy choices and likely consequences [Belton and Stewart, 2002; Montibeller et al., 2006; Swart et al., 2004; Wright and Goodwin, 1999]. The combination of scenario models and target indicators are vital in bridging the gap between knowledge about the risk environment (science), and actions that can be taken in advance of a disaster to reduce vulnerabilities and increase community resilience (policy).

Stage 4: Action Plan

The action plan is a living document that expresses intent with respect to policy goals for risk reduction and disaster resilience. It involves a critique of evidence gathered throughout the risk assessment process, and the approval of strategies that have been formulated to reduce future losses and increase community resilience through strategic investments in mitigation, emergency management and adaptation.

The approval process is based on an assessment of institutional capabilities that will be needed to implement action plan recommendations (technical, operational and economic feasibility), and the development of a policy framework and implementation guidelines that chart a recommended course of action with supporting rationale. The final stages of approval involve adjudication and the formal granting of authority to establish administrative protocols that will be needed to support the implementation and monitoring of risk treatment measures.

Judgment and final approval of action plan recommendations are based on a combination of legislative mandates for emergency management and land use planning at local and regional scales of government, and on thresholds of risk tolerance that are negotiated at the community level. Legislative mandates are focused on the question of whether public and private lands are 'safe for the use intended.' Corresponding land use and emergency management decisions are adjudicated on the basis of target indicators that measure the likelihood of damage to critical assets and the potential for injury or loss of life. Thresholds of tolerable risk are adjudicated on the basis of target indicators that measure expected impacts and consequences of a disaster event in terms of economic losses, lifeline resilience and social disruption (Figure 28).

RESEARCH CONTRIBUTIONS

The United Nations and Canadian platforms for Disaster Risk Reduction (DRR) provide an overarching framework of policies and institutional resources to help guide risk reduction and disaster resilience planning at the national and regional level [Hyogo Framework; United Nations, 2005]. While these efforts have been successful in raising the awareness and commitment to community-based disaster risk reduction more generally, there is an urgent need to develop methods and tools to support practitioners and local governments in understanding the risk environment and in developing strategies that have a potential to reduce intrinsic vulnerabilities and increase the safety and future wellbeing of communities across Canada.

This study provides a detailed assessment of earthquake risk for the District of North Vancouver. We have examined the likely impacts and consequences of a major earthquake scenario in the Georgia Strait (M7.3), and have undertaken a more general assessment of who and what are vulnerable to known earthquake hazards in the region using probabilistic ground motion models similar to those incorporated into the National Building Code of Canada [NBCC, 2010].

Primary contributions of this study include:

Development and refinement of integrated earthquake risk assessment methods to support mitigation and disaster resilience planning at a municipal scale in Canada. These include analytic methods of scenario modelling and multi-criteria decision analysis, and design-based methods of participatory planning and deliberative dialog.

- Testing and validation of a Canadian version of the Hazus loss estimation methodology to support site-level analysis of earthquake impacts and consequences, and the evaluation of mitigation alternatives.
- Development and testing of an integrated assessment framework for earthquake risk that incorporates objective measures of expected impacts and consequences with subjective measures that reflect what the community considers of value and in need of safeguarding. The framework extends the scope of seismic safety guidelines in the National Building Code by focussing on performance measures that help bridge the gap between the science of earthquake risk and disaster resilience planning at a community level.
- A detailed assessment of earthquake risk for the District of North Vancouver that provides a foundation for ongoing disaster resilience planning and sustainable community development. Risk scenarios and target indicators help make evident who and what are vulnerable to known seismic hazards; what can be expected in terms of damages, injuries and socioeconomic losses in the event of a major earthquake; and losses that could be avoided to homes and businesses through investments in mitigation and adaptation.
- Increased knowledge and capabilities for using quantitative risk assessment and structured decision making methods in support of emergency management and disaster resilience planning at the community level.

Study outputs have been used to formulate an earthquake action ready plan for the District of North Vancouver. The plan was developed by District staff with input from the community Natural Hazard Task Force. It is aligned with risk reduction guidelines of the UN Disaster Resilience Cities Program (UNISDR, 2012), and is intended to help increase capacities of the District to reduce future losses and become more resilient to earthquake hazards through strategic investments in mitigation, emergency management and adaptation planning. The action plan is currently under review and scheduled for submission to municipal council in 2015.

Insights and methodologies developed as part of this study are transferrable to other communities who may face similar challenges of managing growth and development in areas exposed to earthquake hazards. They also contribute to broader efforts of the Canadian Safety and Security Program to promote a culture of risk awareness in Canada, and to build capacities for an all-hazard approach to disaster resilience planning at a national scale.

INTENDED AUDIENCE AND REPORT STRUCTURE

This report will be of particular interest to staff who are actively involved in managing risks associated with growth and development in the District of North Vancouver; domain experts and practitioners from other areas who are involved in risk-based planning at the community level, and those working to develop a national framework for disaster risk reduction in Canada. Domain experts include scientists and engineers involved in fundamental and applied research on natural hazard risk assessment, and risk analysts who are responsible for developing methods and/or tools to support disaster resilience planning. Practitioners include land use planners 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).

Part I: Living in Earthquake Country

We begin by looking at the District of North Vancouver in the context of regional earthquake hazards in southwestern British Columbia.

Chapter 2 (Exposure & Vulnerability): is a profile of the community in terms of physical setting, history of development and current risk management practices. We explore how patterns of land use have evolved over the past 100 years and the implications of growth and development in terms of exposure and vulnerability to earthquake hazards. We review current best practices for disaster resilience planning and how they might be extended to include a consideration of earthquake risk in the context of both emergency management and land use decision making.

Chapter 3 (Hazard Potential): is an overview of regional earthquake hazards in the Cascadia region of southwestern British Columbia - one of the most seismically active zones in Canada. The chapter begins with an introduction to earthquake hazards and seismic source zones of concern. These include: 1) large megathrust earthquakes along the plate boundary west of Vancouver Island, 2) deep crustal earthquakes that occur within the pacific plate as it slides beneath North America, and 3) shallow crustal earthquakes that accommodate active deformation within the upper plate of the Cascadia subduction zone. Each of these source zones contributes to earthquake risk in the District of North Vancouver with the potential for catastrophic damage and loss.

Part II: What Can We Expect from a Major Earthquake?

This section examines the impacts and consequences of a hypothetical M7.3 shallow crustal earthquake situated in the Strait of Georgia. The scenario earthquake represents a scientifically plausible event with a potential to generate losses that are consistent with national guidelines for risk reduction and disaster resilience planning.

Chapter 4 (Earthquake Scenario): is a detailed analysis of seismic hazard potential for a M7.3 earthquake triggered by displacement along a zone of deformation and active shallow crustal seismicity in the Strait of Georgia. The analysis includes 1:20,000 scale ground motion models that predict the pattern and intensity of shaking (PGV, PGA, Sa0.3s and Sa1.0s), and areas that are likely to be exposed to extreme liquefaction and earthquake-triggered landslides.

Chapter 5 (Buildings): explores the extent to which buildings in the District are likely to withstand the physical impacts of the Georgia Strait scenario earthquake. Our analysis includes an assessment of overall physical vulnerability, the likelihood of damage to homes and businesses, and expected levels of functionality in the weeks and months following a major earthquake. Damage patterns highlight the vulnerability of buildings constructed prior to the introduction of seismic safety codes in the 1970's.

Chapter 6 (People): examines social characteristics of the community with the aim of identifying who is most vulnerable to earthquake hazards and why. It is based on a geostatistical analysis of population and demographic variables that are known to influence capabilities to withstand and respond to major disaster events. Societal impacts of the scenario earthquake are assessed using target indicators that measure the extent and severity of injuries, expected recovery times, and the level of social assistance that may be required immediately after the earthquake.

Chapter 7 (Lifelines): is an assessment earthquake damage and loss of functionality for utility and transportation systems that provide essential lifeline services to the District of North Vancouver. These include pipelines and distribution systems that supply potable water and manage wastewater effluents for homes and businesses; electric substations and related infrastructure that are needed to supply power; and the network of roads, bridges and rail lines that are essential for social connectivity and the flow of goods and services in the community.

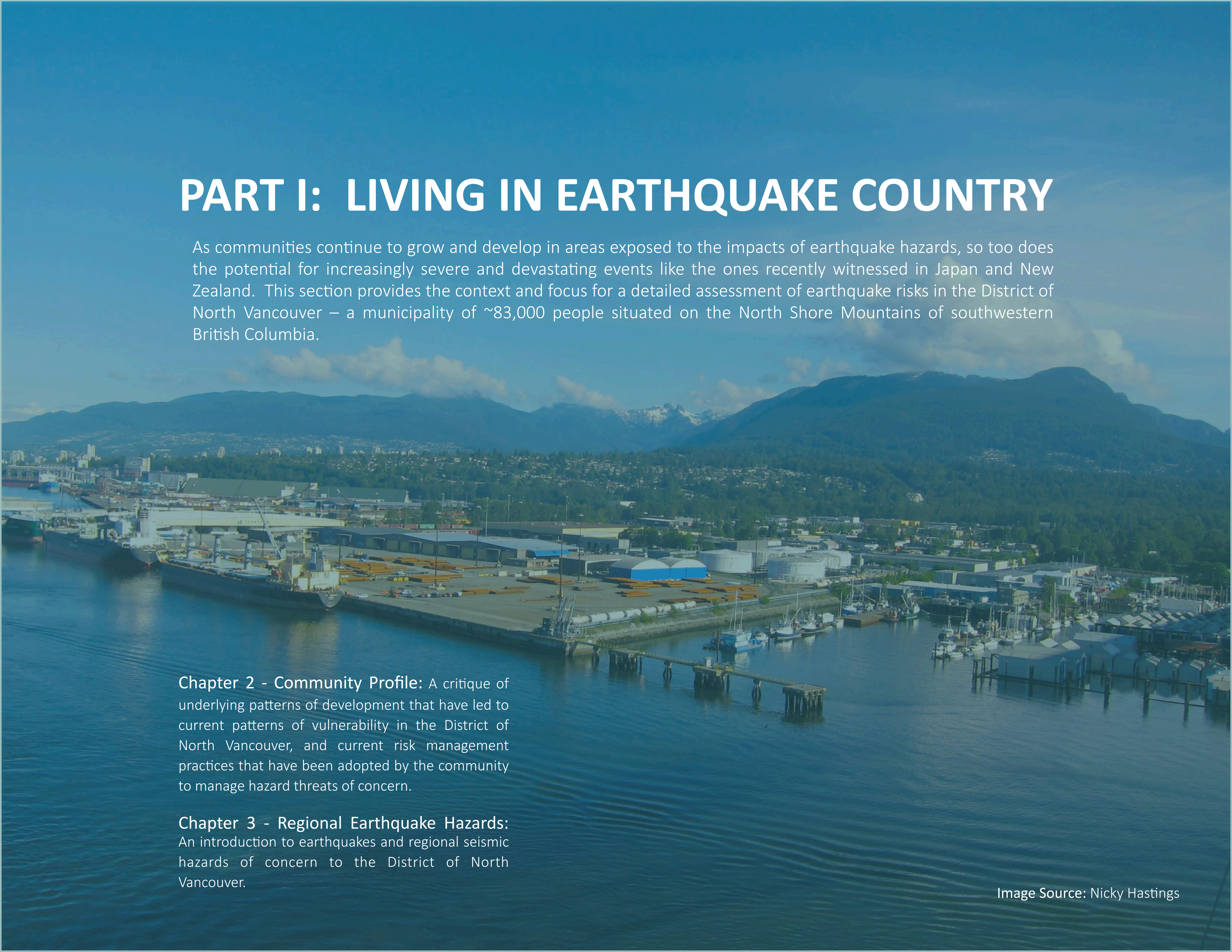
Chapter 8 (Economy): is a profile of community wealth and expected economic losses resulting from the scenario earthquake. It includes an analysis of direct capital losses caused by damages to buildings and critical infrastructure (stocks), and income-related losses sustained as a result of business disruption (flows). Results are used to establish a profile of financial risk over planning horizons that are likely to be of interest for comprehensive land use and infrastructure planning in the community.

Part III: Disaster Resilience Planning

The final section explores strategies for bridging the gap between knowledge about earthquake risk and actions that might be considered to reduce vulnerabilities and increase disaster resilience for the District of North Vancouver. It shifts the focus from an analysis of expected impacts and consequences (risk) to a more general evaluation of strategies that may be effective in reducing future losses and increasing capabilities of the community to withstand and recover from the impacts of an earthquake disaster (resilience).

Chapter 9 (Science-Policy integration): We introduce an integrated framework of target indicators that track baseline conditions of earthquake risk in the District, and the effectiveness of mitigation measures in terms of increased building performance, public safety, lifeline resilience and economic security. Together, these indicators provide a structured framework for exploring thresholds of risk tolerance, and evaluating mitigation alternatives. The framework supports an integrated approach to emergency management and disaster risk reduction, and a means of incorporating principles of disaster resilience into the broader context of sustainable community development.

Chapter 10 (Action Plan): The final chapter of this report utilizes key findings of the study to formulate an earthquake readiness action plan that includes recommendations for mitigation, emergency management and adaptation. The plan was developed by staff at the District of North Vancouver and the North Shore Emergency Management Office (NSEMO), with input from the community Natural Hazards Task Force.



PART I: LIVING IN EARTHQUAKE COUNTRY

As communities continue to grow and develop in areas exposed to the impacts of earthquake hazards, so too does the potential for increasingly severe and devastating events like the ones recently witnessed in Japan and New Zealand. This section provides the context and focus for a detailed assessment of earthquake risks in the District of North Vancouver – a municipality of ~83,000 people situated on the North Shore Mountains of southwestern British Columbia.

Chapter 2 - Community Profile: A critique of underlying patterns of development that have led to current patterns of vulnerability in the District of North Vancouver, and current risk management practices that have been adopted by the community to manage hazard threats of concern.

Chapter 3 - Regional Earthquake Hazards: An introduction to earthquakes and regional seismic hazards of concern to the District of North Vancouver.

Image Source: Nicky Hastings

CHAPTER 2:
COMMUNITY PROFILE

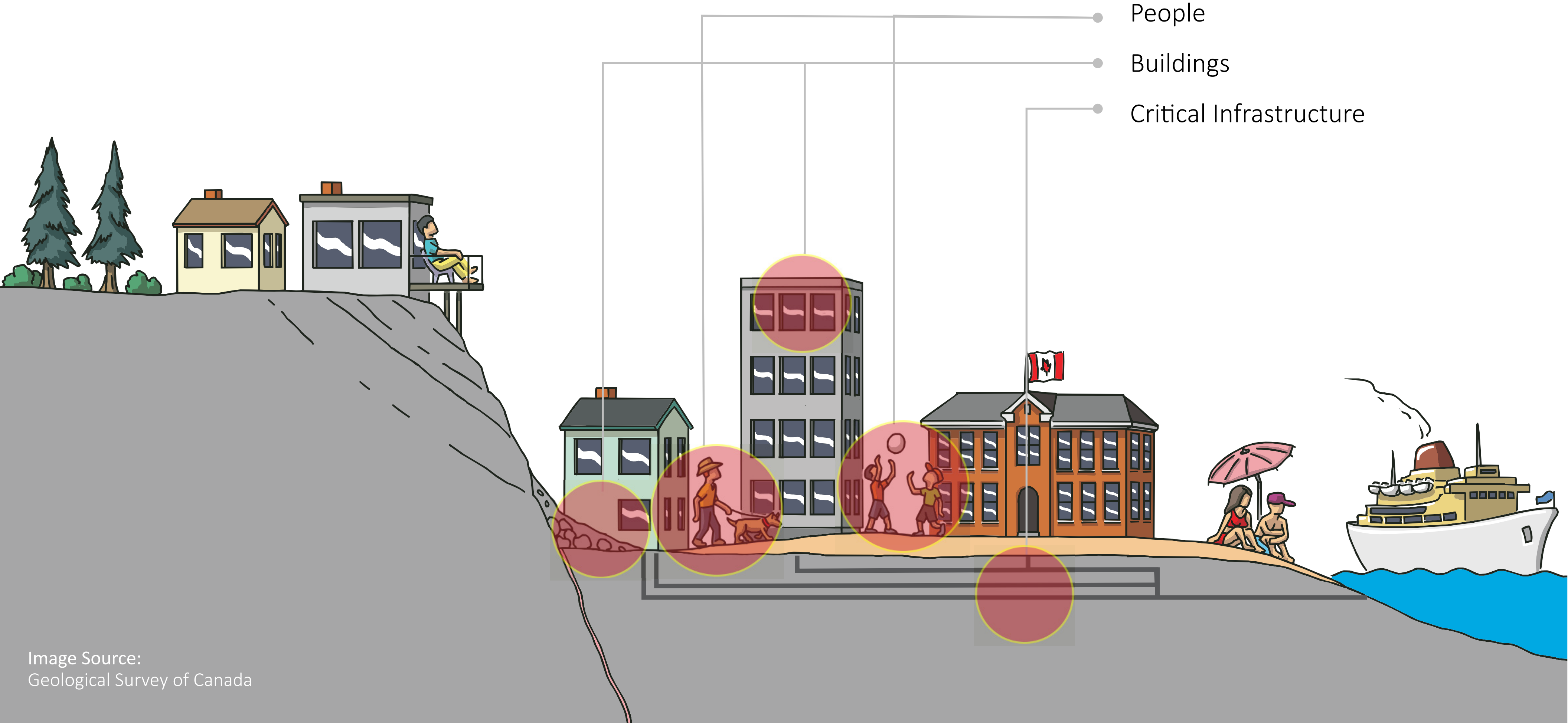


Image Source:
Geological Survey of Canada

CHAPTER 2: COMMUNITY PROFILE

Primary Authors: Journeay, J.M., Dercole, F., and Mason, D.

All too often, emergency management and risk reduction are low on the list of priorities when it comes to negotiating policy goals for a community and allocating public funds to implement plans for comprehensive growth and development. Overcoming this resistance and motivating citizens to take the actions necessary to ensure the safety and longer-term security of their communities can be a daunting challenge.

The District of North Vancouver (DNV) is an example of what can happen when elected officials and municipal staff recognize a need to take the actions necessary to reduce vulnerabilities and increase disaster resilience as part of their comprehensive planning process. It is one of the few communities in Canada where risk management principles and the concept of disaster risk reduction are framed in the broader context of sustainable community development, and where these principles have been made operational at a municipal level through emergency management and land use policies that are endorsed by the community. The DNV is recognized as a leader in risk reduction planning, and in 2011 received the Sasakawa Award for Disaster Risk Reduction by the United Nations Program for Disaster Resilience Cities [UNISDR, 2012].

This chapter explores characteristics of the community that are relevant to our study of earthquake risk and disaster resilience planning. We review key elements of the natural and built environment that are susceptible to earthquake hazards and the history of development that has led to current patterns of vulnerability in the community. We also review patterns of land use and current risk management strategies that have distinguished the District of North Vancouver as a model community for disaster resilience planning.

CONTEXT

The District of North Vancouver is one of three municipalities that make up the ‘North Shore’ region of Metro Vancouver (Figure 30). It is one of 23 local authorities within the broader legislative authority of the Metro Vancouver District, and one of three municipalities that share emergency management services through the North Shore Emergency Management Office (NSEMO). Our study of earthquake risks is limited to areas within municipal jurisdiction of the District and does not include the City of North Vancouver.

The District encompasses several First Nation communities and functions as a sub-region within the broader governance framework of Metro Vancouver. Sub-regions share key infrastructure and in some cases partner in the delivery of services such as the provision of potable water and emergency management. The District works with other communities in Metro Vancouver and with agencies at Provincial and Federal Government levels of government to manage growth and development in ways that contribute directly to the identity and core values of the region. Industrial waterfront areas of the District along Burrard Inlet are part of Canada's largest port facility, and represent a strategic national asset for international trade and commerce.

Natural Setting

The North Shore Mountains form an impressive backdrop to the skyline of Metro Vancouver, rising more than 1,400 metres above sea level and forming the northeast margin of the Georgia Basin – a crustal depression that has accumulated sedimentary deposits shed from mountainous highlands over the past ~85 million years

Figure 30: Regional context and geographic setting of the District of North Vancouver — one of 23 urban municipalities within Metro Vancouver.

of geologic history. Mountain streams have incised through older glacial outwash deposits forming a series of steep river valleys that carry sediments out onto broad deltaic fans along the waterfront.

The Lower Mainland of British Columbia is exposed to a wide range of seismic hazards including severe ground shaking, liquefaction, earthquake-triggered landslides and tsunami — all with a potential for significant damage and loss of life. In addition, the District is exposed to numerous other natural hazards including wild fires and blowdown along the urban-natural interface, severe winter weather and snow avalanches at higher elevations, extreme weather events leading to riverine flooding and coastal storm surge. Anthropogenic hazards of concern include rail derailments, hazardous material spills and toxic gas leaks in populated areas, air crashes and marine accidents, pandemics and other diseases.

The District receives, on average, approximately 2,400 mm of rainfall annually, with most of this falling from November to February. During this period the region is subject to extreme tropical storms, known as ‘pineapple express’ events that commonly produce more than 100 mm of rainfall with intensities exceeding 15 mm per hour. These storms trigger landslides and debris flows that have been responsible for damage and loss of life in the community.

Elements of the natural environment that are likely to be of concern with respect to natural hazards 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 severe weather conditions. Surface and groundwater resources are particularly vulnerable to the impacts of hazardous material spills or floodwaters that have become contaminated with chemical or biological agents and contaminated vulnerable aquifers.

The Built Environment

The current population of ~83,000 people is spread out over a geographic area of more than 160 square kilometres with natural green space accounting for 78% of the total area within the District. There are ~23,000 buildings situated in 45 neighbourhoods and commercial/industrial areas across the District of North Vancouver (See Figure 31). The majority of people (~95%) live in single-family wood frame homes in well-established neighbourhoods with the remaining dwellings situated in multi-family condominium, apartment and townhouse complexes made of wood, steel, concrete and masonry.

There are ~1200 commercial and industrial buildings in the District. Most of these are concentrated in established town centres and in business precincts along the waterfront. There are more than 300 facilities used for public gatherings (government buildings, churches, etc.) and approximately 35 primary and secondary schools in the District. The most vulnerable school facilities are in the process of being seismically upgraded through a province-wide program that is managed through the BC Ministry of Education.

Homes and businesses rely on an extensive network of utility and transportation infrastructure for basic lifeline services such as water, power and communication. Potable water is supplied from two major watersheds in the North Shore Mountains through a ~400 km network of underground pipes, distribution lines, pumping facilities and regional treatment plants. Wastewater is managed through a ~750 km network of pipes and centralized treatment plants that are managed through service partnerships with Metro Vancouver. BC Hydro supplies electrical power through an extensive network of transmission lines and substations that are distributed across the District. Transportation systems include ~1,250 km of highway and secondary roads, 32 bridges and ~50 km of rail lines that are managed through partnerships between the District and the Province of British Columbia.

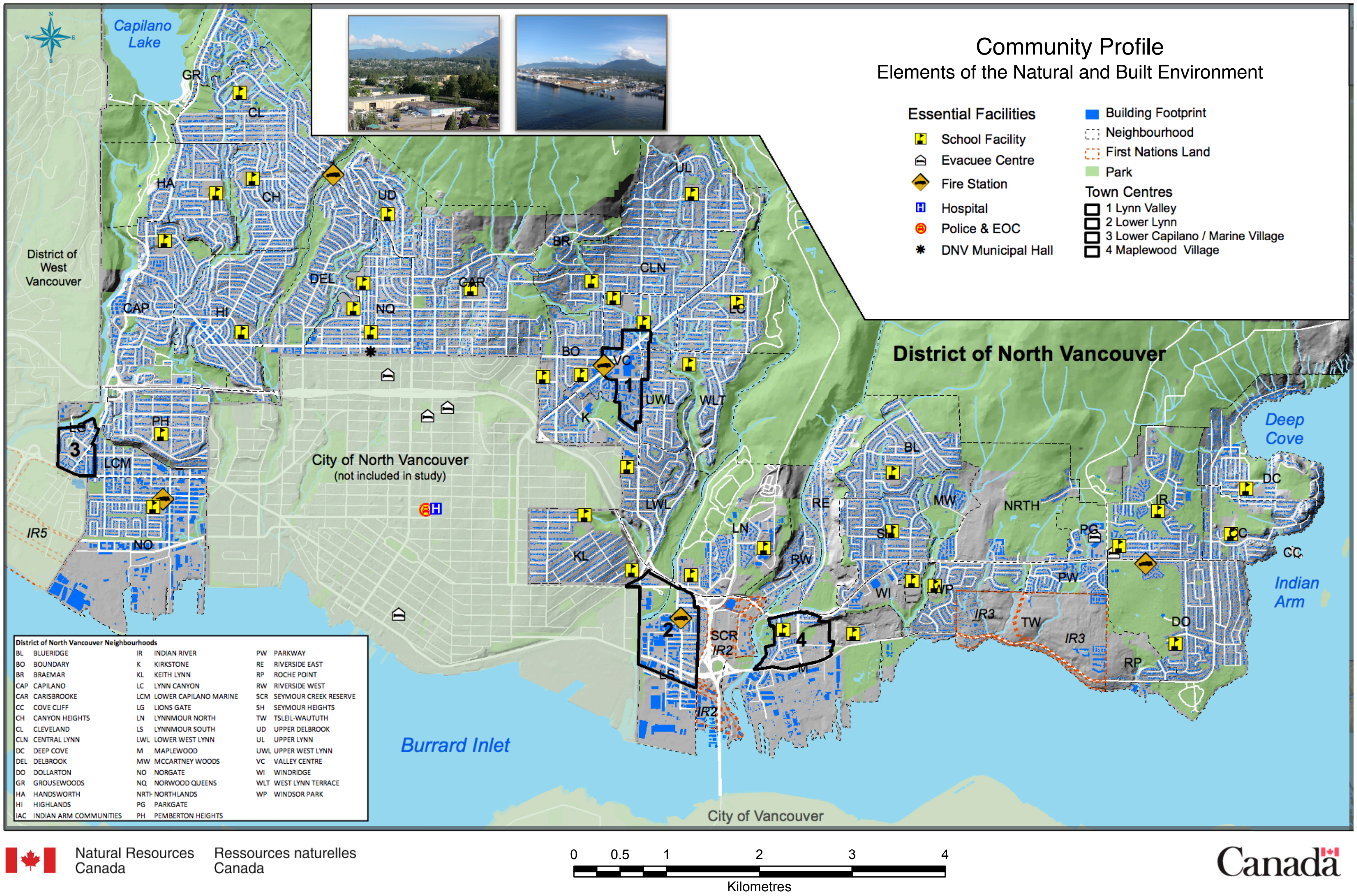
With ongoing community development, these infrastructure systems are becoming increasingly complex, interconnected and in need of upgrades. Failure of any one component would likely have a significant downstream impacts on the entire network of services.

An Evolving Profile of Earthquake Risk

The abundance of natural resources and the proximity to both marine and inland travel routes have been primary drivers of human settlement on the North Shore for several hundred years. Residential development began in the late 1800s and proceeded rapidly through the 1950s to 1970s (Figure 32). Many of the older neighbourhoods and town centres are situated along the waterfront and valley escarpments – areas that have been significantly modified over the years with anthropogenic fill to accommodate increasing demands for growth and development in the community.

Patterns of development and characteristics of the built environment that have evolved over this time frame have inadvertently exposed parts of the community to significant earthquake risk. Of concern are commercial/industrial precincts along the waterfront and older residential neighbourhoods along river escarpments that were established early in the history of development.

The following is an account of growth and development in the District of North Vancouver based on historical information compiled by the North Vancouver Museum and Archives Commission [North Vancouver Museum and Archives Commission, 2010]. The maps in Figure 32 summarize spatial patterns of development for ~30-year time intervals while accompanying graphs document rates of growth over the past ~100 years [District of North Vancouver GIS Department, 2013].



District of North Vancouver Neighbourhoods

BL	BLUERIDGE
BO	BOUNDARY
BR	BRAEMAR
CAP	CAPILANO
CAR	CARISBROOKE
CC	COVE CLIFF
CH	CANYON HEIGHTS
CL	CLEVELAND
CLN	CENTRAL LYNN
DC	DEEP COVE
DEL	DELBROOK
DO	DOLLARTON
GR	GROUSEWOODS
HA	HANDSWORTH
HI	HIGHLANDS
IAC	INDIAN ARM COMMUNITIES
IR	INDIAN RIVER
K	KIRKSTONE
KL	KEITH LYNN
LC	LYNN CANYON
LCM	LOWER CAPILANO MARINE
LG	LIONS GATE
LN	LYNNMOUR NORTH
LS	LYNNMOUR SOUTH
LWL	LOWER WEST LYNN
M	MAPLEWOOD
MW	MCCARTNEY WOODS
NO	NORGATE
NQ	NORWOOD QUEENS
NRTH	NORTHLANDS
PG	PARKGATE
PH	PEMBERTON HEIGHTS
PW	PARKWAY
RE	RIVERSIDE EAST
RP	ROCHE POINT
RW	RIVERSIDE WEST
SCR	SEYMOUR CREEK RESERVE
SH	SEYMOUR HEIGHTS
TW	TSLEIL-WAUTUTH
UD	UPPER DELBROOK
UL	UPPER LYNN
UWL	UPPER WEST LYNN
VC	VALLEY CENTRE
WI	WINDRIDGE
WLT	WEST LYNN TERRACE
WP	WINDSOR PARK

Figure 31: A map overview of the natural and built environment for the District of North Vancouver. The map shows the distribution of buildings, essential facilities, roads, parks, neighbourhoods, First Nation land and outlines for town centres proposed in the Official Community Plan.

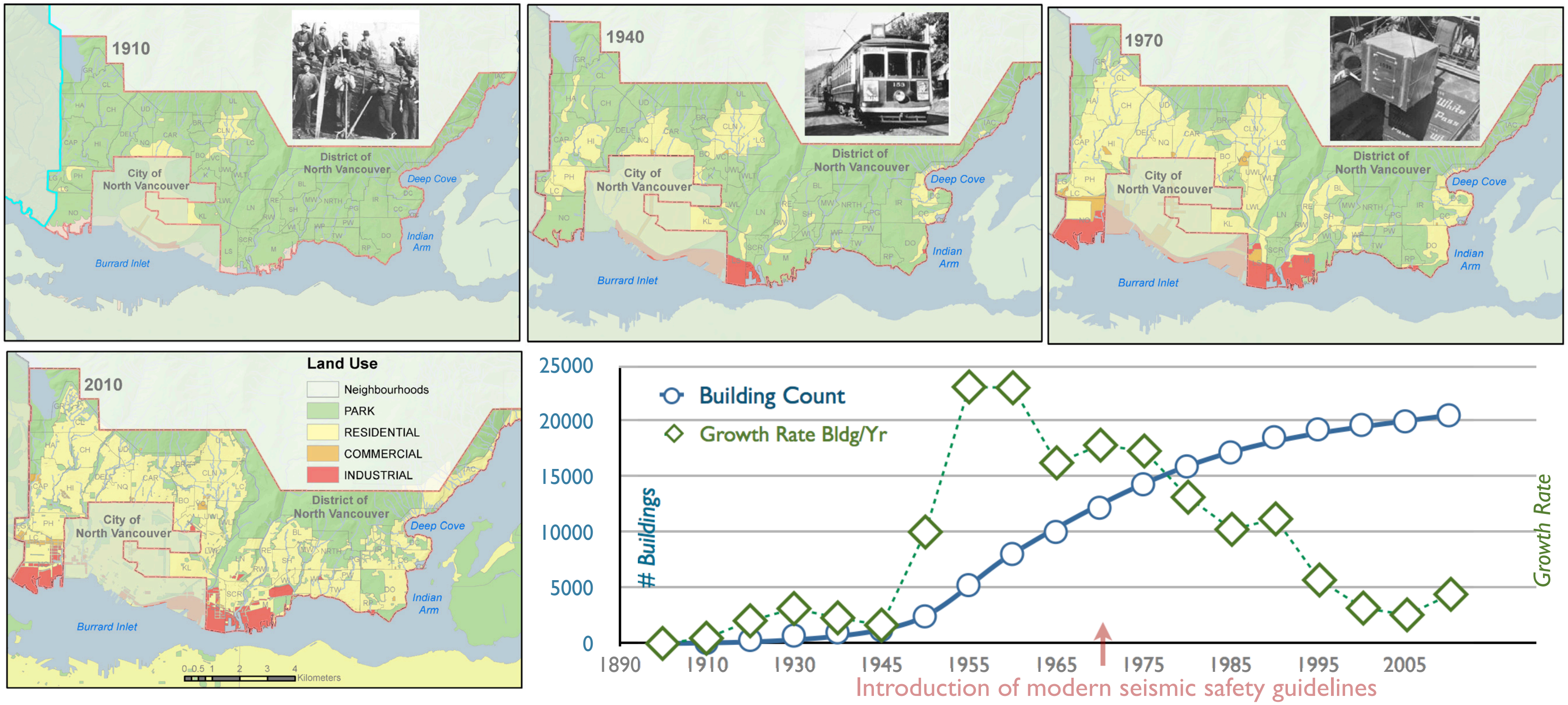


Figure 32: History of settlement for the District of North Vancouver. Patterns of residential, commercial and industrial development that were developed early in the history of the community have directly influenced exposure and vulnerability to earthquake risks.

19th Century (1880-1910): The North Shore of Vancouver has been home to Coast Salish communities of the Tsleil-Waututh, Musqueam and Squamish people for more than 5,000 years. Permanent First Nation settlements have existed along Mosquito Creek, Capilano River, Seymour River and Burrard Inlet since the early 1860s. European settlement along the North Shore began in the mid nineteenth century and was focused around industrial sawmills that flourished along the waterfront in the Lower Lynn and Seymour Valleys. The first and largest of these sawmills was founded in 1865 at the mouth of Lynn Creek. It was accompanied by the development of port facilities in the Lower Lonsdale area, which became one of the primary sources of export revenue in the province at the time. The industrial waterfront became a hub for a thriving community known as Moodyville that boasted a hotel, church, library, post office, telegraph service, school and newspaper. Moodyville was incorporated as the City of North Vancouver in 1907.

Relics of this early settlement are preserved in District neighbourhoods of Keith Lynn, Carisbrooke and Norwood Queens.

Other early settlements in the Capilano Highlands and upper Lynn Valley were developed to support logging operations in the surrounding North Shore Mountains. More than 80 buildings of this vintage have been preserved as heritage structures. Nearly all are of wood frame construction and are used primarily for residential purposes.

Early 20th Century (1910-1940): The period from 1910 to 1940 was marked by a boom and bust cycle of settlement in North Vancouver. Development was driven by the construction of major shipbuilding operations, port facilities and related infrastructure along the waterfront at the mouth of Lynn and Seymour Rivers (Figure 32). Ferry service to downtown Vancouver was established in 1900 and completion of the Second Narrows Bridge in 1925 provided the first road and rail connection to commercial hubs elsewhere in the province.

By the late 1920s, major logging operations on the North Shore were re-locating to more remote locations in the Province and the focus of economic development was shifting to marine transportation, shipbuilding and commerce. However, onset of the Great Depression in 1929 and a marine accident in 1930 that closed the Second Narrows Bridge for nearly four years took their toll on the community. Both the City and the District of North Vancouver went into receivership in 1933 and did not recover for more than ten years.

Nearly 1,000 buildings constructed during this boom and bust cycle are preserved in the District of North Vancouver. The majority of these are single-family wood frame buildings in Pemberton Heights, Norwood Queens, Carisbrooke, Lower Lynn and Deep Cove. A smaller number of buildings along the industrial waterfront are made of unreinforced masonry and/or concrete and are still in service as schools and commercial businesses in the Central Lynn, Keith Lynn and Maplewood areas.

Mid 20th Century (1940-1970): Completion of the First Narrows Bridge in 1938 and the emergence of North Vancouver as a national hub for wartime shipbuilding in the early 1940s marshalled a new era of economic growth and development in the community (Figure 32). The population doubled in less than five years with more than 20,000 people working in shipyards and related industries along the waterfront. Revitalization of waterfront industrial areas at the mouth of the Capilano, Lynn and Seymour Rivers was later spurred by innovations in marine transportation technologies in the 1950s and 1960s (container cargo), and the construction of grain elevators and bulk loading terminals (coal, potash and fertilizer) that established North Vancouver as a major hub for international trade. These new developments were accompanied by diversification in the business sector and the emergence of more specialized engineering services that supported a booming natural resource industry in the province (forestry and mining).

Increased economic opportunities, proximity to recreational activities, and the lure of a suburban lifestyle fuelled an unprecedented period of growth and development in the 1950s and early 1960s. Major developments included the infilling of established neighbourhoods with higher-density residential properties and the establishment of new neighbourhoods in the Canyon Heights, Handsworth, Delbrook, West Lynn, Lower Lynn, Blueridge and Windridge areas.

More than 11,000 new buildings were constructed in the period between 1940 and 1970. Of these, more than 97% are single and multi-family dwellings of wood frame construction. Nearly 250 unreinforced masonry and concrete buildings were constructed in business precincts along the waterfront and in village centres scattered throughout the District during this same time interval. They include single and multi-story structures used for commercial and industrial purposes, several elementary and secondary schools and government facilities. Though valued for their historical significance, these are among the most vulnerable buildings in the District due to their very limited resistance to ground shaking and related ground failure.

Late 20th to Early 21st Century (1970-2010): Patterns of development established in the 1950s and 1960s have continued, but at a much slower rate of growth through the late 20th century (Figure 32). Revitalization of commercial and industrial areas in the period between 1970 and 2010 was accompanied by the construction of over 7,100 new single-family wood frame dwellings in existing neighbourhoods, and the development of more than 800 high-density condominium and townhouse complexes throughout the District. An additional ~400 buildings were added to existing commercial, industrial and mixed use areas along the waterfront and in village centres across the District along with many new schools, a university campus and government facilities. Most of these newer buildings are concrete, steel and reinforced masonry structures that conform to modern design guidelines for seismic safety.

LAND USE

Current land use decisions are governed by policies embedded in the District's Land Use Bylaw [LUB; District of North Vancouver, 2005]. Future growth and development are governed by land use policies recently adopted as part of a 30-year strategic plan for the District [OCP; District of North Vancouver, 2011a]. These legislative policies direct the location and density of future development and will influence changing patterns of vulnerability and disaster resilience in the community.

Current Conditions

The Land Use Bylaw is a set of municipal policies that govern ongoing development in accordance with provincial and federal guidelines. It is an operational blueprint for community development that regulates the density and type of structures permitted in any given area, land use restrictions, lot size, overall, building height, placement, and conformance to safety standards mandated through provincial/territorial legislation and the National Building Code for Canada [NBCC, 2010].

Figure 33 is a map of land use zoning policies that have directed growth and development of the community since 1965. Nearly 60% of the available land base in the District is designated for lower density single-family detached housing in rural residential foothill regions of the Capilano, Lynn and Seymour watersheds, and in coastal regions along Indian Arm. An additional 14% is designated for single-family detached and attached residential development in established neighbourhoods.

Medium density multi-family homes and apartment complexes represent ~5% of the existing land base and are concentrated primarily in established town centres along major transportation corridors. An additional ~4% of the land base is designated for higher-density comprehensive development of multifamily residential apartment complexes and commercial buildings. The remaining 18% is designated for light and heavy industrial uses in historic waterfront precincts of Norgate, Lynnmour-South and Maplewood.

In addition to land use zoning regulations, the District has also established a suite of Development Permit Area (DPA) guidelines to further constrain land use activities in accordance with provincial legislation governing community development in British Columbia [1996]. Development Permit Area maps and accompanying land use guidelines have been established to protect environmentally sensitive areas and riparian habitat, and to minimize potential socioeconomic impacts of wildfire, riverine flooding and landslide hazards.

Apart from a requirement to comply with seismic design guidelines enforced through the National Building Code of Canada [NBCC, 2010], there are no additional provisions in the Land Use Bylaw or accompanying Development Permit Area guidelines to minimize potential impacts and consequences of earthquake hazards in the region.

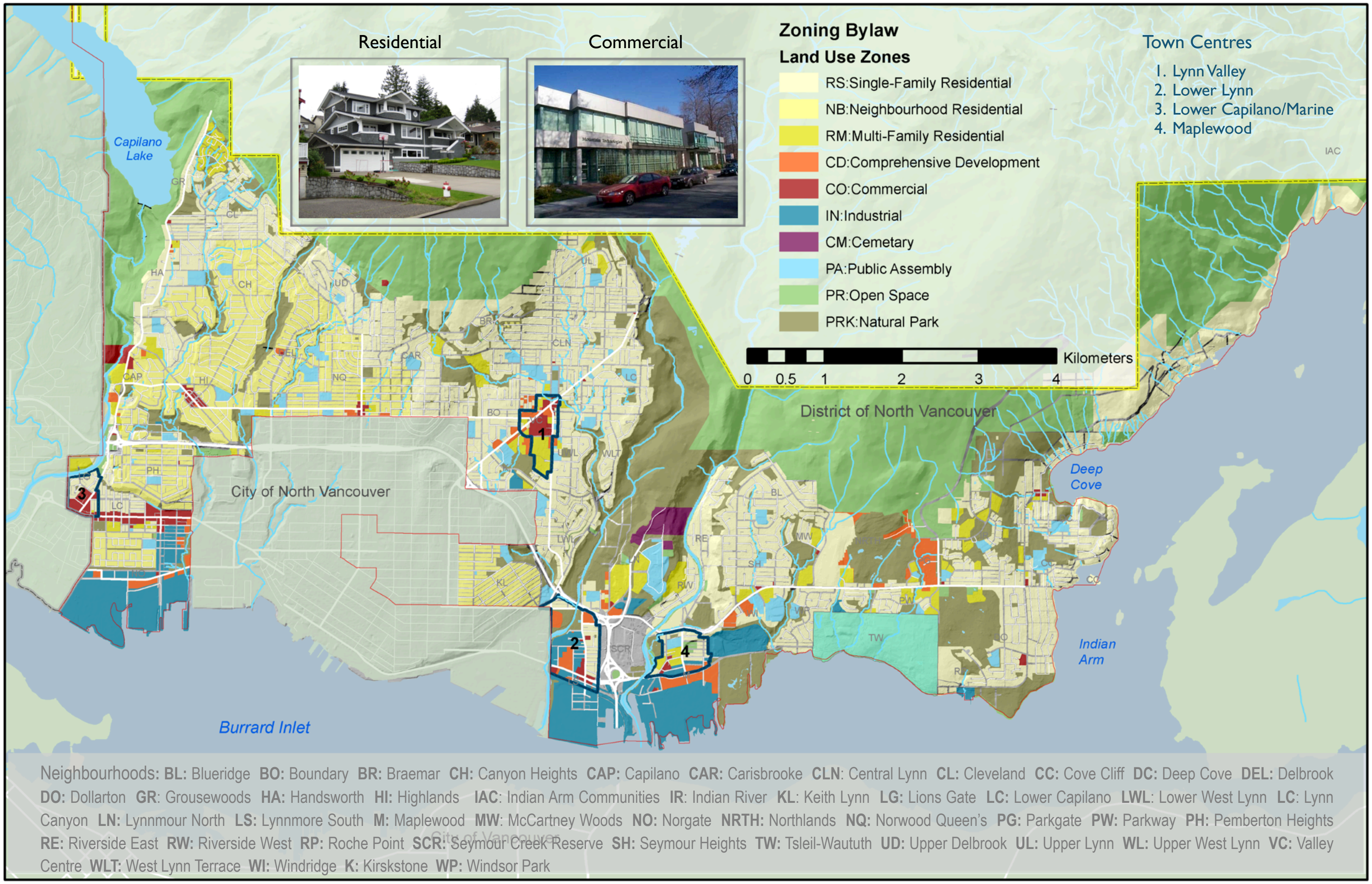


Figure 33: Land use zones for the District of North Vancouver with examples of residential and commercial development.

Sustainable Community Development

The District of North Vancouver is expected to grow at low to moderate rates over the next 30 years with more than 40,000 people moving into the area by the year 2030. In 2011, the District of North Vancouver updated its Official Community Plan (OCP) — an overarching policy framework that guides land use development, strategic planning and corporate management for the community [District of North Vancouver, 2011a].

A core mandate of the new OCP is to manage ~75% of expected new growth through infill and development of higher-density compact communities within established town and village centres (See Figure 31). The OCP provides for an estimated 2,500 new units (5000 people) in Lynn Valley Town Centre; and approximately 3,000 units in Lower Lynn and 2,000 in Lower Capilano-Marine [District of North Vancouver, 2011a]. Current and proposed patterns of development in the OCP have important implications for seismic safety and longer-term disaster resilience of the community.

DISASTER RISK MANAGEMENT

The fatal Berkley landslide in January 2005 triggered a new approach to natural hazards risk management for the District of North Vancouver (Figure 34). A Natural Hazards Management Program was initiated in 2007 with an operational mandate to assess and mitigate risks associated with known hazards of concern, and to promote a culture of disaster resilience within the community. The District utilizes the CAN/CSA Z1-1600 risk management framework to manage natural hazards (2008), and has also adopted a risk-based approach to planning and policy development that is reflected in its Official Community Plan.

Specific goals and objectives of the Natural Hazard Management Program are to:

- Understand hazards and risks using a proactive approach;
- Reduce risk to life, infrastructure and environment by establishing policies and priorities for mitigation that are based on negotiated risk tolerance criteria;
- Educate stakeholders and effectively communicate knowledge of hazards and risks.
- Encourage dialogue about responsibility for the shared management of hazards and risks;
- Maintain a hazard database of geotechnical and hydrogeological information; and
- Liaise with the scientific, academic and government communities to create and follow best practices for disaster risk management.

Figure 34: Operational components of the DNV Natural Hazard Management Program

Risk Tolerance Criteria

There is some degree of risk in most day-to-day activities. People generally have a greater tolerance to risk when the outcomes are considered positive and are self-imposed. Tolerable risk is generally defined as negative impacts and consequences of an unexpected hazard event that a community is prepared to live with — providing that measures are taken to reduce vulnerabilities and future losses within the limits of available resources and in accordance with what the community deems to be of value and in need of safeguarding [Bouder et al., 2007].

In October 2007, the District's Natural Hazards Task Force was formed with a mandate from Council to recommend a tolerable level of risk to life from natural hazards. The task force received presentations from subject matter experts in the topics of natural hazards, risk assessment, mitigation, and the implications of adopting a community-based approach to risk management from both a financial and legal perspective. The task force opted for an objective measure of tolerable risk based on the average annual probability for loss of life. When the task force asked members of the community for their input, 72% of those responding (161 people) placed the tolerable level of risk for loss of life from natural hazards at between 1:10,000 and 1:100,000 risk to life per year.

On the basis of this input, and after carefully reviewing risk tolerance criteria established in other countries, the Natural Hazards Task force recommended the adoption of a two-tiered risk tolerance criteria that is based on a 1:10,000 threshold for existing development and a 1:100,000 threshold for new development [APEGBC, 2010]. The two-tiered framework is aligned with international best practices from other countries such as Australia, Hong Kong and the UK. The task force recommended a 1:100,000 threshold for new development because it is generally more attainable to reduce risk for new developments by altering building location and design features.

Planning and Policy Framework

Natural Hazard DPAs provide a mechanism to ensure that qualified professionals review all proposed development and make recommendations that incorporate available knowledge of hazards threats, and that reduce associated risks to As Low as Reasonable Practicable (ALARP) in addition to meeting the 'tolerable' or 'broadly acceptable' thresholds in accordance with risk tolerance criteria that have been adopted by the community. Current guidelines are focused on risks associated with debris flows, floods and interface fire.

In addition to establishing land use policies and associated guidelines to help manage risks associated with growth and development in the community, the District has also established a framework for disaster resilience planning that is based on guiding principles established by the international community [UNISDR, 2012].

The United Nations Disaster Resilient Cities Program was launched in 2010 to assist local governments in reducing vulnerabilities and potential future losses from natural hazards, and in building capabilities to withstand, respond to and recover from major disasters. Resources developed by the program are intended to "assist mayors, governors, councillors and other local government leaders with a generic framework for risk reduction and points to good practices and tools that are already being applied in different cities for that purpose". At the heart of the program is a ten-point checklist describing actions that are considered essential for increasing disaster resilience at the community level.

The District of North Vancouver was the first Canadian municipality to join the program and was recognized by the United Nations as a role model community for the progress it has made toward these 10 essential goals and objectives for disaster risk reduction [Dercole, 2011].

1) Organization and Coordination: Put in place organization and coordination to understand and reduce disaster risk based on participation of citizen groups and civil society. Build local alliances. Ensure that all departments understand their role to disaster risk reduction and preparedness. DNV actions in this area include:

- Establishment of an multi-stakeholder working group (District staff, school district, social service organizations and first responders) that meets regularly with NSEMO to develop and refine emergency management plans.
- Ongoing consultation with the Natural Hazards Task Force – an eight member advisory group tasked with a mandate to advise Council on tolerable thresholds of risk for the community.
- Championing the Association of Professional Engineers and Geoscientists of British Columbia (APEGBC) in the development of guidelines for professional practice in assessment of the risks associated with landslides and floods on proposed development.

2) Budget for Disaster Risk Reduction: Assign a budget for disaster risk reduction and provide incentives for homeowners, low-income families, communities, businesses and public sector to invest in reducing the risks they face. DNV actions in this area include:

- Ongoing funding for the DNV Natural Hazards Program operations and assignment of an annual budget to support ongoing development of municipal emergency plans, community outreach and maintaining a state of readiness for emergency operations.
- Incentives to homeowners living on the crests of steep unstable slopes to upgrade existing storm drainage systems in an effort to reduce the threat of landslides triggered by extreme rainfall events.
- Development of a 'Geotech-on-Demand' service whereby property owners can access the services of a qualified professional to assess site-level hazards and provide general guidance on strategies to reduce risks from natural hazards.

3) Prepare Risk Assessments: Maintain up-to-date data on hazards and vulnerabilities; prepare risk assessments and use these as the basis for urban development plans and decisions. Ensure that this information and related plans are readily available to the public and fully discussed with them. Relevant DNV actions include:

- Systematic assessment of debris flow and interface fire risks for the District and collaboration with other groups to assess risks associated with riverine flooding and earthquakes (this study).
- GeoWeb – a web based GIS application developed by the District to facilitate public access to information about natural hazard risk in the community.
- Working relationships with members of the real estate community to ensure that knowledge about natural hazards and related risks are disclosed when properties are sold and transferred to new owners.

4) Infrastructure Maintenance: Invest in and maintain critical infrastructure that reduces risk, such as flood drainage, adjusted where needed to cope with climate change. DNV actions in this area include:

- Assessment of infrastructure vulnerability and prioritization of investments in maintenance and/or replacement based on input from the community.
- Investment in forest fire reduction measures and seismic retrofits in areas surrounding critical infrastructure.

5) School Safety: Assess the safety of all schools and health facilities and upgrade these as necessary.

- The responsibility for school safety rests with the BC Ministry of Education who manages a province-wide program for seismic retrofits to schools that are considered most vulnerable to damage and loss of life from known earthquake hazards.

6) Safety of Homes and Businesses: Apply and enforce realistic, risk compliant building regulations and principles of sustainable land use planning. Identify safe land for low-income citizens and develop upgrading of informal settlements, wherever feasible. Relevant DNV actions include:

- Inspection and local enforcement of safety guidelines outlined in the National Building Code of Canada
- Procedures and guidelines to ensure that qualified professionals assess applications for proposed development in accordance with the best available information about natural hazards and risk tolerance criteria established by the community.

7) Education and Outreach: Ensure that education programs and training resources for disaster risk reduction are in place in schools and local communities.

- Workshops are offered through the North Shore Emergency Management Office to promote awareness and understanding of natural hazards and the steps that can be taken by homeowners and businesses to increase levels of emergency preparedness and disaster resilience.

8) Ecosystem Integrity: Protect ecosystems and natural buffers to mitigate floods, storm surges and other hazards to which your city may be vulnerable. Adapting to climate change is based on good risk reduction practices. DNV actions:

- The District has developed an ecosystem-based management framework to assist in meeting policy goals and targets outlined in the 2010 Official Community Plan. Policies include limiting development near streams, regulations governing the removal of trees and requirements for managing surface water runoff.

9) Early Warning: Install early warning systems and emergency management capacities in your city and hold regular public preparedness drills. DNV actions:

- The North Shore Emergency Management Office coordinates a telephone-based rapid notification system and ensures that the Emergency Operations Centre is maintained in a state of readiness. The District participates in earthquake Shakeout drills on a regular basis in collaboration with other levels of government.

10) Disaster Recovery: After any disaster, ensure that the needs of the survivors are placed at the centre of reconstruction with support for them and their community organizations to design and help implement responses, including rebuilding homes and livelihoods. DNV actions:

- The North Shore Emergency Management Office has a plan in place for Recovery Centres, aimed at coordinating the short term social needs of our community post-disaster through the Emergency Social Services volunteers, group lodging facilities and recovery centres.

CHAPTER 3:
REGIONAL EARTHQUAKE HAZARDS

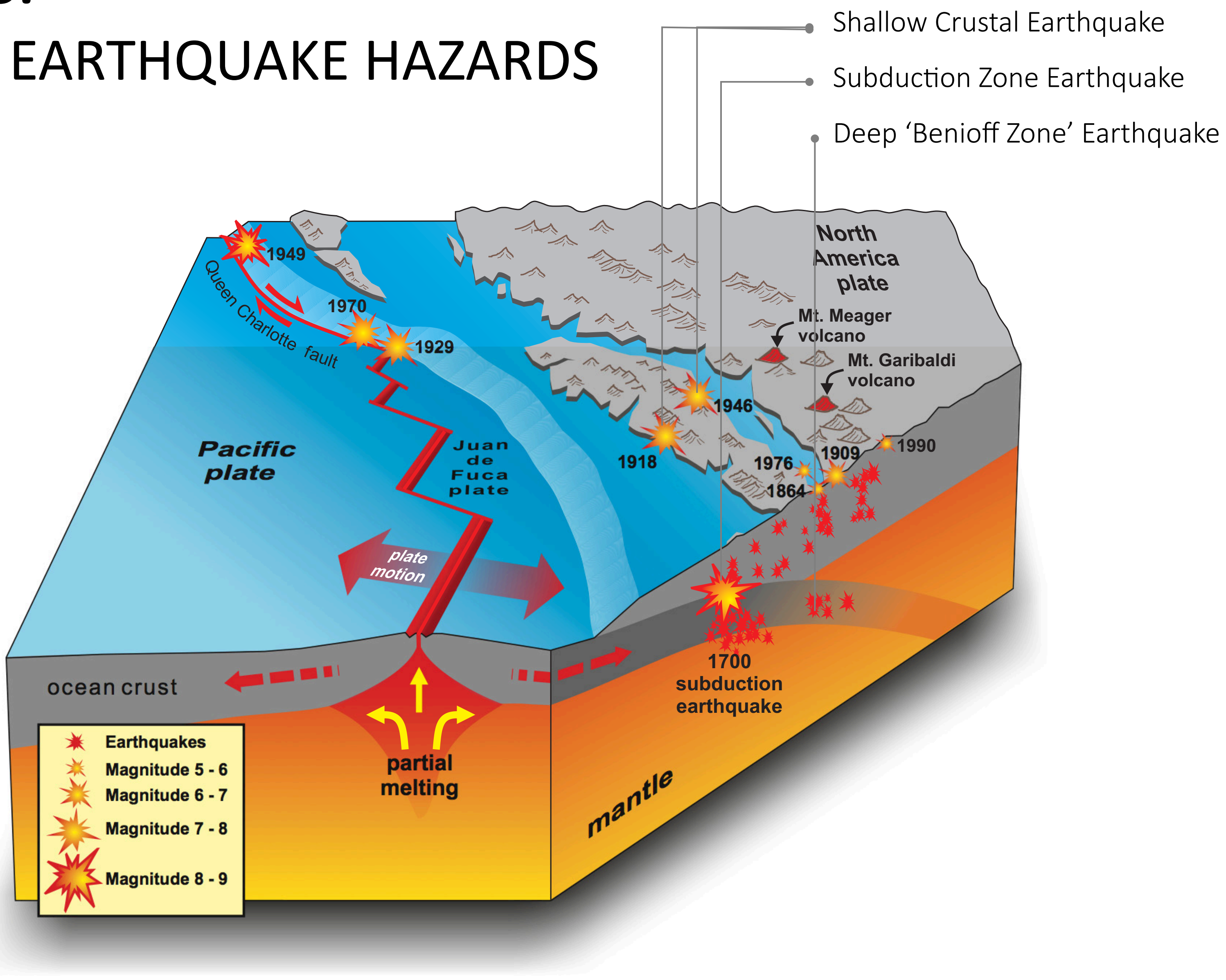


Image Source:
Geological Survey of Canada

CHAPTER 3: REGIONAL EARTHQUAKE HAZARDS

Primary Authors: Journeay, J.M.

The Pacific Northwest region of British Columbia is one of the most seismically active regions in Canada (Figure 35). More than 400 earthquakes occur each year along the northern segment of the Cascadia subduction zone — a region extending from the north end of Vancouver Island to Seattle, Washington. Only a few earthquakes are felt by people in any given year. Most occur in offshore regions and do not pose an imminent threat to people or critical assets. However, as the density of human settlement and urban development increases, so too does the potential for significant losses from a major earthquake. Earthquakes that are capable of causing significant damage occur every decade or so. The most devastating of these occur on average every few hundred years. and are among the World's largest.

So what causes earthquakes in this region? Deep below the surface of Vancouver Island, tectonic forces are pulling oceanic crust of the Juan de Fuca plate north-eastward beneath more buoyant and rigid crustal fragments of the North American Plate at a rate of 2-4 cm/year [Riddihough and Hyndman, 1991]. The boundary between these two tectonic plates is known as the Cascadia Subduction Zone. The plates episodically lock due to frictional forces as they slide past one another along the subduction zone boundary. As a result, the overriding North American plate is bent upward and accumulates increasingly higher levels of strain energy with each passing year — like a stick that is slowly bent upward by compression. At a critical stage in this process, the Earth's crust fails suddenly by fracturing and slipping along fault structures. Rupture along the fault triggers the release of accumulated strain energy that radiates outward away from the earthquake source — like shock waves from an underground explosion.

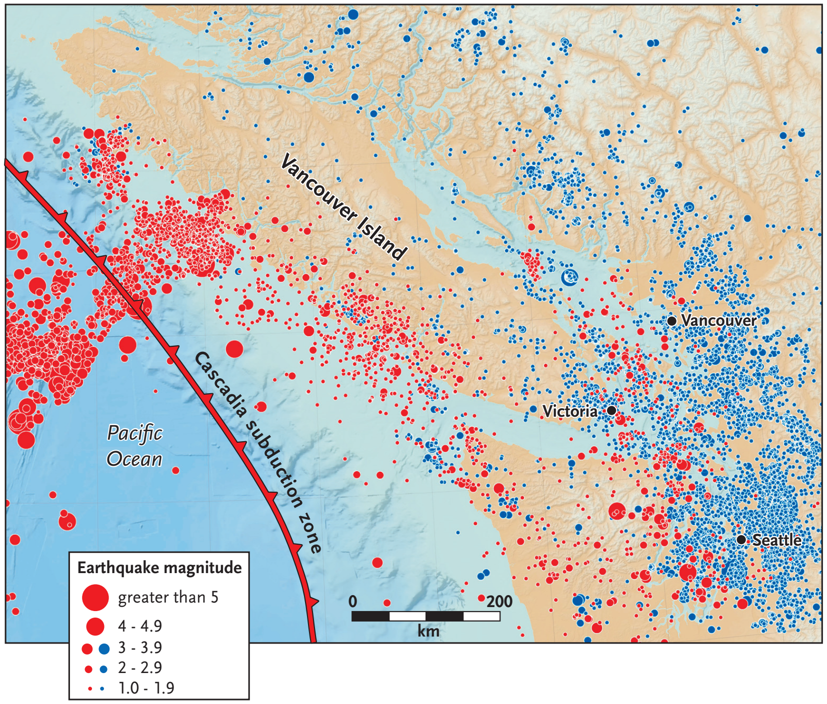


Figure 35: Regional seismicity for the Cascadia region of southwest British Columbia (Canadian National Seismograph Network). Earthquake epicentres scaled by magnitude. Red circles depict seismicity for the Juan de Fuca Plate. Blue circles depict seismicity for North American Plate.

ANATOMY OF AN EARTHQUAKE

Earthquakes are generated by the sudden movement of rocks along a fault zone — a break in the Earth's crust across which rock masses are displaced through an iterative process of strain accumulation, rupture and displacement (Figure 36). The intersection of a fault zone with the Earth's surface is known as a fault line. The source or hypocentre of an earthquake is the location of a point within the Earth's crust where rocks begin to fracture and slide past one another along the fault zone. The epicentre of an earthquake is the location of a point on the Earth's surface, directly above the hypocentre.

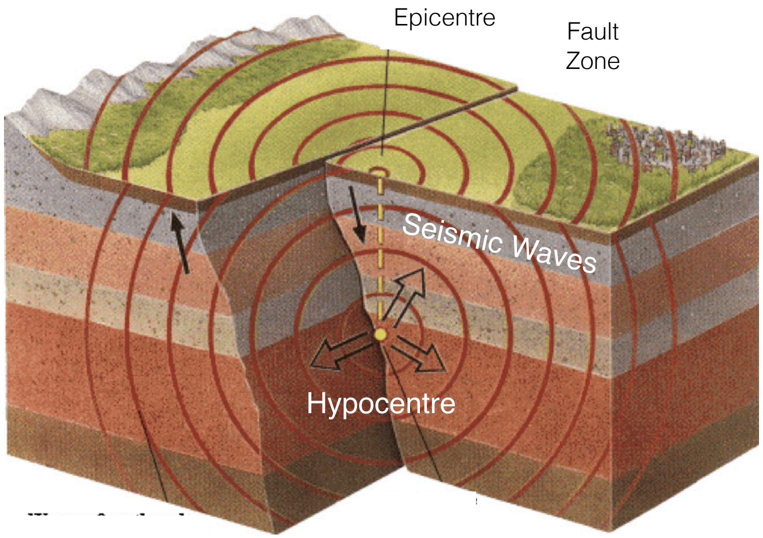


Figure 36: 3D anatomy of an earthquake showing relationships between displacement along a fault zone, and the propagation of seismic waves away from the hypocentre (focus).

The amount of seismic energy released during an earthquake event depends on displacement along the fault and the total area of fault rupture. The amount of displacement can vary from centimetres in smaller earthquakes to many metres in larger faults. Similarly, the area of fault rupture can vary from ~100 square metres for the smallest recorded earthquake to many thousands of kilometres for major plate boundary earthquakes.

There are three fundamental types of faults. Normal faults are caused by extension of the Earth's crust resulting in one block moving down with respect to the other along a fault zone that is inclined in the same direction as movement of the down-dropped block. Thrust or ‘reverse-slip’ faults are caused by compression of the Earth's crust resulting in one block being shoved over the other along a fault zone that is inclined in the opposite direction to movement of the up-thrown block. Strike-slip faults are caused by wrenching of the Earth's crust resulting in one block moving horizontally past another along a steeply dipping fault zone.

Depending on the orientation of the fault with respect to regional tectonic forces, strike-slip faults can result in either right-lateral or left-lateral displacement of one block with respect to another. Oblique-slip faults occur where there is a component of compression or extension across the fault zone resulting in one block moving diagonally up or down with respect to the other. Each type of fault displacement generates a distinctive pattern of seismic waves. The timing and sequencing of these waves is recorded by seismometers at different locations on the Earth's surface and can be used to deduce both the location and depth of the hypocentre and the type of fault that has triggered the earthquake.

Seismic Waves

Seismic energy released during an earthquake radiates outward from the hypocentre of the fault zone in the form of body waves that move through earth materials like the motion of a coiled spring, and as surface waves that move along the ground surface like ripples on a pond (Figure 36). Body waves are resolved into a primary compressional component (P-wave) that travels in the direction of wave propagation with a push-pull motion that causes rumbling and intense shuddering in the early stages of an earthquake. Secondary shear waves (S-wave) travel perpendicular to the direction of wave propagation causing side-to-side movement in solid materials. When body waves reach ground level they are resolved into two types of surface waves. Love waves move the ground with a side-to-side motion and result in lateral forces that can cause significant damage to building foundations. Rayleigh waves move the ground up-and-down and side-to-side in the direction of movement, similar to that of a rolling ocean wave. Most of the shaking and resulting structural damage that is experienced during an earthquake is due to Rayleigh wave motion.

What we feel during an earthquake is a cacophonous mixture of ground motions of varying type, frequency and velocity that reflect the dominant period of seismic waves as they travel along the Earth's surface. The amount of ground shaking at any given location is a function of how seismic waveforms interfere with one another during the earthquake event. Ground motion intensity is measured in terms of the amount and/or rate of displacement of a point at the Earth's surface over a given time interval. Ground motion intensities are recorded in terms of peak ground velocity (PGV: cm/sec), peak ground acceleration (PGA: %g), and spectral accelerations over time frames that are significant with respect to building response characteristics (e.g., Sa0.3 sec, Sa1.0 sec: %g).

P-waves, which are usually higher frequency than S-waves, are first to arrive, though are likely to be attenuated more rapidly. Long-period surface waves are the slowest, but often have the largest amplitudes. They are felt further away from the earthquake epicentre, and are more likely to damage tall structures like high-rise buildings and bridges that are inherently flexible and that tend to resonate at lower natural frequencies. Short-period seismic waves travel slower and diminish in intensity with distance away from the earthquake epicentre. They are more likely to damage shorter structures, like houses and schools, that are inherently stiff and that tend to resonate at higher natural frequencies.

Earthquake Magnitude and Intensity

The relative severity of a seismic event can be measured in terms of earthquake magnitude and/or intensity. Earthquake magnitude is a measure of seismic energy released at the source of rupture, like the power output of a radio signal at its origin. Earthquake intensity is a measure of seismic vibrations felt at some distance away from the source of rupture, like the strength of a radio signal recorded at a distant receiver location.

Earthquake magnitude is commonly reported using the Richter and/or Moment Magnitude scales. Both are logarithmic scales that measure the relative size of an earthquake in continuous values (Figure 37). Each whole number increment of the scale represents a ten-fold increase in the size of an earthquake’s ground-shaking amplitude, and a corresponding increase in the amount of energy released by a factor of ~32.

The Richter scale measures earthquake magnitude in terms the relative amplitude of a seismic wave with respect to a reference standard. It is suitable for reporting small and medium-sized earthquakes (<M6), but has been superseded in most countries by the Moment Magnitude scale, which provides a more robust and internally consistent measure of magnitude for earthquakes of all sizes. Moment magnitude measures the total amount of energy released during an earthquake event. It is a function of the overall mass of rock that has shifted within the Earth's crust, the amount of displacement along the fault surface and the size of the rupture zone.

Minor earthquakes with magnitude values of 1 to 4 occur frequently and are equivalent to the energy released from a powerful bomb or large lightning bolt. Humans rarely feel them and the intensities of ground motion do not pose a significant threat to buildings or critical assets. Moderate and strong earthquakes with a moment magnitude of 4 to 6 are less frequent and equivalent in size to that of a large underground nuclear explosion. They have the capacity for significant property damage

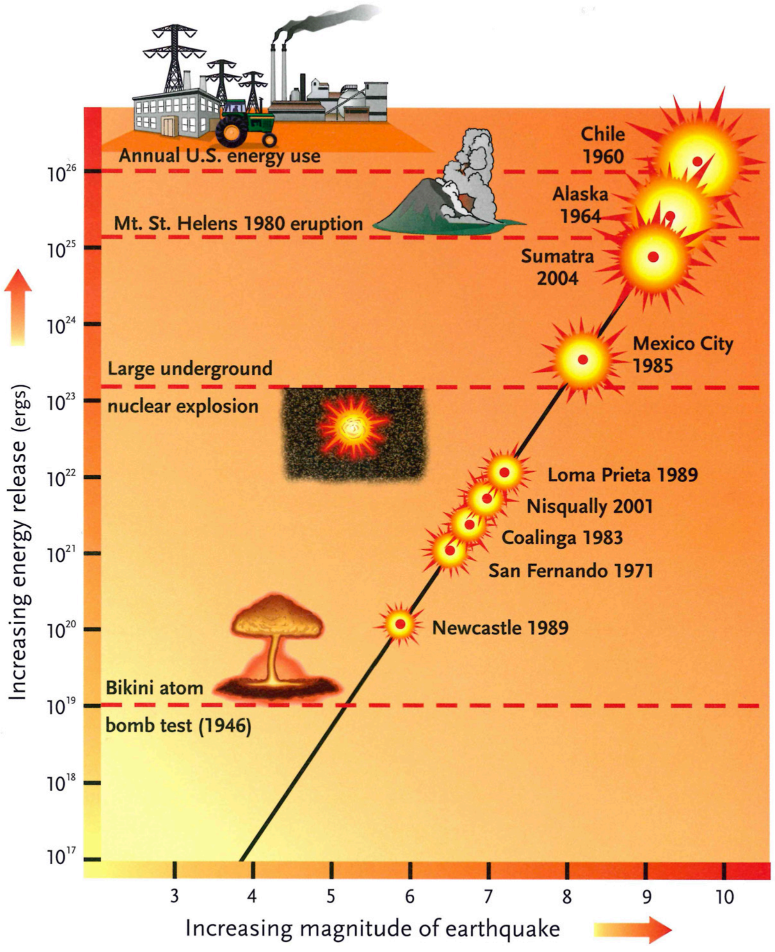


Figure 37: Relationship between earthquake magnitude and destructive power, measured in terms of energy released from fault rupture. Image source: Clague et al., 2006.

and loss of life. Major earthquakes with a magnitude of 7 or greater are infrequent but have the potential to release more energy than the 1980 eruption of Mt. St. Helens. Ground motions triggered by these great earthquakes have the potential to cause severe economic impacts and loss of life in densely populated areas. The 1960 Chile earthquake is the most powerful event ever recorded with a magnitude of 9.5. The energy released during this event was greater than the total amount of energy consumed in North America in any given year and 10 million times greater than that released by the first atomic bomb test of 1946 [Clague et al., 2006].

The intensity of an earthquake is a function of overall magnitude, distance away from the epicentre, and the density of people and physical assets that are vulnerable to damage by shaking and/or ground deformation. Earthquakes of equivalent magnitude in two separate locations with different patterns of human settlement can generate very distinct MMI intensity patterns with different levels of corresponding damage and loss. Earthquake intensity is measured using the Modified Mercalli Index (MMI) — a graduated scale that describes the effects of an earthquake in terms of what people have felt or are likely to experience on the ground, and expected levels of damage to buildings, engineered structures and natural features (Figure 38).

MMI intensity values of I to IV reflect an event that is only barely felt with little or no capacity for structural damage. MMI intensity values of V to VII reflect a moderate ground-shaking level that is felt by all and in which there is potential for slight or moderate damage to buildings that are badly designed and/or poorly built. MMI values of VIII to IX reflect proximity to a major earthquake event in which the level of ground shaking is sufficient to cause general alarm and/or panic, and in which there is potential for severe or complete damage to older buildings, and collapse of brittle masonry and concrete structures that are not designed to withstand the lateral forces associated with chaotic ground motions.

MMI	Perceived Shaking	PGA (%g)	PGV (cm/sec)	Anticipated Impacts
IV	Light	1.3-4.5% *(2.8)*	0.64-3.08 *(1.4)*	Most people indoors feel movement. Hanging objects swing. Windows, dishes, doors rattle and glasses clink. Walls of wood frame buildings creak. Parked vehicles rock.
V	Moderate	4.5-8.5% *(6.2)*	3.08-6.7 *(4.7)*	Almost everyone feels movement. Doors swing open or close. Shutters and pictures on wall move. Sleeping people awakened. Small, unsecured objects move or topple. Liquids in containers may spill.
VI	Strong	8.5-15.8% *(12)*	6.7-13.9 *(9.6)*	Everyone feels movement. People have trouble walking. Objects fall from shelves. Pictures fall off walls. Furniture moves. Weak plaster and masonry crack. Damage slight in poorly constructed buildings. Trees and bushes shake.
VII	Very Strong	15.8-29.3 % *(22)*	13.9-28.7 *(20)*	People have difficulty standing. Drivers on road feel their cars shake. Furniture may overturn and break. Loose bricks fall from buildings and masonry walls. Plaster and masonry crack. Weak chimneys break at roofline. Poorly constructed buildings badly damaged.
VIII	Severe	29.3-54.7 % *(40)*	28.7-59.6 *(41)*	Drivers have trouble steering. Towers, chimneys and other tall structures may twist and fall. Houses not bolted may shift off foundations. Damage considerable in poorly constructed buildings, moderate in well-constructed buildings. Tree branches break and fall. Changes occur in flow or temperature of springs and wells. Cracks appear in wet ground and on steep slopes.
IX	Violent	54.7-139.1 % *(75)*	59.6-177.8 *(86)*	Masonry structures and poorly constructed buildings seriously damaged or collapse. Houses not bolted shift off foundations. Reservoirs seriously damaged. Underground pipes break. The ground cracks and sand craters form in some areas due to liquefaction.

Figure 38: Earthquake intensity, measured using the Modified Mercalli Index, ground motion parameters and anticipated impacts. Adapted from Worden et.al., 2012.

EARTHQUAKE PERILS

Earthquake hazards have the potential to cause significant damage and loss through ground shaking, permanent deformation of the earth's surface and associated second-order events that are triggered as a result of the earthquake. Ground shaking hazards encompass the effects of seismic energy triggered by the earthquake event itself, and the amplification of seismic waves at the Earth's surface by reflection and/or refraction as they propagate through geological structures and surficial materials. Ground failure hazards encompass permanent displacements of the earth's surface caused by any combination of fault rupture, liquefaction and earthquake-triggered landslides. In addition to these primary seismic hazards, earthquakes can induce second-order hazards such as tsunami, fire, floods, and hazardous material spills, all of which have the potential to increase baseline levels damage and loss following the initial earthquake event.

While it is desirable to characterize the complete spectrum of seismic hazard potential for a given community or region, there are limits to our understanding of complex earth system processes that operate over large geographic areas, and our ability to measure and/or model the effects of an earthquake on people and critical assets. The following are descriptions of the most common elements of a comprehensive earthquake hazard assessment. The scope of investigation for any given community or region will depend on the level of vulnerability to specific hazard threats, the potential for negative impacts and consequences, and the availability of knowledge and resources to assess each component of the earthquake hazard.

Ground Shaking

The pattern and intensity of ground shaking will vary as a function of distance from the earthquake source, the attenuation of seismic energy as it moves through the Earth's crust, and the modification of seismic energy by localized geological factors such as soil conditions and bedrock density. The combined effects of attenuation, amplification and de-amplification and can be measured with a ground motion model that shows the spatial distribution and intensity of shaking in terms of velocity (PGV) and/or acceleration (PGA, Sa0.3s and Sa1.0s).

Regional Basin Effects

Regional basin amplification occurs as seismic waves are reflected and/or refracted by subsurface structures resulting in constructive interference and the intensification of earthquake ground motions as they approach the Earth's surface. Conversion of incident shear waves into longer-period and more destructive surface waveforms is caused by the reflection of seismic energy from dense sedimentary layers within the basin and from steep-walled structures along the basin edge. The amplification and modification of seismic energy will vary widely as a function of depth and location of the earthquake within the basin structure and the direction of wave propagation.

The effects of regional basin amplification have been directly observed and measured in recent earthquake disasters such as Mexico City (1985) and Kobe, Japan (1995). Insights gained through modelling and real-time monitoring have shown that earthquake ground motions can be amplified by a factor of ~10 and can resonate more than three times longer than those which have not been influenced by regional subsurface basin structures [Bard and Bouchon, 1980; Graves, 1996; Molnar, 2012; Molnar et al., 2014]. For these reasons, it is essential to consider regional basin effects in situations where there is sufficient knowledge and capacity to model the amplification of seismic waves as they move through the Earth's crust.

Local Site effects

In addition to regional basin effects, the character and intensity of ground shaking at any given location is also influenced by how seismic energy is amplified or dampened by near-surface surficial materials. As illustrated in Figure 39, site amplification occurs in areas where seismic energy is impeded by less dense soft

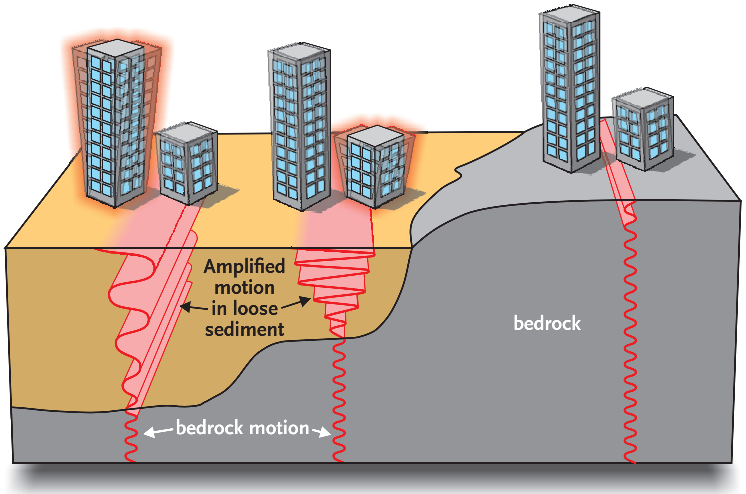


Figure 39: Schematic diagram showing how seismic energy is amplified as it approaches the earth's surface (from: Clague et al., 2006)

sediment and/or focused above buried valleys that are filled with soft sediment.

In general, seismic energy travels at lower velocities through soft sediments resulting in the amplification of shear and surface waves — analogous to an ocean wave as it approaches the shoreline and slows down. Similarly, seismic energy travels faster through dense bedrock material resulting in the dampening of shear and surface waves. Knowing the average shear wave velocities of material down to a depth of 30 metres (Vs_{30}), thus, provides a means of estimating the intensity of ground shaking that is likely to be felt at any given site [Hunter and Crow, 2012]. Ground-shaking intensities can be amplified by a factor of 1.1 to 2.1 in areas dominated by stiff and soft soils (NEHRP Site Classes D and E; Vs_{30} < 360 m/s), and dampened by a factor of 0.5 to 0.9 in areas dominated by denser bedrock units (NEHRP Site Classes A and B; Vs_{30} >760 m/s). The exception to this rule is soft soils in areas of intense shaking that are known to dampen seismic energy in some frequency ranges [Finn and Wightman, 2003].

Foreshocks and Aftershocks

Large earthquake events (>M6) have the potential to trigger swarms of smaller magnitude earthquakes that can occur either before or after the main event. Most aftershocks are caused by incremental strain and displacement within the area of primary fault rupture, or along fault networks that accommodate deformation within adjacent volumes of rock that have been displaced during the main earthquake event. The size and frequency of aftershock events is a function of depth and magnitude of the primary earthquake. Large magnitude shallow crustal earthquakes have the potential to trigger swarms of large aftershock events that can last for days, months and event years after the main event. Over time, the size and frequency of these secondary earthquake events decay to background levels for the region.

The impacts of aftershock events can be devastating, particularly in areas where the structural integrity of buildings has already been compromised by damages associated with the main earthquake event, or where emergency response efforts to protect people and critical assets are in progress. More than 2,500 aftershock events were recorded after the earthquake that struck the Canterbury region of New Zealand in 2011. At least 30 of these aftershock events were greater than M5.0 and contributed to building damage [Institute of Professional Engineers of New Zealand, 2012].

Ground Failure

Large earthquakes (>M6) can also generate ground forces that have a potential to cause permanent deformation of the earth's surface. Ground deformation can include permanent displacements of the earth's surface caused by earthquake-triggered fault rupture, liquefaction of water-saturated soils and/or landslide activity along steep unstable slopes. The spatial extent and pattern of permanent ground deformation is controlled by local factors such as bedrock geology, soil conditions, slope gradient and groundwater hydrology.

Surface Fault Rupture

Surface rupture is measured in terms of expected vertical and/or horizontal displacements as the fault breaks the earth's surface. The amount of displacement will vary from a few centimetres to many metres along the trace of the fault and is a function of both the type of fault and earthquake moment magnitude. Normal and reverse-slip thrust faults result in rupture and vertical displacements of the ground surface in a direction perpendicular to the fault trace. Vertical offsets of ancient surface features record more than 2 metres of displacement along a 25 km long segment of the Seattle Fault during a M6.8 earthquake event more than a thousand years ago [Sherrod et al., 2004]. Horizontal offsets of linear drainage features record similar magnitudes (or larger) of strike-slip and oblique-slip displacement along the San Andreas Fault in California [Schwartz and Coppersmith, 1984].

While deformation caused by surface fault rupture is typically confined to a relatively narrow zone adjacent to the fault line, it is not uncommon for large-scale crustal displacements to be partitioned across a network of active faults — each recording a component of the overall deformation. The identification of active faults requires sophisticated investigative techniques that include remote sensing and high-resolution mapping of landscape topography, trenching and direct observation of buried fault zones, and age dating of organic and inorganic materials that are used to constrain the timing of discrete earthquake events.

Buildings and engineered structures that are built across or adjacent to active fault zones are likely to sustain complete damage from even small amounts of surface displacement. For this reason, the assessment of surface rupture hazards is often mandated in densely populated areas that are exposed to active faults and in which the potential for damage to critical assets and lifeline infrastructure is high. California's Earthquake Fault Zoning Act was passed in 1972 in an effort to mitigate the impacts and consequences of surface rupture that were caused by the 1971 San Fernando Earthquake [California Public Resources Code; Division 2. Geology, 1972; 1990].

The Alquist-Priolo Fault Zoning Act prevents the construction of buildings used for human occupancy on the surface trace of active faults. The act only addresses fault rupture and does not apply to other related seismic hazards. The California Seismic Hazards Mapping Act was passed in 1990 to address other ground failure hazards, such as liquefaction and seismically induced landslides. Similar policies have been considered in other seismically active regions around the world but have yet to be implemented due the scarcity of historic fault ruptures and the difficulty in detecting, mapping and documenting both the location and recurrence histories of active faults.

Liquefaction

Liquefaction describes the behaviour of water-saturated soils that loose strength and internal cohesion as a result of excess pore pressures generated by intense ground shaking (Figure 40). Prior to an earthquake, the weight of buried soils rests on a framework of sand grains that are saturated with groundwater under static conditions. Ground shaking disrupts the sand framework so that the overlying weight of buried sediments is no longer supported along grain boundaries, thereby increasing pore water pressure causing the entrainment and flow of soil particles and loss of internal cohesion. The likelihood of liquefaction at any given location is governed by a number of factors that include the frequency and duration of ground shaking, the degree of groundwater saturation, grain size distribution, and thickness of surficial materials.

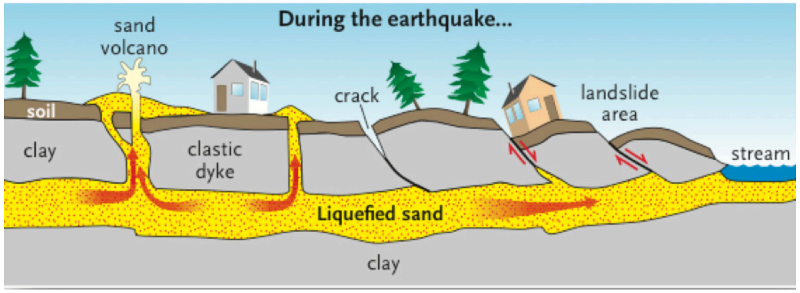


Figure 40: Diagram illustrating the geologic conditions that contribute to liquefaction susceptibility and the effects of liquefaction both during and after and earthquake. Adapted from Institute of Professional Engineers in New Zealand, 2012)

Liquefied sediments under high pore fluid pressure have the potential to fracture overlying soil horizons and flow out onto the land surface causing fissures and overland flooding. Permanent ground failure caused by liquefaction can include lateral spreading as soil horizons fail suddenly and are displaced horizontally in a viscous state and/or vertical settlement caused by changes in soil volume and settling during the shaking event. The amount and type of displacement will vary as a function of ground shaking intensity and localized geologic setting.

Liquefaction displacements can exceed 70 cm of lateral spreading and 20 cm of vertical settlement for large-magnitude earthquakes, such as the one recently witnessed in Christchurch, New Zealand [Institute of Professional Engineers of New Zealand, 2012]. Even smaller amounts of displacement have the potential to cause significant structural damage and related losses.

Seismically Induced Landslides

Landslides triggered by ground shaking during an earthquake are common and have the potential to cause significant levels of additional damage and loss of life. The M7.9 Wenchuan earthquake in 2008 induced several large landslides in the Sichuan region of China that are believed to have claimed as many as 20,000 lives [Gorum et al., 2011; Yin et al., 2009].

Seismically induced landslides are particularly common in mountainous terrain and regions along the coast where rock and soil slopes are weakened through saturation from snowmelt and heavy rains, and have been undercut by glaciers, rivers and/or ocean waves. Landslides include a variety of rock falls and deep-seated slumps of rock and/or surficial materials. They occur primarily on steep slopes where the intensities of ground shaking cause shear stresses that exceed critical thresholds of frictional resistance within rock masses and soil horizons (See Figure 41).

Ground deformation associated with a landslide can be localized along river valleys or distributed across broad unstable slopes, encompassing both the displacement of rock and/or soil along the headwall scarp and the entrainment of material as the landslide moves downslope. Landslide deformation is measured in terms of critical acceleration of the landslide mass, and the magnitude of lateral displacement down the slope. In some cases, seismically triggered landslides can block river drainages resulting in second-order slope failure and/or debris flow hazards that can pose a significant threat to people and critical assets located downstream of the initial slide.

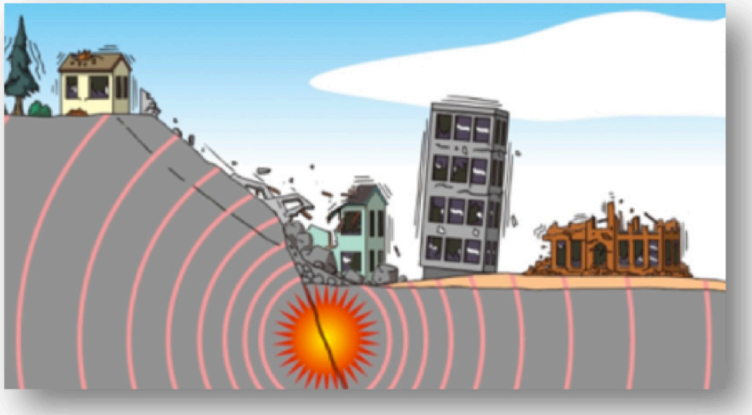


Figure 41: Schematic diagram illustrating hazard potential of earthquake-triggered landslides.

Seismically induced landslide hazards are a major concern in the Pacific Northwest (Oregon, Washington and British Columbia) — an area of active deformation, uplift and heavy rainfall that is dominated by thick glacial deposits and steep topography. Major slope failures and deep-seated landslides are known to have been triggered by ground shaking associated with a M6.7 earthquake along the Seattle Fault ~1100 years ago, and by a ~M7 earthquake that shook north-central Washington State in 1872 resulting in a massive rockslide that blocked the Columbia River for several hours [CREW, 2009].

Secondary Hazards

Earthquake ground motions caused by shaking and/or permanent deformation have the potential to trigger a wide range of secondary hazards that can include tsunami, fire, flooding, and hazardous material spills. Impacts and consequences of these induced hazards can in some cases be equivalent in magnitude to those associated with the initial earthquake event. The most common and potentially devastating of these are earthquake-triggered tsunami and fires generated in dense urban settings following an earthquake.

Tsunami

A tsunami is an extremely large wave of water up to ~40 metres in height that can surge inland several kilometres causing massive loss of life and the destruction of everything in its path. Tsunamis are triggered primarily by earthquakes, but can also be caused by landslides, volcanic eruptions and the impact of meteorites into large bodies of water. Earthquake-triggered tsunamis are caused by submarine fault rupture and vertical offset of the Earth's crust resulting in upward displacement of the overlying water column and the initiation of energy waves that travel in opposite directions away from the fault line (See Figure 42).

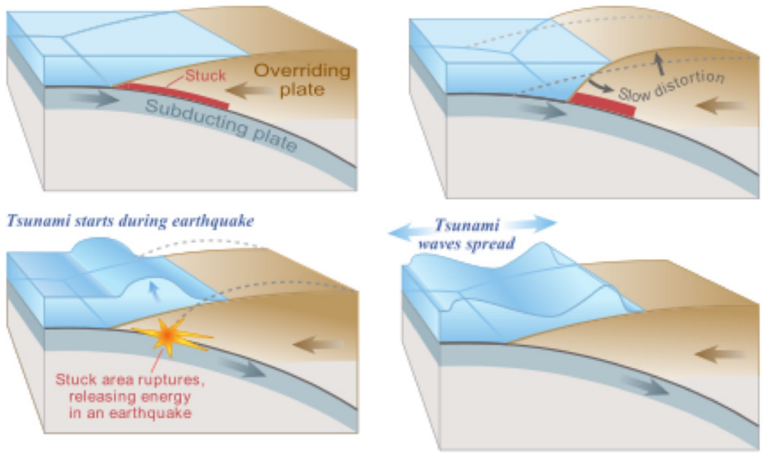


Figure 42: Schematic diagram illustrating hazard potential of tsunami waves generated by a submarine rupture (USGS Wikipedia).

Tsunami waves in the deep ocean are less than a few metres in height but can travel at speeds of several hundred kilometres per hour. As they approach land, tsunami waves slow down and pile up due to frictional forces along their base. This process of shoaling results in wave height amplification and toppling of massive waves of water that crash ashore and surge inland with unimaginable force.

The size of a tsunami wave varies as a function of earthquake magnitude, distance from the source, and bathymetric characteristics of the shoreline that influence both wave height and run-up distance. The impacts and consequences of a tsunami are often devastating, as witnessed by recent media coverage of major disaster events in Sumatra and Japan. Tsunami waves triggered by a M9.0 fault rupture in 2004 along the India-Burma plate boundary in the Sumatra-Andaman Islands region of South Asia claimed the lives of more than 200,000 people in eleven countries bordering the Indian Ocean, and destroyed coastal towns and villages situated within many kilometres of the shoreline.

Ground shaking and tsunami waves triggered by a M9.0 fault rupture along the Pacific Plate off the coast of Tōhoku, Japan in 2011 claimed the lives of ~16,000 people, and destroyed several hundred thousand buildings and related infrastructure including both utilities and transportation networks. The immense forces associated with run-up of tsunami waves along the Japanese coast also triggered a number of second-order hazards including collapse of critical dam facilities and extreme meltdowns of three reactors at the Fukushima Daiichi Nuclear Power Plant complex.

The primary sources of tsunami hazards in southwestern British Columbia are 'megathrust' earthquakes along the Pacific Plate boundary, off the west coast of the Americas, Alaska, Japan, the Philippines and Indonesia. Tsunami waves triggered by the 1964 M9.2 Alaska earthquake and associated landslide activity claimed the lives of more than 100 people and caused significant damage along the coast of British Columbia, Washington and northern Oregon.

Tsunami hazard potential is greatest along the west coast of Vancouver Island. The worst-case scenario is a tsunami triggered by rupture of a ~M9 megathrust earthquake along the Cascadia subduction zone where run-up potential for tsunami waves is up to ~15 metres for exposed communities along the west coast of British Columbia, Washington and Oregon, and up to ~5 metres for more protected coastlines along southern Vancouver Island and the Strait of Juan de Fuca. Run-up potential for tsunami waves generated by submarine fault rupture and landslides within the Strait of Georgia is estimated to be ~2 metres or less [Clague et al., 2006].

Fire

Fire has long been recognized as a significant second-order hazard following a major earthquake. Urban and interface fires are triggered by the rupture of gas lines and the arcing of electrical wires caused by a combination of severe ground shaking and permanent ground deformation. Uncontrolled fires triggered by an earthquake have the potential to burn for days and cause significant levels of damage as emergency crews scramble to clear roads and mobilize fire-fighting resources.

Induced fire hazards were responsible for more than 90% of the damage and associated losses following the great M7.8 San Francisco earthquake of 1906. Rupture and displacement along a ~500 km segment of the San Andreas Fault resulted in significant damage to unreinforced masonry buildings and the rupture of gas lines that ignited more than 30 fires across the city. Fires burned out of control for several days due to broken water mains and limited access to fire-fighting resources. As a result, more than ~25,000 buildings were destroyed in a 520 square block area that left nearly 75% of the population (~300,000 people) homeless for months after the earthquake. Fires caused by the 1995 Kobe earthquake burned a number of city blocks in the heart of the city and were responsible for nearly 6,000 fatalities [Clague et al., 2006].

EARTHQUAKE SOURCE ZONES

There are three primary earthquake source zones in southwestern British Columbia that are of concern to communities in the Metro Vancouver region (Figure 43). They include: (1) thrust faults along the subduction zone interface between oceanic crust of Juan de Fuca Plate and overriding continental crust of the North American Plate (Cascadia Megathrust Earthquakes); (2) extension and normal faults within the down-going slab of oceanic crust as it sinks beneath western North America (Deep Earthquakes); and (3) reverse and strike-slip faults that accommodate margin-normal shortening and oblique-slip displacement of the North American Plate in the upper plate of the Cascadia subduction zone (Shallow Crustal Earthquakes).

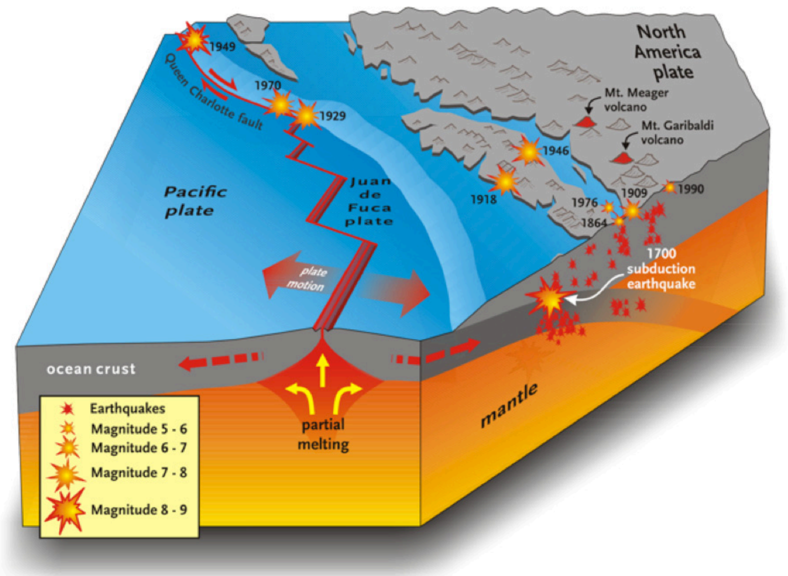


Figure 43: Earthquake source zones and historic record of destructive earthquakes in the Cascadia Subduction Zone of southwest British Columbia (Image: Geological Survey of Canada).

Cascadia Megathrust Earthquakes (Plate Boundary)

Earthquakes occur on an episodic basis along the interface between the Juan de Fuca and North American plates in offshore regions of British Columbia and Washington State (Figure 43). Most of these earthquakes are relatively small in magnitude (<M4), each releasing minor amounts of accumulated strain energy as the plates slide past one another. However, there are sections of the subduction zone that are locked and accumulating significant amounts of strain energy with a potential to trigger giant "megathrust" earthquakes (>M8). Shaking associated with such an event would be intense near the coast and would likely be felt for several minutes, posing a significant threat to buildings that are not designed to sustain prolonged ground motions.

Evidence of historic megathrust earthquakes and related tsunami events are preserved in the geologic record in the form of fault structures, displaced surface features and marine inundation deposits. The observations suggest that a magnitude 9 earthquake occurs along the Cascadia about once every 500-600 years [Atwater et al., 1995]. 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 [Atwater et al., 2005; Lamontagne et al., 2007]. The earthquake was large enough to trigger a tsunami that caused significant damage to First Nation settlements along the coast of North America and to communities across the Pacific Ocean in Japan [Atwater et al., 2005; Atwater et al., 1995; Ludwin and Smits, 2007; Rogers, 1992; Satake et al., 1996].

Subduction zone earthquakes of this magnitude pose an extreme and imminent threat to settled areas along the coast of Vancouver Island and Washington State, including urban areas of Victoria, Bellingham and Seattle. Although seismic energy will be attenuated with distance away from the source zone, it is expected that ground shaking intensities in the Metro Vancouver region will be very strong to severe (MMI VII-VIII). In addition to intense levels of ground shaking, it is likely that a megathrust earthquake would be accompanied by liquefaction, seismically induced landslides and a significant number of aftershock events — each with a potential to cause additional damage.

Deep Earthquakes (Juan de Fuca Plate)

Deep earthquakes occur within the Juan de Fuca plate as it sinks and is deformed by extension and differential slip beneath the overriding North American Plate (Figure 43). The portion of the Juan de Fuca Plate that is subject to active seismicity (known as the Benioff Zone) extends 25 to 100 kilometres beneath the North American Plate in the Georgia Strait-Puget Sound area with the largest and most significant events localized in a zone that is 40-65 km below the surface of the earth.

Frequency-magnitude relationships established from seismic monitoring records indicate that damaging Benioff Zone earthquakes occur on average every 10-30 years in the Puget Sound area. It is estimated that there is an 84% chance of experiencing a damaging Benioff Zone earthquake (>M6.5) in the Puget Sound area within the next 50 years [CREW, 2008]. The largest of these recorded events was a M6.8 earthquake that rattled Olympia Washington in 1949. Other damaging events in the region include the M6.5 Seattle-Tacoma earthquake of 1965, and the M6.8 Nisqually earthquake in 2001 [Ichnose et al., 2006]. Although there is no direct evidence of larger Benioff Zone events from seismic records, studies indicate a potential for larger earthquakes in the region with intensities that could exceed 7.5 [CREW, 2008].

As the locus of significant Benioff Zone seismicity occurs at depths greater than ~40 km, there is no fault rupture of the ground surface and, therefore, no threat of a tsunami. Also the type of fault that occurs in these zones does not typically generate significant aftershock events. Nonetheless, deep focus earthquakes do have a potential to cause significant ground shaking over large geographic areas for up to a minute in duration posing a significant threat to unreinforced masonry and older multi-story buildings.

The intensity and duration of ground shaking can also trigger significant permanent ground deformation hazards such as liquefaction and seismically triggered landslides. Areas in southwestern British Columbia that are susceptible to significant damage from a Benioff Zone earthquake include the greater Metro Vancouver region and smaller communities on the Gulf Islands, the Sunshine Coast, and the east coast of Vancouver Island.

Shallow Earthquakes (North American Plate)

Earthquakes within the North American Plate are caused by displacements along a complex network of faults that accommodate the crumpling and shuffling of buoyant continental fragments (terranes) as they collide with and override oceanic crust of the Juan de Fuca Plate (Figure 43). Shortening in the Puget Lowland and adjacent Georgia Basin is accommodated by displacements along networks of northwest and east-west trending oblique reverse faults that run both parallel to and at high angles to the plate boundary [Blakely et al., 2011; Kelsey et al., 2012; Sherrod et al., 2004].

The geologic record of displacement on these faults and GPS measurements of geodetic strain along the plate margin indicate permanent north-south shortening at rates of ~4 mm/year [Mazzotti et al., 2003; McCaffrey et al., 2007]. Longitudinal shuffling of crustal fragments is accommodated by oblique displacements along steep strike-slip faults that parallel the plate boundary. Steep normal faults occur both within and along the boundaries of crustal fragments as they are displaced along the plate margin.

Shallow crustal earthquakes occur on a regular basis within the upper 30 km of the North American Plate. These are mostly smaller magnitude events (<M5) that appear to be concentrated in discrete zones of active seismicity encompassing the Bellingham Basin, southern Vancouver Island, southern Georgia Basin, and regions of high heat flow along the Cascadia volcanic arc in the southwestern Coast Mountains [Hyndman et al., 2003]. Larger earthquakes are known to have occurred in and along the margins of these zones and pose a significant threat to settled areas throughout southwestern British Columbia. They appear to be localized on faults close to the earth's surface that have a potential to generate intense ground shaking and associated permanent ground deformation. In addition to the primary shaking event, larger magnitude shallow crustal faults are often accompanied by significant aftershocks that can last for months causing additional physical damage during response and recovery phases of the disaster.

Large magnitude shallow crustal earthquakes (>M6) are known to have occurred in the past and have the potential to occur anywhere within the North American Plate once every few decades or so. While most of these events are relatively small and accommodate incremental deformation throughout the North American Plate, there is potential for large magnitude earthquakes to occur along fault segments that have become locked and accumulated significant amounts of strain energy over time. It is estimated that ruptures of 30 km or more could occur every few hundred years along any one of these fault segments [CREW, 2009; Hyndman et al., 2003].

SEISMIC HAZARD ASSESSMENT

The assessment of ground shaking hazards can include probabilistic and/or deterministic methods of analysis. Both methods predict the likelihood and intensity of future events for a given area but from very different perspectives. Probabilistic methods of seismic hazard assessment (PSHA) are designed to quantify the likelihood of exceeding minimum thresholds of ground shaking at a particular location from all known earthquake hazards for a given future time horizon. Results are used primarily to establish safety thresholds and seismic design guidelines for individual buildings and engineered structures, and to develop more generalized risk reduction policies. In contrast, scenario-based methods of deterministic seismic hazard assessment (DSHA) are designed to quantify the likely impacts and consequences of a plausible earthquake event on a collection of community assets. Outputs are used to analyze cause-effect relationships and to evaluate strategies for reducing risk through pre-event planning and mitigation.

Probabilistic Seismic Hazard Assessment (PSHA)

By definition, probabilistic ground motion models represent the likelihood of exceeding a minimum threshold of shaking from all known earthquake sources over a future time horizon. Methods of probabilistic seismic hazard assessment are based on a theoretical understanding of seismic source zone characteristics, associated ground motion relationships, and empirical records of known seismic activity that are used to establish relationships between earthquake magnitude and likelihood of occurrence.

Process-based models that account for the attenuation of seismic energy from fault zone sources are used to predict the likelihood of exceeding minimum thresholds of ground shaking at any given location. Model outputs are used in earthquake engineering to assess whether a structure is likely to withstand minimum thresholds of ground shaking for reference time horizons while maintaining an acceptable level of performance [Baker, 2008].

The National Building Code of Canada (NBCC) utilizes probabilistic ground motion models to establish minimum thresholds of safety and corresponding seismic design guidelines for buildings and engineered structures [Adams and Halchuk, 2003; Halchuk and Adams, 2008]. Figure 44 is a map of expected ground motions for southwestern British Columbia and northwestern Washington based on the USGS seismic hazard model [Petersen et al., 2008]. The map shows the spatial distribution and expected minimum intensities of ground shaking that are likely to occur in any given year for a recurrence interval of 1/2475 years [Petersen et al., 2008]. For this time interval, there is a 2% in 50 year chance (PA=0.000404) that ground-shaking intensities will be greater than the ones shown at any given location on the map.

Deterministic Seismic Hazard Assessment (DSHA)

Deterministic seismic hazard assessment models represent plausible ‘what-if’ scenarios of what might be expected if an earthquake were to occur at some point in the future. Deterministic scenarios utilize process-based models of fault behaviour and seismic attenuation to predict the spatial pattern and intensity of ground motion over broad areas. They can be based on earthquake events that are known to have occurred in the past and/or have the potential to occur in the future.

While earthquake scenarios are effective in establishing cause-effect relationships between ground shaking and related physical impacts for a specific event, they do not represent the overall seismic risk for a particular location or region. For this reason, care must be taken in developing plausible scenarios that reflect the best available scientific knowledge about earthquake hazards for a given region, and that minimize uncertainties with respect to location, magnitude and likelihood of occurrence.

A sampling of scenario-based deterministic ground motion models have been developed to assess earthquake hazards in the Cascadia region of southwestern British Columbia and northwestern Washington (Figure 45). These include a M9 megathrust scenario, similar to the 1700 event that occurred in offshore regions of the Olympic Peninsula; a hypothetical M7.3 shallow earthquake scenario in the Strait of Georgia — similar to the 1946 event that occurred in the Comox - Courtney region of Vancouver Island; and hypothetical shallow crustal earthquake scenarios adjacent to Vancouver and Victoria.

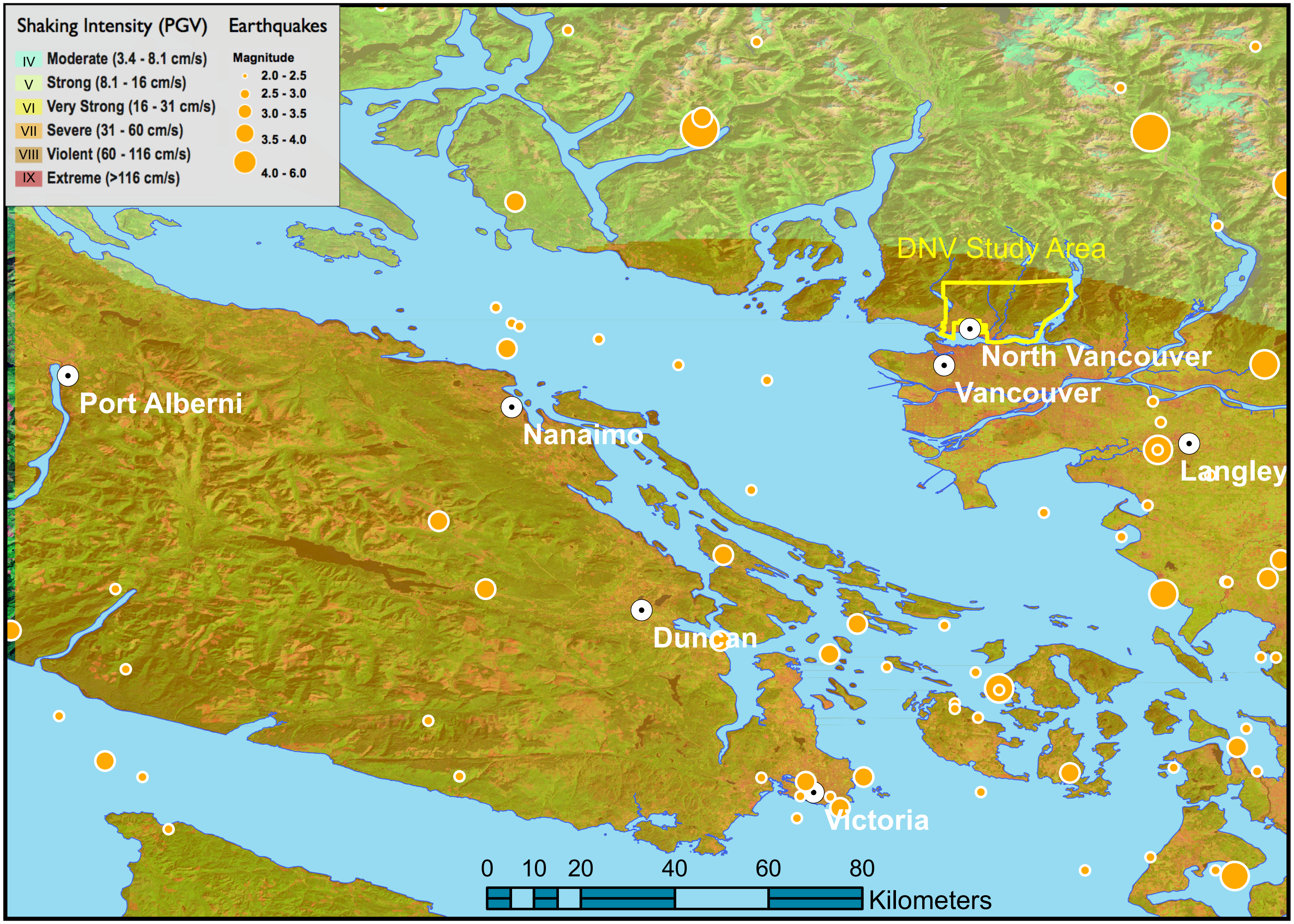


Figure 44: Probabilistic Seismic Hazard Assessment (PSHA) of the Cascadia region showing ground shaking intensities from all known earthquake hazards that are likely to be exceeded for a recurrence interval of 1/2475 year (2%50yr probability). Values are based on the 2008 PSHA calculated by the US Geological Survey for uniform NEHRP soil conditions B/C (V_S^{30} = 760 m/s; (Petersen et al., 2008)

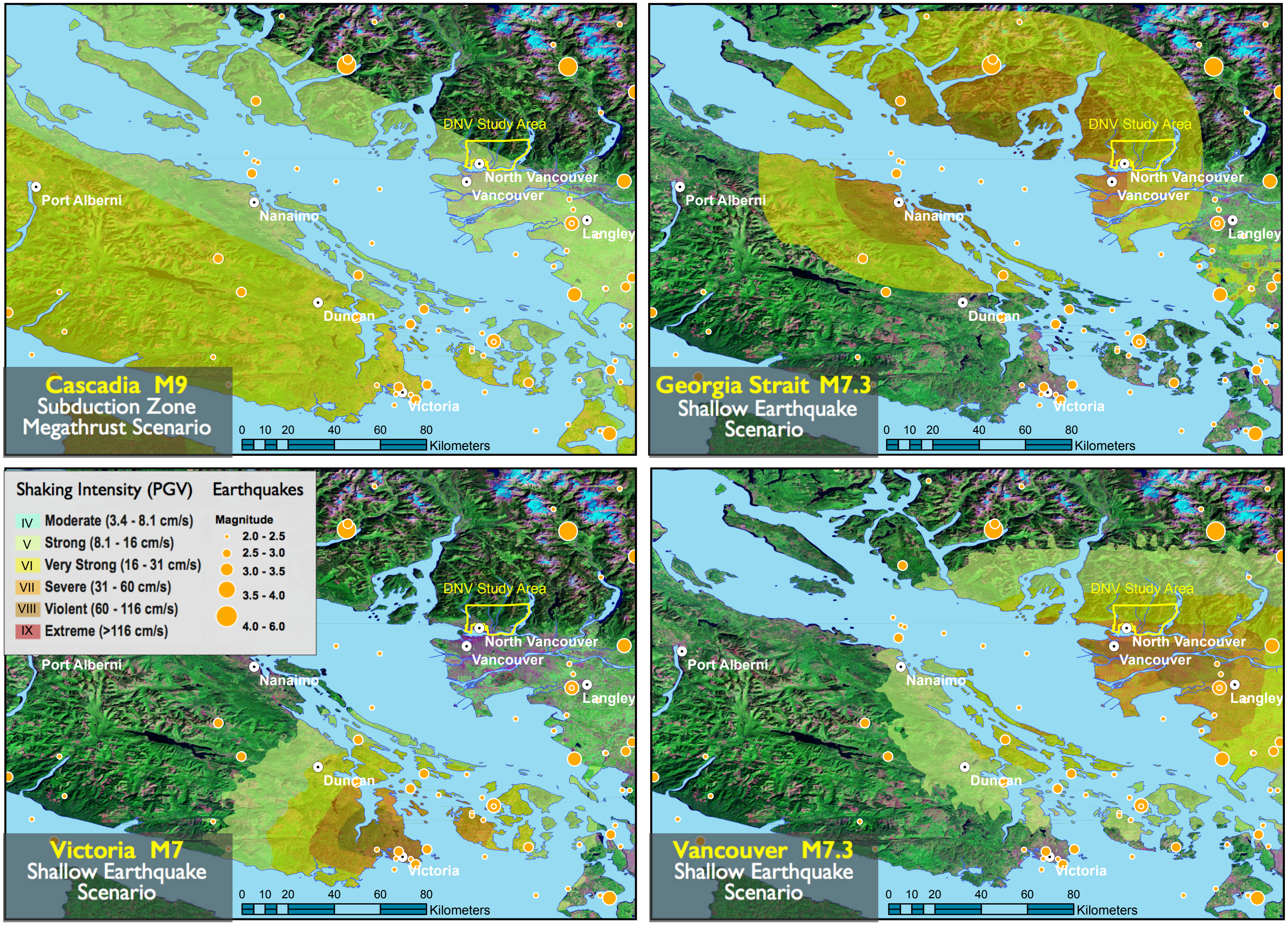


Figure 45: Deterministic ground motion models for the Cascadia region of southwestern British Columbia and northwestern Washington. Ground motions calculated using USGS ShakeMap model (USGS; Wald et. al., 2006),

Ground motions are based on earthquake prediction models implemented in USGS ShakeMap methodology [Wald et al., 2006]. The Cascadia and Georgia Strait scenarios model shaking hazards only, while the Vancouver and Victoria scenarios account for the effects of both seismic attenuation and local site amplification.

Ground shaking intensities for the M9 megathrust scenario (See Figure 45) are severe along the southwestern coast of Vancouver Island (MMI VIII) and diminish to very strong and strong along northwest-trending zone that encompasses Puget Sound, the Georgia Strait, Metro Vancouver, eastern Vancouver Island and the Sunshine Coast (MMI VII). Ground shaking intensities are similar for M7 deep earthquake scenario in the region [Molnar, 2011]. Shaking intensities are severe in the Gulf Island region (MMI VIII), and diminish along the west coast of Vancouver Island, the Fraser Valley and eastern Coast Mountains (MMI VII).

In contrast, patterns of ground motion for shallow crustal earthquakes are very focused with concentric zones of severe and very strong ground shaking within 30-50 km of the epicentre. Areas of severe shaking diminish outward to strong and moderate ground shaking over distances of 70 to 100 kilometres (See Figure 45). The implication is that regions of moderate and heavy damage potential are geographically constrained and highly dependent on local patterns of development.

Ground shaking intensities for the 1946 M7.3 earthquake on Vancouver Island are known to have been very strong to severe (MMI VII-VIII) in the immediate vicinity of the epicentre near Comox, and to have diminished outward to strong and moderate levels (MMI V-VI) in central and southern Vancouver Island [Rogers, 1979]. Ground motion intensities for hypothetical earthquake scenario in the Strait of Georgia and adjacent to Vancouver and Victoria show a similar pattern with localized zones of severe shaking that diminish outward in neighbouring areas.

Of greatest concern for the lower mainland area of Metro Vancouver are near-source shallow earthquakes triggered by displacement along a system of E-W trending reverse faults that are known to be active in the Cascadia forearc; and deep earthquakes that are localized along the Juan de Fuca Plate as it slides beneath North American Plate in the southern Georgia Basin. Both of these source zones have the potential to generate destructive earthquakes that would cause significant damage and socioeconomic disruption throughout the region [Molnar, 2011; 2012; Molnar et al., 2014].

PART II: WHAT CAN WE EXPECT FROM A MAJOR EARTHQUAKE?

Shakeout scenarios are narrative accounts that explain in a general way what could happen if a major earthquake were to occur at some point in the future. They are based on numerical loss estimation models that provide insights on expected physical impacts and associated socioeconomic consequences for a plausible earthquake event. Shakeout scenarios provide a common framework of understanding and the necessary context to explore ways of reducing future losses through mitigation and adaptation.

The following is an account of what might be expected in the District of North Vancouver if a M7.3 earthquake were triggered in the Strait of Georgia at some point in the future. Although plausible, the scenario described in Part II of this study (Chapters 4-7) is not a prediction of what will happen. Rather, it represents a 'what-if' scenario to assist emergency managers and municipal planners in identifying actions that can be taken in advance of a catastrophic earthquake to reduce risk and increase disaster resilience in the community

Chapter 4 - Earthquake Hazards: Expected levels of ground shaking and related ground failure

Chapter 5 - Buildings: Physical vulnerability and likelihood of physical damage to buildings in the DNV

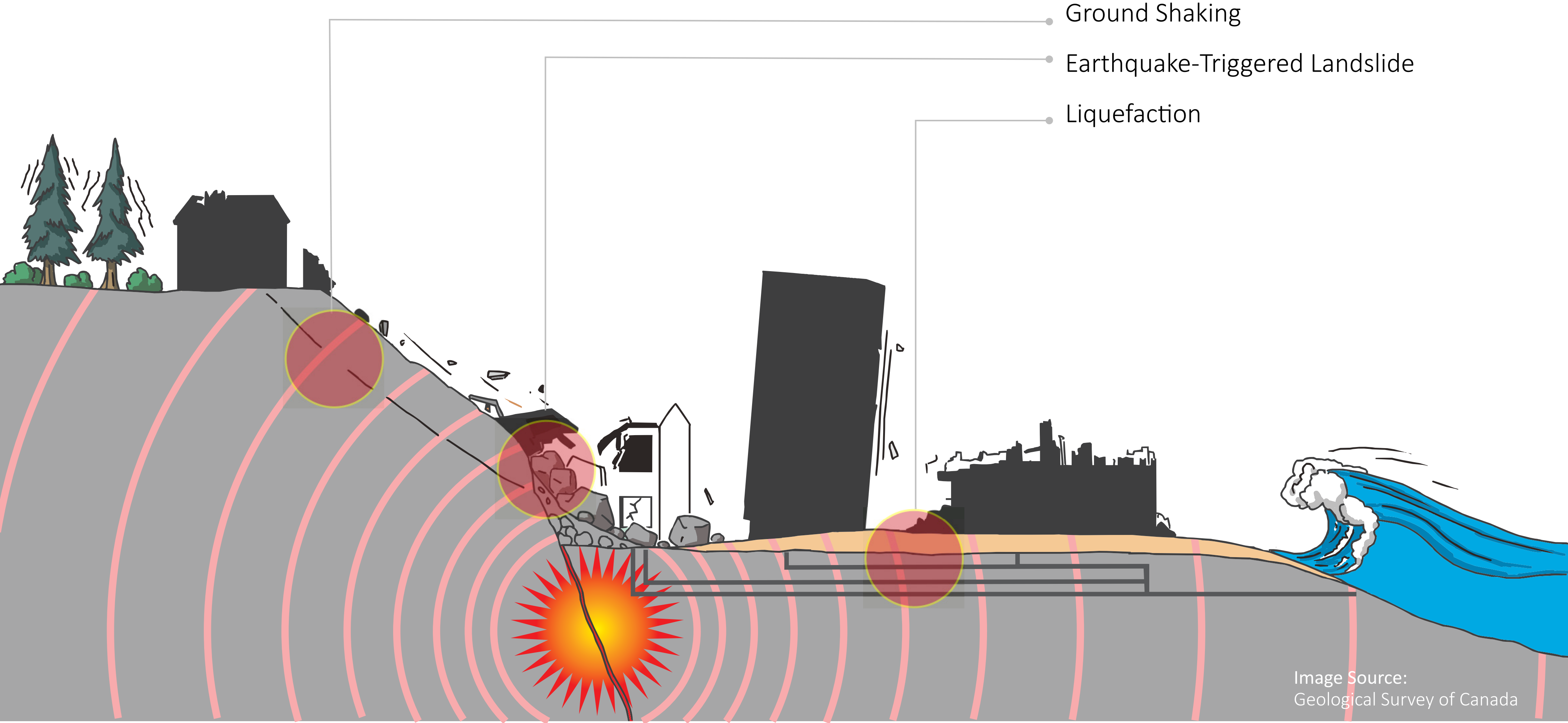
Chapter 6 - People: Social vulnerability and likelihood of casualties and social disruption in the DNV

Chapter 7 - Lifelines: Resilience of essential lifeline systems, including water, power and transportation

Chapter 8 - Economy: Expected losses related to physical damage and business disruption

Image Source:
http://4move2nz.blogspot.ca/

CHAPTER 4:
THE SCENARIO EARTHQUAKE



Ground Shaking

Earthquake-Triggered Landslide

Liquefaction

Image Source:
Geological Survey of Canada

CHAPTER 4: THE GEORGIA STRAIT M7.3 SCENARIO EARTHQUAKE

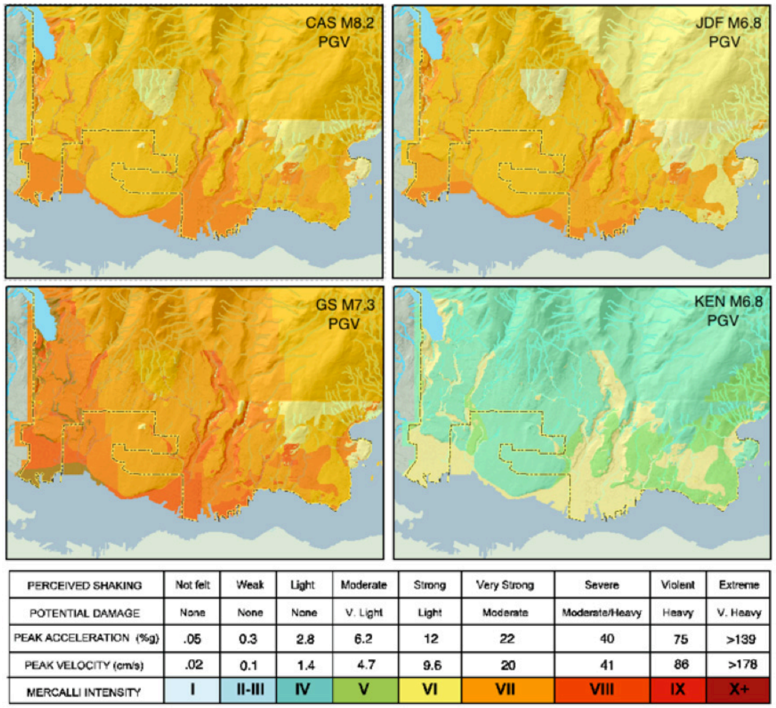
Primary Authors: Journeay, J.M., Prieto, J.A., and Ventura, C.E.

This chapter describes results of a detailed seismic hazard assessment for a hypothetical M7.3 scenario earthquake that is triggered by displacement along a zone of active faulting and seismicity in the Strait of Georgia. The fault zone is part of a regional system of E-W trending structures that accommodate margin parallel shortening in the upper plate of the Cascadia subduction zone, and along which a number of destructive earthquake events have occurred over the past 500 years. Ground motion models for the Georgia Strait scenario earthquake are the basis for an assessment what might be expected from a major near-source earthquake in terms of building damage, casualties, lifeline functionality and economic losses (See Chapters 5 to 8).

APPROACH AND METHODOLOGY

Detailed 1:20,000 scale ground motion models have been developed for the North Vancouver region to assess the likely impacts and consequences of representative earthquake events from each of the seismic source zones that are likely to be of concern to the community [Prieto et al., 2012]. Each of the ground motion models represents just one of many possible rupture scenarios within their respective source zones (See Figure 46).

Representative seismic scenarios include an offshore megathrust earthquake along the Cascadia Subduction Zone (CAS;M8.2), a deep crustal earthquake within the Juan de Fuca Plate in the southern Georgia Basin-Puget Lowland (JDF; M6.8), a near source shallow crustal earthquake in the Strait of Georgia (GS;M7.3), and a more distant shallow crustal earthquake along the Canada-US border near the town of Kendall (KEN;M6.8).



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very Strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	None	None	None	V. Light	Light	Moderate	Moderate/Heavy	Heavy	V. Heavy
PEAK ACCELERATION (%g)	.05	0.3	2.8	6.2	12	22	40	75	>139
PEAK VELOCITY (cm/s)	.02	0.1	1.4	4.7	9.6	20	41	86	>178
MERCALLI INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 46: Deterministic ground motion models of peak ground velocity for representative earthquake scenarios that are likely to be of concern for the District of North Vancouver.

Seismic hazards for each of the earthquake scenarios are compared on the basis of patterns and intensities of peak ground velocity (PGV; %g). With the exception of the Kendall scenario, all are characterized by patterns strong and very strong shaking that decrease to the Northeast, away from seismic source zones.

A complementary suite of probabilistic models have been developed for the DNV to measure the likelihood of exceeding minimum thresholds of ground shaking from all known earthquake hazards in the region [Prieto et al., 2012]. The models are based on analytic methods used to develop the 4th generation probabilistic seismic hazard assessment for Canada [Adams and Atkinson, 2003; Halchuk and Adams, 2008], but with a ground resolution appropriate for site-level analysis. Seismic safety guidelines established in the National Building Code of Canada for building performance and site-level design are based on probabilistic scenarios in which ground shaking intensities meet or exceed minimum thresholds for a recurrence interval of 1/2,475 years (2% in 50 years).

Scenario Selection

The choice of shakeout scenarios for a community depends very much on the planning context and specific requirements of the decision making process. For emergency management and pre-event planning it is common to select a scenario earthquake with a potential for damage and social disruption that exceeds local capabilities for response and recovery, and that tests the full range of operational capacities for disaster risk management at all jurisdictional boundaries. This can be a credible ‘worst-case’ scenario and/or one that is considered ‘most likely’ to occur in the near future.

Mitigation and disaster risk reduction activities require the use of more specific ‘planning scenarios’ that are based on plausible earthquake events with a potential for socioeconomic losses that meet or exceed minimum thresholds of risk tolerance established by a community or organization. In the absence of pre-existing risk tolerance criteria, planning scenarios can be selected on the basis of national guidelines for financial institutions in which expected losses meet or exceed a 0.2% probability of occurrence in any given year [AIR Worldwide, 2013; OSFI, 2013b].

We selected the Georgia Strait scenario earthquake because it represents a scientifically plausible scenario with a potential to generate losses that are relevant to the needs of emergency planning in the DNV, and that are consistent with national guidelines for disaster mitigation and risk reduction planning. Ground motion models include an analysis of expected ground shaking and related ground failure hazards (liquefaction and landslides).

Analytic Methods

Our assessment of earthquake hazards for the DNV is based on the Hazus methodology — an integrated loss estimation model developed in the US by the National Institute of Building Sciences (NIBS) and the Federal Emergency Management Agency (FEMA) to facilitate quantitative analysis of natural hazard risks in support of emergency planning and disaster planning at local/regional scales [NIBS, FEMA, 2004; 2011; 2002]. Key elements of the Hazus earthquake module are summarized in Figure 47, including workflows and input data used in analyzing ground motion and deformation hazards.

The computational process begins with the development of detailed ground motion models for a portfolio of deterministic and/or event-based probabilistic scenarios. The models were generated using a third-party ground motion calculator [Prieto et al., 2012], and utilize attenuation relationships to predict shaking intensities based on the fault rupture mechanism most likely to trigger an earthquake in each of the three major source zones in southwestern British Columbia (Halchuk and Adams, 2008). Deterministic ground motion models are further refined based on the orientation, length and rupture characteristics of the fault zone along which the scenario earthquake occurs; the location and depth of the earthquake hypocentre; and the total expected magnitude of energy released by the earthquake event.

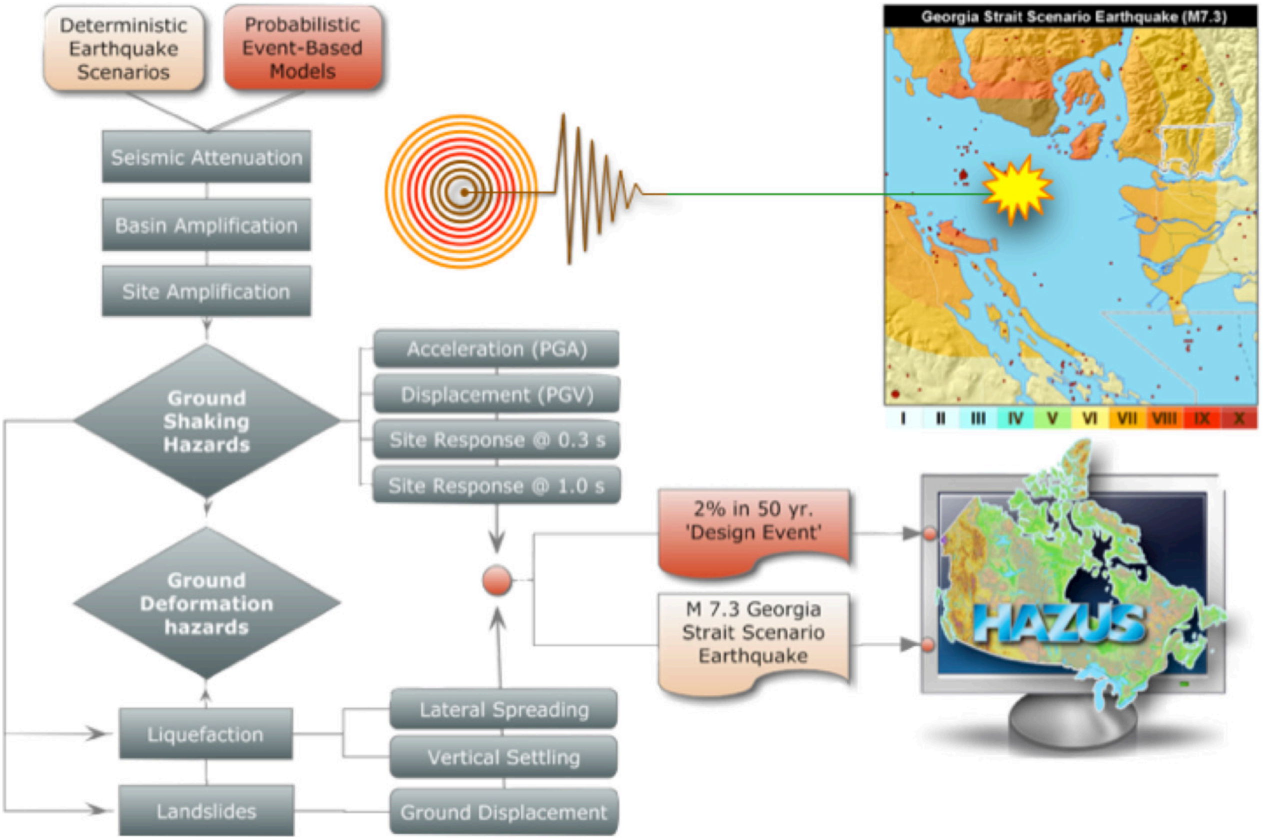


Figure 47: An overview of the Hazus earthquake module and analytic workflows used for assessing ground shaking and associated ground failure in the District of North Vancouver

Outputs of the seismic attenuation model are then adjusted to account for the effects of regional basin and/or local site amplification — each of which has the potential to significantly modify the propagation and the intensity of seismic energy as it travels from the earthquake source to the ground surface. The resulting ground motion model is represented as a map in which the spatial variation and intensity of shaking are measured in terms of peak ground acceleration (PGA), displacement or peak ground velocity (PGV) and spectral accelerations that are used in assessing building response characteristics for both short and long period seismic wave (Sa0.3s and Sa1.0s).

The intensity of seismic shaking at any given location is then combined with information about physiography, surficial geology and groundwater depth to assess the likelihood and magnitude of ground failure by liquefaction and/or seismically induced landslides. Separate ground failure assessments are made for liquefaction settlement and lateral spreading, and for down-slope displacements caused by landslides. The resulting GIS datasets are then combined with corresponding ground motion parameters to generate an integrated seismic hazard assessment that is incorporated as a model input in Hazus to assess damages and related socioeconomic losses for each of the scenario earthquakes [FEMA, 2011].

THE EARTHQUAKE EVENT

On June 24, 1997, an earthquake measuring M4.6 was triggered by displacement along a shallow crustal fault in the Strait of Georgia – midway between Nanaimo and Metro Vancouver (See Figure 48). The earthquake rumbled across a broad region encompassing southern Vancouver Island, the Sunshine Coast and Metro Vancouver. It was felt as far east as Abbotsford and as far south as Seattle. Reports of minor damage included broken glass in Vancouver and a broken water pipe in North Vancouver (MMI III-IV). The earthquake was preceded by a M3.4 foreshock event on June 13, and by numerous small aftershock events. There have been six other significant earthquakes (M>2) in this same zone of active seismicity over the past 40 years. The largest of these was a M4.9 earthquake in 1975 that was accompanied by a strong aftershock sequence.

In the following sections, we consider what might be expected if the Georgia Strait Fault were to rupture again with a displacement capable of causing a M7.3 earthquake. The scenario is similar in magnitude to the 1946 earthquake that occurred along a shallow crustal fault on eastern Vancouver Island near Comox, and is representative of other shallow crustal earthquakes that are believed to have occurred in the Georgia Basin region over the past ~500 years [Hyndman et al., 2003].

Our assessment of ground shaking and ground failure for the scenario earthquake is not a prediction of what is most likely to occur. Rather, it represents a plausible scenario of what could occur if the fault were to rupture again with more force at some point in the future.

Regional Geologic Setting

The history and geological architecture of the Georgia Basin region play an important role in shaping seismic hazards for the District of North Vancouver. The Georgia Basin is a crustal depression that has accumulated sedimentary deposits shed westward from mountain highlands over the past ~85 million years. Igneous and metamorphic rocks that underlie the North Shore Mountains include relics of an ancient crustal fragment that was accreted onto the North American plate margin around 150 million years ago. The Coast Mountains have since been uplifted, tilted and eroded several times during successive episodes of mountain building [Monger and Journeay, 1994; Mustard and Rouse, 1994].

Pleistocene glaciers from higher elevations of the Coast Mountains coalesced nearly 26,000 years ago into a massive ice sheet (>1800 metres thick) that flowed down Burrard Inlet into the Georgia Strait and southward into the Puget Lowland. Advance of the ice sheet resulted in widening of the Capilano, Seymour and Lynn valleys, and isostatic subsidence along a broad coastal shelf that extended southward into the Puget Lowland. The North Shore Mountains and foothill regions along Burrard Inlet are blanketed by thick accumulations of alluvial sediments deposited in marine and fresh-water lake environments during the Fraser Glaciation (26,000 – 11,000 years ago), and by a younger sequence of fluvial sediments deposited in melt water channels as the ice receded [Bednarski, 2013; Clague, 1998].

The modern history of sedimentation in the study area is characterized by reworking of older post-glacial deposits by rivers and occasional debris flows along valley bottoms, and by mass wasting caused by intermittent landslides along valley walls and steep unstable slopes at higher elevations of the North Shore Mountains. The landscape has also been extensively altered by human activity to accommodate ongoing growth and development. This includes major infill and land reclamation along the waterfront to accommodate commercial/industrial development and the expansion of port and rail facilities, localized infill of smaller river valleys for residential development and for the construction of berms to mitigate impacts of flooding and debris flows along major river drainages [Bednarski, 2013].

The Georgia Strait Fault

Physiographic characteristics the Coast Mountains and adjacent parts of the Fraser Lowland reflect active deformation, mountain building and sea level fluctuations along the forearc portion of the Cascadia subduction zone. Geologic observations record ~3 kilometres of uplift over the past 5 million years (~6 mm/year) with adjacent parts of the Georgia Basin subsiding at rates of ~1 mm/year [See:Monger and Journeay, 1994, and referenced cited within].

The horizontal component of deformation appears to have been partitioned across a network of faults that record both margin-normal and margin-parallel shortening of the Cascadia forearc [M Journeay, 2001]. The margin-normal component of shortening appears to be accommodated along a network of NW-trending thrust faults and related structures that extend through the southern Gulf Islands and eastern Vancouver Island.

The Georgia Basin Fault is a WSW-trending zone of brittle deformation that cuts diagonally across older igneous and metamorphic basement rocks of the Cascadia forearc, and overlying sedimentary rocks of the Georgia Basin. It is part of a family of thrust faults that are believed to have formed by margin-parallel compression and shortening of the North American plate over the past 5-7 million years [M Journeay, 2001].

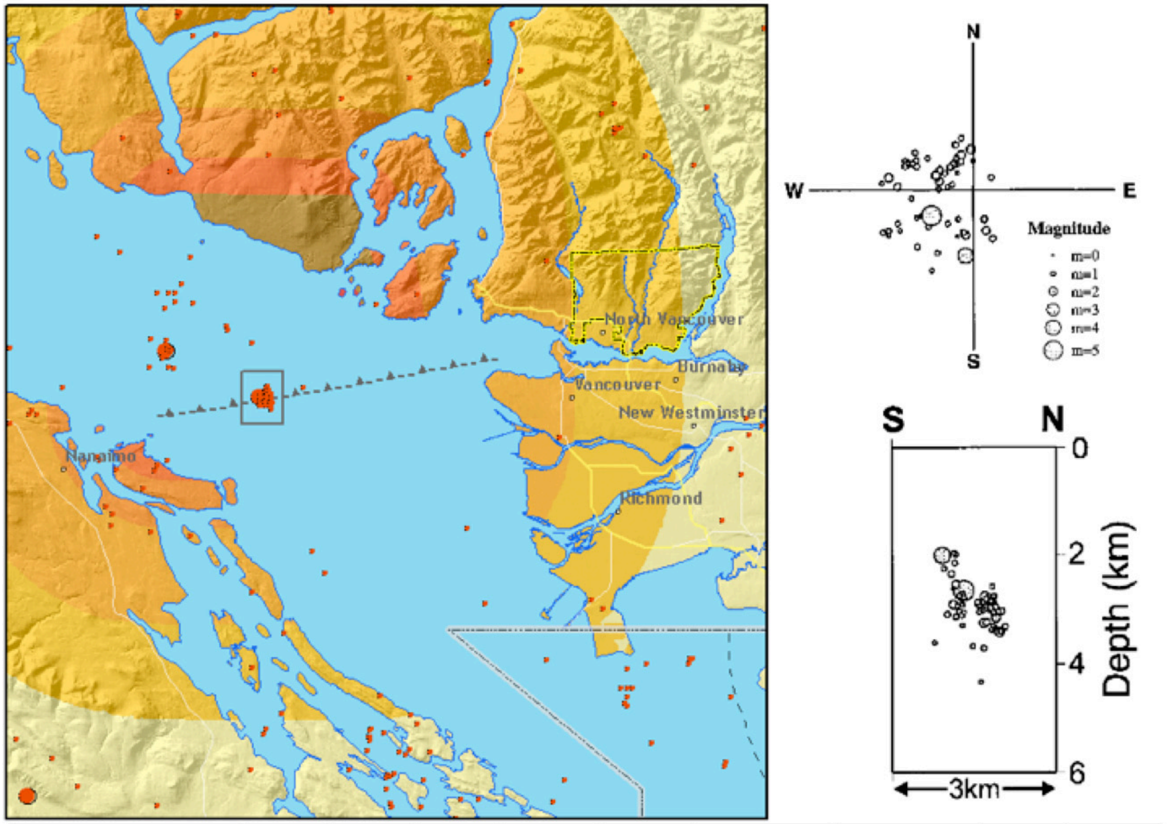
Evidence of Holocene displacement along the Georgia Strait Fault is corroborated by submarine seismic reflection data that delineate a broad WSW-trending zone of deformation in post-glacial sedimentary rocks [Mosher et al., 2000]. Although there is no direct evidence for surface fault rupture, interpretations of seismic reflection data are consistent with reverse displacement along a thrust fault that dips steeply to the NNW. The zone of active deformation is aligned with aeromagnetic anomalies that extend across the axis of the Georgia Basin.

Source Zone Characteristics

Fault plane solutions for the 1975 M4.9 event suggest that it was most likely triggered by reverse-slip along a WSW-trending thrust fault dipping ~50 degrees to the NNW [265/47; Rogers, 1979]. Fault plane solutions for the 1997 M4.6 event are consistent with this interpretation and also suggest reverse slip along a WSW-trending thrust fault dipping 47 degrees to the NNW [262/47; Cassidy et al., 2000].

Relocation of earthquake hypocentres associated with the full sequence of seismic activity leading up to and following the M4.6 event of June 24, 1997, delineate a fault plane at 2-4 km depth dipping to the NNW at 53 degrees, in good agreement with previously modelled fault plane solutions (See Figure 48). Results of these studies provide unambiguous evidence for active faulting in the Strait of Georgia and are consistent with geodetic and regional tectonic interpretations of margin-parallel shortening in the Holocene [Kelsey et al., 2012; Mazzotti et al., 2003].

The likelihood of a M7.3 earthquake on the Georgia Strait Fault is unknown. There is potential for shallow crustal earthquakes of this type and magnitude to occur in the Cascadia forearc every ~400 years [p=0.0025/yr; Hyndman et al., 2003]. The probability of displacement along a segment of the Georgia Strait Fault as shown in Figure 48 is considerably less. On the basis of frequency-magnitude relationships developed as part of the 4th generation probabilistic hazard assessment [Halchuk and Adams, 2008], ground motions equivalent to that of the Georgia Strait scenario earthquake are likely to occur with a recurrence interval of 1/2475 years (p = 0.000404).



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very Strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	None	None	None	V. Light	Light	Moderate	Moderate/Heavy	Heavy	V. Heavy
PEAK ACCELERATION (%g)	.05	0.3	2.8	6.2	12	22	40	75	>139
PEAK VELOCITY (cm/s)	.02	0.1	1.4	4.7	9.6	20	41	86	>178
MERCALLI INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 48: Map showing regional ground shaking intensities associated with the scenario earthquake and the location of significant shallow crustal earthquakes that have occurred in the Georgia Basin since 1975.

A statistical analysis of seismic events recorded over the past ~40 years indicates that the likelihood of a M7.3 along the Georgia Strait deformation zone is relatively small with a recurrence interval of ~1/10,000 years (P= 0.0001; this study). However, the historic record of seismic activity is not sufficient to draw any conclusions about the potential of low probability/high consequences events. As recent events in Japan and New Zealand have clearly demonstrated, statistical probabilities based on a limited seismic record do not necessarily reflect the potential of rare or unforeseen earthquake disasters in regions of active deformation.

Based on source zone characteristics outlined above, we have modelled the scenario earthquake as the outcome of reverse displacement along a blind thrust that ruptures a ~54 km segment of the Georgia Strait Fault. The hypocentre is located at a depth of <10 km and encompasses the same zone of intense shallow crustal seismicity in which previous M4.9 and M4.6 events are known to have occurred. The fault zone dips to the NNW at 53 degrees. The amount of energy released by sudden rupture along the Georgia Strait Fault would be capable of generating a M7.3 earthquake that would be felt throughout the Pacific northwest. Incremental displacement along the fault zone is also likely trigger a swarm of aftershock events that would continue for weeks and months after the initial event.

GROUND SHAKING HAZARDS

The intensity of ground shaking that would be caused by a M7.3 rupture along the Georgia Strait Fault is a function of distance away from the epicentre and the extent to which seismic waves traveling toward and along the earth's surface are modified by subsurface basin structures, and by surficial deposits that have a potential to either attenuate or amplify the intensity of ground motion that is felt at any given location. We have used New Generation Attenuation (NGA) equations of Boore and Atkinson [2008] to model primary ground motions [Prieto et al., 2012] and results of recent seismic studies to evaluate regional basin effects and local site amplification within the District of North Vancouver [Molnar, 2011; 2012; Prieto and Ventura, 2013].

Regional Basin Amplification

Regional basin amplification occurs when seismic waves are refracted and intensified by subsurface structures, and/or converted into longer-period and more destructive surface waveforms by reflection within or along the basin edge. 3D modelling of seismic amplification in the Georgia Basin has shown that ground shaking intensities are likely to be increased by a factor of ~5 for deep earthquakes in the Juan de Fuca Plate, and by a factor of ~10 for shallow crustal earthquakes that are triggered in the North American Plate [Molnar, 2011; Molnar et al., 2014].

The degree of amplification diminishes toward the basin edge but is significant in the Vancouver region where ground motions are amplified by a factor of ~2.3 above ambient background levels for deep crustal earthquakes, and by a factor of ~ 3.0 for shallow crustal faults in the northern Strait of Georgia. The pattern of basin amplification appears to correspond with the location of an EW-trending subsurface depression that extends beneath Vancouver and Burnaby. The effects of basin amplification for a shallow crustal earthquake in the Strait of Georgia decrease along the basin edge and are estimated to be less than a factor of ~1.5 within the District of North Vancouver.

Local Site Amplification

Site amplification can occur in areas where seismic energy encounters softer sediment overlying bedrock, and/or where seismic waves are focused above buried valleys filled with soft sediment. The amplitude, frequency and duration of shaking is strongly affected by the physical characteristics of materials through which the waves travel over the last few hundred meters toward the surface [Hunter and Crow, 2012]. Seismic waves shorten in wavelength and increase in amplitude as they pass from more dense material into softer soils with lower shear wave velocity characteristics [Shearer and Orcutt, 1987].

The map in Figure 49 reflects our interpretation of local site amplification potential for the District of North Vancouver. Amplification factors are based on classification guidelines for soil type and corresponding shear wave velocities (Vs_{30}) established by the National Earthquake Hazard Reduction Program [NEHRP; FEMA, 1994] and adapted for use in seismic assessment for the National Building Code of Canada [Finn and Wightman, 2003]. Our interpretation of NEHRP soil classes and corresponding Vs_{30} characteristics is based on detailed mapping of bedrock and surficial deposits, subsurface information collected from boreholes and direct geophysical measurements [Bednarski, 2013; Molnar, 2012; Prieto and Ventura, 2013].

Standard Penetration Test (SPT) measurements from eighty boreholes were used to validate and refine Vs_{30} estimates for both surface and subsurface materials [Prieto and Ventura, 2013]. An additional ninety in situ micro-tremor measurements from across the District of North Vancouver, and site period measurements for representative soil classes at 3 sites were used to further improve our interpretation of Vs_{30} and seismic response characteristics [Molnar, 2012]. Uncertainties in our interpretation are reflected as a percentage of NEHRP site classes that are likely to be present within each of the generalized map units.

Amplification factors for standard NEHRP soil classes were applied to ambient ground motion values for the Georgia Strait scenario earthquake to assess the distribution and intensity of shaking over a range of frequencies. Resulting ground motion estimates are amplified by a factor of 1.1-2.1 in areas dominated by stiff and soft soils (NEHRP Site Classes D and E: $Vs_{30} < 360$ m/s), and deamplified by a factor of 0.5-0.9 in areas dominated by denser bedrock units (NEHRP Site Classes A and B; $Vs_{30} > 760$ m/s).

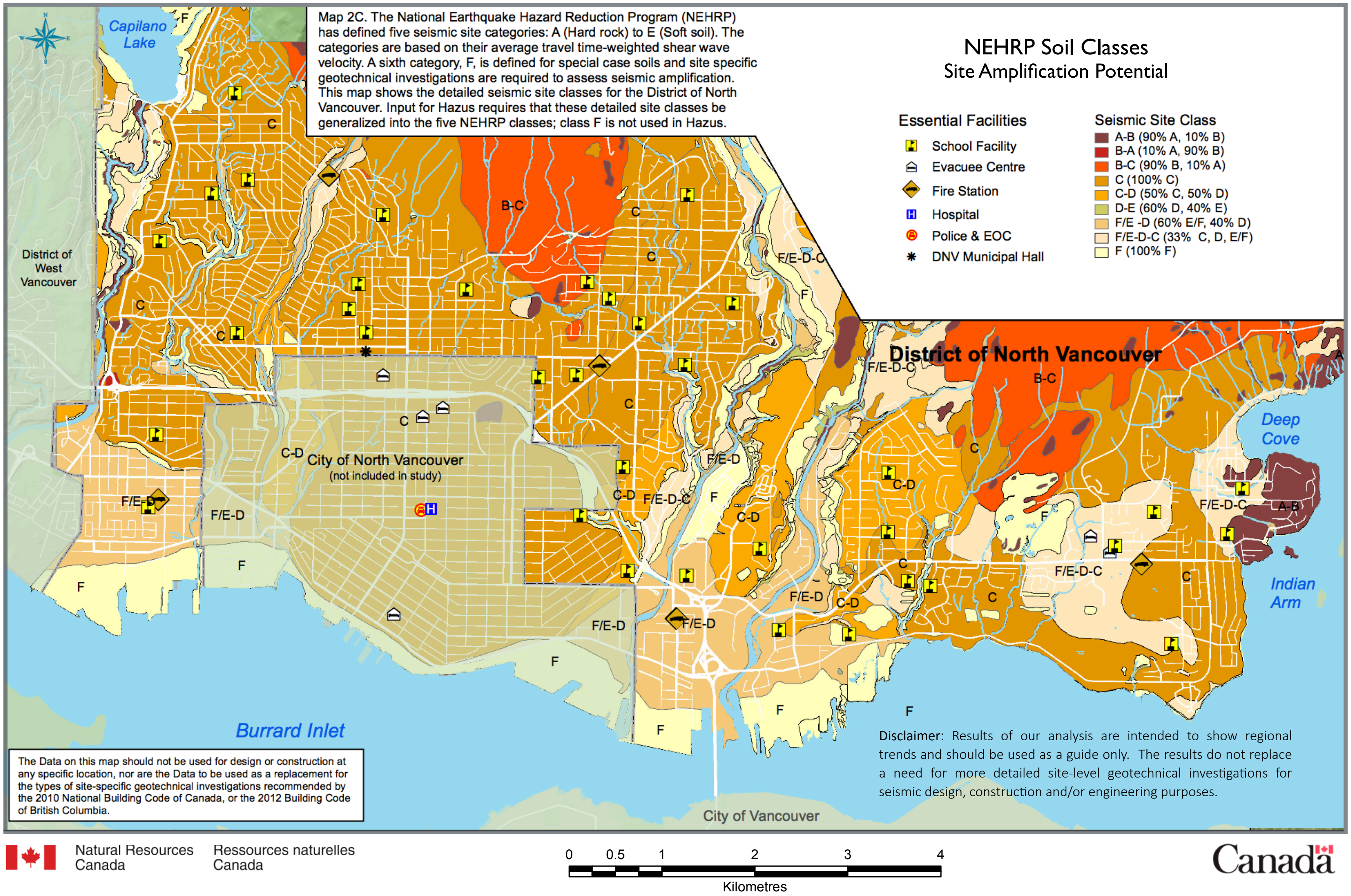
Ground Motion Model

Because the earthquake epicentre is located close to the earth's surface, it would be felt widely throughout the Georgia Basin region with very strong and locally severe ground shaking in the Metro Vancouver region (MMI VII-VIII). The main earthquake event would likely last only 20 and 30 seconds but would be felt as a combination of rumbling pressure waves causing violent push-pull motions, and rolling surface waves that would rock buildings and make it difficult to stand or drive a vehicle.

Figure 50 is a composite ground shaking intensity model that shows the effects of local site amplification for the Georgia Strait scenario earthquake in terms of expected Modified Mercalli Intensity (MMI) values. Each MMI interval is correlated with specific ground shaking parameters that are used in assessing different types of damage for buildings and engineered structures. These include measures of peak ground acceleration (PGA), displacement or peak ground velocity (PGV), and spectral accelerations that are used in assessing building response characteristics for both short and long period seismic waves (Sa0.3s and Sa1.0s, respectively).

In terms of ground shaking intensity, the Georgia Strait scenario is an example of what might be expected for a cumulative portfolio of earthquake hazards with a return period of ~1/500 years (p~12% in 50 years). With respect thresholds used to establish seismic safety guidelines in the 2010 National Building Code of Canada (1/2475 years; p =2% in 50 years), the Georgia Strait scenario ranks ~80% in terms of maximum peak ground velocity (PGV) and ~64% in terms of maximum lateral building displacement (See Figures 51).

Peak ground acceleration (PGA) is a measure of the instantaneous horizontal force (%g) that a particle is likely to experience during an earthquake event. It is used primarily in assessing the potential for seismically induced ground deformation such as liquefaction and earthquake-triggered landslides. Peak ground velocity (PGV) is

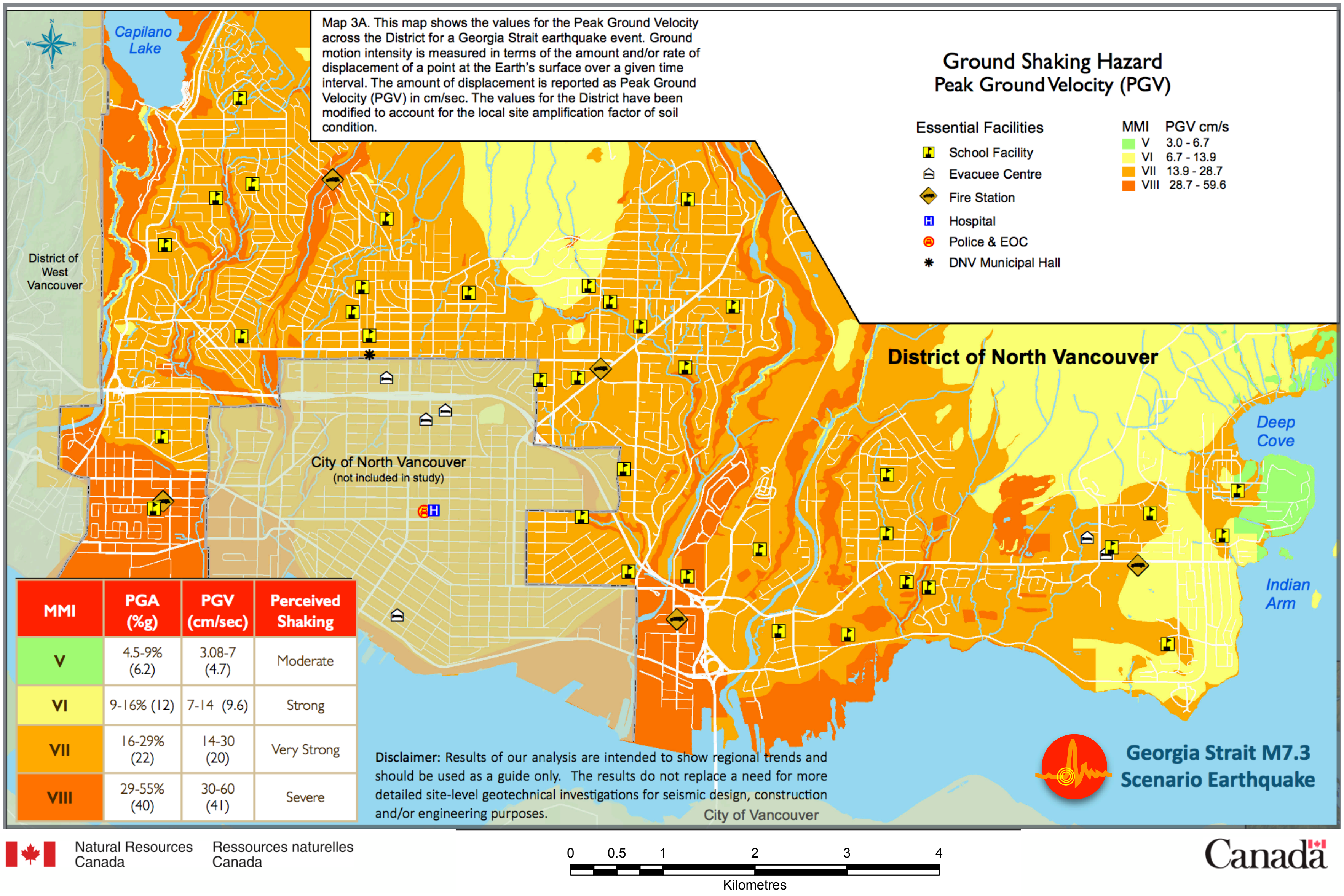


Map 2C. The National Earthquake Hazard Reduction Program (NEHRP) has defined five seismic site categories: A (Hard rock) to E (Soft soil). The categories are based on their average travel time-weighted shear wave velocity. A sixth category, F, is defined for special case soils and site specific geotechnical investigations are required to assess seismic amplification. This map shows the detailed seismic site classes for the District of North Vancouver. Input for Hazus requires that these detailed site classes be generalized into the five NEHRP classes; class F is not used in Hazus.

The Data on this map should not be used for design or construction at any specific location, nor are the Data to be used as a replacement for the types of site-specific geotechnical investigations recommended by the 2010 National Building Code of Canada, or the 2012 Building Code of British Columbia.

Disclaimer: Results of our analysis are intended to show regional trends and should be used as a guide only. The results do not replace a need for more detailed site-level geotechnical investigations for seismic design, construction and/or engineering purposes.

Figure 49: Map showing site amplification potential for the District of North Vancouver based on an interpretation of NEHRP soil class characteristics and guidelines developed as part of the 4th generation national seismic hazard assessment for Canada (Adams and Halchuk, 2003)



Map 3A. This map shows the values for the Peak Ground Velocity across the District for a Georgia Strait earthquake event. Ground motion intensity is measured in terms of the amount and/or rate of displacement of a point at the Earth's surface over a given time interval. The amount of displacement is reported as Peak Ground Velocity (PGV) in cm/sec. The values for the District have been modified to account for the local site amplification factor of soil condition.

MMI	PGA (%g)	PGV (cm/sec)	Perceived Shaking
V	4.5-9% (6.2)	3.08-7 (4.7)	Moderate
VI	9-16% (12)	7-14 (9.6)	Strong
VII	16-29% (22)	14-30 (20)	Very Strong
VIII	29-55% (40)	30-60 (41)	Severe

MMI	PGV cm/s
🟩 V	3.0 - 6.7
🟨 VI	6.7 - 13.9
🟧 VII	13.9 - 28.7
🟧 VIII	28.7 - 59.6

Disclaimer: Results of our analysis are intended to show regional trends and should be used as a guide only. The results do not replace a need for more detailed site-level geotechnical investigations for seismic design, construction and/or engineering purposes.

Figure 50: Composite ground motion model for the District of North Vancouver showing spatial distribution and intensities of shaking with site amplification.

a measure of the instantaneous displacement that a particle is likely to experience during an earthquake event and is a reliable indicator of damage potential. Spectral acceleration provides a more refined measure of what a building is likely to experience for short and long periods of vibration. Short period spectral accelerations at 0.3s are used to predict expected patterns of structural damage for low-rise buildings (1-3 stories) while longer period spectral accelerations at 1.0s are used to predict expected patterns of damage for taller buildings (on the order of 10 stories) and linear engineered structures that have a natural period of oscillation at these longer time intervals.

Ambient peak ground velocities for the Georgia Strait scenario earthquake decrease to the northeast away from the seismic source zone with values that range between 12 and 24 cm/s (MMI VII). As illustrated in Figure 50, ground motions are amplified by a factor of two in post-glacial delta deposits along the Capilano and Seymour valleys (29-41 cm/s; MMI VII), and by a factor of nearly three in areas that have been reclaimed with infill along the waterfront (41-48 cm/s; MMI VIII). Conversely, peak ground velocities are deamplified to 6.3-9.6 cm/s in areas underlain by bedrock and thin glacial till along Indian Arm and in eastern portions of the study area (MMI VI).

Building motions measure the lateral displacement of a building envelope with respect to a fixed point on the surface. Building displacements for the Georgia Strait scenario earthquake are expected to range from less than a centimetre to as much as 15.2 cm in areas of local site amplification (See Figure 51). Though within the range of what is considered safe for recently constructed buildings, lateral displacements of this magnitude are sufficient to cause structural failure and/or collapse in older masonry and concretes buildings that do not conform to current seismic safety design guidelines.

Comparative Analysis of Earthquake Hazard potential	Georgia Strait M7.3 Earthquake Scenario			2% in 50-year Design Earthquake		
	Shaking & PGD			Shaking & PGD		
	Min	Max	Mean	Min	Max	Mean
Ground Shaking						
PGV (cm)	6.4	48.1	20.3	17.4	58.9	35.2
PGA (%g)	0.1	0.4	0.3	0.4	0.5	0.5
Sa0.3s (g)	0.2	0.7	0.5	0.7	0.9	0.8
Sa1.0s (g)	0.1	0.5	0.2	0.2	0.6	0.4
Building Motion						
Displacement (cm)	0.4	15.3	1.3	1.2	24.0	2.5
Acceleration (%g)	0.1	0.4	0.3	0.2	0.6	0.4
Liquefaction						
L. Spreading (cm)	0.0	99.3	21.3	0.0	382.9	137.0
V. Settling (cm)	0.0	15.2	4.8	0.0	15.2	4.9
Eq-Landslides						
Displacement (cm)	5.1	152.4	27.8	7.6	165.1	90.9

Figure 51: Comparative analysis of representative ground motions for the Georgia Strait M7.3 scenario earthquake and the 2% in 50 year 'Design' earthquake.

GROUND FAILURE HAZARDS

The initial quake would be likely followed by lesser magnitude but significant aftershock events that could last for several months. In addition to intense shaking, the Georgia Strait scenario earthquake would also cause liquefaction in low-lying areas and seismically triggered landslides in steeper terrain along valley escarpments. The intensity of shaking and related ground deformation hazards would be similar to those experienced during the powerful M6.3 earthquake that struck Christchurch, New Zealand in 2011.

Liquefaction

Lateral spreading and vertical settlement potential were estimated using the Hazus methodology [FEMA, 2011]. Results of our analysis are very comparable to observed patterns of liquefaction following the February 2011 earthquake in Christchurch, New Zealand [Cubrinovski et al., 2011]. As it turns out, the two areas are very similar in terms of geologic setting and ground shaking characteristics. Both are underlain by glacial deposits of sand and gravel in low-lying areas of shallow groundwater flow. Peak ground acceleration (PGA) for the Georgia Strait scenario earthquake ranges from 34-38 %g in areas susceptible to liquefaction hazards. Ground motions recorded in the Central Business District of Christchurch are ranged from 37-52% g.

Our assessment of lateral spreading is based on procedures outlined in the Hazus technical manual [FEMA, 2011], which combines the Liquefaction Severity Index (LSI) developed by Youd and Perkins [1978] with ground motion attenuation relationships established by Sadigh et. al., [1986] and tabulated by Joyner and Boore [1988]. Though our assessment highlights the potential for liquefaction spreading, the specific location and magnitude of deformation at any given site is highly variable and dependent on local soil type, proximity to stream valley and waterfront features where lateral spreading can occur, and groundwater levels and degree of saturation during the earthquake.

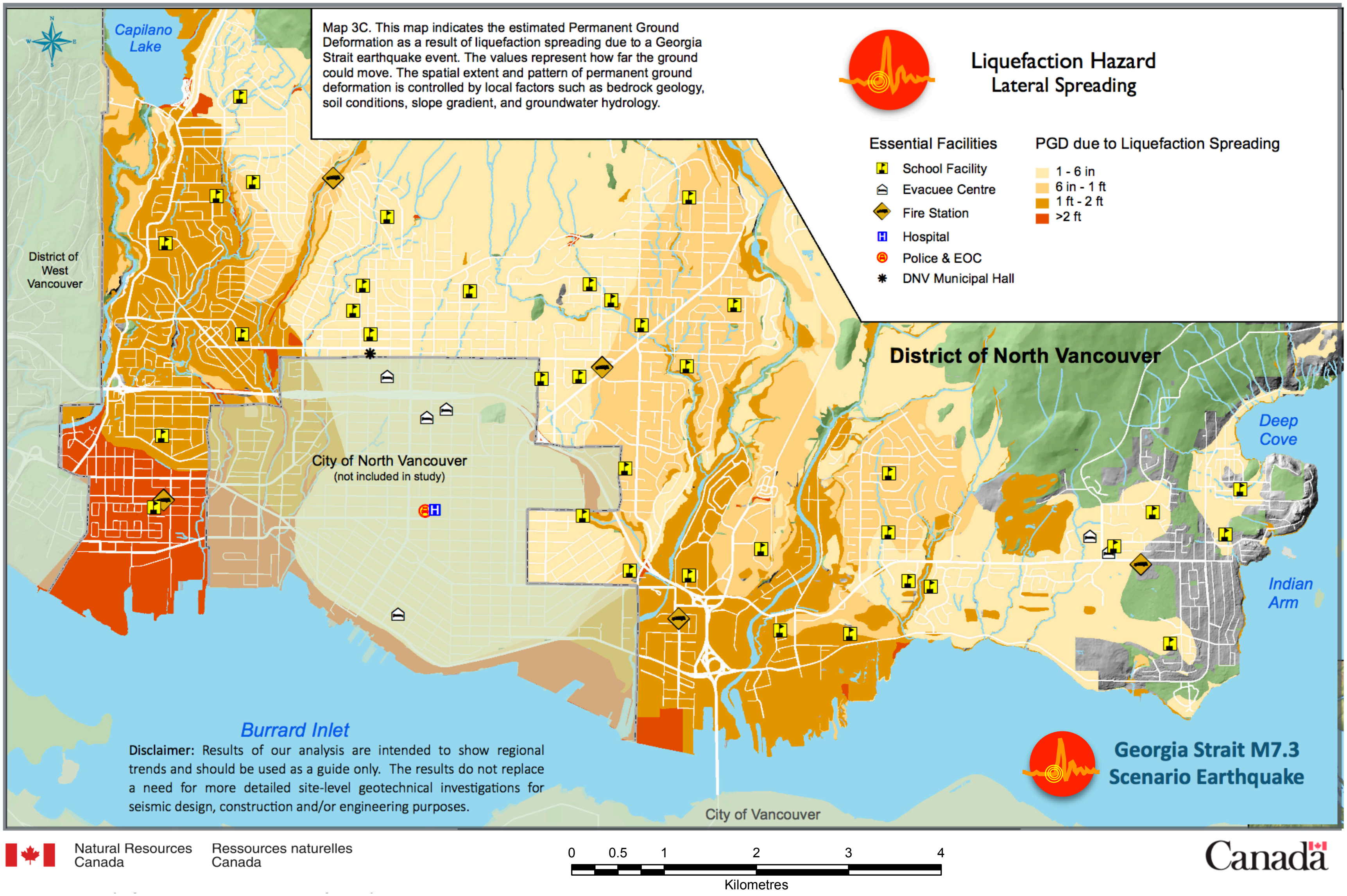
Areas underlain by landfill materials along the waterfront are of greatest concern (sand, gravel and crushed rock), with lateral displacements that are estimated to be up to a metre and in some places greater than 2 metres (See Figure 52). Other areas of concern include delta and outwash terrace deposits of sand and gravel in the lower Capilano and Seymour valleys, where lateral displacements are estimated to be less than a metre.

The component of vertical settlement caused by liquefaction was assessed using standard Hazus procedures [FEMA, 2011], which incorporate methods developed by Tokimatsu and Seed [1987]. Delta terrace and landfill deposits of sand and gravel in the Lower Capilano and Lynn Valleys are particularly susceptible with vertical displacements estimated to be on the order of 15-30 centimetres. Outwash deposits forming terraces along middle reaches of the Capilano and lower reaches of the Seymour River valleys are also susceptible to settlement with displacements estimated to be on the order of 10 centimetres or less.

The effects of liquefaction are well documented for the February 2011 Christchurch earthquake (Cubrinovski et al., 2011) in which more than 1,000 buildings were damaged beyond repair. Many of these structures were adversely affected by deformation caused by liquefaction, including lateral spreading of up to 60 centimetres along the Avalon River, and vertical settlement of 15-30 centimetres throughout much of the Central Business District. Displacements of this magnitude are sufficient to cause tilting, toppling, and the potential collapse of buildings and other structures that have not been engineered to withstand the effects of lateral spreading and settlement. Unreinforced masonry buildings and those without foundations engineered for lateral and vertical displacements were particularly vulnerable to structural damage.

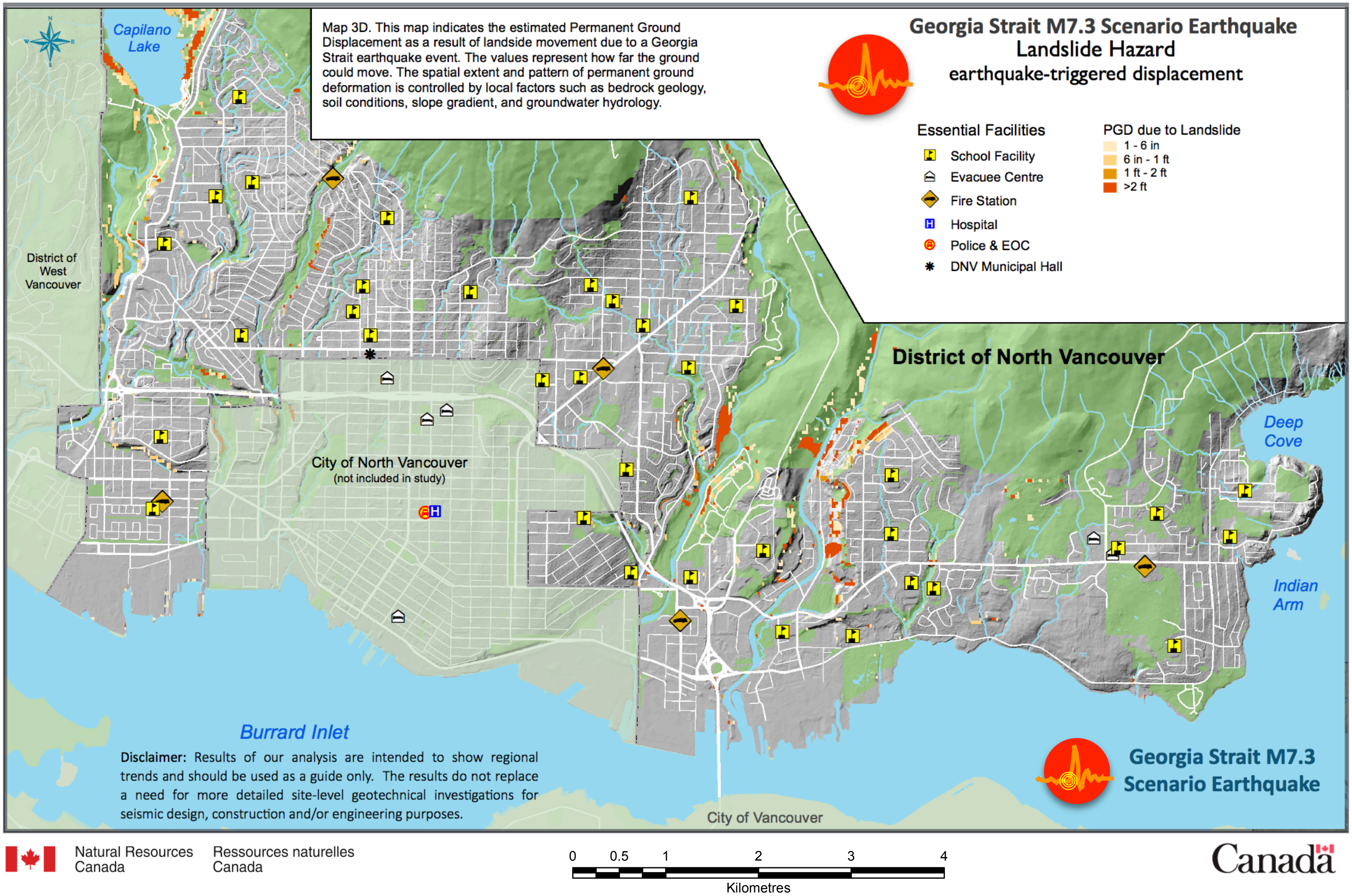
Seismically Induced Landslides

Earthquake-triggered landslides have the potential to occur along steep unstable slopes where vertical and horizontal ground motions result in lateral forces that are strong enough to overwhelm the internal shear strength of surficial materials and the gravitational forces that hold them in place on the hillside. The magnitudes of downslope displacement for coherent landslides triggered by the Georgia Strait M7.3 scenario earthquake were


Map 3C. This map indicates the estimated Permanent Ground Deformation as a result of liquefaction spreading due to a Georgia Strait earthquake event. The values represent how far the ground could move. The spatial extent and pattern of permanent ground deformation is controlled by local factors such as bedrock geology, soil conditions, slope gradient, and groundwater hydrology.

Disclaimer: Results of our analysis are intended to show regional trends and should be used as a guide only. The results do not replace a need for more detailed site-level geotechnical investigations for seismic design, construction and/or engineering purposes.

Figure 52: Liquefaction hazards for the District of North Vancouver. Estimates of lateral spreading are based on intensity of gored shaking and soil conditions.



Map 3D. This map indicates the estimated Permanent Ground Displacement as a result of landside movement due to a Georgia Strait earthquake event. The values represent how far the ground could move. The spatial extent and pattern of permanent ground deformation is controlled by local factors such as bedrock geology, soil conditions, slope gradient, and groundwater hydrology.

Disclaimer: Results of our analysis are intended to show regional trends and should be used as a guide only. The results do not replace a need for more detailed site-level geotechnical investigations for seismic design, construction and/or engineering purposes.

Figure 53: Earthquake-triggered landslide hazards for the District of North Vancouver. Estimates of based on intensity of gored shaking and soil conditions.

estimated using procedures outlined in the Hazus technical manual [FEMA, 2011]. The approach is based on methods developed by Wilson and Keefer [1985], which use static landslide susceptibility and modelled ground motions to assess the critical acceleration needed for failure, and methods derived from Makdisi and Seed [1978], which are used to compute downslope displacement based on the ratio of induced peak ground acceleration (PGA) and critical acceleration of the slide mass.

Results of our analysis are shown in Figure 53. The locations of predicted earthquake-triggered landslides are consistent with landslide deposits preserved in the geologic record [Bednarski, 2013], and with areas of high hazard landslide potential identified by independent geotechnical studies commissioned by the District of North Vancouver [M Porter et al., 2007]. Areas of particular concern include steep valley walls and preserved outwash terraces underlain by late glacial sediments and colluvium along the East shore of Capilano Reservoir, upper reaches of the Capilano River, Mackay Creek, Mosquito Creek, Lynn Creek and the Seymour River.

Magnitudes of downslope displacement for coherent soil slumps and block slides in these areas range from 30 centimetres to a metre or more in places, and are consistent with independent spot-checks carried out using more refined methods based on guidelines for legislated landslide assessments of residential development established by the Association of Professional Engineers and Geoscientists of British Columbia [APEGBC, 2010]. Our analysis does not take into account the effects of second-order landslide hazards such as rock falls and debris flows that might also be triggered as a result of ground shaking and associated downslope displacement.

CHAPTER 5: BUILDINGS

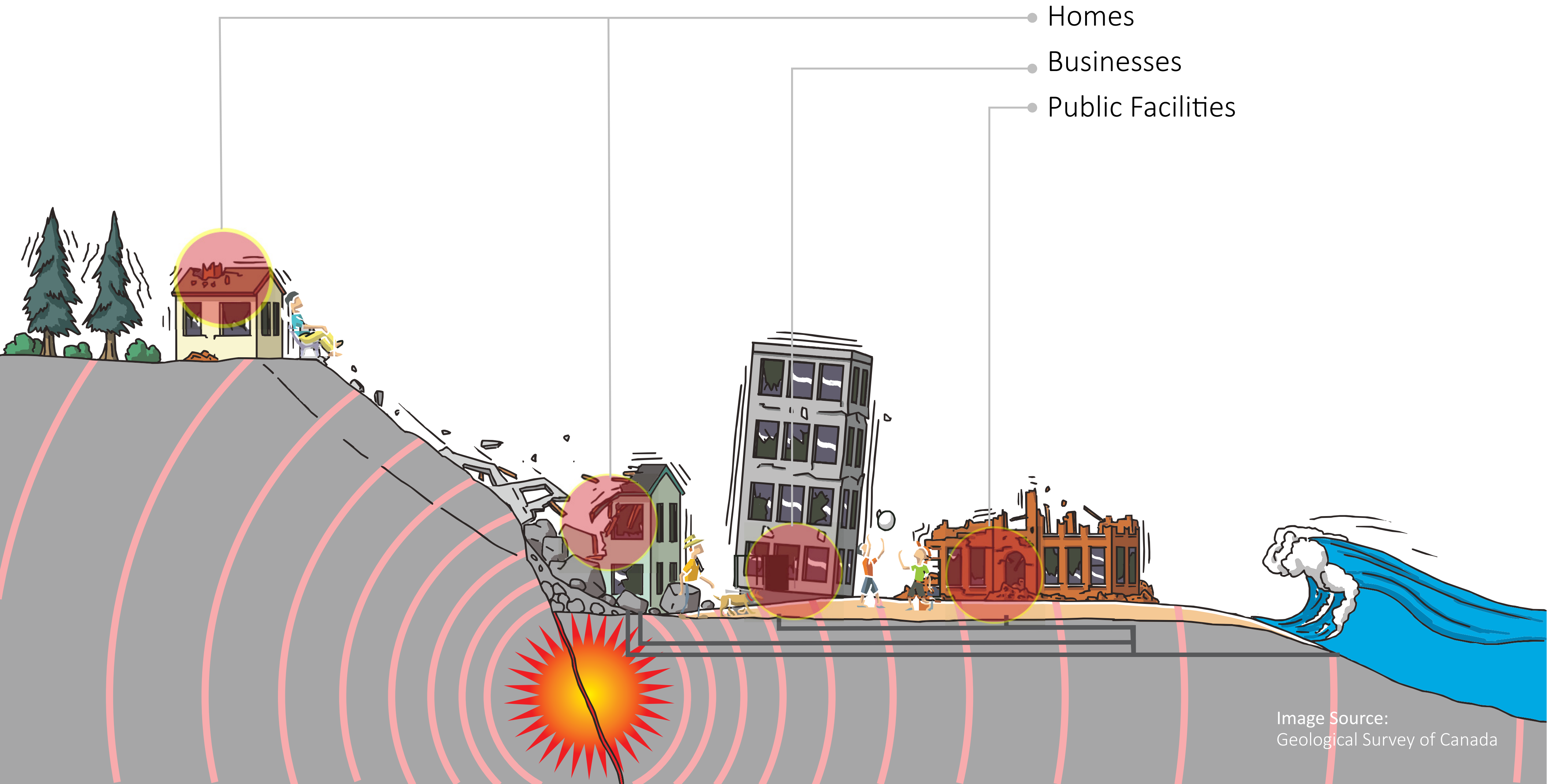


Image Source:
Geological Survey of Canada

CHAPTER 5: BUILDINGS

Primary Authors: Journeay, J.M., Wagner, C.L., Ventura, C., Lotze, A. and Chang, S.

Land use decisions have a direct bearing on the physical vulnerability of a community and the potential for loss in the event of a major earthquake. This chapter explores how trends in community development have shaped land use decisions and resulting patterns of vulnerability in the District of North Vancouver, and the extent to which the built environment is likely to withstand the physical impacts of a major earthquake. Our assessment is focused on damages that are likely to occur as the result of a M7.3 scenario earthquake in the Strait of Georgia.

Results of our study show that the majority of homes and newer buildings conforming to modern seismic design guidelines are likely to sustain little or no damage in the scenario earthquake. Buildings that predate the introduction of seismic safety codes in the early 1970s are vulnerable to significant levels of damage in areas exposed to both extreme ground shaking and liquefaction hazards.

Of particular concern are older wood frame, unreinforced masonry, and concrete buildings in established neighbourhoods and commercial/industrial zones along the waterfront and valley escarpments. An estimated ~840 buildings would likely be destroyed or damaged beyond repair as a result damages to load-bearing structures during the scenario earthquake. An additional ~1000 buildings would sustain structural and non-structural damages that would require inspection and repair during the recovery process.

GENERAL BUILDING CHARACTERISTICS

The District of North Vancouver encompasses an inventory of approximately 24,000 buildings in a ~36 km^2 area along Burrard Inlet, Indian Arm and foothill regions of the North Shore Mountains (Figures 54, 55 and 56). Our assessment of building exposure was carried out at the site level and is based on information provided by District staff and by windshield surveys compiled by Carlos Ventura and colleagues at the UBC Earthquake Engineering Research Facility. For each building, we compiled available information about the type and age of construction, building use (occupancy class) and square footage. On the basis of this information, we estimated replacement costs, business income, and the numbers of people present during different times of day using best practice guidelines [FEMA, 2011].

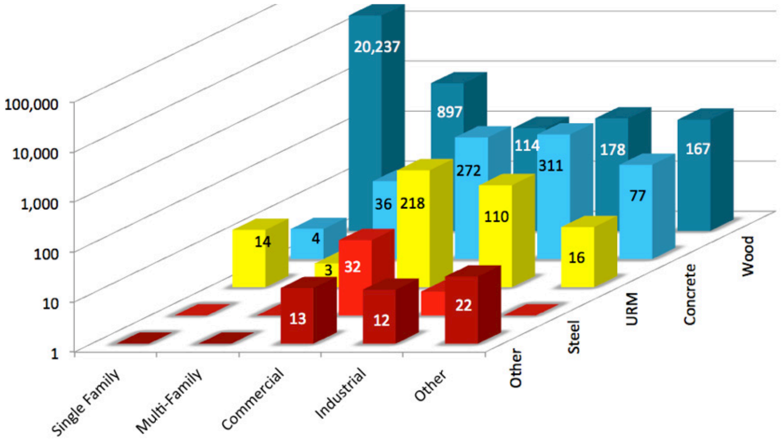
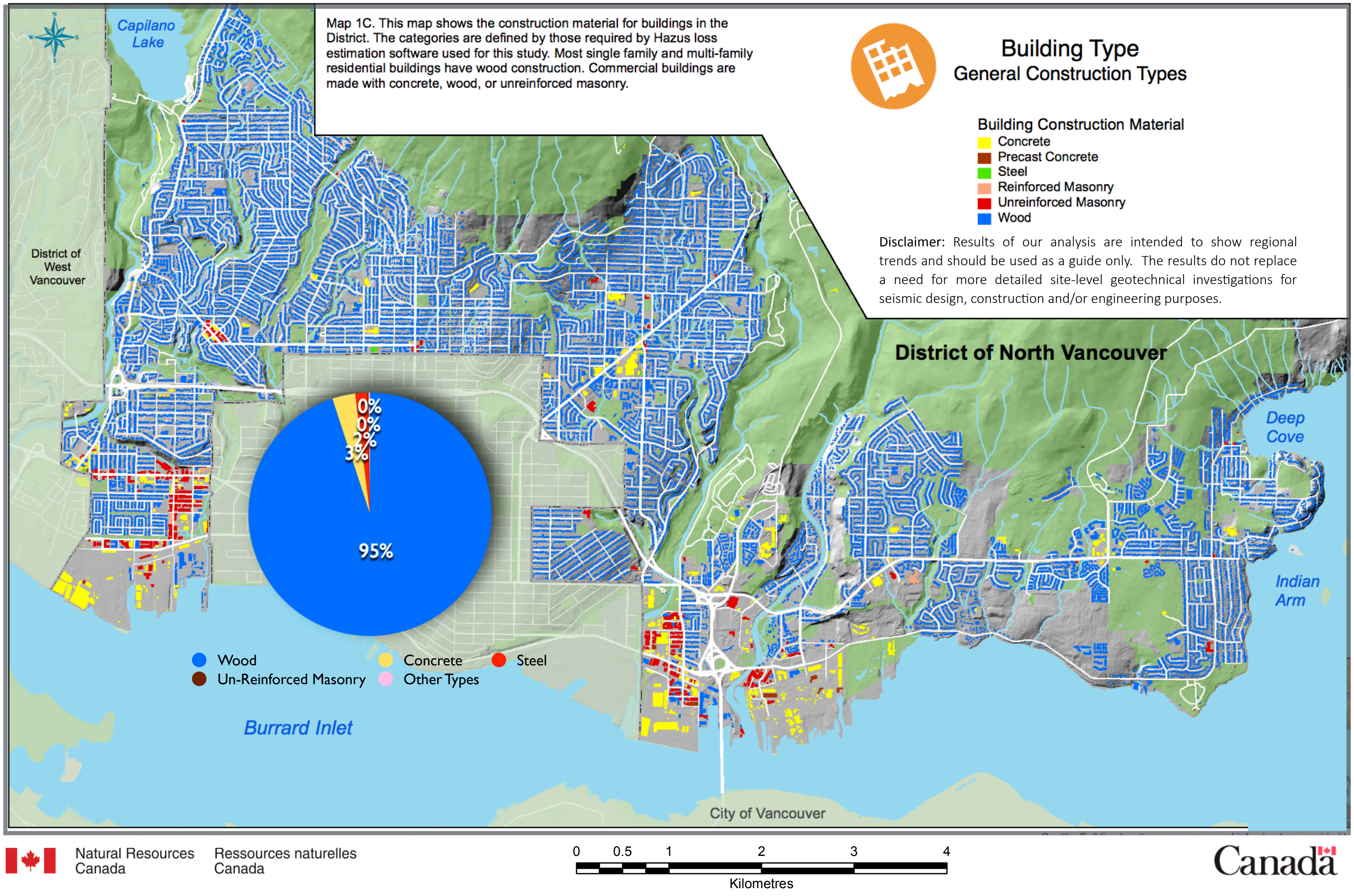


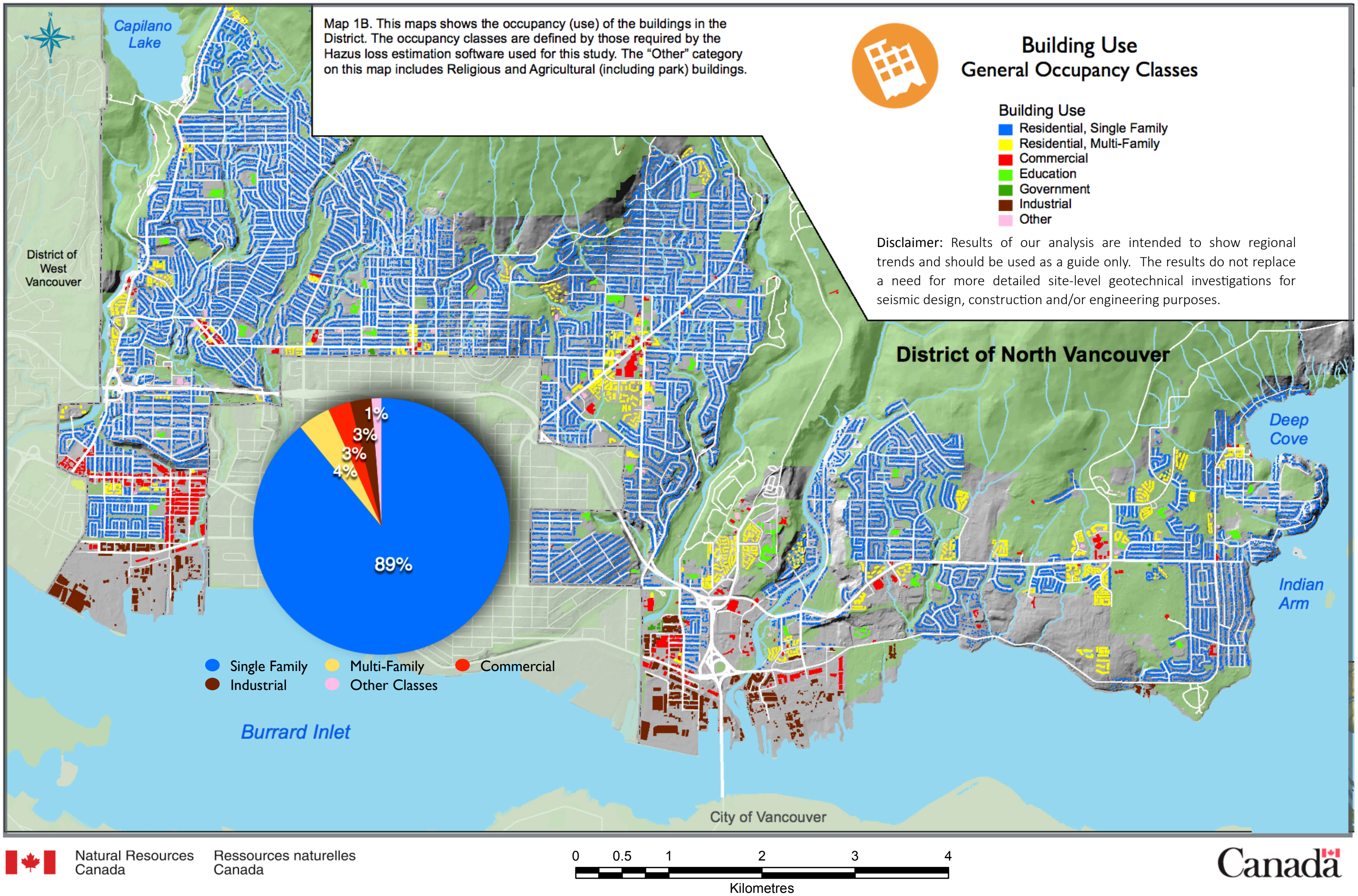
Figure 54: Building characteristics for the District of North Vancouver. Classification based on building taxonomy used in Hazus methodology (FEMA,2011).



Map 1C. This map shows the construction material for buildings in the District. The categories are defined by those required by Hazus loss estimation software used for this study. Most single family and multi-family residential buildings have wood construction. Commercial buildings are made with concrete, wood, or unreinforced masonry.

Disclaimer: Results of our analysis are intended to show regional trends and should be used as a guide only. The results do not replace a need for more detailed site-level geotechnical investigations for seismic design, construction and/or engineering purposes.

Figure 55: Building construction types for the District of North Vancouver. Classification classes based on building taxonomy used in Hazus methodology (FEMA,2011).



Map 1B. This maps shows the occupancy (use) of the buildings in the District. The occupancy classes are defined by those required by the Hazus loss estimation software used for this study. The "Other" category on this map includes Religious and Agricultural (including park) buildings.

Disclaimer: Results of our analysis are intended to show regional trends and should be used as a guide only. The results do not replace a need for more detailed site-level geotechnical investigations for seismic design, construction and/or engineering purposes.

Figure 56: Building use for the District of North Vancouver. General occupancy classes based on building taxonomy used in Hazus methodology (FEMA,2011).

Residential Sector

Buildings in the residential sector represent more than 93% of the overall inventory with ~ 20,260 single-family homes (89% of total) and ~940 multi-family apartments and townhouses (4% of total). Most single-family homes in the District are large two-story wood frame structures with a mean floor area of 3,900 ft^2. Multi-family residential buildings include ~745 duplex and townhouse complexes of wood frame construction, and ~170 medium-rise apartment complexes that include a mix of timber frame, pre-cast concrete, moment frame and concrete shear wall structures. Though generally resistant to ground shaking, most residential structures in the District are not engineered to withstand ground deformation hazards caused by liquefaction and/or earthquake triggered landslides.

Business Sector

The business sector represents ~6% of the overall building stock in the District with ~650 commercial and ~610 industrial structures concentrated in well-established precincts along the waterfront and in deltaic fan deposits along the Capilano, Lynn and Seymour rivers (Figure 55). Commercial buildings include office, store and warehouse facilities used for a wide variety of purposes including wholesale and retail trade, professional and technical services, financial services, health care, entertainment and recreation. Many of the commercial buildings in these older business precincts are unreinforced masonry and concrete moment structures that predate modern design guidelines for seismic safety. Newer buildings are mostly concrete shear wall and steel frame structures that are engineered to withstand known ground shaking hazards.

Industrial buildings include a mix of factories and warehouse facilities used for the production of materials, processing of natural resource materials, construction and marine transportation. Many of these structures are part of the broader port authority of Metro Vancouver - a strategic national asset in terms of both trade and commerce. More than 60% of all industrial structures in the District are older concrete moment frame or unreinforced masonry structures that are situated in areas exposed to both ground shaking and related ground deformation hazards.

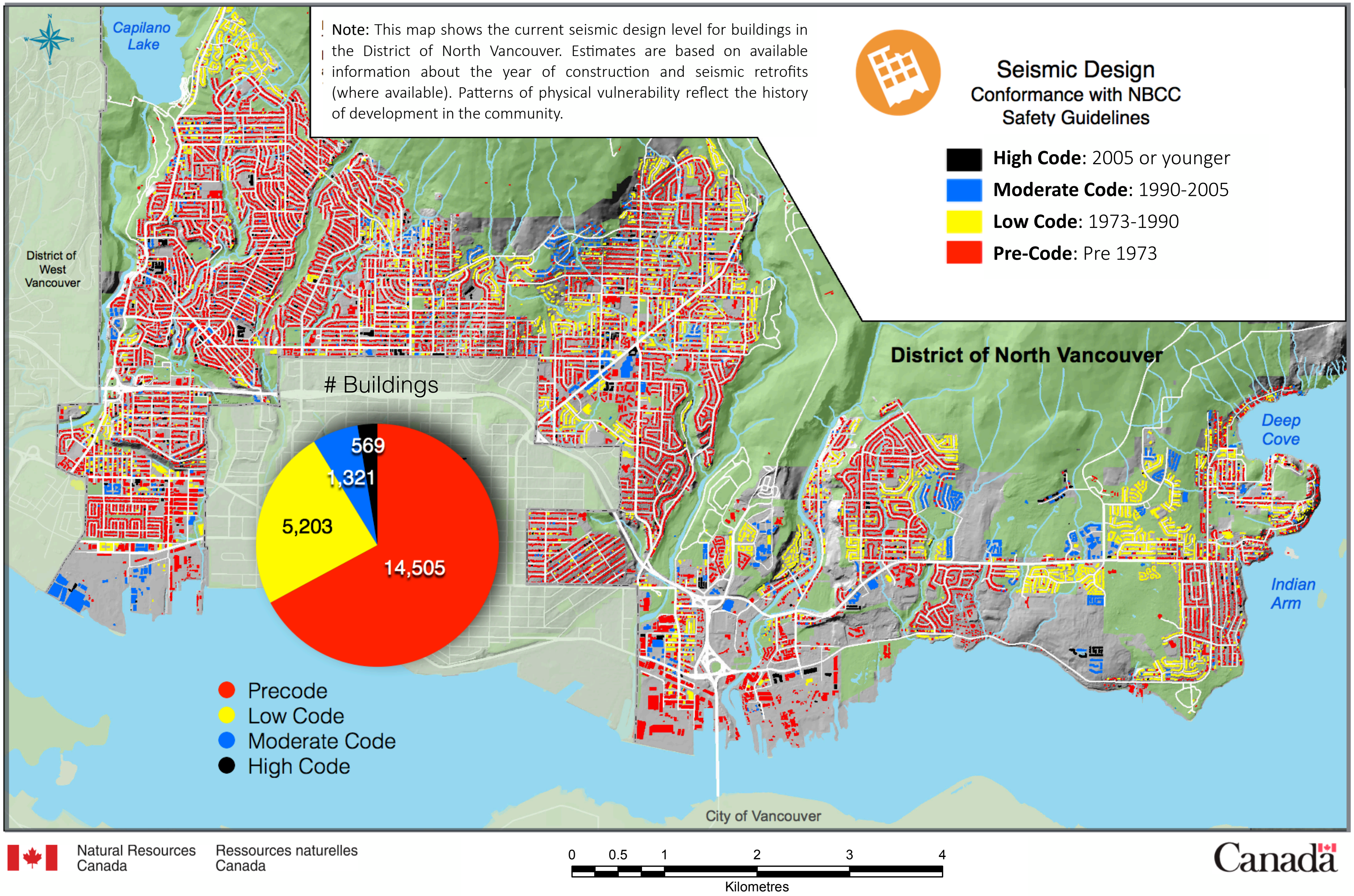
An additional ~285 buildings of varying age and construction type make up the balance of the inventory (1% of total). The majority of these are older wood frame, concrete and unreinforced masonry structures used for educational, agricultural governmental or religious purposes.

Seismic Design

Performance-based guidelines were introduced into the National Building Code of Canada in the early 1970s to reduce levels of damage and to ensure minimum thresholds of safety for people in areas exposed to earthquake hazards. It is clear from recent earthquakes in Chile and New Zealand that adoption of modern seismic design guidelines has been effective in saving lives and reducing injuries in newer buildings [Heidebrecht, 2003]. However, enforcement of these guidelines only applies to new construction and/or buildings undergoing significant renovation as part of the development approval process.

A secondary consideration is that existing standards for seismic design do not take into account non-structural impacts and consequences. These can include damages and related injuries caused by the failure of facades, ceilings and other non-load bearing architectural elements during the shaking event, and damages to mechanical and electrical systems that are essential for ongoing building functionality.

While the building may survive the immediate effects of ground shaking and provide minimum safety thresholds, the impacts of non-structural damages can be substantially greater than those inflicted by structural damage alone [Naumoski et al., 2002], often rendering a building unusable and in need of major repair or



Note: This map shows the current seismic design level for buildings in the District of North Vancouver. Estimates are based on available information about the year of construction and seismic retrofits (where available). Patterns of physical vulnerability reflect the history of development in the community.

Figure 57: Seismic Design level for the District of North Vancouver. Classification based on year of construction and inferred conformance with NBCC (2010).

replacement. The number of older buildings that pre-date or were designed to lower design thresholds in the District of North Vancouver far exceeds the number of buildings that conform to modern building codes.

Figure 57 is a summary of existing seismic design levels for buildings in the District of North Vancouver. The assessment is derived from available information on the age and type of construction, and whether the building has been seismically retrofitted since the time of construction. Nearly 67% of all buildings (15,314 structures) were constructed prior to the adoption of modern seismic design codes in 1973.

The majority of these structures (93%) are single and multifamily residential structures of wood-frame construction. Less than 33% of all the buildings in the District were constructed after 1973. Of these, only 9% (2,116 structures) conform to modern performance-based seismic design thresholds established in 1990. Of particular concern are older concrete and unreinforced masonry buildings that were constructed during a period of rapid growth and development between 1945 and 1960. More than 1,000 of these structures are located in commercial/industrial precincts along the waterfront and do not currently provide adequate levels of protection for expected levels of ground shaking liquefaction in the event of a major earthquake.

PHYSICAL VULNERABILITY

Physical vulnerability is a measure of the extent to which buildings and people are likely to be impacted by a hazard event in terms of damages and related injuries. The potential for earthquake damage will vary from location to location depending on hazard exposure, the intrinsic capacity of buildings to withstand the impacts of shaking and related ground failure, and the effectiveness of mitigation measures that are put in place to resist anticipated levels of vertical and lateral ground motion. The extent and likelihood of damage can be estimated based on the results of seismic engineering studies that simulate building performance under varying conditions of ground shaking and/or forensic studies that have established empirical relationships between measured ground motions and observed earthquake damage. Results of these studies have shown that building fragility varies as a function of hazard intensity, the type and quality of construction, and the extent to which seismic safety measures have been incorporated into the initial design and/or renovation of the building. The most effective way of increasing disaster resilience in areas exposed to earthquake hazards is to structurally retrofit the most vulnerable buildings in the community to withstand anticipated levels of shaking and/or ground failure.

Analytic Methods

Our assessment of physical vulnerability and damage potential for the District of North Vancouver is based on procedures outlined in the Hazus loss estimation methodology for both aggregate and building specific analysis [DHS and FEMA, 2011; FEMA, 2011]. As illustrated in Figure 58, the likelihood of building damage is a function of hazard exposure, type of construction and conformance to National Building Code guidelines for seismic safety. At the heart of the Hazus methodology is an extensive library of fragility curves that are used to analyze damage potential as a function of ground motion intensity and structural resistance.

Thirty-six building types are used in the Hazus model to classify specific characteristics of construction within the general categories of wood, steel, concrete, masonry and mobile homes. In addition, twenty-eight occupancy classes are used to distinguish between different types of building functionality within the general categories of residential, commercial, industrial, and other land use classes. The capacity of these structures to withstand the impacts of ground shaking is assessed on the basis of seismic design level and overall quality of construction. Building type and seismic design level are used to predict the extent of physical

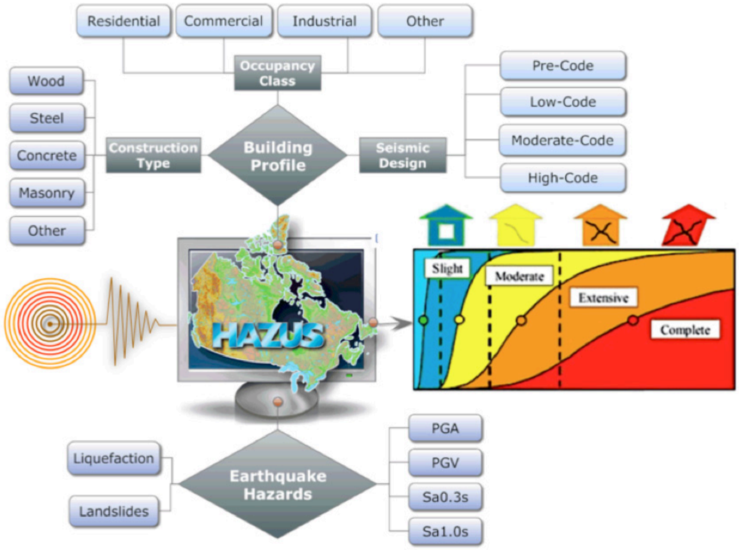


Figure 58: Analytic workflow for assessing physical vulnerability and damage probabilities for individual buildings and building aggregates using Hazus methodology (FEMA,2011).

damage, which in turn is used to determine the potential for injury and loss of functionality for any given level of ground shaking. Occupancy class is used to determine the extent of economic loss and social disruption that is expected based on building functionality (residential, commercial, etc.), and the level of physical damage sustained as a result of the earthquake event.

For each combination of building type and seismic design level there is a corresponding fragility curve that is used in the generic Hazus model to analyze the probability of damage for individual structures and/or an aggregate group of structures. Site-level analysis is based on building-specific damage functions that are developed by the user on the basis of capacity curves defined by a qualified building engineer (Level III analysis; Advanced Engineering Building Module). At this most detailed level of analysis, Hazus can be used to evaluate the effectiveness of risk reduction strategies by altering building fragility curves to simulate the effects of mitigation, then comparing the results with and without mitigation measures in place.

Likelihood of Damage

Hazus uses fragility curves to assess the probability of exceeding minimum thresholds of damage for a given level of shaking and related ground failure. Damage probabilities are calculated for each of five states: None, Slight, Moderate, Extensive and Complete (See Figure 59).

Building performance is reported on the basis of damage states with the highest probability of occurrence for an individual building or collection of buildings. Slight and moderate damage states describe physical impacts that exceed the yield point of a building but that do not compromise structural integrity. Extensive damage states are those in which load-bearing structural elements of a building are compromised beyond repair. Complete damage states are those in which there is a likelihood of structural failure by tilting and/or toppling with a potential for total collapse.

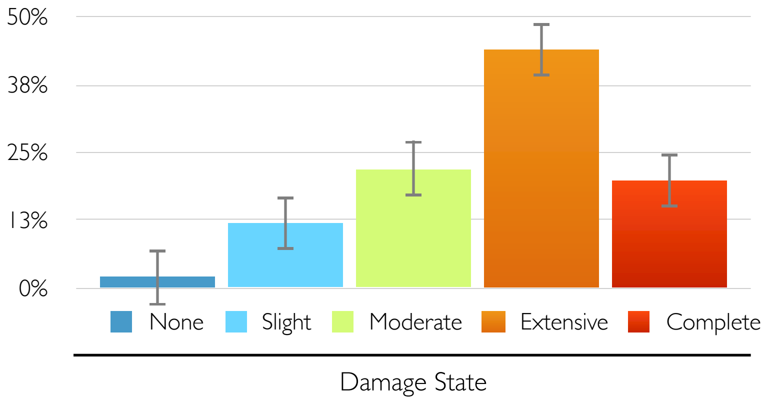


Figure 59: An example of damage probabilities calculated by Hazus for a hypothetical building.

DAMAGE POTENTIAL

Knowing which buildings are vulnerable and why provides important insights on the capacity of a community to withstand and recover from the impacts of a major earthquake, and bears directly on strategies to increase disaster resilience through structural mitigation. This section explores overall patterns of earthquake vulnerability for buildings in the District and some of the underlying root causes.

Figure 60 is a summary of damage potential for a M7.3 scenario earthquake in the Strait of Georgia. Figure 61 illustrates the expected spatial pattern and intensity of damage based on a site-level analysis of ~24,000 buildings using the Hazus Advanced Engineering Building Module [AEBM: DHS and FEMA, 2011]. More than ~1,000 buildings are expected to sustain slight and/or moderate levels of damage that would require inspection and repair during the recovery process. An additional ~840 buildings are expected to sustain extensive and/or complete damage to load-bearing systems that would result in partial collapse or complete destruction. Results of our analysis are considered a robust 1st order approximation of damage potential at the site-level. They provide both context and focus for more detailed follow-up studies that would need to be carried out by a qualified professional seismic engineer to establish thresholds of seismic safety for existing or proposed buildings.

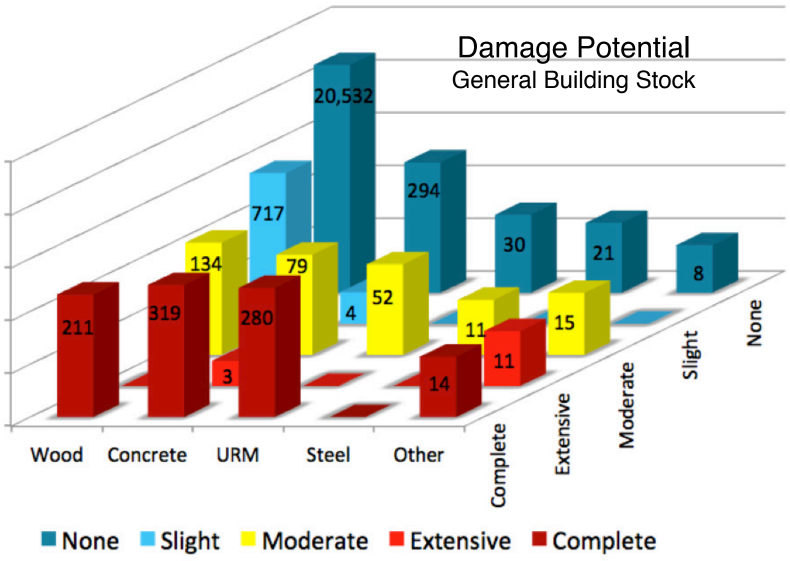
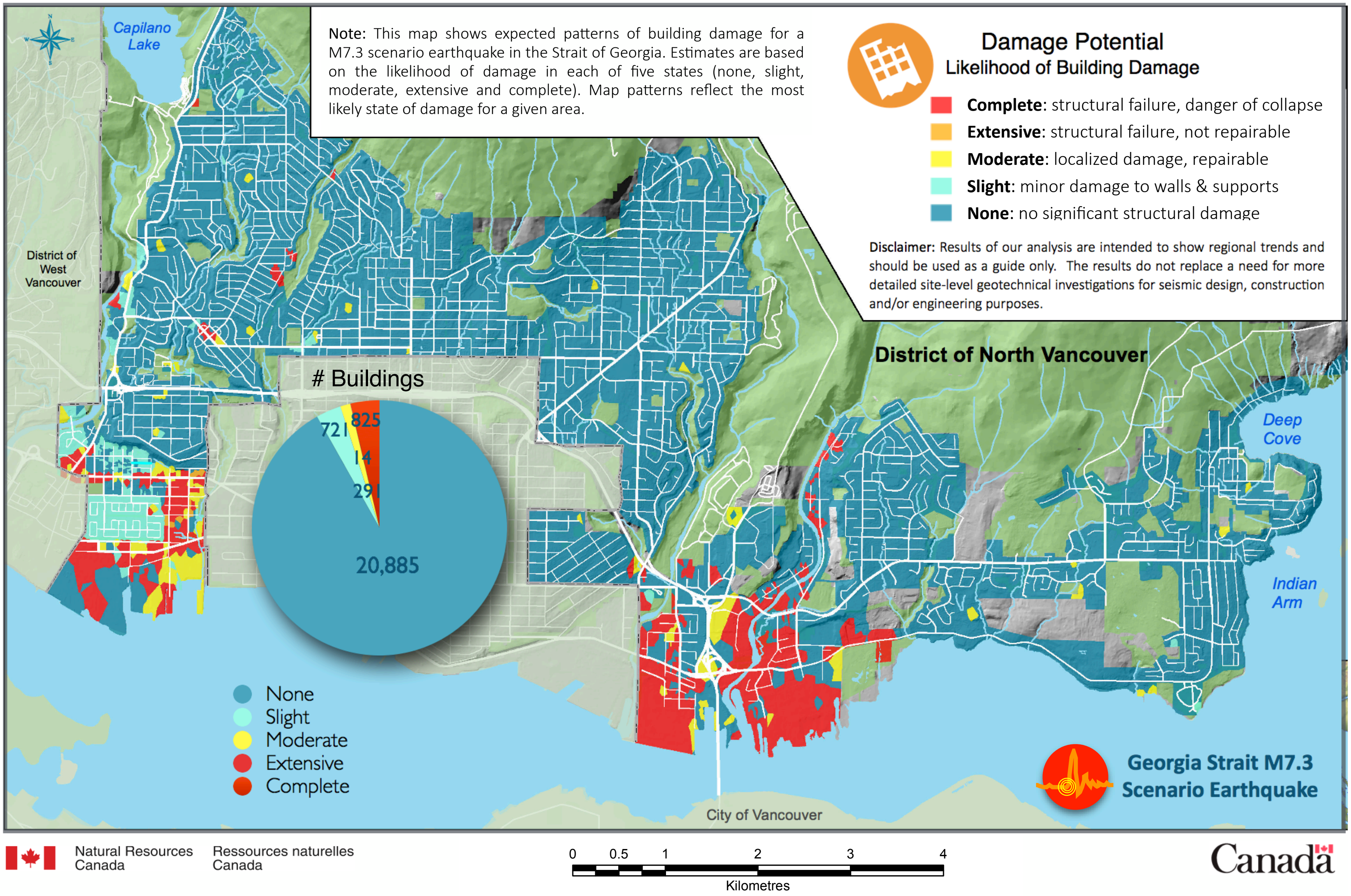


Figure 60: Damage state profile for general building types in the District of North Vancouver based on Hazus methodology (FEMA, 2011).

Pre-Code Wood Frame Buildings

Wood frame buildings that conform to modern North American construction standards are inherently resilient to earthquake loading and are known to perform well under conditions of very strong and severe ground shaking [K Porter et al., 2006]. There are ~ 21,600 wood frame buildings in the District of North Vancouver (95% of total). Nearly two-thirds of these structures were built prior to the adoption of national seismic design guidelines in the early 1970s. Factors that contribute to the vulnerability of these older buildings include stucco-finished exterior walls that lack sheathing to distribute seismic loads; masonry chimneys and/or external facades that are susceptible to toppling; framed floors with post-and-pier supports; and perimeter cripple frame walls that are not securely bolted to the foundation to withstand the effects of shear and/or lateral drift.

A relatively small number of wood-frame buildings (~1,000 structures) are expected to sustain damages as a result of the scenario earthquake. Of these, approximately 210 structures are in danger of permanent structural failure and/or collapse. Almost all of these structures are situated in areas exposed to severe ground shaking (MMI VIII) and/or lateral displacement caused by liquefaction and earthquake-triggered landslides (See Figure 50).



Note: This map shows expected patterns of building damage for a M7.3 scenario earthquake in the Strait of Georgia. Estimates are based on the likelihood of damage in each of five states (none, slight, moderate, extensive and complete). Map patterns reflect the most likely state of damage for a given area.

Damage Potential
Likelihood of Building Damage

- 🟥 **Complete**: structural failure, danger of collapse
- 🟧 **Extensive**: structural failure, not repairable
- 🟨 **Moderate**: localized damage, repairable
- ▨ **Slight**: minor damage to walls & supports
- 🟦 **None**: no significant structural damage

Disclaimer: Results of our analysis are intended to show regional trends and should be used as a guide only. The results do not replace a need for more detailed site-level geotechnical investigations for seismic design, construction and/or engineering purposes.

Figure 61: Map showing damage potential for the District of North Vancouver. Assessment based on Hazus methodology (2011).

It is clear from results of our study that seismic retrofits to these older wood frame buildings would increase overall safety and substantially reduce the number of buildings that would require repair and/or replacement in the event of a major earthquake. Specific measures that might be considered include the strengthening of foundation connections, bracing of frame and floor systems, the addition of timber shear walls and a variety of other measures to help dissipate seismic energy.

Unreinforced Masonry Buildings

Unreinforced masonry buildings (URM) are characterized by bearing walls made of brick, concrete and/or adobe blocks that lack structural reinforcement to accommodate lateral movements caused by seismic loading. Experience from earthquakes around the world has shown that URM structures perform very poorly under conditions of moderate or stronger ground motions [L M Jones et al., 2008]. Factors that contribute to increased vulnerability of these structures include: thin and weak masonry walls that are inherently brittle and prone to crumbling; the lack of adequate anchoring between roof, walls and floors to resist lateral shear; open-front construction of three-sided lower floors that are susceptible to twisting and horizontal deflection; and inadequate support to external facades and parapets that are not secured to the building frame and prone to collapse onto neighbouring buildings.

There are ~360 unreinforced masonry buildings within the District of North Vancouver. Most of these structures (~77%) were built prior to the adoption of modern seismic design codes and are likely to sustain damages beyond repair in the scenario earthquake. Nearly all are located in older commercial/industrial precincts along the waterfront (See Figure 56). Factors driving the extreme vulnerability of these structures include inherent structural weaknesses of URM construction and their location with respect to areas of severe ground shaking and liquefaction.

Mitigation measures that might be considered to increase building safety include: the anchoring of URM walls to roof and floor framing; bracing and/or structural reinforcement of openings and bearing walls to reduce the potential for failure; and reinforcement of external facades and parapets to minimize secondary hazards caused by toppling. While seismic retrofitting will increase building performance and save lives in the event of a major earthquake, it is estimated that ~20 of these older buildings would still remain vulnerable to structural damages that would warrant major repair or replacement.

Older Concrete Buildings

Older concrete buildings built prior to ~1970 are second only to URM structures in terms of intrinsic vulnerability and the potential for significant damage in the event of a major earthquake. Construction types that are common in North America include reinforced moment frame, shear wall and tilt-up concrete structures. Experience from previous earthquakes has shown that these types of concrete buildings perform very poorly under moderate and severe conditions of ground shaking. While the rate of collapse is less than for URM buildings, the potential for structural failure of bearing walls is high and poses a significant threat for serious injury and/or loss of life. Factors that contribute to the vulnerability of these structures are similar to those for URM buildings. They include: inadequate anchoring between roof, walls and floors to resist lateral shear; weak lower floors with open-front construction that are susceptible to twisting and collapse; and a limited capacity of concrete bearing walls to absorb and dissipate seismic energy during an earthquake.

There are ~700 concrete structures in the District of North Vancouver. More than two-thirds of these structures were constructed prior to 1973 and do not conform to modern seismic safety guidelines (505 buildings). Almost all of these pre-code concrete structures are susceptible to at least moderate levels of damage in the scenario earthquake with ~320 buildings expected to sustain extensive and/or complete levels of damage.

The majority of these buildings are located along the waterfront in areas of significant ground shaking and/or liquefaction hazard (See Figure 56). Concrete buildings that are expected to sustain little or no damage in the scenario earthquake (~300 structures) either post-date the introduction of seismic design guidelines and/or are situated on firm ground where the effects of site amplification and liquefaction are minimized.

The reduced vulnerability of newer concrete structures is a testament to performance-based seismic guidelines that are incorporated into the National Building Code for Canada. Results of our study suggest that seismic retrofitting of older vulnerable concrete structures to modern standards would be effective in reducing building damages and related socioeconomic consequences. Mitigation measures that might be considered include increased anchoring between roof, walls and floors to resist lateral shear; bracing of weak lower floors with open-front construction to prevent soft-story collapse; and the addition of seismic dampening devices to increase the capacity of existing concrete bearing walls to absorb and dissipate seismic energy during an earthquake

Other Building Types

Other types of construction that are represented in the DNV include steel, pre-cast concrete, reinforced masonry and manufactured home buildings. Although less than 1% of the total inventory (~80 structures), more than half are likely to sustain at least moderate levels of damage in the scenario earthquake with ~26 buildings expected to sustain damages that would require major repair or replacement. Almost all of these are older structures situated in areas of severe ground shaking (MMI VIII) and/or liquefaction.

HOTSPOTS OF CONCERN

Scenario models provide a spatial context for developing situational awareness and a more complete understanding of what to expect in the event of a major earthquake. This section describes anticipated impacts of the scenario earthquake on residential and business structures and community assets. Community structures include municipal buildings, emergency response facilities (EOC, police, fire and hospitals), schools, and facilities used for both child and elder care.

Hotspots of concern include residential and business neighbourhoods in Norgate, Lynnmour-South, Maplewood, the Seymour River Reserve and valley escarpments in Riverside-East and Riverside-West (See Figure 61). Isolated pockets of damage are also expected in older neighbourhoods of the Highlands, Lynnmour-North, Dollarton and Deep Cove. The concentration and extent of damage within these areas would likely result in significant disruption to the community during the recovery process, similar to what has occurred in Christchurch, New Zealand following the M6.3 earthquake of 2011.

Residential Sector

The majority of residential structures in the District (~99%) are wood frame buildings that are not expected to sustain significant levels of damage in the scenario earthquake (See Figure 62). Notable exceptions are pre-code wood frame buildings and older concrete apartment complexes that are not designed to withstand severe ground shaking or lateral shear caused by liquefaction and earthquake-triggered landslides. Hotspots of concern include older neighbourhoods built on deltaic deposits of sand and clay along the waterfront and unstable glacial and valley fill deposits along the Capilano, Lynn and Seymour rivers.

Approximately 650 pre-code wood frame homes in low-lying areas of Norgate and valley escarpments along the Capilano River are expected to sustain slight and moderate levels of damage in the

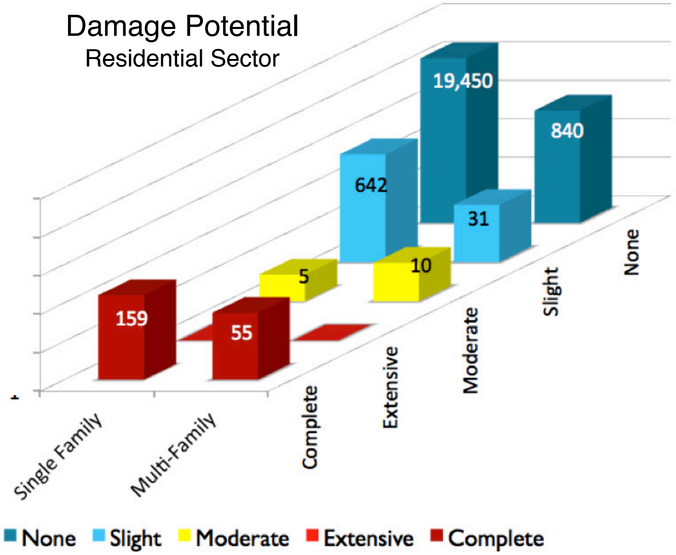


Figure 62: Damage state profile for residential buildings in the District of North Vancouver based on Hazus methodology (FEMA, 2011).

scenario earthquake. Concentrated pockets of extensive and/or complete damage are expected in the older residential neighbourhoods of Norgate, Pemberton Heights, Highlands, Edgemont, Lynnmour-South and Riverside – areas that would be exposed to a combination of both extreme shaking and ground failure during a major earthquake.

More than 215 residential buildings are likely to sustain permanent structural failure and would be in imminent danger of collapse in these areas. The majority of these (159 structures) are single-family wood frame buildings in areas of extreme seismic hazard. The remaining 55 structures are multi-family apartment complexes of concrete and unreinforced masonry construction that pre-date modern design guidelines for seismic safety.

Business Sector

There are more than 3,400 licensed businesses operating in ~1,860 buildings scattered across the District of North Vancouver (See Figure 63). The majority of these (~73%) of these are small businesses that are sole occupants of the building. Larger businesses are concentrated in established town centres (Lower Capilano/Marine Village, Edgemont, Lower Lynn, Lynn Valley and Maplewood), and in commercial/industrial precincts along the waterfront in Norgate, Lynnmour-South and Maplewood.

While the majority of businesses in the District are expected to sustain little or no damage in the scenario earthquake (~80%), more than 380 buildings used for commercial and/or industrial purposes are vulnerable to damages that would require significant repair or replacement during the recovery process. The most vulnerable of these are larger businesses situated in commercial/ industrial zones along the waterfront and in flat-lying areas that are susceptible to higher levels of ground shaking and liquefaction.

It is estimated that ~1,300 buildings are used as home-based businesses in the District (73% of total). The majority of these are wood-frame structures that are expected to sustain little or no damage in the scenario earthquake. At least 30 buildings are likely to be damaged beyond repair (Figure 63). The most vulnerable of these are pre-code wood frame and unreinforced masonry buildings located in the Lower Capilano/Marine, Edgemont, Lynnmour and Riverside areas. Larger businesses are concentrated in mixed-use neighbourhoods and commercial/industrial zones that happen to be situated in areas exposed to higher levels of ground shaking and liquefaction (See Figure 61). Hotspots of concern include concentrations of older commercial buildings in Lower Capilano/Marine, Norgate, Edgemont, and Lower Lynn; and established industrial facilities situated along the waterfront in Norgate, Lynnmour-South and Maplewood.

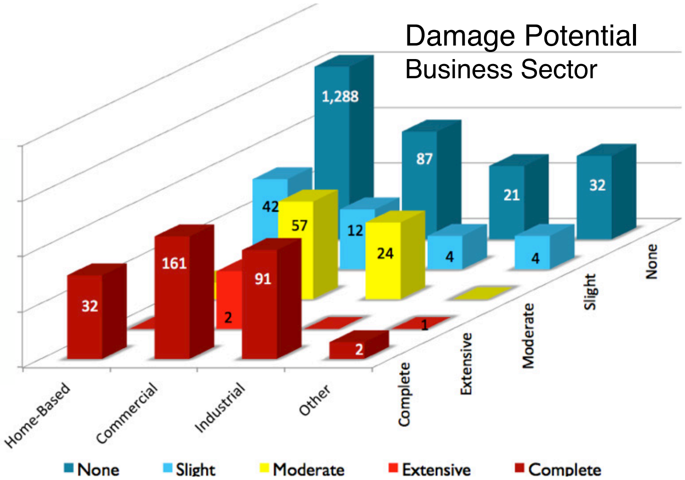


Figure 63: Damage state profile for business sector buildings in the District of North Vancouver based on Hazus methodology (FEMA,2011).

More than 250 buildings in these areas are likely to be damaged beyond repair as a result of severe ground shaking (MMI VIII), liquefaction and toppling of taller buildings. The majority of these are older concrete and unreinforced masonry structures built prior to the introduction of modern seismic design guidelines in the early 1970s. The extent and concentration of damage in these areas would be significant and likely result in large parts of the business district being cordoned off during the recovery and re-building process. Loss of building functionality and related business service capacity for an extended period of time would have serious socioeconomic consequences for the community.

Municipal Buildings and Essential Facilities

There are ~150 municipal buildings and related essential facilities in the District of North Vancouver. Buildings owned and operated by the municipality support a wide range of public services including government operations, emergency response, utilities, garbage and recycling, parks and recreation, library facilities, assisted housing and social services.

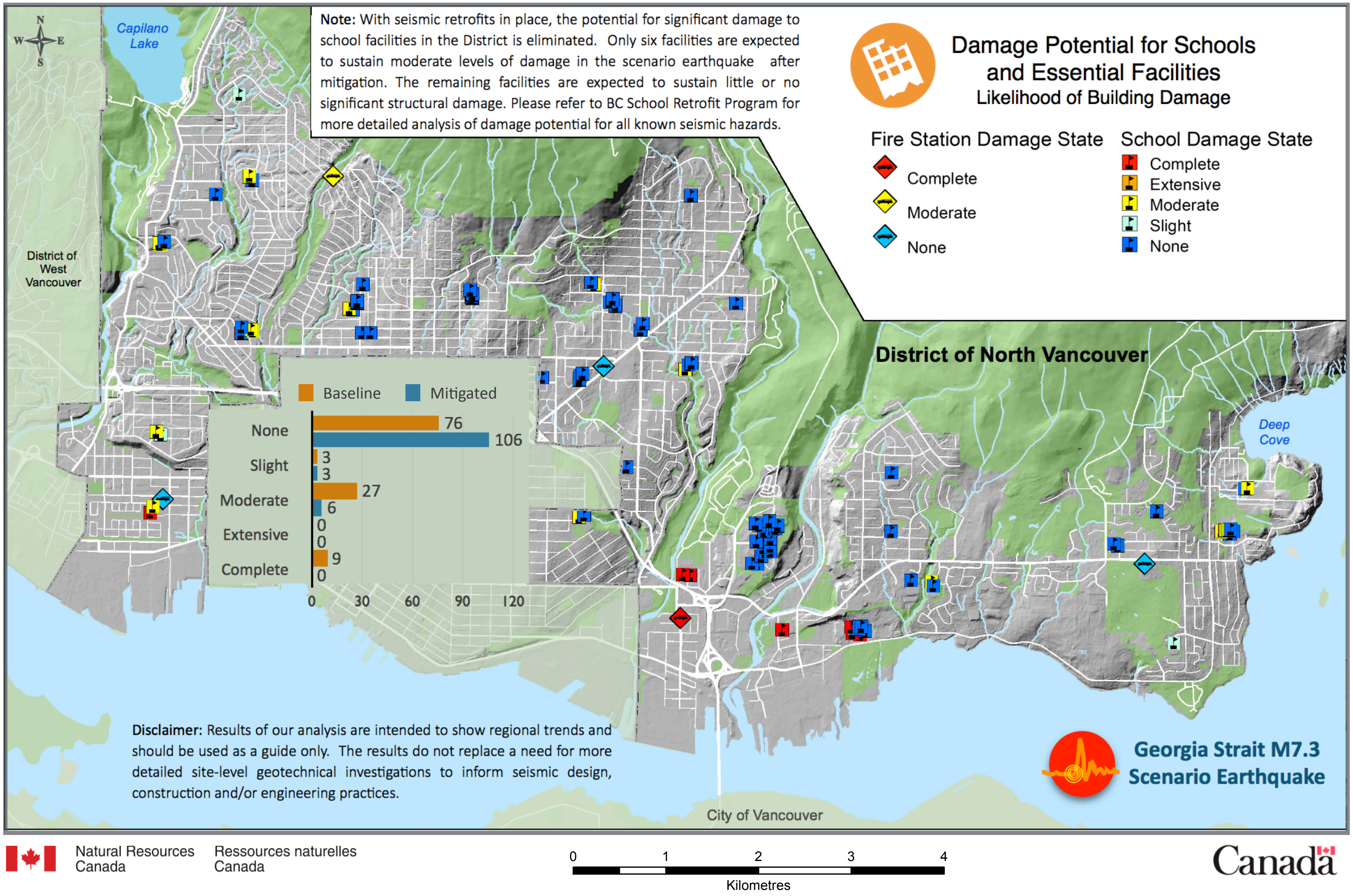
The majority of these structures (80%) are expected to sustain little or no damage in the event of a major earthquake. At least 30 municipal facilities are expected to sustain significant levels of damage in the scenario earthquake, ~20 of which are likely to be damaged beyond repair. Buildings of concern include the DNV operations centre and related structures in Lower Lynn, and a variety of historic buildings and recreational facilities in Norgate, Edgemont, Delbrook, Maplewood and Dollarton.

Emergency response facilities operated within the District of North Vancouver include 5 fire stations, training facilities and an emergency supply storage facility. Police and the North Shore Emergency Operation Centre (EOC) are co-located in a newer building adjacent to the Lions Gate Hospital in the City of North Vancouver. Both the EOC and hospital facilities are situated on firm ground and are expected to perform well in a major earthquake. However, emergency fire and paramedic services within the District are likely to be impacted (Figure 64).

Fire Hall #2 and nearby emergency supply storage and training facilities in the Lower Lynn area are susceptible to damages caused by severe ground shaking and liquefaction and are expected to be operating at less than 25% capacity in the days following a major earthquake event. Fire Hall #3 is exposed to severe ground shaking and landslide hazards adjacent to Mosquito Creek but has recently been seismically upgraded and is expected to be operational but at a reduced capacity.

Schools

Since 2001, the province of British Columbia has invested more than $2.2 billion in a seismic mitigation program to upgrade or replace 213 schools that do not meet current design guidelines for life safety [BC Ministry of Education, 2014]. An additional $600 million has been allocated to address 104 schools still considered



Note: With seismic retrofits in place, the potential for significant damage to school facilities in the District is eliminated. Only six facilities are expected to sustain moderate levels of damage in the scenario earthquake after mitigation. The remaining facilities are expected to sustain little or no significant structural damage. Please refer to BC School Retrofit Program for more detailed analysis of damage potential for all known seismic hazards.

Disclaimer: Results of our analysis are intended to show regional trends and should be used as a guide only. The results do not replace a need for more detailed site-level geotechnical investigations to inform seismic design, construction and/or engineering practices.

Figure 64: Map showing damage potential for schools and essential facilities in the District of North Vancouver. Assessment based on Hazus methodology (2011).

to be at risk in the province. There are 28 public schools, 7 private schools, and a major university in the District of North Vancouver that collectively encompass more than 115 buildings and related facilities. Three elementary schools have been upgraded as part of the Provincial seismic retrofit program and three secondary schools are in the process of being retrofitted to comply with current design guidelines for life safety.

As a result of these mitigation efforts, nearly 70% of all school facilities in the District (classrooms and auxiliary structures) are expected to sustain little or no damage in the scenario earthquake. It is estimated that ~25 school facilities are vulnerable to moderate levels of damage that would require extensive repairs during the recovery process. Most of these are older concrete buildings that support auxiliary functions (recreation, school operations, etc.), and temporary structures (portables) that are used as overflow classrooms (See Figure 64).

While most school facilities in the District are expected to perform well in an earthquake, at least 9 structures are likely to sustain extensive and complete levels of damage. Only three of these are primary buildings. These rest are secondary auxiliary buildings. Hotspots of concern for existing conditions include older concrete buildings and related facilities that have yet to be seismically upgraded in Norgate, Lynnmour-South and Maplewood areas that are known to be exposed to severe levels of ground shaking and liquefaction.

With seismic retrofits in place, the potential for significant structural damage to school facilities in the District is eliminated. Only six facilities are expected to sustain moderate levels of structural damage in the scenario earthquake. The remaining facilities are expected to sustain little or no significant structural damage. The increased performance of school buildings is a testament to the effectiveness of seismic retrofit measures that are incorporated into the National Building Code of Canada to ensure life safety in the event of a major earthquake.

Child and Elder Care Facilities

Like schools, child and elder care facilities are intended to provide a safe and secure environment for the most vulnerable members of a community. There are over 90 child and elder care facilities in the District of North Vancouver. They include a mix of public and private facilities in commercial and residential buildings that are exposed to a wide range of seismic hazards.

More than 95% of the buildings that provide child and elder care in the District are likely to sustain little or no significant damage in the scenario earthquake. As expected, the most vulnerable of these care facilities are located in older concrete and unreinforced masonry buildings that are situated in areas of severe ground shaking and liquefaction in low-lying areas along the waterfront. Hotspots of concern include day care facilities in Lower Lynn and Norgate.

CHAPTER 6: PEOPLE

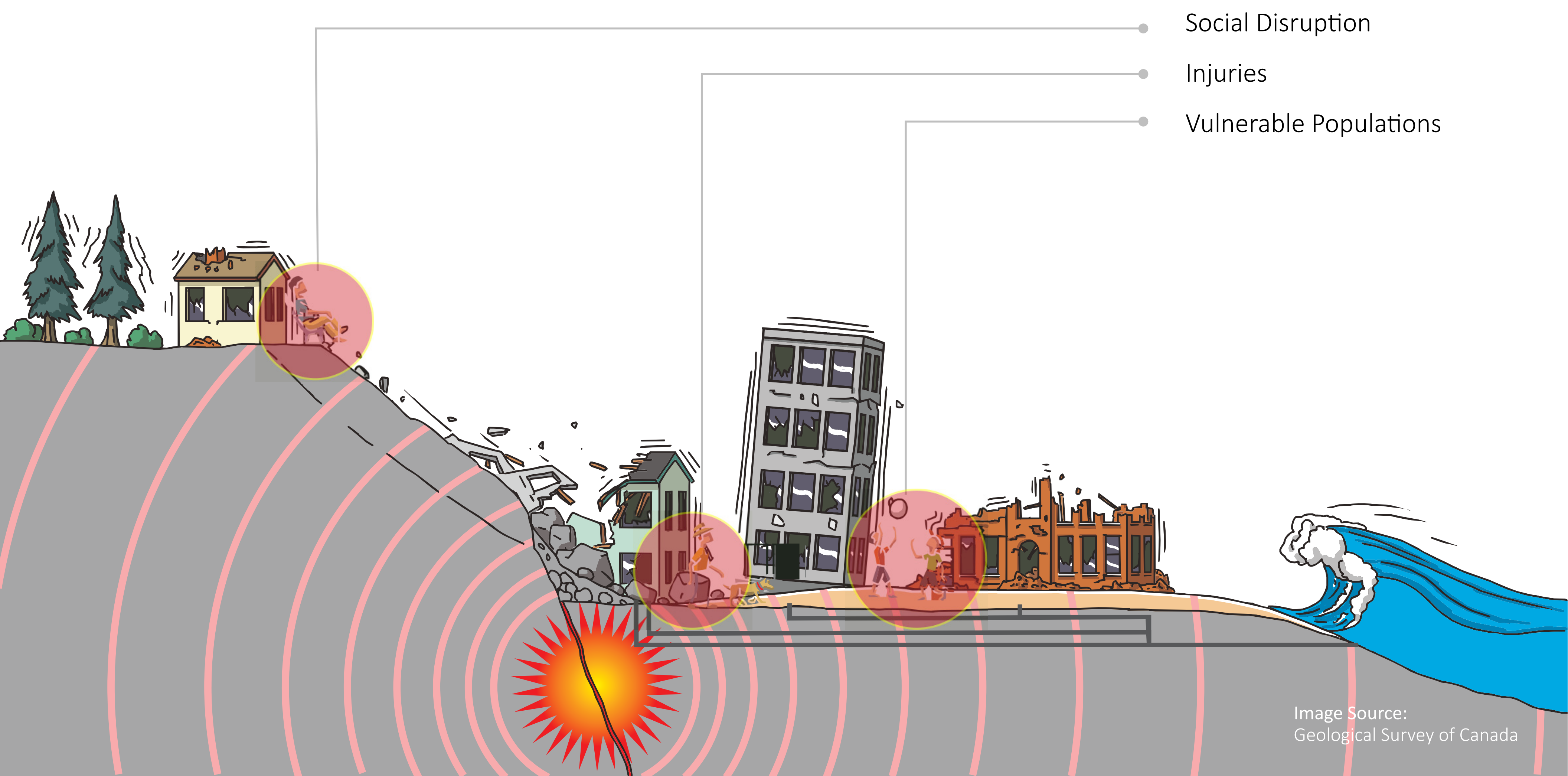


Image Source:
Geological Survey of Canada

CHAPTER 6: PEOPLE

Primary Authors: Journeay, J.M., and Wagner, C.L.

Public safety encompasses the protection of individuals from injury and loss of life as well as the provision of shelter and social services following a disaster event. It is a function of hazard exposure, intrinsic social vulnerabilities, and the capacities of individuals to withstand and recover from physical impacts of a disaster event. The goal is to minimize the potential for injury and social disruption through investment in mitigation measures that reduce the potential for damage to buildings and lifeline systems, and the implementation of emergency planning measures that increase the capacities of individuals to respond and adapt to disaster events before they occur.

This chapter explores social characteristics of the District with the aim of identifying who in the community is most vulnerable and why. Societal impacts of the M7.3 Georgia Strait scenario earthquake are measured in terms of indicators that track the extent and severity of injuries, and levels of social assistance that may be required immediately after the earthquake. As it turns out, the most vulnerable populations are situated in areas exposed to some of the highest levels of ground shaking and liquefaction in the District.

It is estimated that more than two thousand people would require immediate medical attention if the earthquake occurred during the day. Several hundred individuals are expected to sustain life-threatening injuries that would result in hospitalization and/or death. The number of serious injuries requiring advanced medical care in the District alone would likely overwhelm the capacity of existing hospital resources that serve north shore communities of the Vancouver Coastal Health Authority. In addition, more than 500 homes are likely to sustain damages that would render them uninhabitable during the recovery process. As a result, it is anticipated that several hundred people would be seeking short-term shelter and social assistance in the weeks and months following the earthquake.

Insights gained from our analysis provide a context for understanding root causes of social vulnerability in the community and for evaluating strategies that may be effective in reducing the impacts and consequences of future disaster events. Actions taken before a major earthquake have the potential to reduce the number of injuries requiring hospitalization by ~100 people and the number of critical life-threatening injuries by ~50 people. Investment in mitigation and emergency planning measures would also be effective in reducing underlying social vulnerabilities and increasing capacities of the community to withstand and respond to future disaster events of all types.

DEMOGRAPHIC PROFILE

The District of North Vancouver is a vibrant and diverse community of more than 83,500 people with a stable ten-year growth rate of less than 3% — well below the regional average of 15% for Metro Vancouver and other urban municipalities with similar social and economic characteristics.

The movement of people in the community varies dramatically as a function of both time of day and patterns of land use (Compare Figures 65 and 66). Night-time population density varies from ~200 people/km^2 in sparse single-family rural-residential settings along the waterfront to more than 4000 people/km^2 in multi-family residential neighbourhoods in highland regions across the District. Daytime population patterns are reversed with densities that vary from ~200 people/km^2 in single-family residential areas

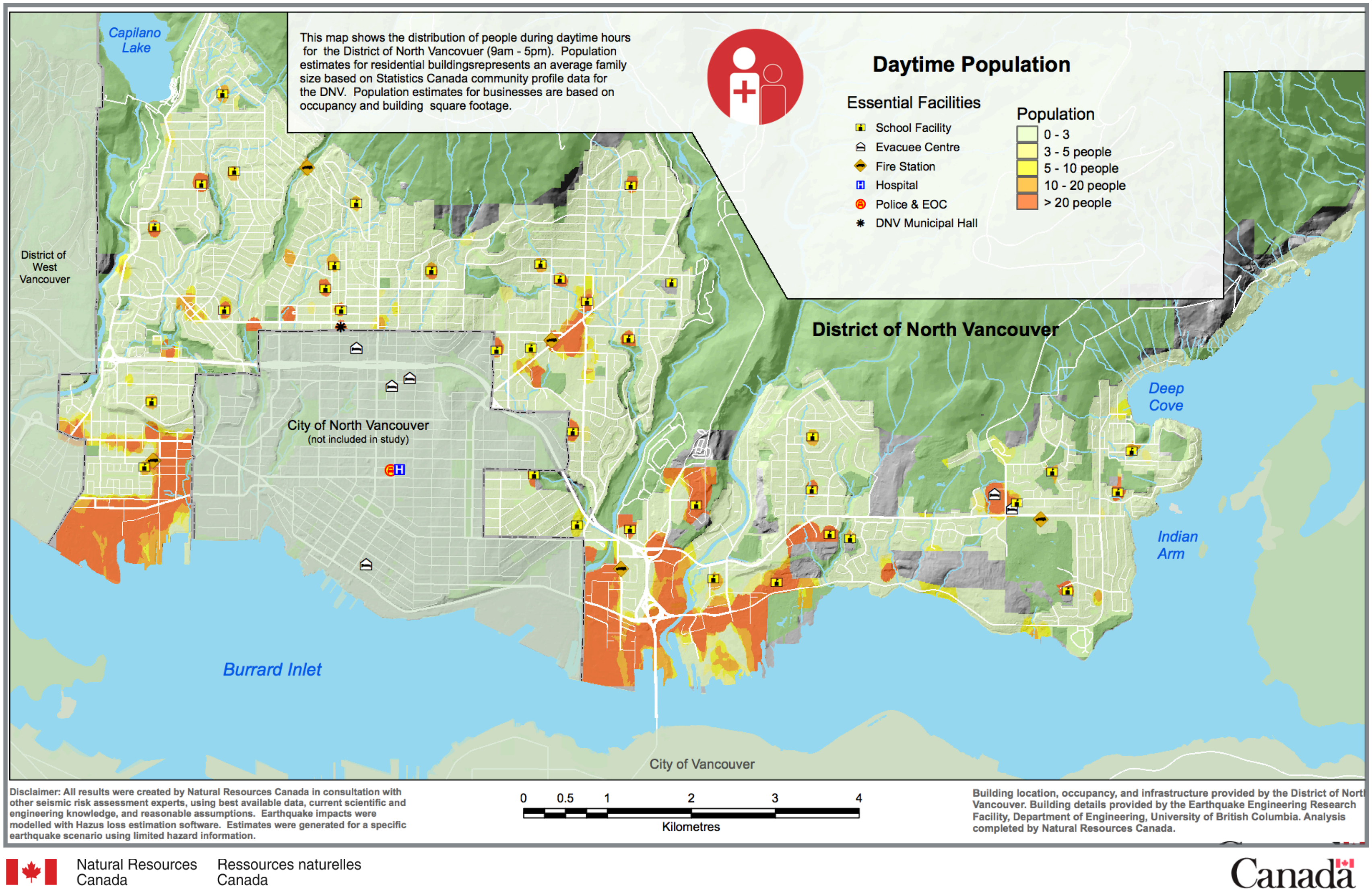
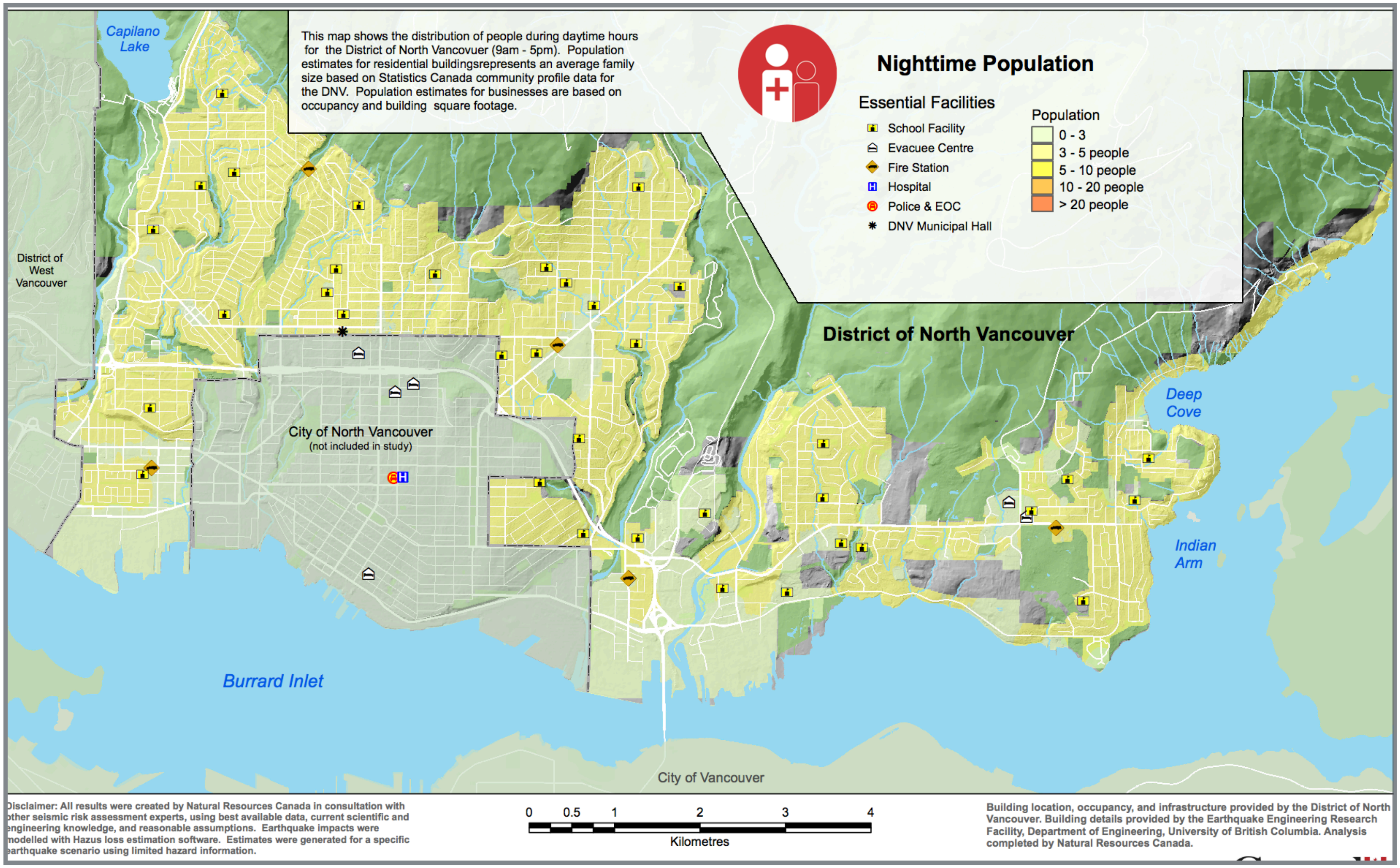


Figure 65: Map showing distribution of daytime population for the District of North Vancouver. Estimates for residential population are based on building occupancy and Statistics Canada data on average family size. Estimates for employee populations are based on building use and square footage.



Nighttime Population

This map shows the distribution of people during daytime hours for the District of North Vancouver (9am - 5pm). Population estimates for residential buildingsrepresents an average family size based on Statistics Canada community profile data for the DNV. Population estimates for businesses are based on occupancy and building square footage.

Disclaimer: All results were created by Natural Resources Canada in consultation with other seismic risk assessment experts, using best available data, current scientific and engineering knowledge, and reasonable assumptions. Earthquake impacts were modelled with Hazus loss estimation software. Estimates were generated for a specific earthquake scenario using limited hazard information.

Building location, occupancy, and infrastructure provided by the District of North Vancouver. Building details provided by the Earthquake Engineering Research Facility, Department of Engineering, University of British Columbia. Analysis completed by Natural Resources Canada.

Natural Resources Canada Ressources naturelles Canada

Canada

Figure 66: Map showing distribution of night-time population for the District of North Vancouver. Estimates for residential population are based on building occupancy and Statistics Canada data on average family size. Estimates for employee populations are based on building use and square footage.

to concentrations of 15,000-20,000 people/km^2 in established town centres and commercial/industrial precincts along the waterfront. Where people are located at any given time of day has a direct bearing on patterns of vulnerability and the potential for injury and social disruption following an earthquake.

Age and Gender

Age and gender statistics for the District mirror those of other communities in the region with some notable exceptions (Figure 67). It is an aging population with one in four residents over the age of 55. The total number of seniors (65+) has increased nearly fourfold over the past 30 years. Age distributions for adult cohorts over the age of 45 are consistently above the norm when compared to the greater Metro Vancouver region and peer communities across Canada. Based on population projections, it is expected that dependency rates for the elderly will increase from ~22% to nearly ~29% over the next ten years.

Although the proportion of young children (<14 years) is higher than regional and provincial norms, the total number of individuals in this age category has been in steady decline over the past 10 year, leading to ongoing school closures in the District. The trend is even more alarming for young adults (20-40 years) whose overall representation is 5-6% below regional and provincial norms. Rates of dependency for young children are expected to decrease from current levels of ~28% to ~25% over the next ten years. Steady declines in the total number of young adults means there are likely to be fewer new families choosing to stay or move into the District and a much smaller number of individuals in this age cohort to support local economic growth in the years to come.

Aboriginal Peoples

According to the 2011 National Housing Survey, there are over 1,075 people of Aboriginal identity in the District of North Vancouver [Statistics Canada, 2011]. Of these, more than half (57%) reported a First nations identity while ~40% reported a Métis identity only. Aboriginal children under the age of 14 represent 20.5% of the total Aboriginal population and 1.5% of all children in the District of North Vancouver.

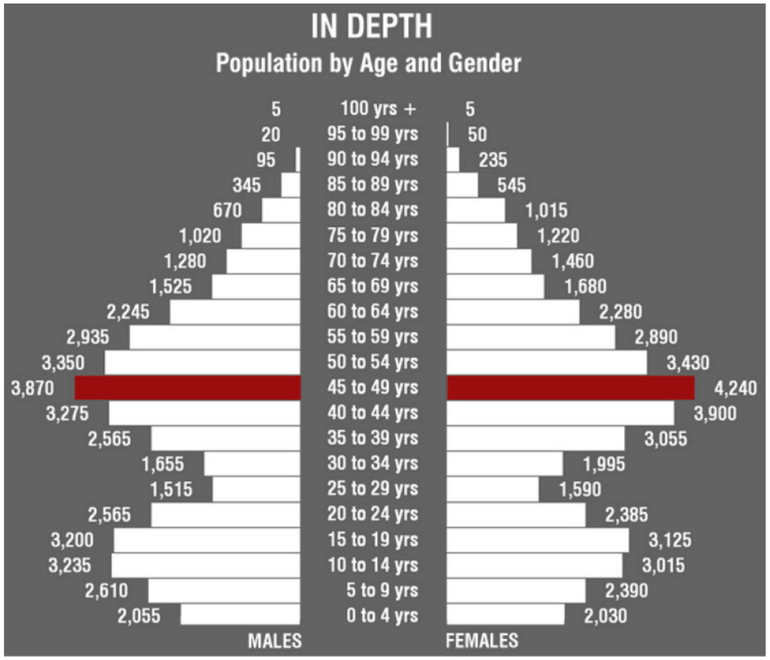


Figure 67: Age and gender characteristics for the District of North Vancouver. Adapted from DNV Official Community Plan (2011).

Ethnicity and Language

The District of North Vancouver has a diverse and vibrant ethnic community with nearly one in three residents having emigrated from outside of Canada. According to the 2011 National Household Survey, nearly 14% of all immigrants living in the District arrived in Canada sometime after 2006 [Statistics Canada, 2011]. Nine out of ten people in the community are Canadian citizens with the majority of these individuals being over the age of 18.

The most common countries of origin are the United Kingdom (18.3%) and Iran (17%). Visible minorities account for 22% of the total population as compared with ~27% for British Columbia. The largest visible minority groups living in the District are Chinese and West Asian. Two out of three immigrants speak English and/or French in the home with the most common non-official languages being Persian (Farsi), Korean and Cantonese.

Labour

The labour force is more than 46,000 strong with the majority of people (62%) working outside the District in manufacturing and general labour (36.1%); technical trades and other highly skilled occupations (26.7%); professional services in the natural and applied sciences (23%), and management services (14.3%). Business, finance and administration are the most common occupations for women while management and professional/ technical services are the most common occupations for men.

One out of three people live and work in the District, either in commercial and industrial businesses or home-based occupations. Commercial service providers represent more than 50% of the local business sector with the balance distributed across mining, construction and transportation industries (18%), wholesale and retail trade (15%), finance, insurance and real estate (8%), manufacturing (5%) and health services (3%). Collectively, these businesses contribute ~30% of the overall property tax revenue for the District.

There has been a steady decline in the local labour force over the past ten years with the District loosing ~1,000 jobs at a time when neighbouring communities in the Metro Vancouver region have gained ~150,000 new jobs and corresponding economic prosperity. These trends translate into fewer opportunities for residents to live and work in the District and a greater reliance on businesses and regional economic networks that are located outside the community. Business dependencies are primarily in the public sector, construction and tourism with increasingly lesser reliance on forestry, mining and fishing.

Income

The aggregate annual income for the District is $3.56 billion dollars [Statistics Canada, 2011]. Approximately 93% of the total income is derived from market sources (employment, investments and retirement pensions), well above the norm for British Columbia and other parts of Canada (~88%). The median employment income level for individuals in the labour force is ~ $62,000, nearly $13,000 more than those working elsewhere in British Columbia. Median earnings for those working in the most common occupations of business, finance, professional services and specialized management positions range from ~$73,000 to ~ $92,000.

These trends are mirrored in all categories of family income. The median after-tax income for families and couples in 2010 was ~ $89,000 and ~$96,000, respectively. For lone parent families and those living alone or with non-relatives the median after-tax income was ~$54,000 and ~$32,000, respectively. For comparison, the median after-tax income for other parts of British Columbia were ~$68,999 for families, ~$73,000 for couples, ~$41,000 for lone parent families and ~$26,000 for those living alone or without relatives.

As with other parts of the country, there is a growing gap between those in the highest and lowest income brackets. One out of three people in the District are in the bottom-half of the adjusted after-tax distribution in Canada with ~8% of the total population (~7,500) in the lowest decile. The majority of those in the top half of the Canadian distribution are in the highest income brackets with ~23% of the total population (~19,000) in the uppermost decile as compared with ~10% for counterparts in the rest of British Columbia.

Family Structure

Family structure statistics for the District are on par with other parts of British Columbia, though skewed somewhat because of rapid changes in population trends for children under the age of 14 years and young adults [Statistics Canada, 2011]. Nearly two-thirds of the census families in the District (~64%) have children living at home, slightly above the provincial average of 59%.

The average number of people in all census families is 3.1, slightly above the provincial average of 2.9. The majority of these are married couple families with nearly one in four lone parent households as compared to the provincial average of 26%. Of the ~3,200 lone parent families in the District, more than 80% are female dominated, similar to the provincial norm. Nearly 17% of the total population is characterized by unattached individuals living alone or with non-relatives.

Housing

It is estimated that there are approximately 30,555 households in the District of North Vancouver. The majority of these are single-family detached homes built prior to 1980 with the remainder being multi-family dwellings in duplex, row house and apartment building complexes. The rate of home ownership is ~80%, well above the provincial average of 70%. Average monthly shelter costs for homeowners is $1,630 with nearly one in four spending 30% or more of their total income on shelter [Statistics Canada, 2011].

With an extremely low vacancy rate and dwindling supply of rental housing stock available in the District (~19%), there are few options for renters [District of North Vancouver, 2011a]. The average monthly shelter cost for renters is $1,271, well above the provincial average of $989, and the Canadian average of $848. The percentage of renters spending 30% or more of available total income on shelter is 42%.

It is estimated that nearly 10% of all single-family detached homes in the District currently have only one person living in them. As the population ages and household size decreases, an increasing number of people will be looking to downsize into higher-density residential neighbourhoods. As outlined in Chapter 4, the District has identified a number of mixed-use town centres that would accommodate the anticipated demand for affordable multi-family housing. These include Lynn Valley Centre, Seylynn Village, Maplewood and the Lower Lynn and Lower Capilano areas along Marine Drive.

SOCIAL VULNERABILITY

Social vulnerability focuses on intrinsic characteristics of a community that create unsafe conditions and have the potential to amplify the negative impacts and consequences of a disaster event. Determinants of social vulnerability reflect underlying causal structures that are specific to a particular community and cannot be assumed on the basis of prevailing theories of social disadvantage and behavioural change [Andrey and Jones, 2008].

Patterns of social vulnerability can change abruptly and are influenced by a wide range of variables including political stability, economic vitality, cultural norms, and shifting demographic patterns that influence the movement of people from place to place over time. Key factors include the extent to which people are susceptible to the physical impacts of a major earthquake (exposure); social and economic variables that enable some to take actions that minimize the impacts of a hazard event while forcing others to succumb (agency); and demographic variables that influence capabilities to cope with and recover from the impacts of a disaster event (capacity).

Assessment Methods

Our analysis of social vulnerability is part of a regional assessment that was undertaken to identify trends for Metro Vancouver. The analysis is based on the well-known ‘hazards of place’ model, which utilizes empirical methods of geo-statistical analysis to detect and rank patterns based on a wide range of demographic variables that profile complex social and economic interactions at a neighbourhood level [Cox et al., 2006; Cutter, 2001; Cutter et al., 2000; Dwyer et al., 2004; Morrow, 1999; Wisner, 2004]. Population and demographic variables used in our assessment of social vulnerability are derived from information gathered as part of the 2006 long form census [Statistics Canada, 2006].

Variables selected as proxies for hazard exposure include housing characteristics and reliance on sector employment. Proxies for social agency include income, ethnicity, language and mobility. Variables selected as proxies for coping capacity include age, family structure and education. Numerical values for each of these variables were transformed into a common frame of reference using linear scaling and standardization methods to ensure internal coherence [B Jones and Andrey, 2007; Yoe, 2002]. A Principal Component Analysis (PCA) with Varimax rotation was then used to identify underlying patterns and to assess the strength of correlation across the full set of variables [Boruff et al., 2005; Brooks, 2003; Cox et al., 2006; B Jones and Andrey, 2007].

Vulnerable Populations

Results of our analysis provide insights on who are the most vulnerable population in the District and why (See Figure 68). Twelve principal component factors were identified that collectively explain 62% of the statistical variance in the dataset. Each of the components is characterized by dominant variables that are known to influence situational exposure, agency and coping capacity. The most dominant of these variables include: family structure, elderly citizens living alone, education level, low family income, mobility, and language.

Spatial patterns of vulnerability were determined at a neighbourhood scale by aggregating standardized values corresponding to variables with the highest factor loading for each of the principal components (Figure 68). We used a linear un-weighted method of aggregation to minimize the influence of different numbers of variables for each principal component. Higher values of social vulnerability represent neighbourhoods in which negative impacts are likely to be amplified during and after a disaster event. Lower values represent neighbourhoods that are more resilient to the impacts and consequences of a disaster.

Areas with higher levels of intrinsic vulnerability are concentrated in older established neighbourhoods. Of greatest concern are older neighbourhoods along the waterfront in which physical impacts caused by severe ground shaking and liquefaction are likely to be amplified by a more limited capacity of residents to respond and recover on their own. These are areas in which the demand for emergency social services is likely to be the greatest during and after a disaster event. Knowing who is most vulnerable and the underlying socioeconomic drivers provides insights on the types of emergency services that are likely to be needed in these areas during response and recovery operations.

EARTHQUAKE INJURIES

Hazus provides a capability to estimate the extent and likelihood of injuries based on predicted levels of structural and non-structural damage during an earthquake. Structural damages can lead to failure and/or collapse of load bearing systems in a building (walls, pillars, slabs, girders, etc.) with a potential for serious injury or death. Non-structural damages can lead to internal toppling of building components (and/or failure of external facades), also with a potential for serious injury or death. Casualty estimates are calibrated on the basis of empirical data gathered from historic earthquake events and are limited to physical impacts caused by earthquake damage. Not considered in the analysis are the effects of secondary health issues (e.g., heart attack, psychological effects) or accidents that may occur during emergency response/recovery operations.

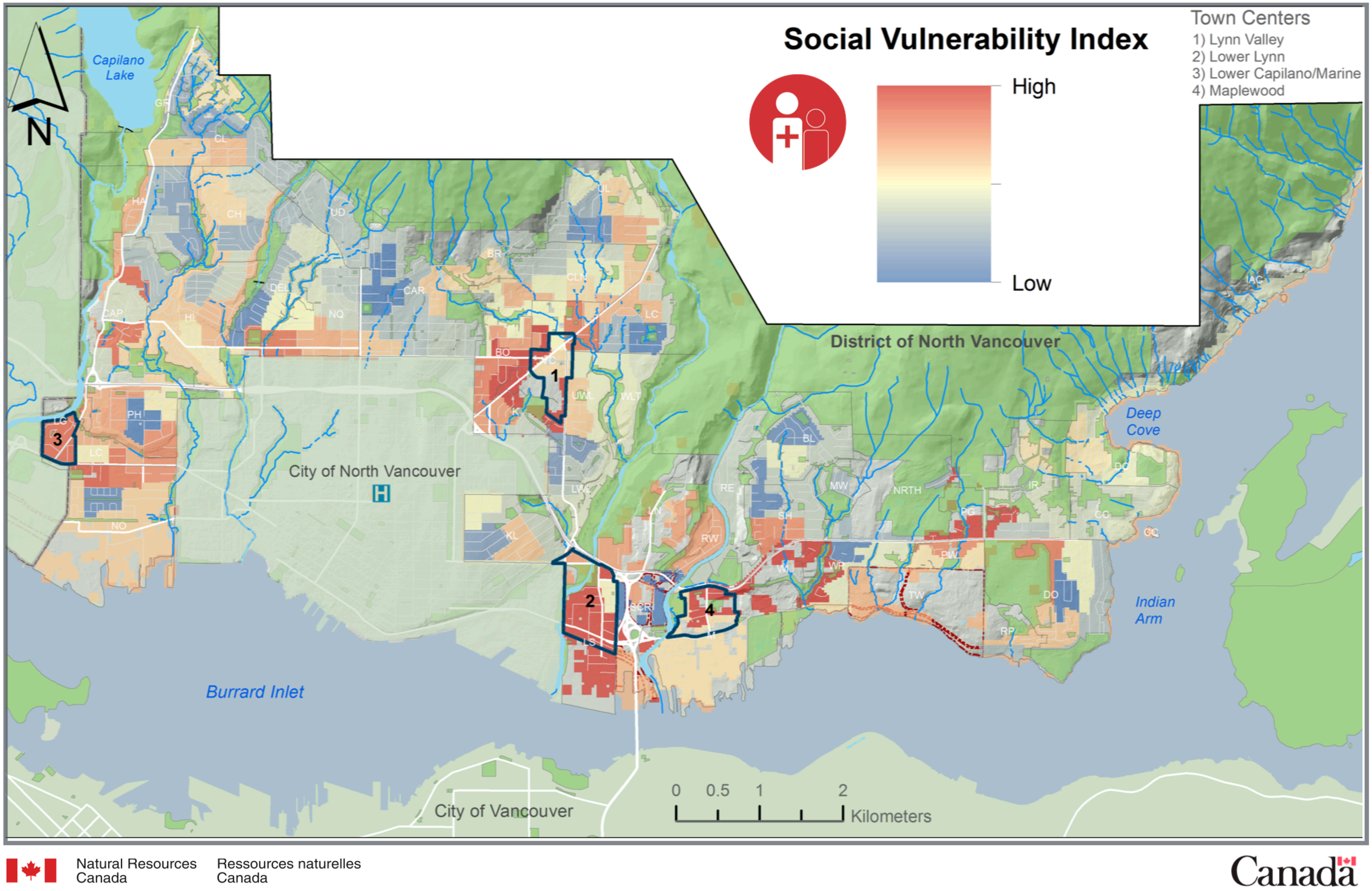


Figure 68: Map showing vulnerable populations for the District of North Vancouver. Results based on geo-statistical analysis of StatsCan variables (2006).

As shown in Figure 69, the analytic workflow for estimating casualties from an earthquake utilizes an event-tree model that begins with the scenario event and follows a possible course of events that each have a potential to cause injury and/or loss of life. Model inputs include hazard potential and time of day for the scenario earthquake, the distribution of people in each building during the earthquake, and characteristics of building type and seismic design that will determine the extent of damage by shaking and/or ground failure. For each node of the event tree, Hazus estimates the likelihood and rate of injury at four levels of severity based on damage state probabilities.

Level 1 injuries include severe cuts, first and second-degree burn, sprains, bruises and head injuries that do not result in loss of consciousness. These are injuries that would require basic medical aid that would be administered in the field by paramedics or those trained in emergency first aid. Hazus does not estimate the number of Injuries that are less severe and that could be self-treated. Level 2 injuries include more severe burns, fractured bones, dehydration and head injuries that would result in loss of consciousness. These are injuries that would require a greater degree of medical care but are not expected to be life threatening. Level 3 injuries are more severe and may include uncontrolled bleeding, spinal injuries and damages to internal organs caused by physical crushing beneath heavy objects that have toppled or fallen during the earthquake. These are injuries that may pose an immediate life threatening condition if not treated expeditiously by trained medical professionals. Level 4 injures include fatal wounds caused by toppling and/or building collapse that result in death before emergency care can be administered.

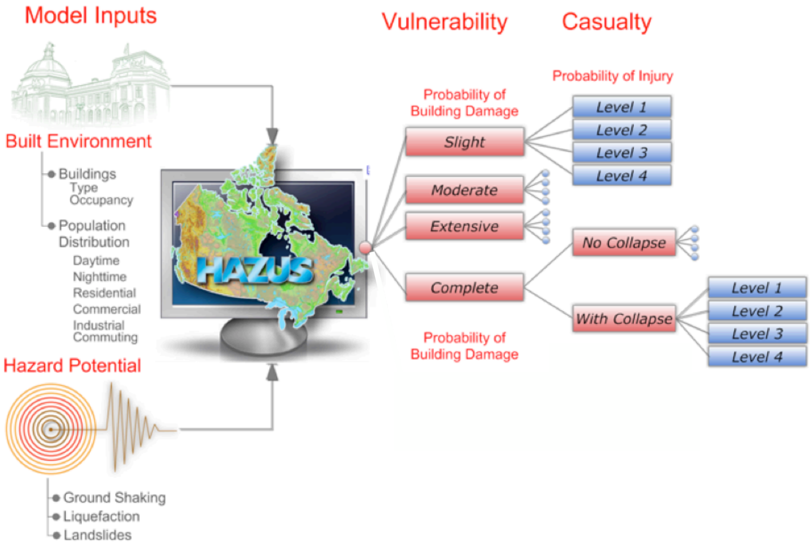


Figure 69: Analytic workflow used for estimating casualties based on the Hazus loss estimation methodology (FEMA, 2011).

Casualty rates measure the proportion of people in a building at the time of the earthquake who are expected to sustain injuries that would require medical attention or that might result in loss of life. Information about the spatial distribution and rates of injury for hotspot areas in the community provides important insights on public safety requirements that can be used in developing emergency plans and prioritizing disaster response operations

We implemented an enhanced version of the Hazus casualty model to estimate likelihood and severity of injuries for each of ~24,000 buildings in the District of North Vancouver for the Georgia Strait M7.3 scenario earthquake [AEBM: DHS and FEMA, 2011; FEMA, 2011]. Spatial patterns and rates of injury for the scenario earthquake are a function of damage potential and the distribution of people at different times of day (See Figures 70, 71 and 72). The map in Figure 71 shows the spatial distribution and rate of injury for a daytime earthquake scenario while accompanying charts (Figures 70 and 72) summarize the total number of expected casualties in each of four severity levels based on building characteristics and time of day.

Daytime Injuries

For a daytime scenario, it is estimated that a total of ~2,500 people would be injured as a result of structural and non-structural damages to buildings that are situated in areas exposed to severe shaking and/or ground failure (Figure 71). The majority of these are Level 1 injuries (~1,725 people; 69% of total) that would require medical attention by paramedics or those trained in emergency first aid.

An additional ~530 people (21%) would sustain more serious injuries that would require specialized medical care that is typically available only in a hospital (e.g., x-rays, diagnostic tests, minor surgery, etc.). At least 80 people (~3%) are likely to sustain critical life-threatening injuries that would require immediate medical attention. An additional ~165 people (7%) are likely to be killed as a result of being trapped in buildings that sustain significant levels of structural damage during the earthquake event.

As expected, casualty hotspots are concentrated along the waterfront and other low-lying areas exposed to severe ground shaking and liquefaction where more than half of all those injured during a daytime scenario are likely to be at work in commercial/industrial buildings or public facilities when the earthquake strikes (See Figure 71). Areas of concern include Lower Capilano/Marine, Norgate, Edgemont, Lynnmour-South, Maplewood and Seymour Creek Reserve, where at least one in four people are likely to be injured during the scenario earthquake. The majority of injuries at all levels of severity are concentrated in older unreinforced masonry and concrete buildings that are vulnerable to significant structural damage and/or collapse during the scenario earthquake (~78% of total).

Casualty rates are highest in older commercial/industrial buildings and public facilities (government buildings, schools, care facilities, etc.) in which larger numbers of people are likely to be present during business hours (~2,275; 90% of total). Approximately 1,000 injuries are possible in the business community alone with about 100 of these being life threatening injuries or fatalities caused by structural failure or collapse of older buildings (See Figure 70). Municipal facilities that are vulnerable to earthquake hazards are expected to sustain over 350 injuries. While the majority of these are not critical, it is estimated there could be as many as ~25 fatalities and at least a dozen life-threatening injuries. Schools and care facilities for the very young and elderly are likely to sustain a similar number of fatalities and life-threatening injuries.

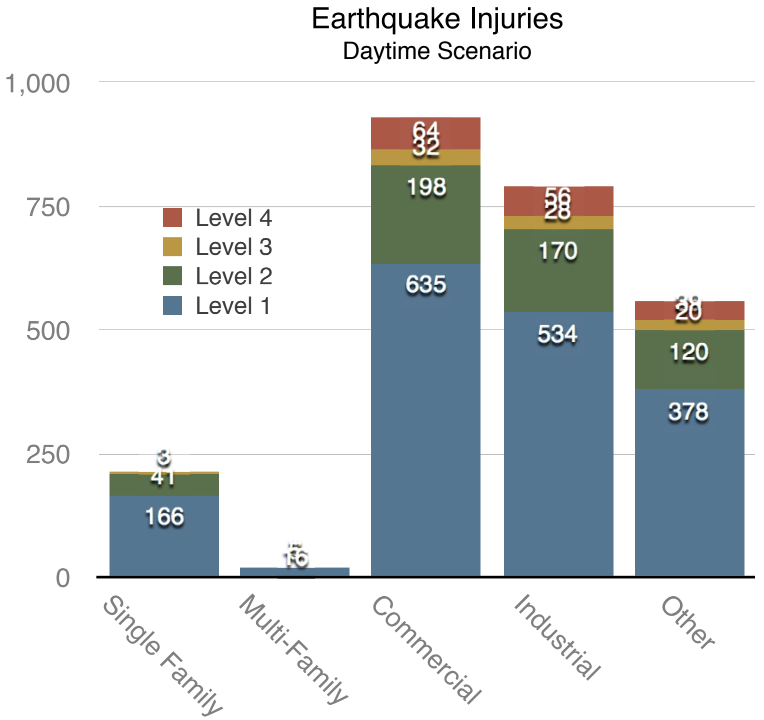
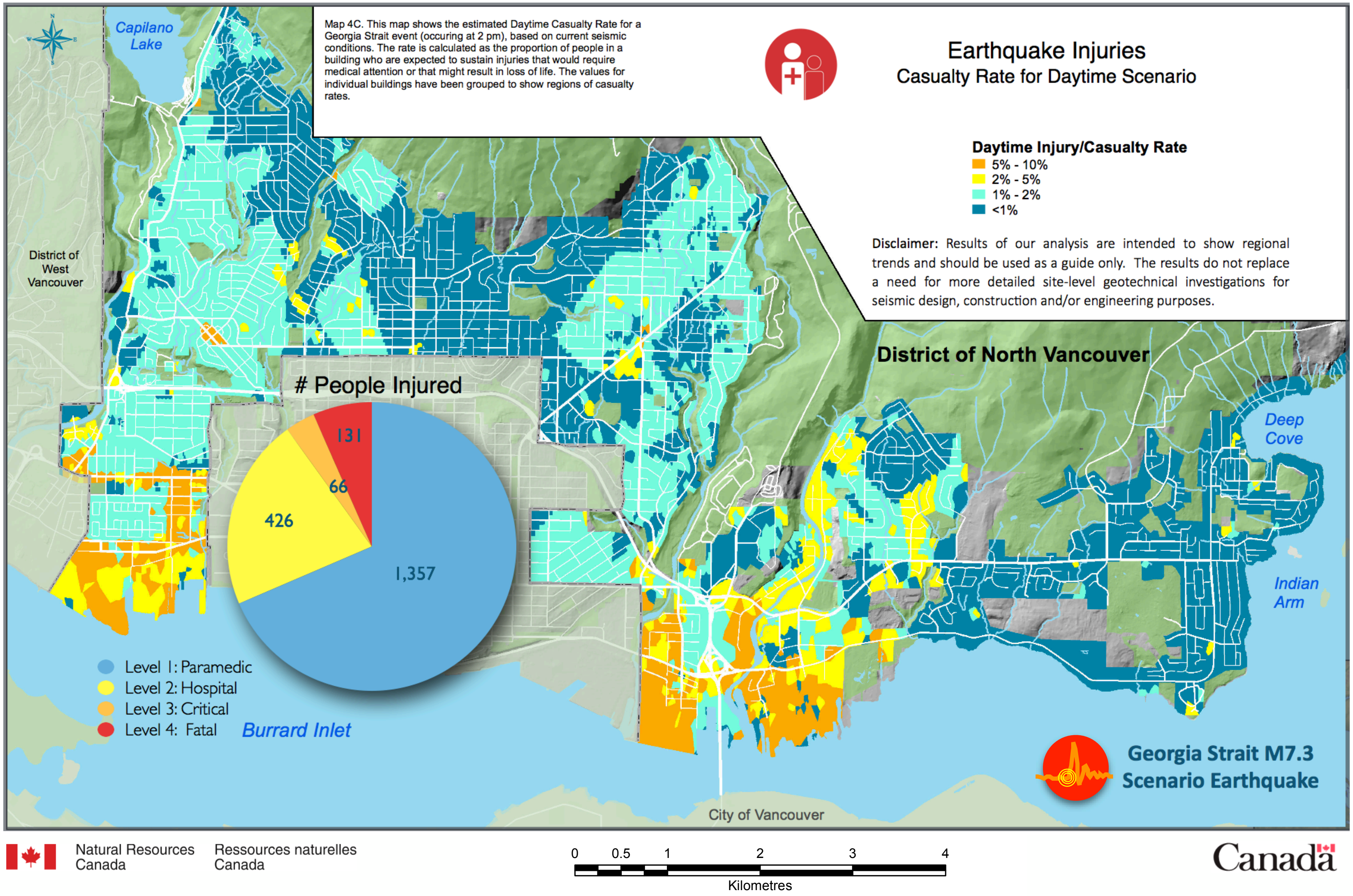


Figure 70: Chart showing daytime injuries for scenario earthquake. Analysis based on Hazus methodology (FEMA, 2011).



Map 4C. This map shows the estimated Daytime Casualty Rate for a Georgia Strait event (occuring at 2 pm), based on current seismic conditions. The rate is calculated as the proportion of people in a building who are expected to sustain injuries that would require medical attention or that might result in loss of life. The values for individual buildings have been grouped to show regions of casualty rates.

Disclaimer: Results of our analysis are intended to show regional trends and should be used as a guide only. The results do not replace a need for more detailed site-level geotechnical investigations for seismic design, construction and/or engineering purposes.

Figure 71: Map showing pattern and severity of casualties for the District of North Vancouver. Assessment based on Hazus methodology (2011).

Night-Time Injuries

The distribution of injuries is similar between daytime and night-time scenarios. However, the number and severity of injuries are expected to be significantly less if the scenario earthquake were to strike after business hours when people are at home. For a night-time scenario, it is estimated that a total of ~925 people would be injured as a result of earthquake damages (Figure 72).

More than 90% of all injuries are concentrated in older wood-frame, unreinforced masonry and concrete buildings in established residential neighbourhoods. The majority of these (~715; 77% of total) are Level 1 injuries that would require medical attention by paramedics or those trained in emergency first aid. An additional ~175 people would sustain more serious injuries that would require hospitalization and access to more specialized medical care. At least a dozen people are likely to sustain critical life-threatening injuries that would require immediate medical attention. It is estimated that another 20 people are likely to be killed as a result of extensive structural damage and/or collapse of older buildings that are vulnerable to shaking and ground failure.

Hotspots of concern include vulnerable buildings in Lower Capilano/Marine, Norgate, Edgemont, Lynnmour-South, Maplewood and Seymour Creek Reserve, where less than one in four people are likely to be injured during the scenario earthquake. Lower casualty rates in other areas of the District are attributed to the number of people living in homes of wood frame construction that are known to perform well under conditions of severe ground shaking. While the number and severity of injuries is relatively low for a nighttime earthquake scenario, the distribution of people requiring medical attention is significantly greater and would present a different set of challenges for emergency response operations.

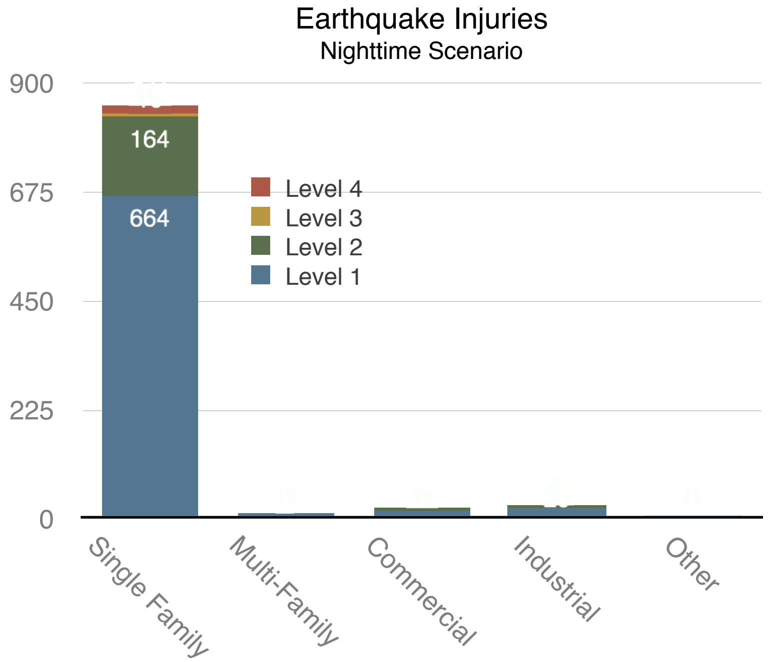


Figure 72: Chart showing nighttime injuries for scenario earthquake. Analysis based on Hazus methodology (FEMA, 2011).

Response Capacity

The number and severity of injures that are projected as a result of the scenario earthquake would very likely exceed the capacity of paramedic and acute health care facilities that serve the District of North Vancouver. Lions Gate Hospital is the fourth busiest in the Metro Vancouver area providing a full range of general and specialized acute care services including seven operating rooms, a trauma centre, advanced diagnostic equipment and a bed capacity of ~270. While hospital and adjoining emergency operation centre facilities are expected to sustain only minor damage during the scenario earthquake, the number of injures requiring specialized acute medical care would exceed current service capacities of by a factor of 2 or more for the District alone.

Emergency response facilities in areas hardest hit by the earthquake are expected to sustain structural and non-structural damages that would significantly reduce functional capacities in early stages of emergency response operations. More than 1,000 people are expected to sustain serious injuries that would require immediate medical care in the Lynnmour-Maplewood area alone.

Fire Hall #2 provides emergency services to the area but is likely to be operating at less than 25% of its functional capacity as a result of damages sustained in the earthquake. More than 650 people are expected to need paramedic services in the Norgate area. However, Fire Hall #5 is likely to be operating at ~60% of its functional capacity for the first few days after the earthquake and the 3 remaining essential facilities in the District are not likely to have a capacity to meet the demand for emergency services.

SOCIAL IMPACTS

Social disruption encompasses a wide range of direct and indirect consequences that are governed by the capacities of people to withstand and recover from the physical and psychosocial impacts of a major disaster. Direct social impacts vary as a function of earthquake damage and are measured in terms of displacement, shelter requirements and loss of functionality [FEMA, 2011]. Indirect social impacts encompass a wider range of psychological, emotional and health-related issues that are more difficult to predict. They include post-traumatic stress disorders, depression, anxiety, relationship issues (interpersonal, family, and occupational), and loss of self-reliance resulting from shock and/or fear experienced during the earthquake. Longitudinal studies have shown that psychosocial impacts have the greatest effect on the most vulnerable members of a community with symptoms that can persist for years after a disaster event [Norris et al., 2002].

Disruption and Recovery Time

Hazus provides a capability to assess levels of social disruption following a destructive earthquake by using the extent and probability of site-level damage to estimate the time required for repair and recovery of buildings and related infrastructure [FEMA, 2011]. Results of our analysis for the Georgia Strait scenario earthquake are summarized in Figure 73. The map shows areas in the community that would be disrupted by earthquake damage and the amount of time required to restore baseline levels of functionality. Our assessment does not consider the effects of indirect psychosocial impacts of a major earthquake on vulnerable populations, though we recognize these are likely to be significant and will have a lasting impact on the community.

The extent and duration of social disruption will vary from place to place depending on the time required to repair and recover from damages caused by the earthquake. Repair time includes initial building inspections, cleanup of disaster debris, and any additional time that may be needed to renovate and/or reconstruct buildings that have sustained significant earthquake damage. In general, smaller buildings with lower functional capacities (e.g., residential & commercial) will take less time to repair than larger and more complex structures that support mixed-use functions (industrial, government and education). Recovery is the time required to restore baseline levels of functionality to homes and businesses in a community. It encompasses both repairs and additional delays that may be required to arrange financing, apply for permits and reconstruct buildings that have sustained significant damage as a result of the earthquake.

Estimated recovery times for the scenario earthquake range from a few days to several years depending on building functions and the extent of damage (See Figure 73). Homes and smaller businesses are expected to be out of operation for 1-6 months in areas of slight and moderate damage — depending on the amount of time required for restoration of essential lifeline

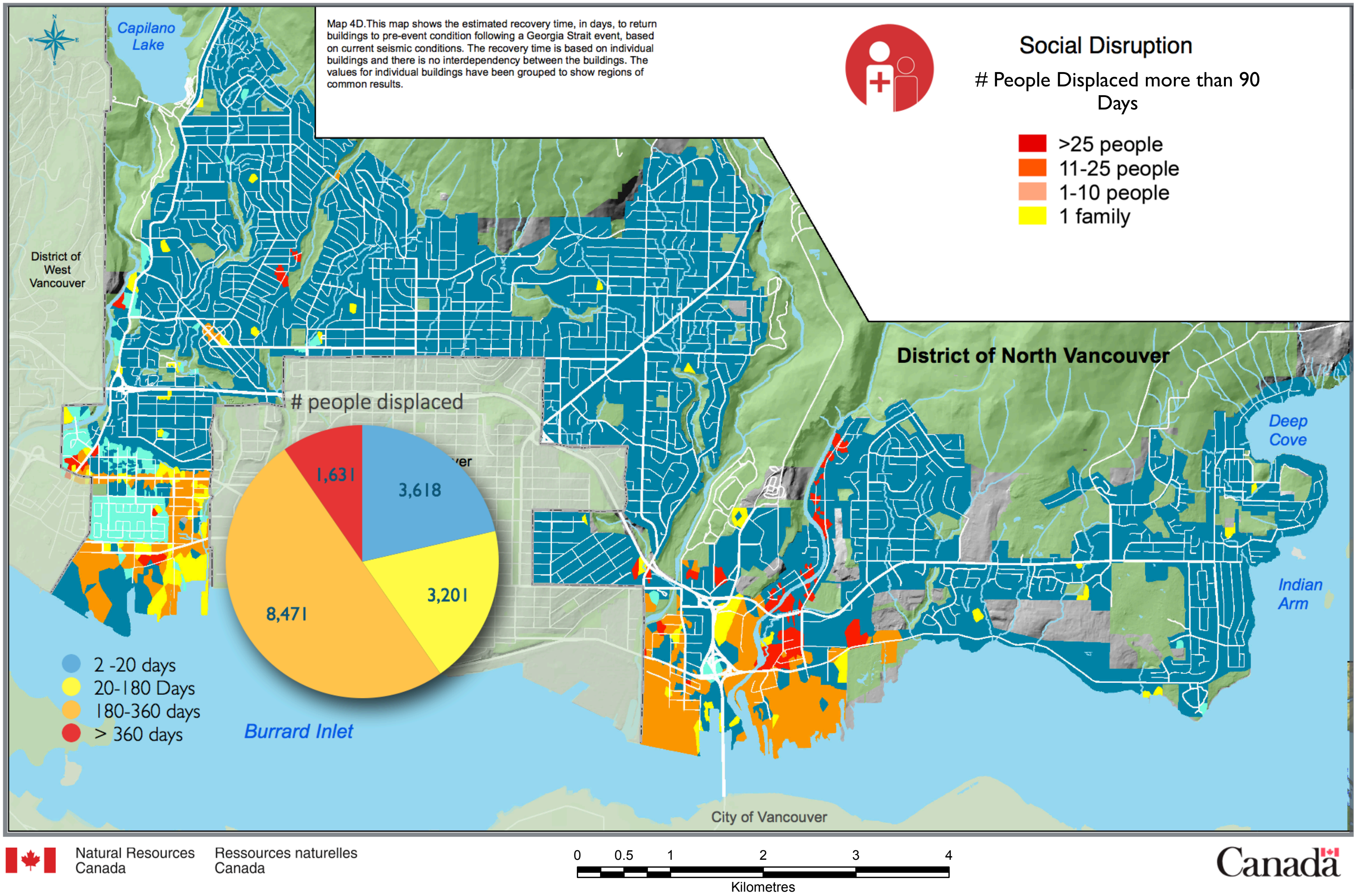

Map 4D.This map shows the estimated recovery time, in days, to return buildings to pre-event condition following a Georgia Strait event, based on current seismic conditions. The recovery time is based on individual buildings and there is no interdependency between the buildings. The values for individual buildings have been grouped to show regions of common results.

Figure 73: Map showing earthquake recovery time for the District of North Vancouver. Assessment based on Hazus methodology (2011).

services (power and water), cleanup of disaster debris, and minor repairs.

Areas of more extensive damage and building collapse are likely to be cordoned off for up to a year during the recovery process. Hotspots of concern include business districts along the waterfront (~200 hectares), and neighbourhoods situated along valley escarpments of Mosquito Creek and the Seymour River (~35 hectares). The total area affected in the District alone is almost a third of that cordoned off in the Christchurch Business District following the Canterbury earthquake in 2011.

Displacement and Shelter Requirements

While the majority of people in the District are expected to shelter in place, damages sustained during the scenario earthquake are expected to displace ~4,250 people from their homes. An additional ~12,500 people are likely to be displaced from businesses that are damaged during the earthquake. Over 60% of those residents evacuated from their homes (2,600 people) are expected to return within 20 days, allowing time for building inspections and cleanup of disaster debris. An additional 300 people are expected to return after six months to begin the process of repair and recovery. More than 1,300 people would be displaced for up to a year with an additional 1,500 people likely to be displaced for several years in areas hardest hit by the earthquake.

Most people displaced by the earthquake will seek short-term shelter with family and friends while others will stay in motels or arrange rental accommodation in areas with little or no damage. Those who have lost the use of their homes and businesses may be forced to relocate during the recovery process. It is estimated that several hundred people will not have the means to provide for themselves and are likely to seek public shelter and emergency services that are provided by relief organizations.

Commercial and industrial businesses that sustain moderate or extensive damage are likely to find alternate ways of continuing their operations by relocating to areas that have not been impacted by the earthquake. Those with business continuity plans and earthquake insurance policies will fare better and may even benefit by adapting to and capitalizing on new market opportunities while others may be forced to close. The economic consequences of business disruption are expected to be significant (See Chapter 8).

CHAPTER 7: LIFELINES

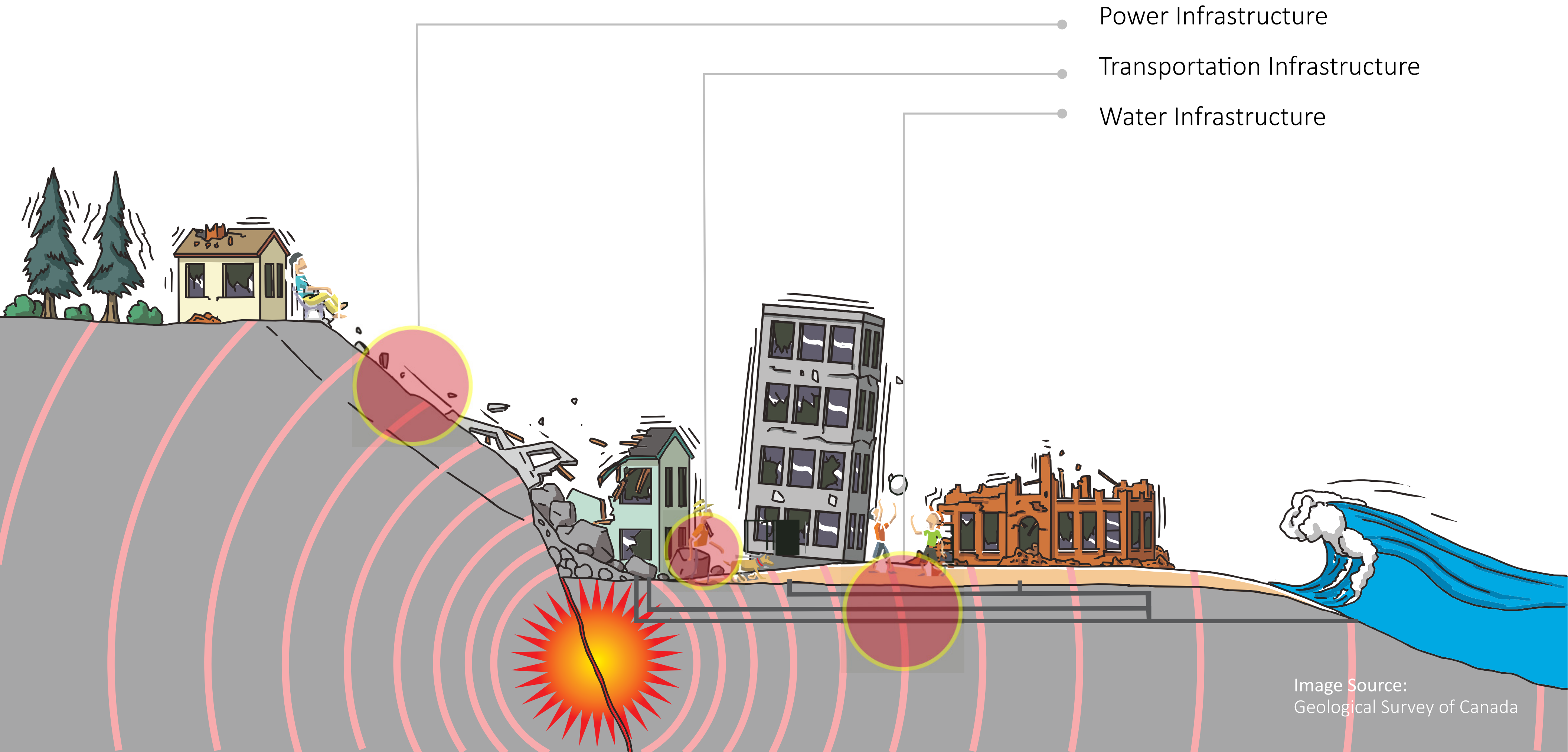


Image Source:
Geological Survey of Canada

CHAPTER 7: LIFELINES

Primary Authors: Journeay, J.M., and Wagner, C.L.

Critical infrastructure is defined as the system of engineered structures, and networked processes that provide access to food, water, energy and transportation — lifeline services that are essential for day-to-day functioning of homes and businesses and to meet basic human needs in the event of a disaster [Public Safety Canada, 2010b]. The National Strategy for Critical Infrastructure and the accompanying action plan for Canada is aimed at safeguarding critical assets for the benefit of Canadians through a collaborative all-hazards risk management framework that acknowledges the interconnected nature and shared ownership of lifeline services across government and private sectors [Public Safety Canada, 2014]. The strategy recognizes that the impacts of disruptions caused by anthropogenic and natural hazards have the potential to cascade across sectors and jurisdictions with significant consequences to the safety and security of Canadians.

This chapter examines the vulnerability and disaster resilience of critical infrastructure in the District of North Vancouver based on a M7.3 scenario earthquake in the Strait of Georgia. The results are representative of what might be expected for a destructive near-source earthquake event, and are relevant for both emergency management and infrastructure planning. Our assessment is focused on utility and transportation systems that are managed by the District, or that are jointly owned or operated with other public/private sector partners

Utility systems in the District that are expected to sustain damage and loss of functionality are concentrated in low-lying areas along the waterfront and in older residential neighbourhoods at higher elevations where there are higher proportions of older non-ductile pipes that are susceptible to damage from ground shaking and lateral displacement caused by liquefaction. Of particular concern are water facilities adjacent to the Capilano Reservoir and pumping stations that service the neighbourhoods of Cleveland, Upper Lynn and Northlands.

Transportation systems are also expected to sustain damage and loss of functionality in areas along the industrial waterfront, and in neighbourhoods bordering the Capilano, Lynn and Seymour River valleys. While it is expected that damages to highway and rail segments would be repaired in the days and weeks following the earthquake, loss of functionality immediately after the event and the presence of disaster debris along urban roadways would seriously compromise emergency response and recovery efforts.

Results of our study provide a basis for incorporating earthquake risk into the broader decision-making framework used by DNV staff to prioritize actions that can be taken in advance to increase the longer-term resilience of lifeline systems that serve the community. Information about the lifeline functionality following a major earthquake is also vital for emergency management and response operations, and for assessing the extent of disruption to homes, businesses, and governance in the community for purposes of post-event recovery planning.

LIFELINE CHARACTERISTICS

The District of North Vancouver relies on an extensive system of reservoirs, dams, pipes, pumps, roads, rails, bridges and related engineering systems to supply a variety of essential lifeline services to the community. The system of transportation and utility infrastructure is jointly owned and operated across several levels of government and the private sector. It is inherently complex, interconnected and increasingly in need of upgrades to meet the needs of ongoing growth and development in the region. Failure of any one component as a result of natural and/or anthropogenic causes has the potential to disrupt essential lifeline services for the community and the Metro Vancouver region as a whole.

Most of the critical infrastructure in the District of North Vancouver was built during a period of rapid growth and development between 1950 and 1970 [District of North Vancouver, 2011a]. Major infrastructure developments during this time period included: completion of the Cleveland Dam in 1954 and the construction of major water and power utilities; building of major transportation networks such as the Upper Levels Highway and its connection to the Trans-Canada Highway system via the Second Narrows and Lions Gate bridges; and installation of power and water distribution systems to service new residential and commercial/industrial developments that flourished during this period.

Maintenance and replacement of aging infrastructure within the District is administered by the Asset Management Steering Committee who are responsible for waterworks, sewers, municipal roads and bridges, recreation centres and libraries. Management of municipal water systems is prioritized through a structured decision making process that utilizes an objective ranking system to evaluate current infrastructure assets in terms of life cycle costs and the risk of failure due to natural and anthropogenic causes. The District is one of only a few municipal governments in Canada to adopt a formal risk-based approach to managing ongoing maintenance and replacement of its critical infrastructure assets [Carter, 2012].

Scope of Analysis

Our assessment of earthquake risks to critical infrastructure in the District of North Vancouver is based on an analysis of over 1,300 kilometres of water pipes, sewers, and distribution lines; 20 pumping stations and related water treatment and distribution facilities; 13 power substations; 500 kilometres of highways and secondary roads; 36 bridges; and 60 kilometres of rail line and related cargo facilities. Assessment of lifeline exposure was carried out at the site level and is based on asset information provided by District staff and methods outlined in the Hazus technical manual [FEMA, 2011].

For each lifeline asset, we compiled available information from District planning staff about the length, material type, and age of construction for pipes (Figures 74 and 75). We used default building types for utility and transportation facilities and we measured or calculated the lengths and areas of highway and road segments. Replacement costs were provided by District planning staff for utility and transportation systems under municipal jurisdiction. Characteristics for other elements of the lifeline inventory were estimated using recommended default values [FEMA, 2011]. We did not analyze system components in instances where there was not a sufficient level of information to make informed judgments about construction types and/or replacement costs.

Utility infrastructure assets not considered in our study include water reservoirs, dams, treatment plants and water distribution systems managed by Metro Vancouver, and the network of communication and energy systems (oil and gas) managed independently by the private sector. Also not included in our assessment are marine transportation infrastructure assets along the waterfront (Vancouver Port Authority and BC Transit), major bridges connecting the North Shore with Metro Vancouver (Lion’s Gate and Iron Workers Memorial), and other related land-based systems managed by the regional transportation authority. While we acknowledge the importance of addressing system interdependencies for planning and policy development, the analysis of cascading effects within and across sectors is not directly addressed within the Hazus methodology and was, unfortunately, beyond the scope of our study.

Utility System Inventory

Component	Quantity	Comments
Potable Water		
-Production Wells	-	No production wells
-Storage Tanks	15	Shared Ownership/Limited Info
-Pumping Stations	11	Shared Ownership/Limited Info
-Treatment Plants	10	Shared Ownership/Limited Info
-Pipelines & Distribution Lines	510 km	445 km owned by DNV
Wastewater		
-Collection Pipes & Sewers	780 km	Owned & Operated by DNV
-Treatment Plants & Lift Stations	-	Private - No Information Available
Electric Power		
-Power Generation Plants	-	BCHydro - No Information
-Substations	13	BCHydro - Limited Information
-Distribution Lines & Circuits	-	BCHydro - No Information
Communication		
-Broadcast Facilities	-	Private - No Information Available
-Transmission Facilities	-	Private - No Information Available
Oil & Gas		
-Production Facilities	-	Private - No Information Available
-Distribution Facilities	-	Private - No Information Available
-Pipelines	-	Private - No Information Available

Figure 74: Inventory of Utility systems and availability of information for assessment of damages and losses.

Utility Infrastructure

Potable water and wastewater services are provided to the District and other municipalities in the lower mainland through a system of storage reservoirs, water mains, pumping stations, collection pipes, sewers, and water treatment systems that are managed by Metro Vancouver (See Figure 74). The District of North Vancouver is responsible for pumping stations, pipelines and water storage facilities within municipal jurisdiction.

BC Hydro owns and operates a regional network of power generation and transmission facilities that provide electrical power services to homes and businesses the District. They are recognized as an industry leader in risk management practices and routinely update their assessment of seismic risks to critical infrastructure assets in the region as new information becomes available. In addition to water and electrical power utilities, there is also a vast network of communication infrastructure, and oil and natural gas systems located within the study area. Unlike public utilities, these are privately owned and operated systems. While many of these utility companies undertake detailed risk assessments as part of ongoing business continuity planning activities, information about earthquake risks to assets of concern is not currently available in the public domain.

Potable Water Facilities

The Capilano and Seymour reservoirs are located in highland regions of the District and together supply more than 60% of the total daily demand for drinking water in the Metro Vancouver region (>1 billion litres). A twin tunnel system is currently under construction to treat water from both the Capilano and Seymour reservoirs.

In 2007, seismic upgrades to the Seymour dam were completed in order to comply with guidelines regulated by the Canadian Dam Association to ensure minimum thresholds of safety to withstand the impacts of a maximum credible earthquake or an earthquake with an annual exceedance probability of 1/10,000 [Siu et al., 2004]. The Cleveland dam was seismically upgraded in 1992 and will undergo further seismic stability assessment in 2014. It should be noted that Hazus does not directly analyze earthquake damages to dams or water reservoirs. The model assumes that the supply of water to distribution systems and treatment plants is constant in the days and weeks following a major earthquake and focuses primarily on the vulnerability of downstream utility assets.

In addition to major reservoirs administered by Metro Vancouver, there are 15 water storage tanks in the District, all of which have been seismically retrofitted in 2010 in accordance with American Water Works Association Standards (District of North Vancouver, 2011a). Three of the 11 pumping stations in the water distribution system are owned and operated by the District while the remaining facilities are under the jurisdiction of Metro Vancouver water services [District of North Vancouver, 2011a]. Water quality is managed through a network of 10 water treatment facilities, all of which are managed by Metro Vancouver water services. With the exception of the recently commissioned Seymour-Capilano filtration plant, all of the primary water treatment facilities within the District were assessed in terms of earthquake damage and potential loss of functionality. In the absence of reliable replacement costs, we were not able to assess earthquake-related losses to Metro Vancouver water treatment facilities.

Potable Water Pipelines

There are approximately 419 kilometres of potable water pipelines in the District of North Vancouver, the majority of which (445 Km; 87%) are owned and operated by the municipality. The balance comprises water mains and infrastructure that is administered by Metro Vancouver. The pipe network is predominantly made up of ductile iron and steel pipes (65%), although a large percentage of pipes are constructed of asbestos cement, cast iron, and other brittle materials. Asbestos cement pipes are particularly prone to catastrophic break and are in the process of being replaced by ductile iron as part of an annual replacement plan. The average age for pipeline segments in the network is 51 years.

A risk-based decision support system is currently being developed by the District to prioritize the replacement of aging pipe infrastructure based on objective measures of risk and what the community considers to be most vulnerable and in need of upgrading. Objective measures of risk (likelihood and consequences) are based on a system of indicators that track the number of historic breaks, material pressure, pipe diameter, number of people potentially without service, fire protection needs, ground slope angle, building type, soil conditions, and road service [Carter, 2012]. There does not appear to be any significant correlation between the age of the pipe and breakage potential. The water main replacement program has the potential to but does not currently account for the risk of breakage due to ground shaking and/or liquefaction in an earthquake event.

Wastewater Pipelines

Metro Vancouver operates a primary wastewater treatment facility at the north end of the Lions gate Bridge in West Vancouver and a supporting network of trunk sewers and pumping stations that connect with municipal systems in the North Shore region of Vancouver. Collectively, these systems manage more than 1 billion litres of wastewater daily with nearly 80% of this coming from homes and businesses and the balance from storm water generated by surface runoff.

As part of this network, the District of North Vancouver owns and operates ~770 kilometres of collection pipes and sewers with an average age of 40 years. The majority of pipeline infrastructure in the District (~90%) is constructed of concrete, asbestos cement, and other brittle materials that are inherently prone to leakage and/or rupture caused by severe ground shaking or displacement during an earthquake. The system is gradually being replaced on an as-needed basis with more ductile but costly materials such as steel, plastic, and ductile iron.

Transportation Infrastructure

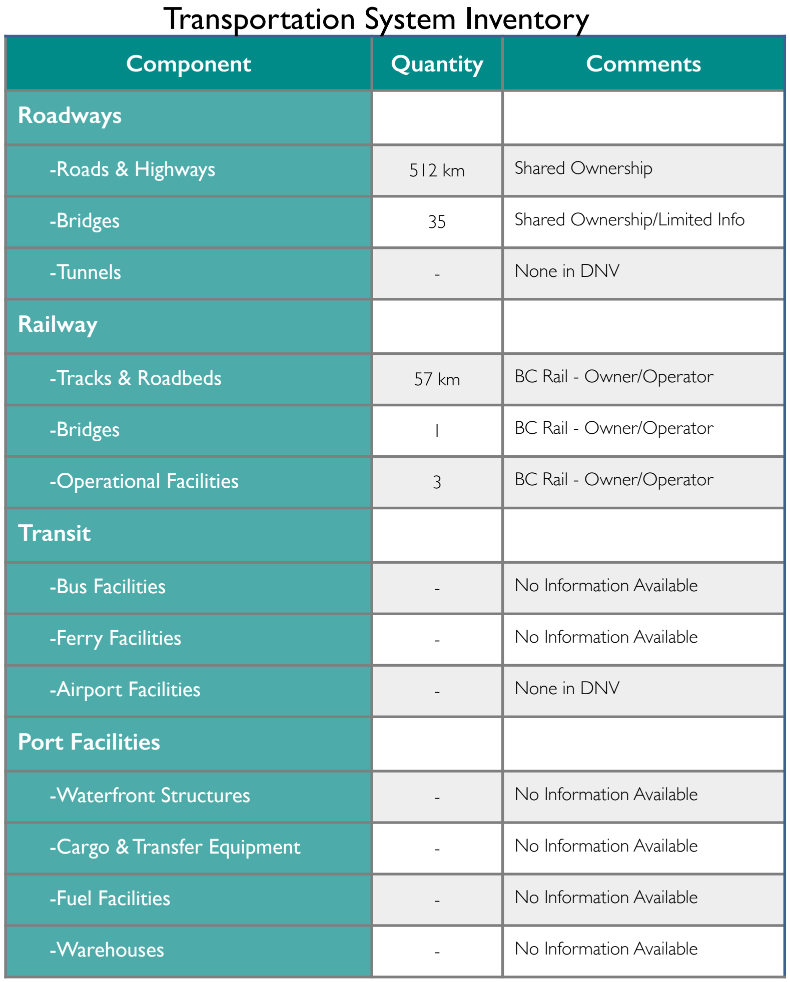
The District of North Vancouver relies on an extensive transportation system network that is jointly owned and operated by municipal, provincial and federal agencies (See Figure 75). More than 30,000 people commute each day from the District into the greater Metro Vancouver region across the Lions Gate and Iron Worker’s Memorial bridges, or by ferry into the downtown core. An additional 24,000 people are at home or in transit within the community on any given day. Commercial and industrial businesses rely on this same network of roads, bridges, and rail lines for the conveyance of goods and services — the lifeblood of both local and regional economies.

Roadways

There are more than 500 kilometres of highway, arterials and secondary roadways in the study area. The Trans-Canada Highway is a primary transportation corridor that connects arterials and secondary roadways in the District with other regional transportation networks via the Lions Gate and Iron Workers Memorial bridges. Nearly 75% of the transportation infrastructure is owned and operated by the District under joint administration with the regional transportation authority and other jurisdictions. Primary arterials and secondary roads of varying widths make up more than 85% of the network (~435 km) and are almost entirely of asphalt construction. Gravel, dirt and mixed surface roadways make up the balance (~66 km) and provide vital access to critical infrastructure, recreational facilities, and satellite communities in the highlands and along the shores of Burrard inlet.

Railways

Rail lines and related infrastructure provide essential transportation services for the movement of manufactured goods and raw materials to and from port facilities in the Metro Vancouver region. Nearly 60 kilometres of railway tracks, roadbeds and associated cargo storage facilities are situated in the District of North Vancouver, primarily along the industrial waterfront in Norgate, Lynnmour-South and Maplewood. Rail line infrastructure is owned and operated by BC Rail and is connected



Transportation System Inventory

Component	Quantity	Comments
Roadways		
-Roads & Highways	512 km	Shared Ownership
-Bridges	35	Shared Ownership/Limited Info
-Tunnels	-	None in DNV
Railway		
-Tracks & Roadbeds	57 km	BC Rail - Owner/Operator
-Bridges	1	BC Rail - Owner/Operator
-Operational Facilities	3	BC Rail - Owner/Operator
Transit		
-Bus Facilities	-	No Information Available
-Ferry Facilities	-	No Information Available
-Airport Facilities	-	None in DNV
Port Facilities		
-Waterfront Structures	-	No Information Available
-Cargo & Transfer Equipment	-	No Information Available
-Fuel Facilities	-	No Information Available
-Warehouses	-	No Information Available

Figure 75: Inventory of Utility systems and availability of information for assessment of damages and losses.

to transcontinental networks in the Metro Vancouver region via the CN Rail Bridge over Burrard Inlet.

Bridges

There are 35 highway bridges and 1 railway trestle within the District of North Vancouver. Nearly half of the bridges in the study area are owned and operated by the District of North Vancouver with remaining bridges administered by the regional transportation authority. While many of these bridges are in the process of being seismically upgraded, we were only able to assess earthquake risks for those assets owned and operated by the District. Although vital elements of the transportation infrastructure, we did not assess earthquake risks for major road and rail bridges that cross Burrard Inlet and connect the District to other parts of the Metro Vancouver region. These include the Lions Gate and Iron Worker's Memorial roadway bridges, and the CN Rail Bridge.

Port Facilities

The industrial waterfront along Burrard Inlet is part of Canada's largest port facility and is a strategic national asset in terms of trade and commerce. It includes several marine transport facilities that collectively manage cargo shipments, and process and store raw materials for distribution to national and international markets. Viability of these port facilities is dependent on waterfront structures and cargo transfer equipment that are connected to the broader regional network of roadways, bridges and rail lines.

Because of their location along the waterfront, marine transport facilities are particularly vulnerable to earthquake damages and loss of functionality. The Vancouver Port Authority acknowledges the potential impacts and consequences of a major earthquake on marine transport facilities in the region. As part of a separate but complementary study, they are in the process of conducting an independent analysis of earthquake risks to safeguard and increase the resilience of strategic assets within the broader Metro Vancouver region. Our contribution is to provide information about earthquake exposure, vulnerability, and potential risks to the network of roads, bridges and rail lines that serve vital port facilities within the District of North Vancouver.

LIFELINE DAMAGE AND RESILIENCE

Resilience measures the capacity of critical infrastructure to withstand, absorb, and recover from the impacts of sudden shocks that may threaten the coherence and functional integrity of systems and processes that provide essential lifeline services to a community. From the perspective of planning and policy development, the goal is to implement measures with a potential to increase resistance and reduce the amount of time required to restore essential functions and lifeline services to pre-disaster levels.

Physical vulnerability is a more specific measure of the extent to which lifeline systems are likely to resist the impacts of a disaster in terms of damages and loss of functionality. The potential for earthquake damage will vary from location to location depending on hazard exposure, the intrinsic capacity of facilities and infrastructure to withstand the impacts of shaking and related ground failure, and the effectiveness of mitigation measures that are put in place to resist anticipated levels of vertical and lateral ground motion.

In addition to impacts from seismic ground shaking, lifeline systems are also vulnerable to the impacts of surface fault rupture, liquefaction, and earthquake-triggered landslides. These secondary hazards can displace, bury, and/or rupture lifeline segments with a potential to significantly reduce the functionality and service capacity of lifeline systems well beyond the impacts of ground shaking alone. The extent and likelihood of damage can be estimated based on the results of seismic engineering studies that simulate system performance under varying conditions of ground motion and/or forensic studies that have established empirical relationships between measured ground motions and observed earthquake damage.

Analytic Methods

Our assessment of the physical vulnerability and resilience of critical infrastructure in the District of North Vancouver utilizes analytic procedures outlined in the Hazus loss estimation methodology for lifeline systems [FEMA, 2011]. Results are based on expected ground motions associated with the Georgia Strait scenario earthquake.

Physical vulnerabilities of potable water and wastewater pipelines are described in terms of the number of leaks and/or breaks and the estimated rate of repair. Two damage functions are used in the analysis. The first accounts for damages caused by severe ground shaking and is based on measured peak ground velocity in the vicinity of the pipeline. It is assumed that ~80% of the damage related to ground shaking will result in leakage at pipe joints with the remaining 20% results in breaks caused by pipe failure.

The second damage function accounts for the effects of permanent ground deformation and is based on the potential for lateral displacement of individual pipeline segments. It assumes that the majority of damage (80%) will be physical breaks caused by pipe failure. The vulnerability functions are calibrated for brittle pipes on the basis of observed earthquake damages to utility system components in California and Mexico. Damage estimates for newer and more resistant pipeline materials are based on evidence that suggests they are 30% less vulnerable to both ground shaking and lateral ground displacements. Outputs of the analysis are used to estimate the number of leaks and/or breaks for each pipeline segment.

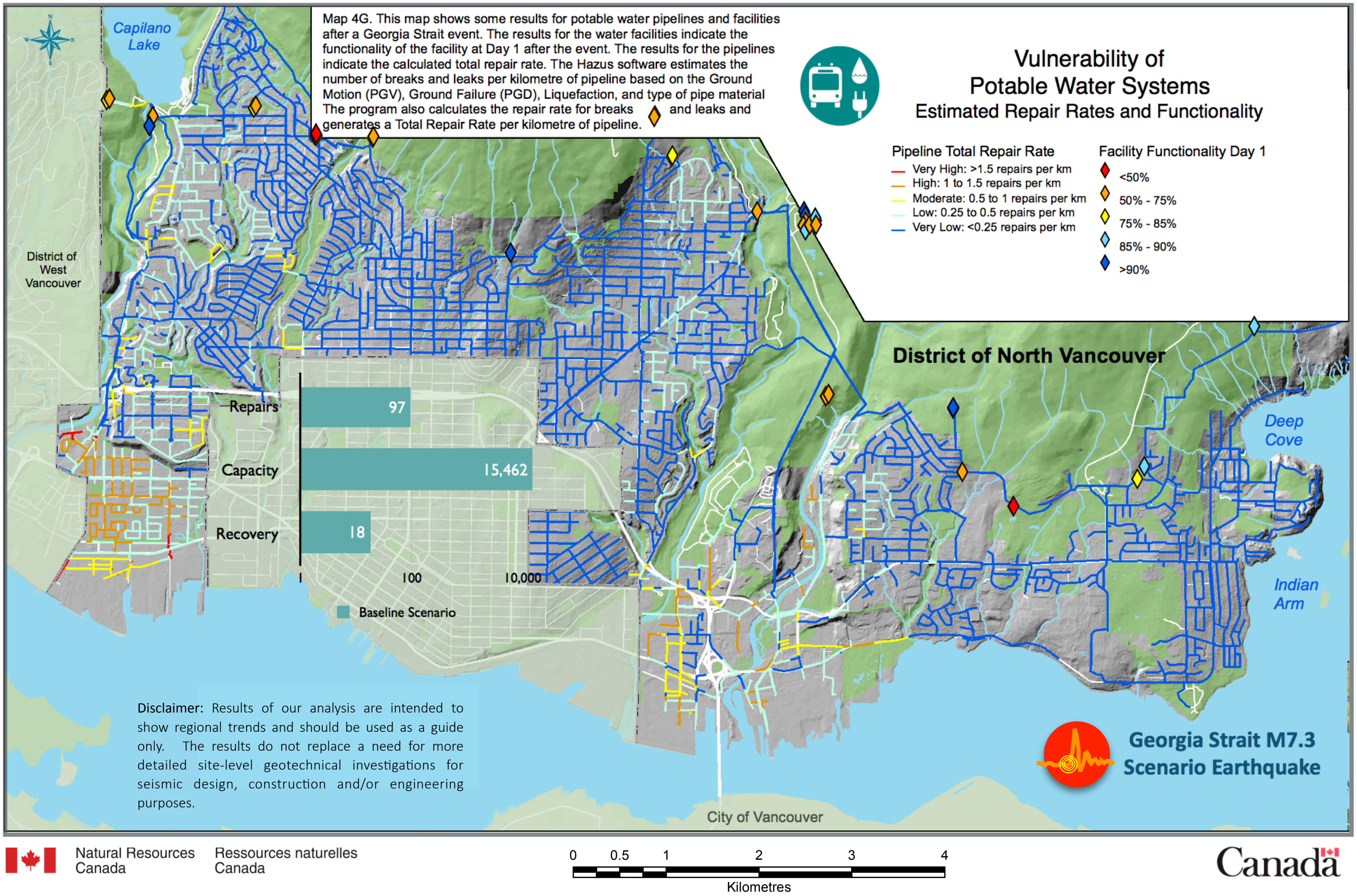
System resilience is measured on the basis of a combined rate of repair for each pipeline segment and the level of functionality with respect to baseline levels. The expected number of repairs for any given pipeline component is estimated by multiplying the repair rate for each type of pipe by its corresponding length and summing the values for all pipes in the network. The average repair rate is then computed as the ratio of the expected total number of repairs to the total length of pipe in the network.

System performance is estimated using restoration curves that track the level of functionality in the days and weeks following an earthquake based on the extent of damage, repair rates, and resources available to restore service capacity. Restoration curves describe the fraction or percentage of the component that is expected to be open or operational as a function of time following the earthquake. For example, an extensively damaged pipeline segment might be non-operational (0% functional) immediately following the earthquake, but 100% functional after 30 days. The level of functionality has important implications for service capacity following an earthquake and overall resilience of the infrastructure system.

Utility Systems

Utility and related lifeline services are particularly vulnerable to earthquake damage and loss of functionality in areas of severe ground shaking, and in older neighbourhoods where pipelines are constructed of older brittle materials that are less resistant to settling and lateral displacements caused by earthquake-triggered liquefaction. It is estimated that nearly one-third of the utility infrastructure in the District would be impacted by a major earthquake event (See Figures 76 and 77).

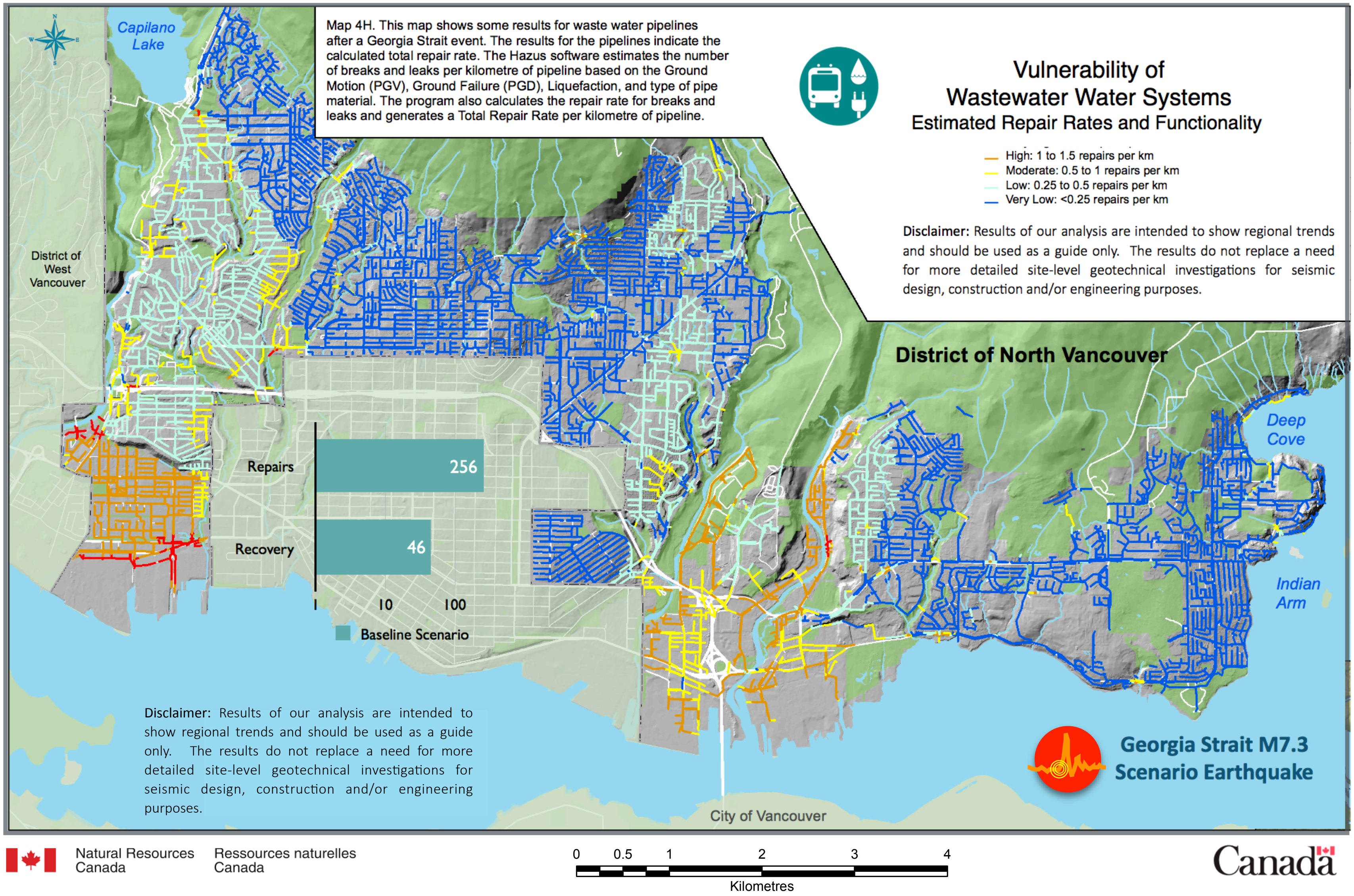
Expected damages to potable and wastewater pipelines are measured in terms of the number of leaks and breaks that are likely to occur within the network. For potable water pipelines, it is estimated that there are likely to be ~40 leaks at pipe joints and 60 breaks resulting in localized pipeline failure.



Map 4G. This map shows some results for potable water pipelines and facilities after a Georgia Strait event. The results for the water facilities indicate the functionality of the facility at Day 1 after the event. The results for the pipelines indicate the calculated total repair rate. The Hazus software estimates the number of breaks and leaks per kilometre of pipeline based on the Ground Motion (PGV), Ground Failure (PGD), Liquefaction, and type of pipe material The program also calculates the repair rate for breaks and leaks and generates a Total Repair Rate per kilometre of pipeline.

Disclaimer: Results of our analysis are intended to show regional trends and should be used as a guide only. The results do not replace a need for more detailed site-level geotechnical investigations for seismic design, construction and/or engineering purposes.

Figure 76: Map showing earthquake damage and loss of functionality for potable water systems in the DNV. Assessment based on Hazus methodology (2011).



Map 4H. This map shows some results for waste water pipelines after a Georgia Strait event. The results for the pipelines indicate the calculated total repair rate. The Hazus software estimates the number of breaks and leaks per kilometre of pipeline based on the Ground Motion (PGV), Ground Failure (PGD), Liquefaction, and type of pipe material. The program also calculates the repair rate for breaks and leaks and generates a Total Repair Rate per kilometre of pipeline.

Vulnerability of Wastewater Water Systems

Estimated Repair Rates and Functionality

- High: 1 to 1.5 repairs per km
- Moderate: 0.5 to 1 repairs per km
- Low: 0.25 to 0.5 repairs per km
- Very Low: <0.25 repairs per km

Disclaimer: Results of our analysis are intended to show regional trends and should be used as a guide only. The results do not replace a need for more detailed site-level geotechnical investigations for seismic design, construction and/or engineering purposes.

Disclaimer: Results of our analysis are intended to show regional trends and should be used as a guide only. The results do not replace a need for more detailed site-level geotechnical investigations for seismic design, construction and/or engineering purposes.

Figure 77: Map showing earthquake damage and loss of functionality for wastewater systems in the DNV. Assessment based on Hazus methodology (2011).

Areas of concern for potable water systems are concentrated in two north-south corridors in the District of North Vancouver (See Figure 76). The western corridor encompasses potable water facilities and pipeline infrastructure that run through the neighbourhoods of Handsworth, Capilano, Pemberton Heights, Lions Gate and Norgate. At least one pumping station at the Capilano Reservoir and both water main and distribution pipelines are expected to sustain damage and loss of functionality.

For wastewater pipelines, it is estimated there are likely to be ~100 leaks and 160 breaks. While the majority of potable water facilities in the network are likely to sustain little or only moderate damage in the earthquake, at least two facilities are expected to have reduced functionality in the days following the earthquake. At least nine of the thirteen electrical substations are expected to sustain moderate levels of damage.

Wastewater infrastructure that would be impacted along the western corridor includes primary trunk lines, secondary pipes and storm sewers (See Figure 78). Electrical substations near the Capilano Reservoir and adjacent to the Capilano River are also expected to sustain damage and loss of functionality. The central corridor includes pumping stations, water lines and wastewater infrastructure along the Lynn and Seymour valley escarpments and within the neighbourhoods of Lynnmour-South and Maplewood. Damages and corresponding loss of functionality are expected for portions of the water main and secondary distribution lines in the Lynnmour and Maplewood areas, pumping stations in Upper Lynn and Northlands area, and electrical power substations in the Seymour Creek Reserve.

The resilience of utility systems is measured in terms expected loss of service capacity following the earthquake event and the time required to restore baseline levels of functionality (See Figure 78). Electrical and water systems are both expected to sustain ~50% drop in service capacity on the day of the earthquake with as many as ~14,700 homes without power and ~15,000 homes without access to potable water. Electrical power is expected to be restored relatively quickly to nearly 90% of baseline levels one week after the earthquake with only ~3,250 homes and businesses without access to electrical services. Full recovery of electrical services is expected to take several months.

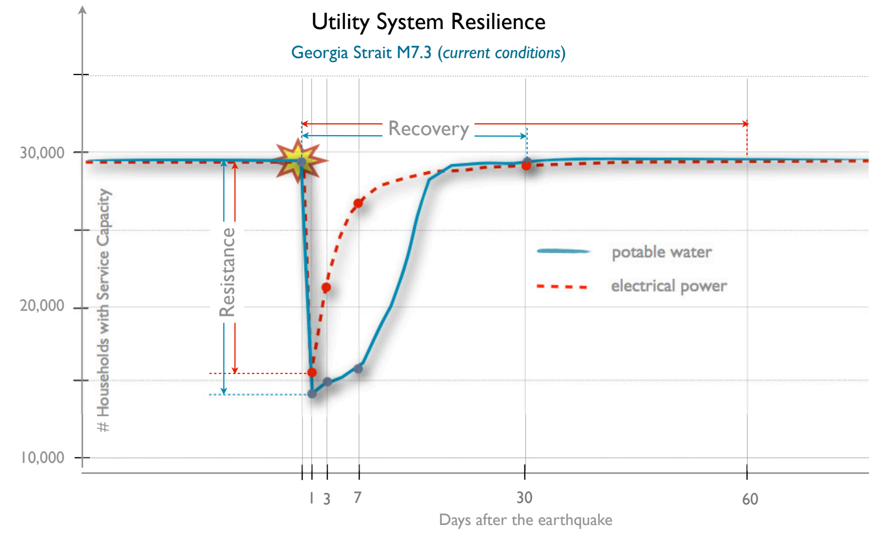


Figure 78: Resilience of utility systems following the scenario earthquake. Assessment based on Hazus methodology (2011).

The profile of recovery for potable water systems is more gradual in the first few weeks after the earthquake and highly dependent on the number of people who will be available to repair leaks and breaks to water pipelines. It is estimated that nearly half of all homes and businesses in the District will still be without access to potable water one week after the earthquake. Full service capacity is not likely to be restored for at least a month after the earthquake. Damages to regional water mains, wastewater trunk lines, and related pumping facilities in the western and central corridors will also have a significant impact on service capacities for other municipalities in the Metro Vancouver area who rely on shared infrastructure along the Capilano and Seymour valleys for access to drinking water and waste water management.

Transportation Systems

Seismic upgrades to bridge facilities in the past few years have improved overall resilience of the transportation network. Nonetheless, roadways and related infrastructure in the District are vulnerable to damages caused by severe ground shaking and liquefaction. Anticipated roadway damage includes slumping, caving, and lateral displacement of retaining walls and reinforced earth structures causing local rupture of highway segments in areas underlain by soft sediments that are susceptible to liquefaction. Second-order impacts will likely include significant vehicle damage and hazardous material spills that have a potential to cause additional injury and loss of life.

Areas of particular concern include designated disaster response routes along the waterfront and major east-west transportation corridors that cross the Capilano, Lynn and Seymour valleys (Figure 79). Portions of the disaster response route that are expected to sustain damage and loss of functionality during the earthquake include a short segment of the Trans-Canada Highway north of the Iron Workers Memorial Bridge and associated off ramps; a ~1 km section of highway crossing the Seymour and Lynn valleys; and a shorter section of highway near the Lynn Valley exit.

Other important connectors that are likely to be impacted include east-west sections of the Dollarton Highway and Seymour Parkway where they cross the Seymour valley, and short sections of Mountain Highway and Capilano Road where they cross the Trans-Canada Highway. Secondary boulevards and avenues are also likely to be damaged and in need of repair in the neighbourhoods of Maplewood, Lynnmour-South, Seymour Creek Reserve and Riverside. Rail lines along the industrial waterfront are expected to remain operational in the Maplewood and Lynnmour-South areas but are likely to sustain damages that would require repair in Norgate and Lower Capilano.

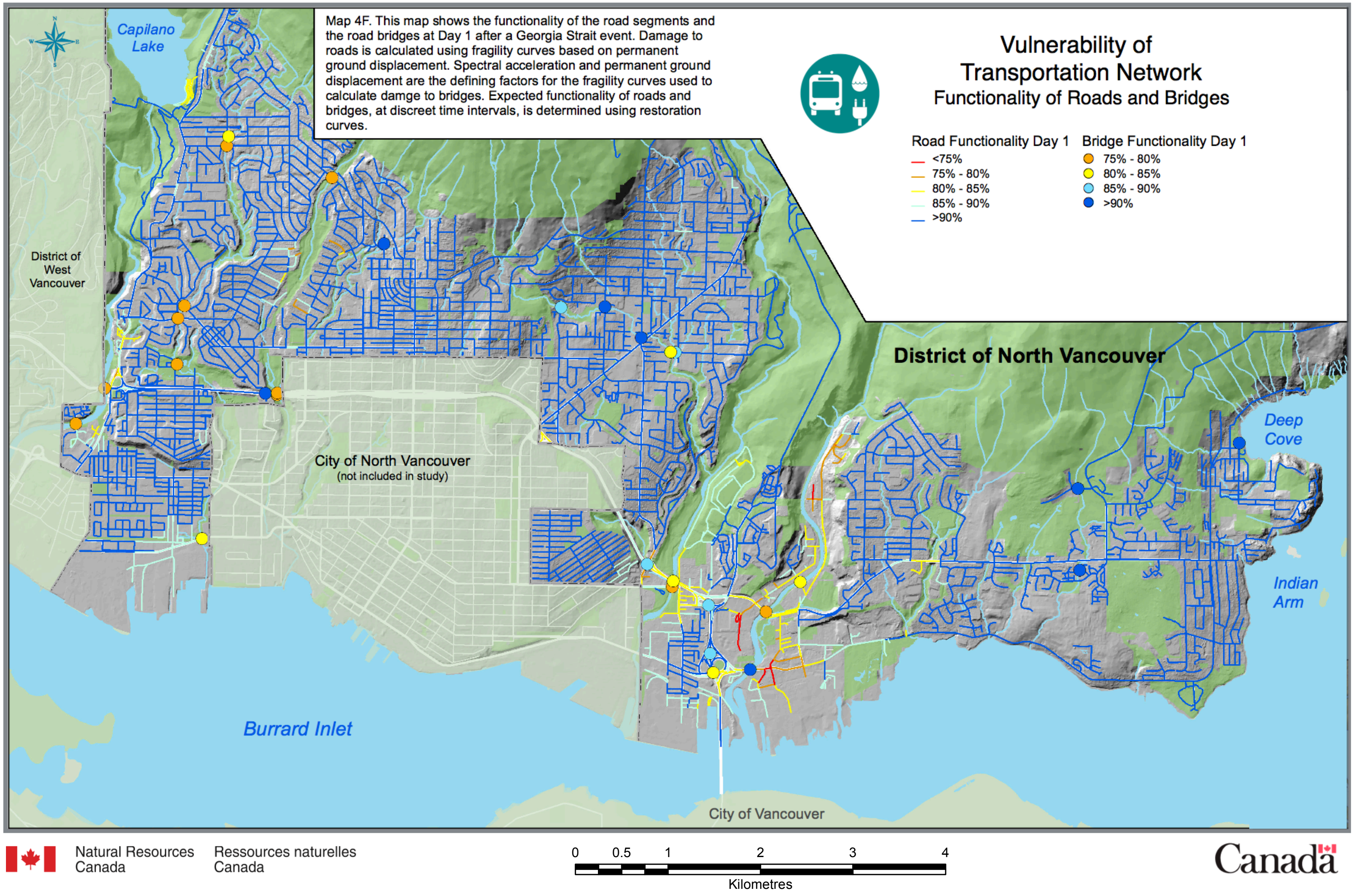
Though areas of damage to roads, rails and bridges are relatively small, it is expected that loss of functionality in key areas of the transportation network will likely result in significant social disruption to the region overall. Of particular concern is the impedance of emergency response efforts in the days and weeks following a major earthquake, delays in the repair of vital lifeline services (water and power), and significant interruptions to the flow of goods and services that will be essential during the recovery process.

Disaster Debris

Debris generated as a result of physical damages to buildings during an earthquake has proven to be a significant issue in both response and recovery phases of a disaster. Fallen debris can pose a direct threat to individuals who are outside during an earthquake, and can also block roads and restrict access to hardest hit areas by first responders for days and weeks following the disaster event. The amount of debris generated during an earthquake can be significant and adds a significant cost to the recovery process in terms of both time and expense. It can take months to remove and dispose of the debris properly, and it has the potential to limit access to road and rail networks that are vital during the response and recovery process.

Hazus uses a generalized empirical model to estimate the types and amount of disaster debris that are likely to be generated as a result of ground shaking and related building damage. There are two different categories of disaster debris — large blocks of steel and/or reinforced concrete that must be broken into smaller pieces by heavy equipment before being hauled away; and smaller aggregates of brick, wood, glass and building contents that are more easily moved with bulldozers and light machinery. The amount of debris is dependent on building types and the extent of damage in more densely settled areas and is estimated at the level of individual census tracts.

It is estimated that a total of 280,000 tons of disaster debris is likely to be generated as a result of the scenario earthquake. As expected, areas with the largest volume of disaster debris are

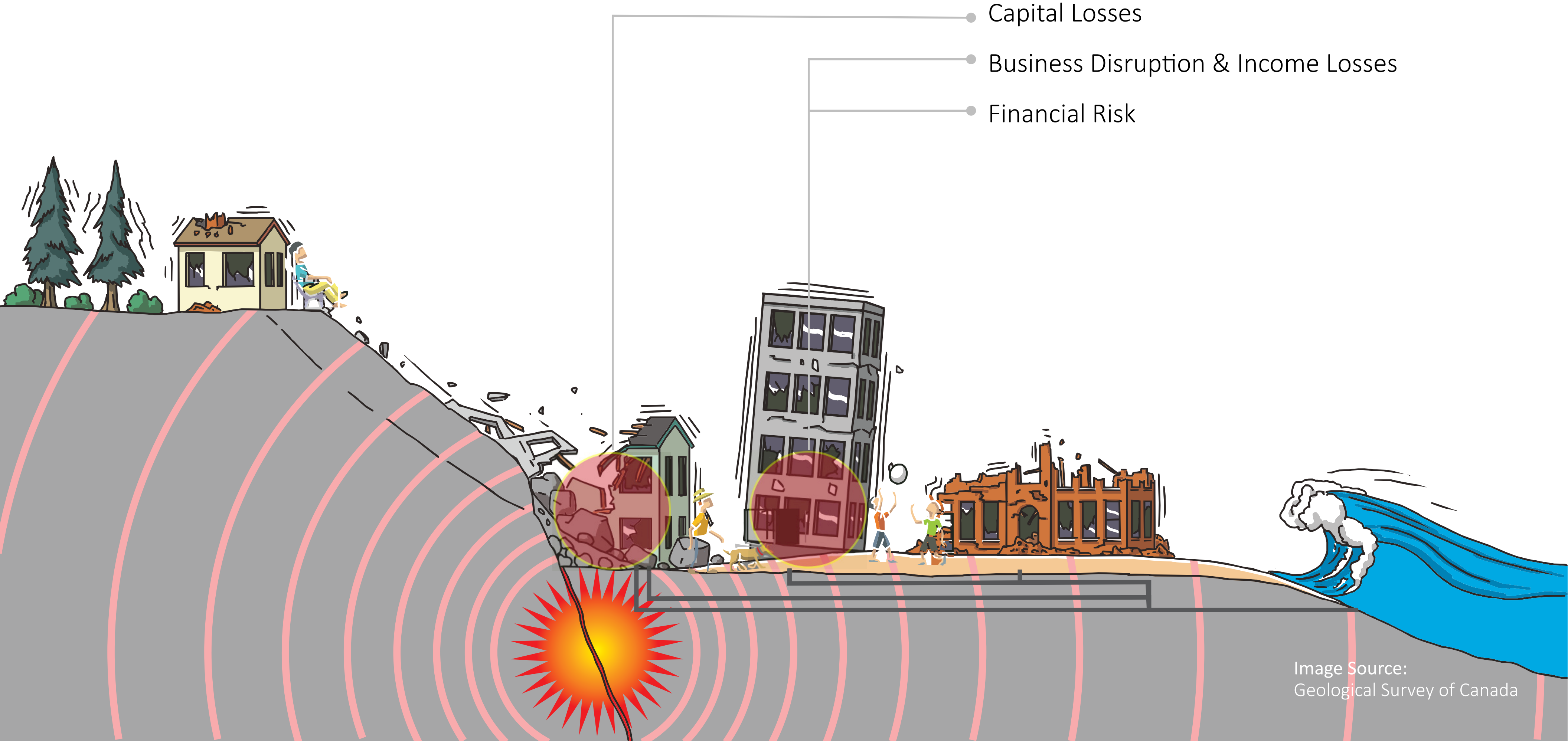


Map 4F. This map shows the functionality of the road segments and the road bridges at Day 1 after a Georgia Strait event. Damage to roads is calculated using fragility curves based on permanent ground displacement. Spectral acceleration and permanent ground displacement are the defining factors for the fragility curves used to calculate damge to bridges. Expected functionality of roads and bridges, at discreet time intervals, is determined using restoration curves.

Figure 79: Map showing earthquake damage and loss of functionality to roadways and bridges in the DNV. Assessment based on Hazus methodology (2011).

concentrated in higher-density town centres and older neighbourhoods that have a higher proportion of buildings that are likely to sustain extensive and/or complete damage from severe shaking and/or permanent ground deformation. This includes nearly 160,000 tons of steel and concrete (57% of total) and ~120,000 tons of mixed wood, brick, glass and general building debris. In addition to the time and resources required to manage the volume of debris on-site, it is estimated that it would take ~11,200 truckloads (at 25 tons/truck) to remove and dispose of waste materials generated by the earthquake.

CHAPTER 8: ECONOMY



Capital Losses

Business Disruption & Income Losses

Financial Risk

Image Source:
Geological Survey of Canada

CHAPTER 8: ECONOMY

Primary Authors: Journeay, J.M., Lotze, A. and Chang, S.

Economic security is a measure of community wealth and the capacity of local and regional economies to withstand and recover from the consequences of a major disaster event. It is influenced by the location and exposure of monetary assets, the extent and duration of business disruption, and the degree to which any potential losses are covered by insurance or related risk transfer mechanisms.

Indicators of economic security track critical assets and the flow of goods and services that sustain a community or region; direct and indirect losses that are expected as the result of a disaster event; and the effectiveness of risk reduction measures in protecting financial investments over time. From a policy perspective, the goal is to maximize the security of community assets through strategic investments in mitigation and/or adaptation measures that have a potential to reduce vulnerabilities and yield a positive rate of return over time horizons of interest to the planning process.

This chapter investigates the economic costs of a M7.3 scenario earthquake for the District of North Vancouver. We address direct losses caused by earthquake damage (stocks) as well as income-related losses sustained as a result of business disruption (flows). Our analysis is limited in scope to local economic factors and does not consider upstream or downstream consequences of business disruption, or the role of insurance in managing property risk during the recovery process.

Direct economic losses for the District of North Vancouver are estimated to be ~$3 billion with a mean loss ratio of ~17%, higher than that of the 2011 Christchurch earthquake (~12%). Anticipated capital losses resulting from the earthquake are estimated to be $2.3 billion (78%) with an additional $645 million in lost revenue caused by service disruption in the weeks and months following the earthquake. The business sector is expected to bear the largest burden of financial risk with a potential for up to 90% loss in gross daily revenue generation for the duration of the recovery process. The combined losses to homeowners, businesses and government operations would have a profound and lasting impact on economic security and resiliency of the community.

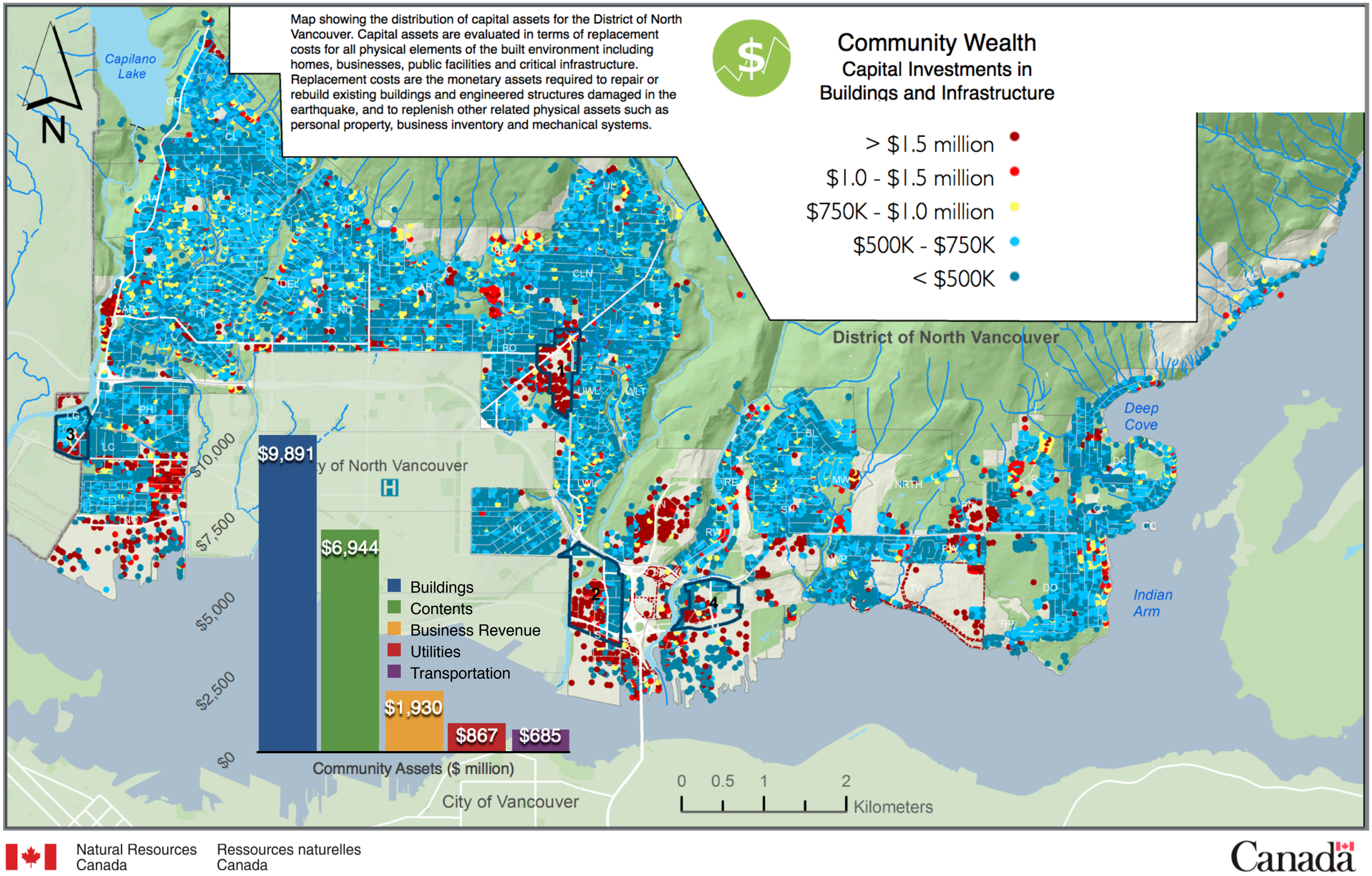
COMMUNITY WEALTH

Economic wealth for the District of North Vancouver is estimated to be in excess of $20.3 billion. This includes $18.4 billion of capital investments in buildings and critical infrastructure, and $1.9 billion in gross annual revenues generated by the flow of goods and services in the business sector (Figure 80). Our assessment of wealth is limited to monetary assets and does not include other dimensions of natural and social capital that are vital to overall resilience of the community.

Capital Assets (Stocks)

Capital assets for the District of North Vancouver are estimated on the basis of replacement costs for buildings and related infrastructure. Replacement costs are the financial resources required to repair and/or replace physical property at a given location with other property of comparable material and quality used for the same purpose.

Replacement costs include building materials, contents and business inventory. They do not include land prices, and are not



Map showing the distribution of capital assets for the District of North Vancouver. Capital assets are evaluated in terms of replacement costs for all physical elements of the built environment including homes, businesses, public facilities and critical infrastructure. Replacement costs are the monetary assets required to repair or rebuild existing buildings and engineered structures damaged in the earthquake, and to replenish other related physical assets such as personal property, business inventory and mechanical systems.

Figure 80: Map showing the distribution of capital assets for the District of North Vancouver (replacement costs for buildings & contents).

influenced by variations in market value. Our assessment of replacements costs for the District of North Vancouver are based on industry guidelines that have been incorporated into a Canadian version of the Hazus methodology [FEMA, 2011].

Buildings

Figure 81 is a breakdown of building-related assets for the District of North Vancouver based on construction type and occupancy class. Replacement costs for each of the ~23,700 buildings in the inventory were estimated on the basis of square footage and industry-standard mean construction values for specific occupancy classes [FEMA, 2011; Ulmi et al., 2014]. The majority of these investments are in wood frame buildings (86%) that are generally resistant to earthquake shaking. However, more than $3.7 billion (13%) is currently invested in older concrete and unreinforced masonry buildings that are likely to sustain significant structural losses as a result of earthquake damage. Nearly $12.5 billion is invested in single and multi-family residential homes (85%) with an additional $2.36 billion (11%) in the businesses, sector and the remaining $972 million (5%) in government operations, schools and churches.

Replacement costs for building contents and business inventory are calculated as a percentage of structural replacement values

Capital Stocks - Building Assets

General Building Stock	Number of Assets	Replacement Costs	Building Contents	Business Inventory	Total
Construction Type					
Wood	21,594	$ 8,522,001,523	$ 4,522,690,172	$ 15,189	$ 13,044,706,884
Concrete	699	$ 931,575,189	$ 938,826,393	$ 938,826,393	$ 2,809,227,975
Steel	362	$ 201,319	$ 18,085,553	$ 192	$ 18,287,064
Un-Reinforced Masonry	33	$ 397,314,550	$ 484,423,963	$ 27,509	$ 881,766,022
Other Types	48	$ 39,698,282	$ 41,404,276	$ 1,057	$ 81,103,616
Occupancy Class					
Single Family Homes	20,257	$ 6,738,035,863	$ 3,369,017,850	-	$ 10,107,053,713
Multi-Family Homes	936	$ 1,650,268,135	$ 825,134,017	-	$ 2,475,402,152
Commercial	648	$ 550,431,984	$ 550,418,279	$ 28,967	$ 1,100,879,230
Industrial	611	$ 504,177,294	$ 754,657,279	$ 44,016	$ 1,258,878,590
Other Classes	284	$ 465,765,419	$ 506,202,932	$ 2,089	$ 971,970,440
Total	**22,736**	**$9,890,790,864**	**$6,005,430,357**	**$938,870,340**	**$16,835,091,561**

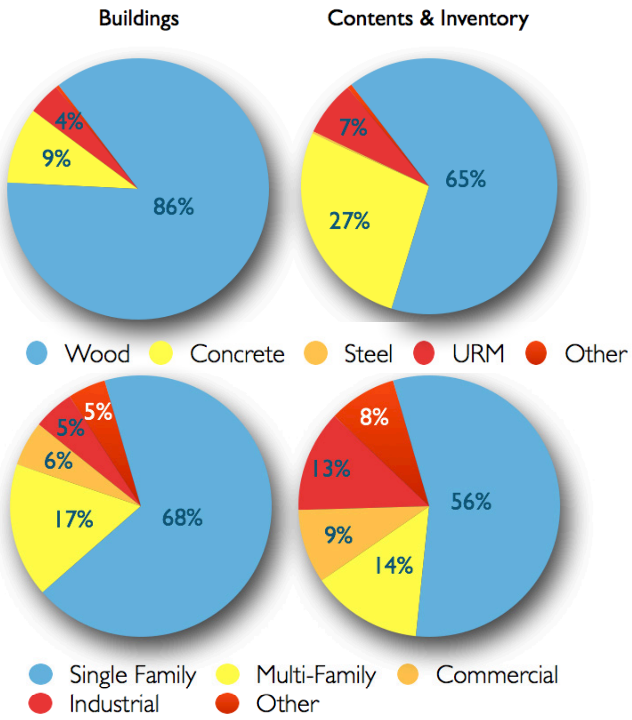


Figure 81: Table and charts summarizing capital investments in buildings and contents by type of construction and occupancy .

[Refer to Table 3.10; FEMA, 2011], and are estimated to represent ~40% of the overall capital asset for DNV. Personal effects for single and multi-family homes account for the majority of these assets with a total value of over $6 billion. Investments in business inventory for commercial and industrial buildings is estimated to be $940 million.

Critical Infrastructure

Capital investments in utility and transportation infrastructure in the District of North Vancouver are estimated to be on the order of $1.56 billion dollars. Valuations are based on replacement costs obtained from District financial records for more than 1,250 km of water and waste pipelines, and mean values derived from the literature for roads, rail lines, bridges, and related facilities [FEMA, 2011].

Water utilities represent more than half of the total infrastructure asset with ~$290 million in potable water and ~$580 million in waste water utilities. Roads and bridges account for nearly 40% of infrastructure assets (~$600 million) with the remaining 5% represented by rail lines systems that serve port and industrial facilities along the waterfront.

Business Income (Flows)

Businesses play an integral role in the functioning of a community — as revenue generators, employers, and providers of goods and service. The resumption of operations by local businesses is critical to a community's recovery in the aftermath of a disaster. It is imperative, therefore, that potential impacts to the business community be considered as part of a comprehensive of hazard risk assessment, along with ways to reduce those impacts within the broader community through resiliency-building initiatives.

Sector Profile

The District of North Vancouver has more than 3,400 licensed businesses representing a wide range of sectors [District of North

Capital Stock Assets
- Infrastructure

Critical Infrastructure	# of Assets/ Segments	Replacement Costs
Potable Water		
Potable Water	5,216	$ 288,600,000
Wastewater	15,808	$ 578,800,000
Sub Total		**$ 867,400,000**
Transportation		
Roads	3,619	$ 556,400,000
Rail Lines	267	$ 84,300,000
Bridges	33	$ 41,200,000
Facilities	3	$ 2,800,000
Sub Total		**$ 684,700,000**
Total		**$ 1,552,100,000**

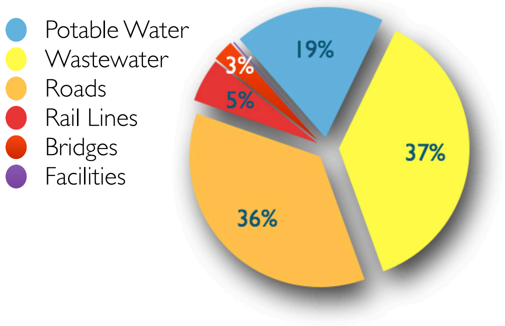


Figure 82: Table and charts summarizing available information on capital investments in utility and transportation infrastructure for the DNV.

North American Industry Classification System (NAICS)	# Employees	Estimated* Annual GDP by Industry ($)
Retail trade	2,670	$ 113,701,392
Educational services	2,405	$ 164,535,771
Scientific and technical services	2,310	$ 140,594,618
Manufacturing	2,120	$ 149,540,610
Health care and social assistance	1,945	$ 112,721,013
Accommodation and food services	1,695	$ 52,057,107
Other services	1,445	$ 70,640,134
Transportation and warehousing	990	$ 89,761,697
Finance and insurance	955	$ 123,037,719
Arts, entertainment and recreation	885	$ 29,343,577
Wholesale trade	880	$ 84,269,327
Construction	830	$ 70,873,891
Real estate, rental and leasing	695	$ 467,229,938
Administrative	695	$ 34,586,020
Information and cultural industries	620	$ 77,217,668
Public administration**	620	$ 81,080,690
Mining and oil and gas extraction	70	$ 37,710,842
Utilities	55	$ 25,843,373
Agriculture and forestry	50	$ 2,947,462
Company management	10	$ 2,571,698
TOTAL	**21,945**	**$ 1,930,264,546**

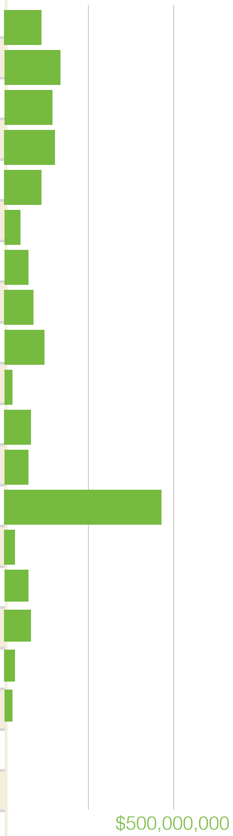


Figure 83: Sector profile based on employment and GDP. Annual GDP based on provincial rates/employee/industry and DNV employee counts/industry.

Vancouver, 2011a]. Service providers are the most numerous of these (~52%), followed by industrial businesses involved in mining, construction, transportation, communication, and utilities (18%), wholesale and retail trade (15%,) financial institutions (8%), manufacturing (5%) and health care (5%). Collectively, these businesses employ nearly 22,000 individuals [Statistics Canada, 2006]. Extrapolating from provincial annual industry employment counts and gross domestic product (GDP) data, the DNV business community generates an estimated $1.93 billion dollars in annual GDP.

The majority of businesses in the District are small and often home-based (fewer than 50 employees). This is reflective of broader sector profiles for Metro Vancouver where small businesses account for 98% of the total with ~80% considered micro-businesses with 5 or fewer employees [Metro Vancouver, 2012]. This is especially relevant to community resiliency planning initiatives as small independent businesses typically have fewer resources available to devote to mitigation and business continuity planning than do franchised or large businesses. Support provided by the local municipality to bolster these capacities for small businesses plays a vital role in promoting overall disaster resilience of the community.

Building Type and Distribution

The location, type and size of buildings in which a business resides are all significant factors in assessing potential economic loss from a natural hazard. We cross-referenced business license registry and building type information from DNV records to identify both the construction type and intensity of use for each building category (See Figure 84). The resulting data indicate that a majority of businesses in DNV are situated in light wood frame structures, which are generally expected to perform well during a major earthquake. These are primarily small businesses that are the sole occupants of the buildings.

Of concern are high concentrations of businesses (5 or more) in older concrete and unreinforced masonry structures along the waterfront that are known to be vulnerable to earthquake hazards. Nearly 45% of all DNV buildings containing five or more

	Building Structural Type	# of Businesses	%
🔵	Wood, Light Frame (>5,000 sq. ft.)	1,514	44.0%
🟡	Unreinforced Masonry (Low-Rise)	899	26.0%
🟠	Wood, Greater than 5,000 sq. ft.	354	10.0%
🔴	Concrete Shear Walls (Low-Rise)	301	9.0%
🔴	Concrete Moment Frame (Low-Rise)	140	4.0%
🟣	Concrete Shear Walls (Mid-Rise)	67	2.0%
🔵	Reinforced Masonry (Low-Rise)	40	1.0%
🟡	Structural Type Unidentified	37	1.0%
🟠	Concrete Shear Walls (High-Rise)	25	1.0%
	Steel Moment Frame (Low-Rise)	15	0.0%
	Precast Concrete Tilt-Up Walls	12	0.0%
	Mobile Homes	4	0.0%
	Concrete Moment Frame (Mid-Rise)	2	0.0%
	Precast Concrete(Low-Rise)	1	0.0%
	TOTAL	3,411	100.0%

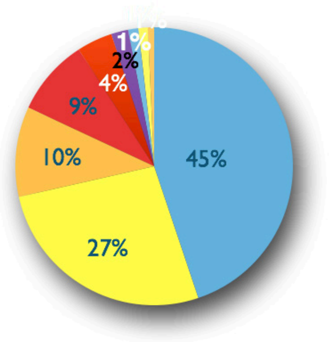


Figure 84: Table and charts summarizing characteristic building types and the corresponding number of businesses in each.

businesses are unreinforced masonry structures (53 of 119 structures).

Areas of highest business concentration along the waterfront are also exposed to some of the highest levels of shaking and related liquefaction. Commercial and industrial hubs are situated in close proximity to rail line and waterfront port facilities, and are characterized by systems and processes that are complex and highly independent. Damage that renders any component of the system.

Interdependencies

Businesses are not independent entities — they rely on complex support networks to function. Infrastructure and lifelines play a vital role in those support networks. Public utilities such as water and power are critical to daily operations. Businesses also rely on transportation networks to facilitate the movement of goods, employees and customers. Disruption or damage to any of these systems will impact the businesses that rely on them. Some industry operations are more sensitive to certain types of utility loss than others, which must also be considered when assessing risk and potential risk reduction measures [Chang et al., 2008].

In addition to infrastructure dependencies, businesses also rely on supporting industries and supply chain partners for necessary goods and services to operate. While an individual business may be unaffected by a disaster event, the indirect impacts of disruption to its partner businesses may still have serious impacts on that business's operational capability and revenue [A. Rose and Guha, 2002].

For example, shutdown of an upstream supplier or transportation company that is essential for the flow of goods and services may cause a business to falter, even if there is no significant damage to the building in which the business operates. There are many such business interdependencies within the District and neighbouring regions of Metro Vancouver, particularly among Port-based industries that are situated along the waterfront.

CAPITAL STOCK LOSSES

Capital stock losses that are likely to be sustained as a result of the Georgia Strait scenario earthquake were estimated at the site level using the Advanced Engineering Building component of the Hazus earthquake model [FEMA, 2011]. Economic loss potential is a function of the extent to which buildings and critical infrastructure are exposed to earthquake hazards (location and asset value), and the probability of damage caused by shaking and ground failure.

As shown in Figure 85, damage state probabilities are combined with information about building occupancy, replacement costs, and annual gross sales to assess direct economic losses in terms of a dollar value. Economic losses to utility and transportation infrastructure are estimated on the basis of average repair costs only and do not take into account interdependencies between lifeline system components such as power and water.

Building Repair and Replacement Costs

Estimates of direct economic losses for the Georgia Strait scenario earthquake are summarized in Figure 86. The map shows the extent and distribution of capital losses in terms of overall loss ratio while the accompanying charts and tables summarize loss

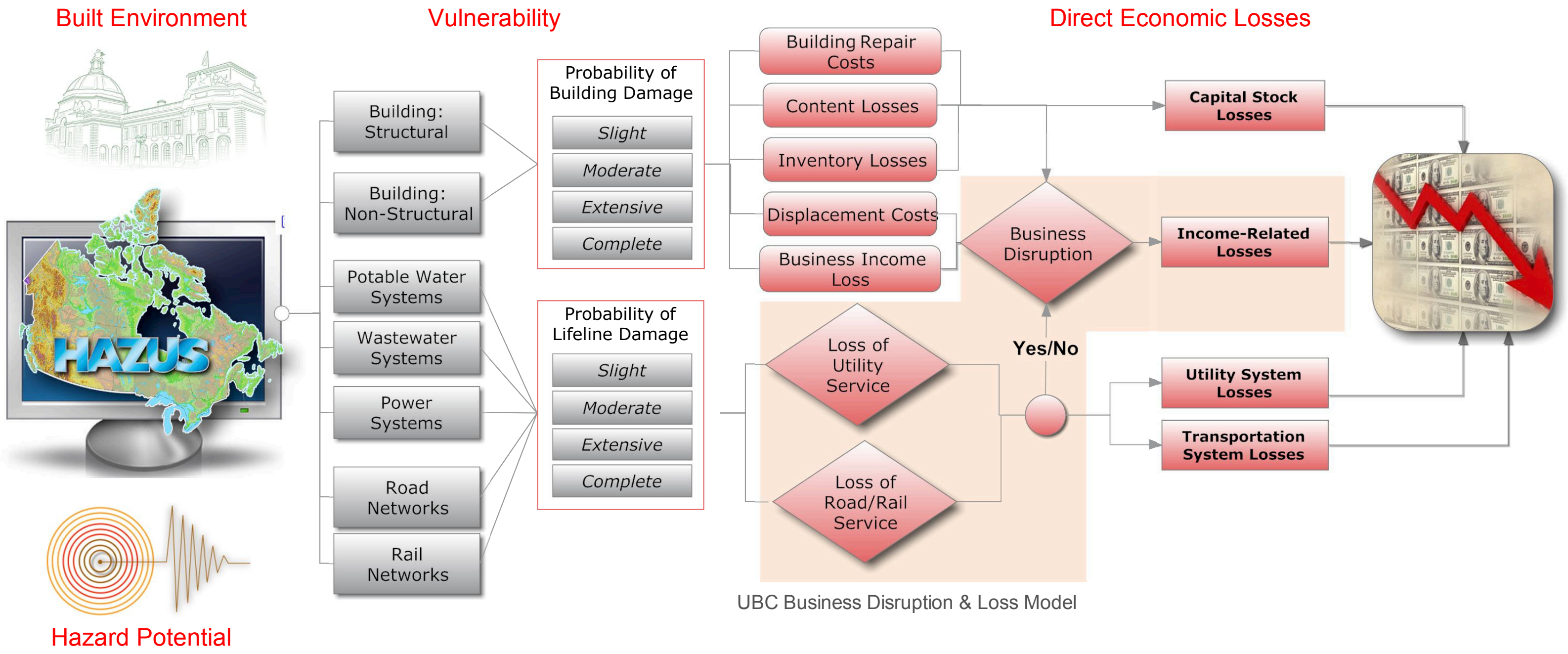
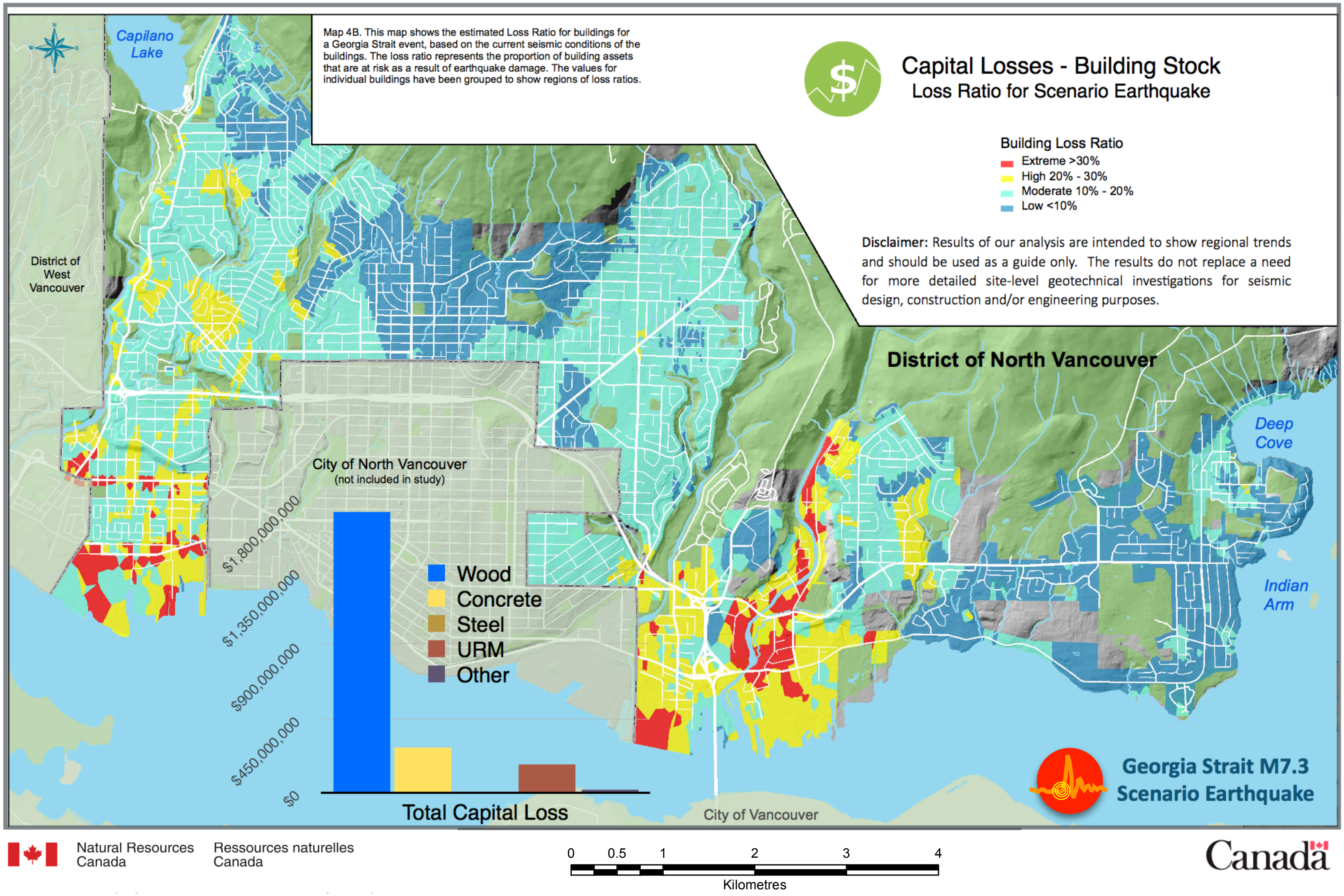


Figure 85: Analytic workflow for estimating capital stock losses caused by earthquake damage. Based on Hazus-MH 2.1methodology (FEMA, 2011)



Map 4B. This map shows the estimated Loss Ratio for buildings for a Georgia Strait event, based on the current seismic conditions of the buildings. The loss ratio represents the proportion of building assets that are at risk as a result of earthquake damage. The values for individual buildings have been grouped to show regions of loss ratios.

Disclaimer: Results of our analysis are intended to show regional trends and should be used as a guide only. The results do not replace a need for more detailed site-level geotechnical investigations for seismic design, construction and/or engineering purposes.

Figure 86: Map showing distribution of building losses in the District of North Vancouver based on Hazus methodology (2011).

Capital Losses - General Building Stock

	# buildings	Total Asset Value	Mean Replacement Cost	Total Capital Loss	Mean Loss/ building	Mean Loss Ratio
Occupancy Class						
Single Family	20,257	$ 10,107,053,713	$ 498,941	$ 1,326,765,606	$ 66,036	13.3%
Multi-Family	936	$ 2,475,402,152	$ 2,644,660	$ 314,949,791	$ 345,280	13.2%
Commercial	648	$ 1,100,850,263	$ 1,698,843	$ 173,278,166	$ 363,412	18.8%
Industrial	611	$ 1,258,834,574	$ 2,060,286	$ 233,371,906	$ 501,248	23.9%
Other	284	$ 971,968,351	$ 3,422,424	$ 118,485,268	$ 445,110	14.2%
Sub-Total	**22,736**	**$ 15,914,109,052**	**$ 2,065,031**	**$ 2,166,850,737**	**$ 344,217**	**16.7%**
Building Type						
Wood	21,594	$ 13,044,691,695	$ 604,089	$ 1,706,486,397	$ 80,199	13.3%
Concrete	699	$ 1,801,858,812	$ 2,577,767	$ 274,009,484	$ 472,058	20.5%
Steel	33	$ 36,174,703	$ 1,096,203	$ 4,812,327	$ 163,391	7.5%
URM	362	$ 881,738,513	$ 2,435,742	$ 161,980,623	$ 636,950	26.6%
Other	48	$ 149,645,329	$ 3,117,611	$ 19,561,906	$ 651,832	21.1%
Sub-Total	**68,208**	**$ 47,742,327,155**	**$ 2,020,145**	**$ 6,500,552,210**	**$ 369,976**	**17.8%**

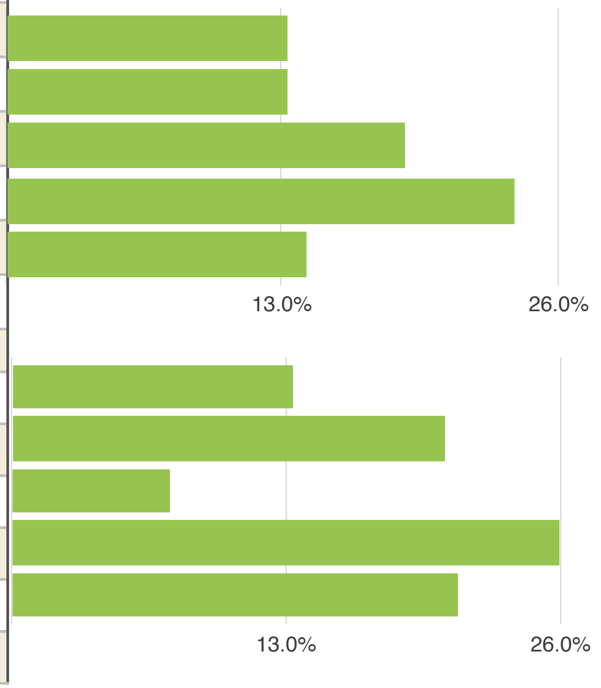


Figure 87: Summary of direct capital stock losses for building stock sustained as a result of the scenario earthquake. Losses reported on the basis of occupancy class and building type

statistics with respect to building type. Economic loss ratios represent the proportion of building assets that are at risk as a result of earthquake damage.

Loss estimates are calculated for each damage state probability and occupancy class based on standard building replacement values reported in the Hazus technical guidelines [See Tables 15.2 - 15.4; FEMA, 2011]. Dollar loss estimates for buildings are derived from damage state probabilities, overall floor area, building occupancy, and costs per square foot for both structural and non-structural repairs in each damage state category (Slight, Moderate, Extensive and Complete).

Total capital losses for the scenario earthquake are estimated to be ~$2.3 billion. Loss ratios are less than 14% for most of the DNV and below 10% in newer developments where buildings are more resistant to earthquake damage. Loss ratios of greater than 20% are coincident with areas of greatest damage potential and social disruption. Hotspots of concern include older residential neighbourhoods in the Highlands, Edgemont, Lower Capilano, Norgate, Lynnmour-South, Maplewood, and Riverside neighbourhoods along the lower Seymour River.

The mean loss ratio for residential homes is ~13%, which translates into an average capital loss of ~$66,000 for single-family buildings and ~$345,000 for multi-family apartment and condominium complexes. The mean loss ratio for commercial buildings is ~18.8% with expected average capital losses of ~ $363,000. Mean loss ratios for industrial buildings are nearly double that of residential structures (~24%) with average expected capital losses of ~$500,000. As expected the profile of loss is skewed by the vulnerability of older concrete and unreinforced masonry buildings in commercial/industrial zones along the waterfront. Concrete structures have a mean loss ratio of ~20% with a relatively high degree of variability (± 9.6%) depending on the age of construction and conformance to building safety codes. Unreinforced masonry buildings have a mean loss ratio of ~27% (± 5.7%) with an average expected capital loss of ~$637,000.

Content and Inventory Losses

Building content and inventory losses are included in the overall assessment of capital stock losses reported in Figure 87. Content losses are assessed on the basis of non-structural damage caused by building acceleration during an earthquake and are estimated to be ~$597 million for the scenario earthquake. Estimates are based on the costs of replacing furniture and other building equipment (computers, supplies, etc.) that may be overturned or toppled by abrupt lateral movement. Damage ratios are computed at the site level as a function of ground acceleration and damage state probabilities [See Table 15.5; FEMA, 2011]. The cumulative loss ratio for building contents is 16.1%

Business inventory losses are assessed on the basis of gross annual sales and can vary widely as a function of business type, square footage and damage state probabilities. Inventory losses reflect the costs of replacing equipment, supplies, and/or merchandise that may be overturned, toppled and/or damaged by water from pipes that are broken during the earthquake event. Inventory losses for small retail stores will be substantially less than for large industrial operations. As with building contents, damage ratios for business inventory are calculated on the basis of damage state probabilities for non-structural acceleration [See Table 15.8; FEMA, 2011]. The cumulative inventory-related loss ratio for the scenario earthquake is estimated to be 16.1%.

Critical Infrastructure Losses

Direct economic losses for lifeline systems are based on repair costs, damage state probabilities, and computed damage ratios for individual components such as roads, bridges, pipelines, and related facilities. Hazus computes losses sustained by structural damage caused by the earthquake event but does not account for additional time dependent losses related to business disruption during the recovery period. As with other elements of the built environment, capital losses for lifeline systems are estimated using repair cost ratios that are calibrated for individual damage state probabilities [See Tables 15.18-29; FEMA, 2011]. Repair cost ratios for pipelines are calculated on the basis of probabilities for both leaks and breaks.

Total capital losses for lifeline systems damaged in the scenario earthquake are estimated to be ~$26 million with nearly 63% of these losses related to the costs of repairing roads damaged by ground failure. Capital losses to water utility systems damaged in the scenario earthquake are estimated to be ~$5.4 million (See Figure 88). Losses to potable water systems are $2.3 million with more than half of these losses caused by damage to treatment and pumping facilities and the balance dispersed between pipelines and water distribution lines. Losses to wastewater

Capital Losses -Lifeline Systems

	Replacement Costs	Capital Losses	Mean Loss Ratio %
Potable Water			
Pipelines	$266,700,000.0	$480,060	0.18%
Facilities	$13,700,000.0	$1,322,050	9.65%
Distribution Lines	$8,300,000.0	$528,710	6.37%
Sub Total	**$288,700,000**	**$2,330,820**	
Wastewater			
Pipelines	$563,200,000.0	$1,408,000	0.25%
Distribution Lines	$15,500,000.0	$1,714,300	11.06%
Sub Total	**$578,700,000**	**$3,122,300**	
Highways			
Roads	$556,410,000	$16,469,736	2.96%
Bridges	$36,230,000	$210,134	0.58%
Sub Total	**$592,640,000**	**$16,679,870**	
Railways			
Rail Lines	$84,260,000	$3,185,028	3.78%
Bridges	$5,000,000	$2,000	0.04%
Facilities	$2,780,000	$995,796	35.82%
Sub Total	**$92,040,000**	**$4,182,824**	
TOTAL	**$1,552,080,000**	**$26,315,814**	**1.70%**

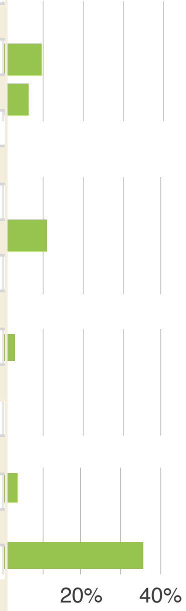


Figure 88: Table and charts summarizing capital losses for utility and transportation infrastructure in the DNV. Based on Hazus (FEMA, 2011).

systems are ~$3.1 million and are evenly allocated between pipelines and distribution lines. Although damage state probabilities were calculated for electrical power facilities, we did not have sufficient information about replacement costs for major facilities to estimate capital losses. Similarly, we did not have information about natural gas pipelines and communication facilities to estimate damages or related losses.

Direct losses to transportation systems (road and rail networks) are estimated to be ~$20.1 million (See Figure 88). The estimate includes $16.5 million to repair highways and secondary roads, and an additional $3.2 million to repair rail lines. Bridge repair costs are estimated to be relatively small ($210,000), though our assessment was limited to replacement costs for municipal infrastructure. Rail infrastructure that serves port facilities along the waterfront is expected to sustain losses of nearly $1 million.

Not included in our analysis are direct economic losses to bus, ferry and port facilities in the District. We expect that capital losses to port facilities will be substantial as they are likely to sustain significant damage caused by severe shaking and liquefaction along the waterfront. Prolonged disruption of port operations would likely interrupt international trade with a profound impact on both regional and national economies.

INCOME-RELATED LOSSES

The process of modelling income-related losses following a major earthquake is complex. It involves deliberate choices of how to conceptually frame the problem; how to model system interdependencies; which of the many potential impact factors the model should include; geographic and temporal scales for the modelling; how to quantify uncertainties; and how to deal with limited availability of financial information.

Variations on input-output models and computable general equilibrium equations are typically used to analyze indirect economic loss from disasters [Bernkopf et al., 2001; L M Jones et al., 2008; Adam Rose, 2004a; A Rose, 2004b; A. Rose and Guha, 2002]. Common among these models is an economy-wide, multi-sector approach emphasizing the interdependent nature of economic factors within a system and the impact of indirect effects on economic production. Refer to Chang and Rose [2012] for an overview of current post-disaster economic recovery research and a discussion of key themes and challenges.

Model Process

A combined business disruption and economic loss model was applied to the DNV business profile to quantify potential losses based on business sector characteristics, average economic production level, location, building construction, and access to lifeline services (Figures 85 and 89). The model considers the impacts of building damage and lifeline outages to individual businesses, and is based on empirical studies of lifeline interdependencies and the economic consequences of business disruption following major earthquakes in California [Chang et al., 2008; Chang and Shinozuka, 2004; Chang et al., 2002; Shinozuka et al., 1998].

Business survey data collected after the Northridge earthquake [Tierney, 1997] has been used to develop an algorithm that evaluates overall business disruption based of three factors — building damage, electric power outage, and water outage. These three model variables are combined to develop an indicator of disruptiveness that is measured in terms of the probability of temporary business closure. The probability of closure and normal production level (average daily GDP rate per business per sector) is used to calculate expected business economic loss due to disruption. Note that indirect economic losses (i.e., those due to economic interdependencies, such as damage to a business' supplier, rather than to the business itself) are outside the scope of this analysis.

Like its predecessors, the UBC model uses a Monte Carlo simulation to produce 100 deterministic outputs of potential business disruption patterns according to the probabilistic distributions of business disruption for representative sectors. The average results of these simulations are discussed in the following sections. It is important to note that this model differs from the methodology used by Hazus in several key ways.

First of all, the Hazus model uses general occupancy classes whereas the UBC model uses detailed information about

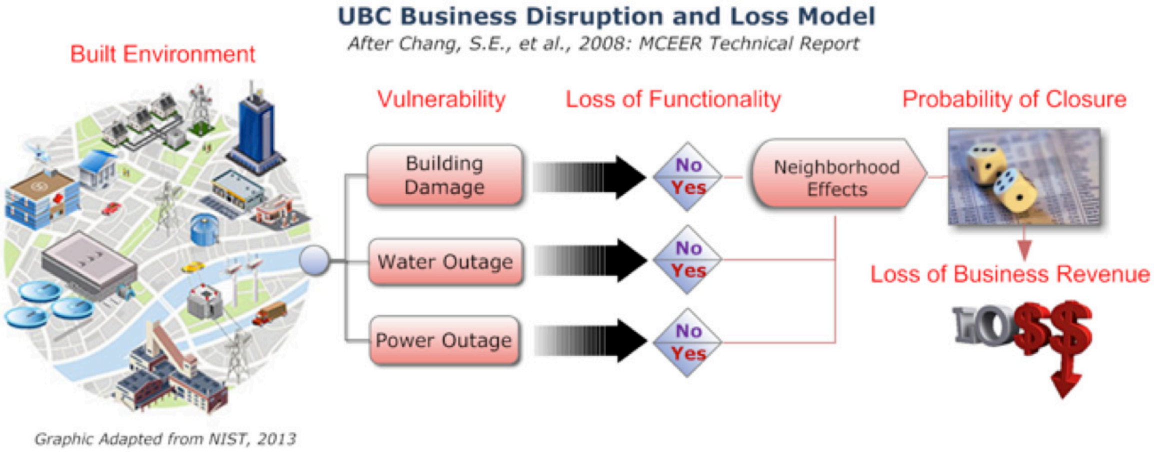


Figure 89: : Schematic outline of the UBC business disruption and economic loss model based on Chang et al., 2008

individual businesses to better capture correlations between sector characteristics, size, and building type. Secondly, Hazus computes direct economic losses sustained as a result of earthquake damage whereas the UBC model extends the scope of analysis to include building-specific losses resulting from simultaneous impact of structural damage and lifeline outage. Finally, Hazus uses generalized analytic functions to estimate business disruption and corresponding losses, whereas the UBC model uses empirical relationships derived from recent earthquake disasters to estimate the probability of temporary closure and corresponding economic losses based on a range of factors. These factors include damage state probability, loss of service functionality and other neighbourhood factors. In particular, lifeline outage has been shown to have a significant impact on business operating capacity, so it is an Important dimension to capture in assessing direct economic loss.

Data inputs to the UBC model include: business license registry of all local businesses [District of North Vancouver, 2011a]; Hazus building damage state probabilities for each building in the asset inventory (See Chapter 5); and an estimated average daily GDP rate per business per sector in the District. As noted earlier, GDP data is not available at the local level. We extrapolated values based on available information on average daily rates using provincial employment counts and industry-specific annual GDP data provided by Statistics Canada [2006].

Business Disruption Scenarios

The initial model considers two potential outcomes: one in which all businesses have full utility service after the earthquake (no disruption of water or power) and are impacted only by building damage; and a second extreme scenario, where businesses experience a complete loss of water and power service in addition to varying levels of building damage (See Figure 90). Neither situation would be a realistic depiction of what might be expected in Georgia Strait earthquake scenario. However, the two scenarios are useful in representing the ends of the economic loss spectrum with respect to lifeline impact and provide lower and upper limits to what might be expected in the event of a major earthquake.

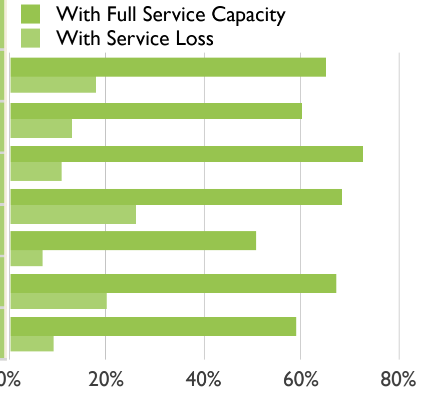
Three subsequent models were developed to illustrate what can be termed the “neighbourhood effect.” The neighbourhood effect refers to the fact that while an individual business may be functioning at normal production levels, the damage to and/or closure of surrounding businesses will likely impact customer traffic to the open business, thus reducing its production level. Three different sets of criteria were used to define different neighbourhood patterns in each model, based on factors such as pedestrian traffic, natural barriers, zoning classifications, and building proximity (NHID 1-3: See Figure 90).

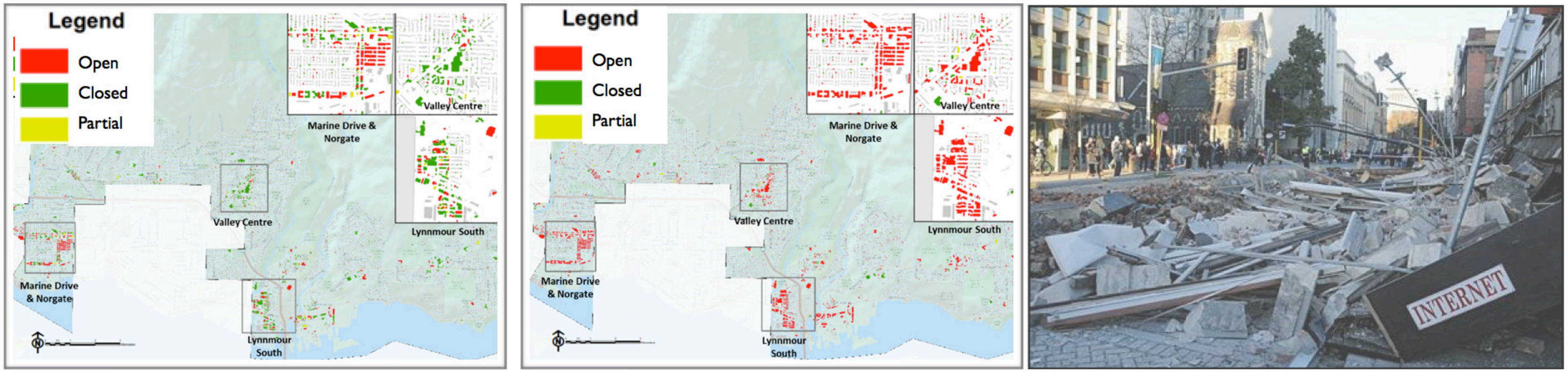
A 50% threshold was selected, meaning that if 50% or greater of the businesses within a neighbourhood were estimated to be closed after running the initial model, then all businesses within that neighbourhood were considered closed in the neighbourhood model. Each of the three neighbourhood models was run through 100 simulations for both full utility service and complete utility service loss scenarios. The average daily business operation rates by sector for each of the four models are reported below.

The full utility service scenario in the initial model estimates that just over two-thirds of businesses will remain open when accounting only for the impact of building damage on business operations. The complete service loss scenario demonstrates the substantial impact of utility service loss on business closures. Across all business sectors in the initial model, an additional 41% of businesses will close if water and power are lost.

The models also demonstrate the significance of considering neighbourhood scale disruption on business operations. The application of a neighbourhood effect produces the estimated closure of an additional 5-6% of businesses in the full service

Scenario	With Full Service Capacity					With Service Loss				
	Initial Model	NHID-1	NHID-2	NHID-3	Average	Initial Model	NHID-1	NHID-2	NHID-3	Average
TOTAL	**69%**	**64%**	**63%**	**64%**	**65%**	**28%**	**15%**	**15%**	**14%**	**18%**
FIR	65%	59%	58%	59%	**60%**	25%	10%	10%	8%	**13%**
HTH	75%	72%	72%	72%	**73%**	21%	8%	8%	7%	**11%**
MCT	72%	68%	67%	67%	**69%**	33%	25%	25%	22%	**26%**
MFG	58%	51%	46%	48%	**51%**	22%	2%	2%	3%	**7%**
SVC	71%	66%	66%	67%	**68%**	28%	18%	18%	16%	**20%**
TRD	65%	57%	56%	58%	**59%**	25%	4%	4%	4%	**9%**





Full Service Capacity (NHID-2) With Service Loss (NHID-2) Christchurch Earthquake (2011)

Figure 90: Outputs of UBC Business Disruption and Loss Model (Chang et al., 2008) summarizing operational capacities of representative business sectors with and without loss of service capacity for the District of North Vancouver.

scenarios, and more than double that (an additional 13-14%) in the service loss scenarios.

Health sector operations are the least affected by building damage while manufacturing operations are the most disrupted. Given the larger space requirements and equipment-intensive nature of manufacturing work, it is not surprising that building damage would have such a strong impact on these operations. On the other hand, when lifelines are lost, heath services become the sector most susceptible to disruption. The dependence on uninterrupted sources of water and electricity for medical instrumentation and sanitation requirements in health care may help explain this reversal of status.

Manufacturing, and retail trade industries are also significantly impacted by the effects of neighbourhood disruption in all three scenarios, with low operational capacities of 2% and 4% respectively (Figure 90). Magnified impacts of the neighbourhood effect on the operational capacities of manufacturing companies and retail businesses is an expected consequence as they are often clustered to take greatest advantage of customer traffic patterns.

Business Losses

Using the previously described average DNV daily GDP business rate per industry, the model translates the business disruption values detailed above into direct economic dollar loss, summarized in Table 91. The total average daily GDP loss across all sectors increases nearly 120% from baseline levels estimated on the basis of structural damage alone. Furthermore, including the neighbourhood effect increases losses from baseline levels by nearly 20% on average across both utility service scenarios.

It is worth noting that the total average daily economic loss is between 88%-89% of DNV's estimated average total daily GDP rate in all neighbourhood scenarios that simulate complete utility disruption (Table 8-8). This indicates a massive loss of daily economic production relative to normal levels. Prolonged continuation of business disruption at this level would have a substantial and lasting impact on the local economy.

Business Disruption - Economic Losses

Daily GDP = $4,962,940	With Full Utility Service ($million)	Without Utility Service ($million)	% of Average Daily GDP	
			Full Utility Service	Utility Service Loss
INITIAL MODEL	$ 1,643,286	$ 3,633,173	33%	73%
NHID-1	$ 1,949,989	$ 4,352,974	39%	88%
NHID-2	$ 1,998,950	$ 4,350,350	40%	88%
NHID-3	$ 1,953,505	$ 4,433,156	39%	89%

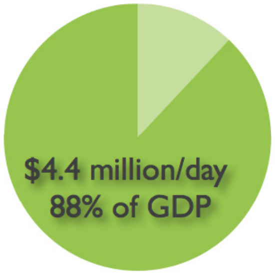


Figure 91: Outputs of UBC Business Disruption and Loss Model (Chang et al., 2008) highlighting the effects of utility service loss and potential impacts on average daily GDP for the District of North Vancouver.

FINANCIAL RISK

Financial risk is a function of maximum credible losses resulting from a disaster event (consequences), the likelihood of these losses occurring over a specified time horizon (probability), and the potential to reduce future losses through a combination of mitigation, business continuity planning and/or risk transfer (capacity). Maximum credible losses if the Georgia Strait scenario earthquake were to occur sometime in the next year are estimated to be ~$3 billion for current conditions. So, what are the associated financial risks if the scenario earthquake were to occur over planning horizons of interest to the community, and how might this information be used to establish tolerable thresholds of financial risk?

Probable Maximum Loss (PML) is defined as the dollar value above which losses caused by an unexpected financial shock are considered unlikely for a given time interval [OSFI, 2013e]. It is a useful metric in assessing thresholds of financial risk for low probability/high consequence events like earthquakes and for developing strategies that may be needed to manage intolerable levels of risk in the context of ongoing community development.

Figure 92 is a summary of probable maximum losses for the scenario earthquake over time horizons that are likely to be relevant for community development and infrastructure planning in the District of North Vancouver. Trend lines in the accompanying graph show how probable maximum losses vary as a function of time.

The average annual loss for the Georgia Strait scenario earthquake in any given year is estimated to be ~$7.5 million under current conditions and ~$5.6 million if investments were made to reduce capital loss potential through structural mitigation. Equivalent losses in any given year for the 2% in 50 year 'design' event are estimated to be $1.7 million.

Thirty years is often used as the time horizon for land use planning and sustainable community development. It is also a familiar time frame for managing risks associated with capital investments in homes or businesses (mortgages, bank loans, etc.). The 30-year probable maximum loss for the Georgia Strait scenario earthquake is estimated to be ~$220 million for baseline conditions and ~$160 million with structural mitigation measures in place.

Probable maximum losses for longer time horizons that are relevant for strategic land use and infrastructure planning (~100 years) are estimated to be ~$665 million for baseline conditions and ~$490 million with mitigation measures in place. Economic losses associated with the scenario earthquake are overshadowed for longer time horizons by the effects of less frequent but potentially catastrophic earthquake sources that are used in the National Building Code to establish minimum thresholds of life safety (2% in 50 year 'design' event).

Earthquake Risk Profiles

		Probable Maximum Loss (PML) over time horizons of interest					
Earthquake Scenario	Expected Loss	1 yr	10 yrs	30 yrs	100 yrs	1,000 yrs	2,500 yrs
◉ GSM7.3 scenario	$ 3,001	$ 8	$ 74	$217	$664	$2,755	$ 2,955
◉ 2%/50-yr Design	$ 4,269	$ 2	$ 17	$ 51	$167	$1,408	$ 2,699

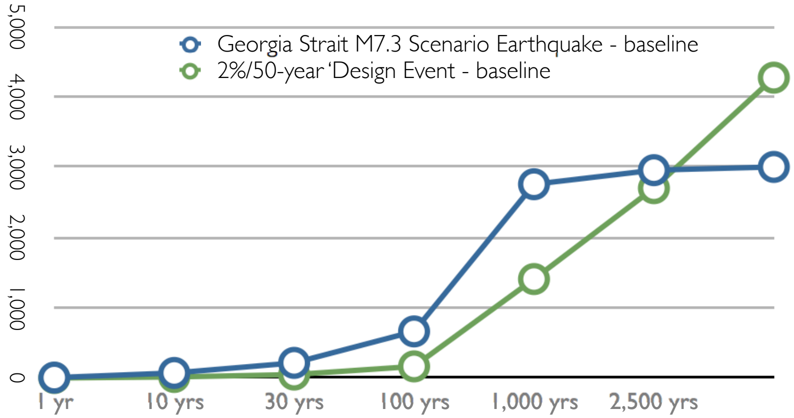


Figure 92: Financial risk profiles for the Georgia Strait M7.3 scenario earthquake and the 2% in 50 year 'Design Event.' Average annual losses

PART III: Disaster Resilience Planning

Risk-based planning is about managing opportunities for growth and development in ways that minimize potential future losses and that promote longer-term community resilience. It requires a common understanding of the risk environment, and the development of strategies that are framed by policy goals, informed by scientific knowledge, and tempered by the need to make practical choices between diverse and often competing social values and preferences.

We have adopted a framework for disaster resilience planning that is based on principles of integrated assessment and scenario modelling. The framework is built around a system of indicators and target criteria that are used to transform knowledge about earthquake risks into strategies that have a potential to reduce vulnerabilities and increase community resilience through investments in mitigation, emergency management and adaptation.

The framework is used to evaluate the costs and benefits of investing in seismic retrofit measures for the District of North Vancouver in terms of increased building performance, public safety, lifeline resilience and economic security. The framework offers support for an integrated approach to emergency management and disaster risk reduction, and a means of incorporating principles of disaster resilience into the broader context of sustainable community development. The final chapter presents an earthquake readiness action plan that charts a general path forward for the community.

Chapter 9 - Science-Policy Integration: Navigating a path from knowledge about earthquake risk to actions that have a potential to increase disaster resilience through mitigation, emergency management and adaptation.

Chapter 10 - The DNV Earthquake Ready Action Plan: Recommendations for reducing earthquake risk and increasing disaster resilience in the community.

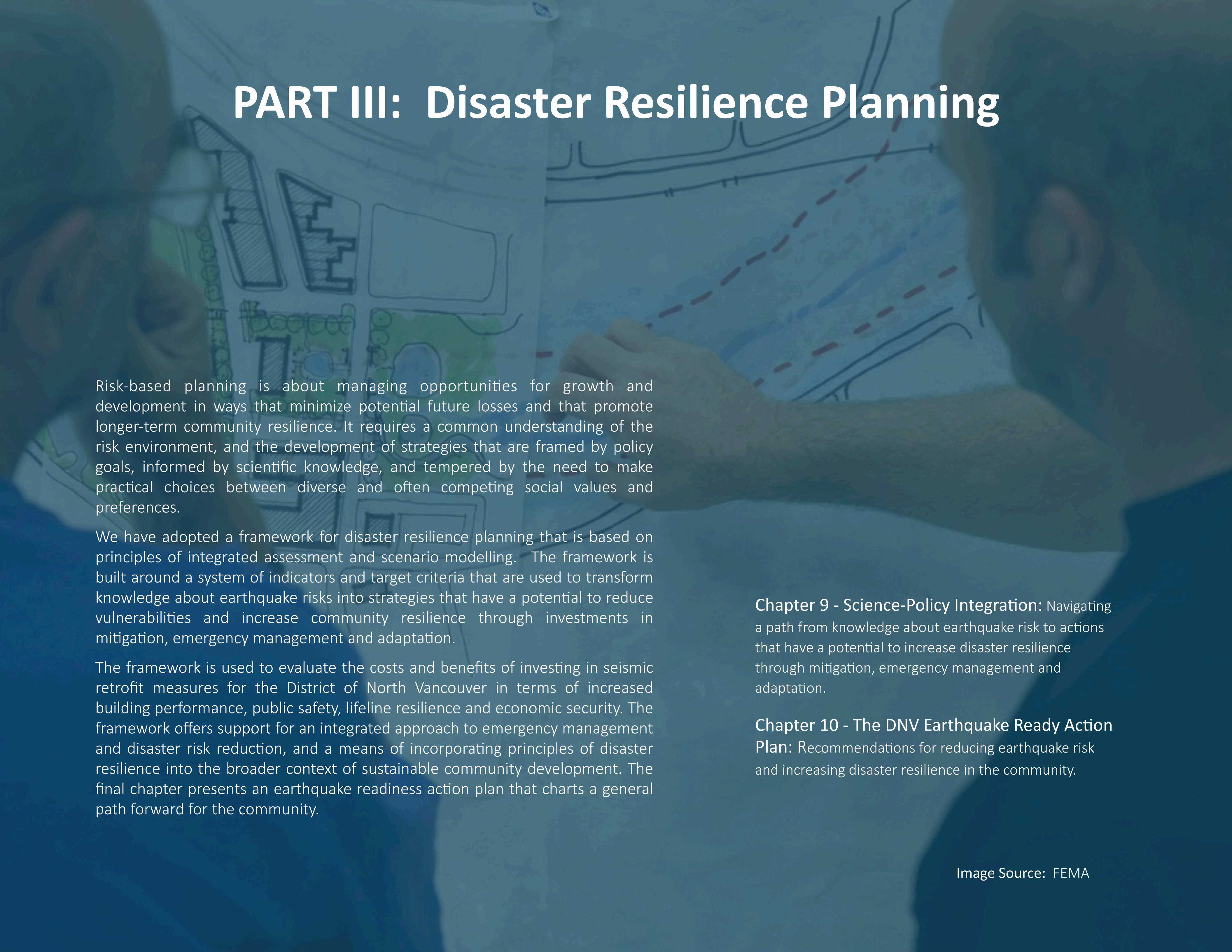


Image Source: FEMA

CHAPTER 9: Science-Policy Integration

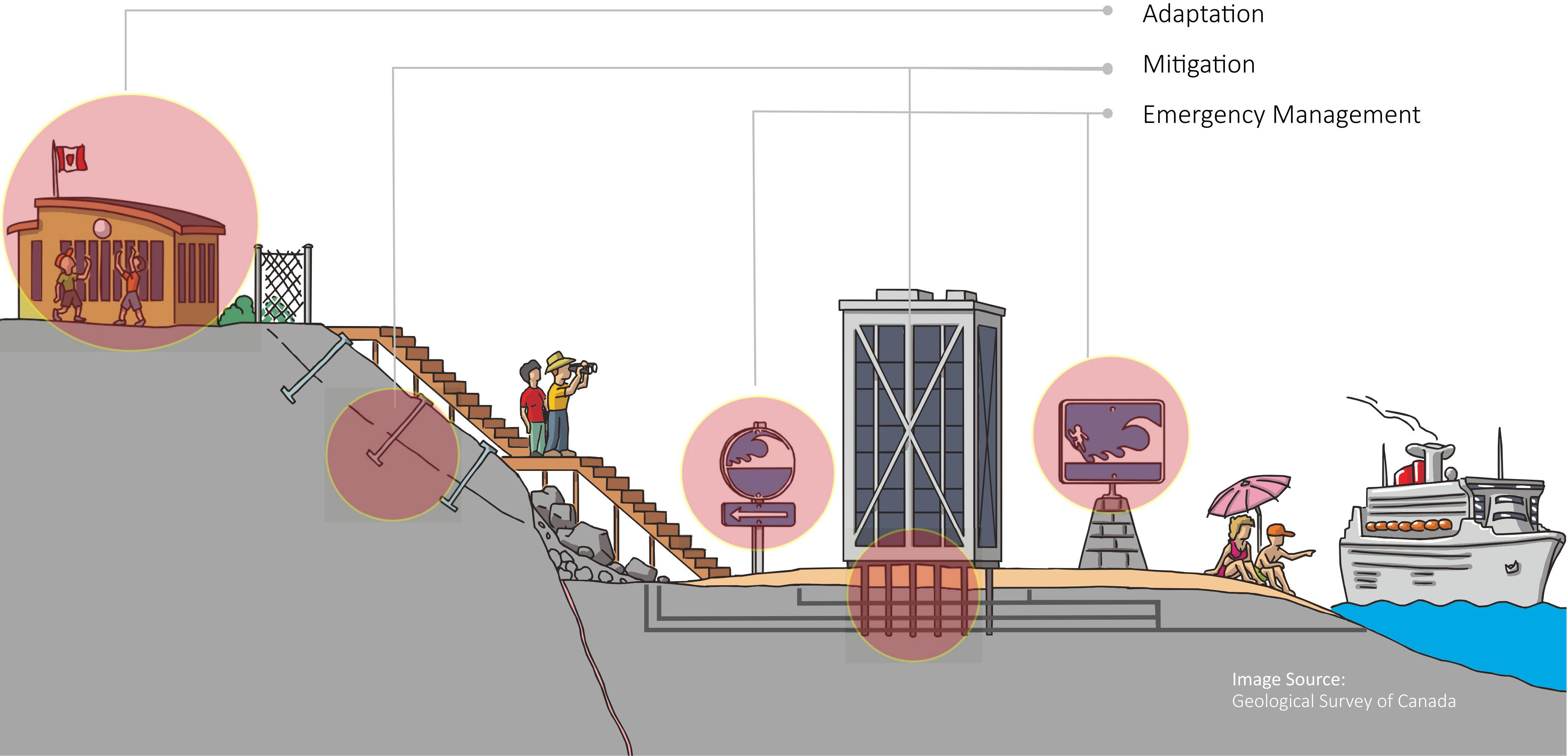


Image Source:
Geological Survey of Canada

CHAPTER 9: SCIENCE-POLICY INTEGRATION

Primary Authors: Journeay, J.M.

Disaster resilience is an iterative process of planning and policy development through which knowledge about societal risk is transformed into actions that increase the capacities of a community to withstand, respond to, and recover from unexpected hazard events. In isolation, disaster resilience measures are effective in reducing intrinsic vulnerabilities and optimizing specific policy targets that promote the safety and security of a community. When framed within the broader context of land use and comprehensive development, disaster resilience measures increase the capabilities of a community to anticipate and manage the dynamic forces of change, and to bounce back from catastrophic events that might otherwise undermine longer-term sustainability goals.

National policy guidelines for emergency management in Canada recognize the importance of disaster resilience planning at the community level [Public Safety Canada, 2007; 2010a; b]. Although progress is being made to refine the scientific knowledge and methods needed to analyze societal risks, there are still significant challenges in understanding how to incorporate this information into the broader context of planning and policy development.

- What are the likely impacts and consequences of natural hazards at the community level?
- What are the costs and benefits of investing in risk reduction and disaster resilience measures?
- What constitutes a tolerable threshold of risk for a specific geographic area or community, and who decides?
- Who bears the consequences of a natural disaster and how should collective risk be managed in the public domain?

These are questions that typically involve high levels of complexity, scientific uncertainty and political ambiguity. If addressed at all, issues of societal risk are most often negotiated on a case-by-case basis by planners and elected officials at the community level who must balance concerns about safety and security with ongoing pressures to manage growth and development.

This chapter describers how methods of integrated assessment and scenario modelling might be used to help bridge the gap between the science of earthquake risk and disaster resilience planning for the District of North Vancouver. Knowledge about likely cause-effect relationships for the Georgia Strait M7.3 scenario earthquake are used to develop what-if scenarios that model reductions in vulnerability and losses that could be avoided through proactive investments in structural mitigation. The benefits of mitigation are evaluated using indicators that monitor increased levels of building performance, public safety, lifeline resilience and economic security with mitigation measures in place. Mitigation costs are assessed for representative building types using the results of municipal risk reduction programs that have been successfully implemented in California.

Results are reported in terms of target criteria that provide a benchmark to assist the community in evaluating thresholds of earthquake risk tolerance and exploring opportunities to build disaster resilience through strategic investments mitigation and adaptation. Insights gained as part of this study are transferrable to other communities who may face similar challenges of managing growth and development in areas exposed to earthquake hazards, and contribute to broader efforts aimed at developing an all-hazard approach to disaster resilience planning in Canada [Public Safety Canada, 2012; 2013].

INTEGRATED RISK ASSESSMENT

We have adopted a framework for disaster resilience planning that is based on principles of integrated assessment and scenario modelling [J M Journeay, 2015]. The framework is built around a system of indicators and target criteria that are used to evaluate the strengths and weaknesses of risk reduction alternatives in terms of policy goals that reflect both scientific understanding of cause-effect relationships and community values with respect to safety, security and resilience (Figure 92).

Integrated risk assessment offers an evidence-based approach to disaster resilience planning that is informed by scientific analysis and predictive modelling, and governed by community values that reflect who and what are considered vulnerable and in need of safeguarding [Alcamo and Rothman, 2004; Engels, 2005; Jaeger, 1998; Pahl-Wostl et al., 2000; J Rotmans, 2006; Jan Rotmans and Van Asselt, 2000; Turner et al., 2003]. Knowledge and understanding developed through analysis and exploration of scenario alternatives is used to evaluate policy alternatives based on a multi-criteria framework of indicators that seek to balance trade-offs between growth opportunities and the constraints of development in areas exposed to natural hazards.

Figure 93: Analytic workflow for evaluating the strengths and weaknesses of risk scenarios using performance measures as a bridge between science, policy and decision-making

Analytic components of integrated risk assessment are focussed on objective measures that are combined into a framework of indicators used to monitor existing conditions of earthquake risk in the community (baseline scenario), and to explore opportunities for reducing underlying vulnerabilities and future losses through strategic investments in mitigation and adaptation (planning scenarios). Baseline and planning scenarios were developed using the Hazus methodology and are based on an analysis of cause-effect relationships for the Georgia Strait M7.3 scenario earthquake with and without seismic retrofits in place.

Deliberative components of integrated risk assessment are focused on subjective measures of risk, including the identification of community values, policy goals and target criteria that are used to evaluate mitigation alternatives in terms of building performance, public safety, lifeline resilience and socioeconomic security. The appraisal of earthquake risk is based on expected impacts and consequences, levels of concern for people and critical assets, and capacities to withstand, respond to and recover from a disaster event. Deliberations for this study were facilitated through a series of design-based workshops with District staff and the Natural Hazards Task Force – a voluntary advisory group representing homeowners and businesses in the community.

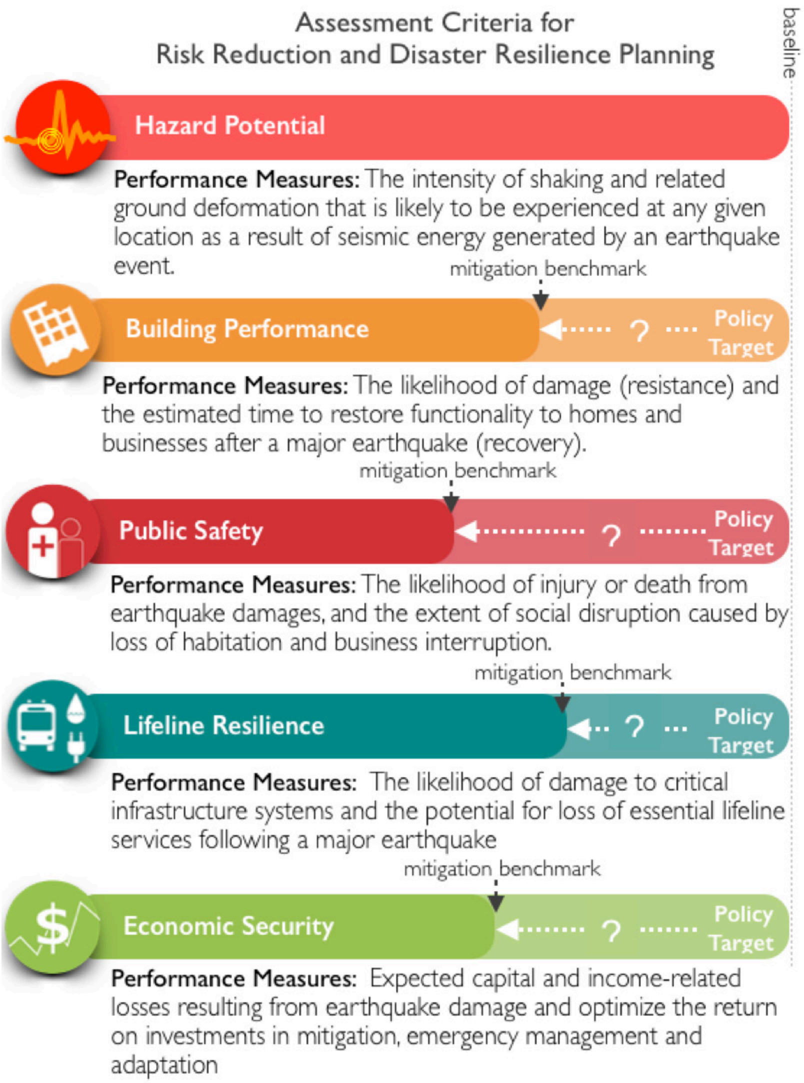
Outputs of our assessment provide a capability to evaluate whether existing or planned activities meet regulatory guidelines and are considered “safe for the intended use”; and whether they are consistent with what the community considers a “tolerable threshold of risk”. Planning scenarios that meet these minimum thresholds are advanced for further policy analysis and the selection of actionable strategies that can be implemented within the limits of available resources. Planning scenarios that fail to meet these minimum thresholds can be modified by adjusting seismic design measures to increase the performance of selected target criteria, or re-negotiating levels of risk that the community is willing to live with.

When formulated with a desired future state in mind, planning scenarios offer a forward-looking perspective for characterizing thresholds of tolerability based on community values, and for evaluating the efficacy of mitigation and/or adaptation strategies through the lens of local preferences and established policy guidelines. When incorporated into the full cycle of risk-based planning, the outputs of integrated risk assessment and scenario modelling offer decision makers a structured, transparent, and evidence-based framework for evaluating policy alternatives and choosing a course of action that advances overall community objectives while minimizing any potential negative impacts on people and critical assets.

Target Criteria and Indicators

Target criteria provide a mechanism of integrating objective and subjective measures of risk (indicators) to inform planning and policy making as part of a broader process of risk governance and sustainable community development [Birkmann, 2007; Cardona et al., 2005; Carmichael et al., 2005; Folke et al., 2002; Pelling, 2004; Phillips, 2003]. They express intent with respect to a desired set of outcomes and provide a framework for exploring thresholds of risk tolerance. Indicators are used to measure existing conditions of risk, and to model the performance of policy choices that seek to reduce underlying vulnerabilities and increase community resilience through mitigation, emergency management and adaptation.

Performance measures for this study include a system of indicators that monitor conditions of public safety, building performance, lifeline resilience and economic security for existing baseline conditions, and for ‘what-if’ planning scenarios in which mitigation measures have been implemented (Figure 94). The framework of performance measures extends the scope of seismic safety thresholds and design guidelines used in the National Building Code of Canada [NBCC, 2010], which are based primarily on ground shaking intensity (hazard potential). It also broadens



Assessment Criteria for
Risk Reduction and Disaster Resilience Planning

Performance Measures: The intensity of shaking and related ground deformation that is likely to be experienced at any given location as a result of seismic energy generated by an earthquake event.

Performance Measures: The likelihood of damage (resistance) and the estimated time to restore functionality to homes and businesses after a major earthquake (recovery).

Performance Measures: The likelihood of injury or death from earthquake damages, and the extent of social disruption caused by loss of habitation and business interruption.

Performance Measures: The likelihood of damage to critical infrastructure systems and the potential for loss of essential lifeline services following a major earthquake

Performance Measures: Expected capital and income-related losses resulting from earthquake damage and optimize the return on investments in mitigation, emergency management and adaptation

Figure 94: Assessment criteria used in establishing policy targets for risk reduction and disaster resilience planning.

the scope of risk tolerance criteria that are currently used by the District to inform land use planning and policies that govern sustainable growth and development in areas exposed to natural hazards in the community [District of North Vancouver, 2011c].

RISK REDUCTION POTENTIAL FOR THE DNV

We explore the potential for risk reduction in the District of North Vancouver by using performance measures to analyze expected impacts and consequences of the Georgia Strait M7.3 scenario earthquake — with and without mitigation measures in place. Our analysis is focussed on the effectiveness of investing in seismic retrofit measures for approximately 1,900 buildings that do not comply with current seismic safety guidelines in the National Building Code of Canada [NBCC, 2010], and that are expected to sustain extensive or complete damage in the event of a major earthquake (2% in 50-year design event).

Indicators of building performance, public safety, lifeline resilience and economic security were developed for each building in the mitigation portfolio using the Hazus methodology to model expected impacts and consequences for baseline conditions and with seismic retrofit measures in place. Results are reported in terms of a reduction in damages, injuries and losses for the full portfolio.

Differences between loss profiles for mitigated and baseline scenarios are used to establish mitigation benchmarks to assist the community in exploring thresholds of risk tolerance and formulating policy to guide future growth and development. Policy targets represent specific risk management objectives for the community. They are informed by available scientific knowledge about the risk environment — and community values with respect to who and what are considered vulnerable and in need of safeguarding within the limits of available resources (ALARP principle).

Hazard Potential

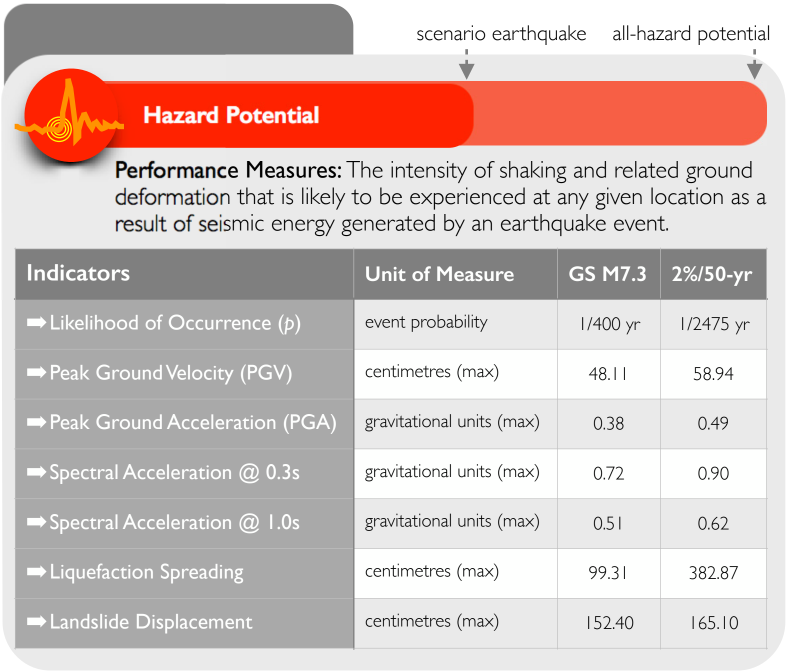
Hazard potential is a measure of the intensity of shaking and related ground deformation that is likely to be experienced at any given location as a result of seismic energy generated by an earthquake event. In this analysis, we compare the intensity of shaking and ground failure for the Georgia Strait M7.3 scenario earthquake with that of lower probability but higher consequence earthquake hazards used to establish seismic safety thresholds for the 2010 National Building Code (NBCC, 2010).

The Georgia Strait scenario was selected because it represents a plausible earthquake event with a potential for loss and social disruption that would likely test local capabilities for response, but that would not overwhelm the community with respect to longer-term economic recovery. The scenario earthquake has the capacity to generate losses that are similar in magnitude to the 2011 earthquake disaster in Christchurch, New Zealand. However, it is not a worst-case scenario when compared with lower probability earthquakes hazards that are known to occur in the region.

Ground Shaking

The Georgia Strait scenario is an example of what might be expected for a cumulative portfolio of earthquake hazards with a return period of ~1/500 years (p~12% in 50 years). With respect thresholds used to establish seismic safety guidelines in the 2010 National Building Code of Canada (1/2475 years; p =2% in 50 years), the Georgia Strait scenario ranks ~80% in terms of maximum peak ground velocity (PGV) and ~64% in terms of maximum lateral building displacement (See Figure 95).

The main earthquake event would likely last only 20 and 30 seconds but would be felt as a combination of rumbling pressure waves causing violent push-pull motions, and rolling surface waves that would rock buildings and make it difficult to stand or drive a vehicle. Predicted ground motions vary considerably across the study area as a function of distance from the earthquake epicentre, geologic setting and the effects of local site amplification. Peak ground velocity (PGV) is a measure of instantaneous shaking at the surface and is often used as reference for assessing the relative intensity of an earthquake event at any given location. PGV values for the District are expected to range from 6.4 cm/second in highland areas underlain by solid bedrock — to a maximum of 48.1 cm/second in lowland areas where seismic waves are amplified by underlying layers of relatively soft sediment (See Figure 96).



Performance Measures: The intensity of shaking and related ground deformation that is likely to be experienced at any given location as a result of seismic energy generated by an earthquake event.

Indicators	Unit of Measure	GS M7.3	2%/50-yr
➡ Likelihood of Occurrence (*p*)	event probability	1/400 yr	1/2475 yr
➡ Peak Ground Velocity (PGV)	centimetres (max)	48.11	58.94
➡ Peak Ground Acceleration (PGA)	gravitational units (max)	0.38	0.49
➡ Spectral Acceleration @ 0.3s	gravitational units (max)	0.72	0.90
➡ Spectral Acceleration @ 1.0s	gravitational units (max)	0.51	0.62
➡ Liquefaction Spreading	centimetres (max)	99.31	382.87
➡ Landslide Displacement	centimetres (max)	152.40	165.10

Figure 95: Assessment criteria used in monitoring expected conditions of shaking and ground deformation for earthquake hazards of concern.

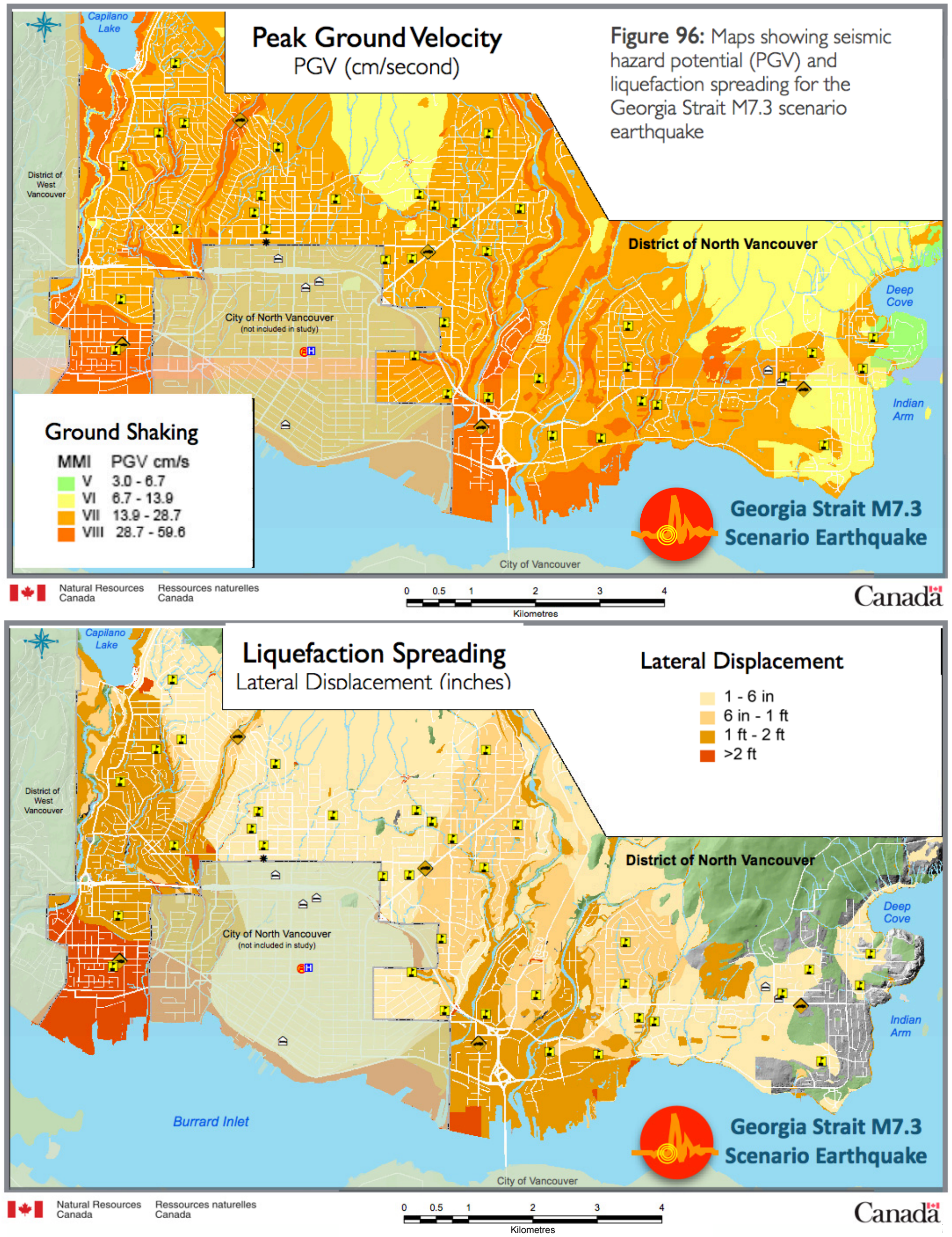
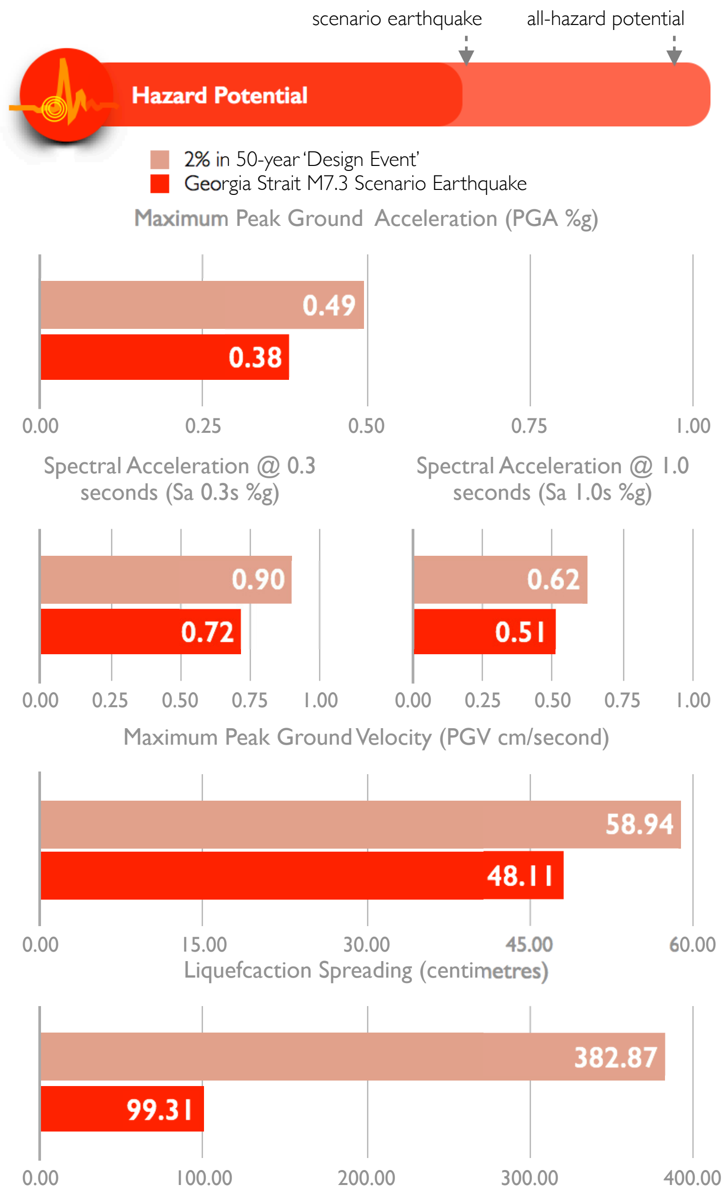


Figure 96: Maps showing seismic hazard potential (PGV) and liquefaction spreading for the Georgia Strait M7.3 scenario earthquake



Disclaimer: Results of our analysis are intended to show regional trends and should be used as a guide only. The results do not replace a need for more detailed site-level geotechnical investigations for seismic design, construction and/or engineering purposes.

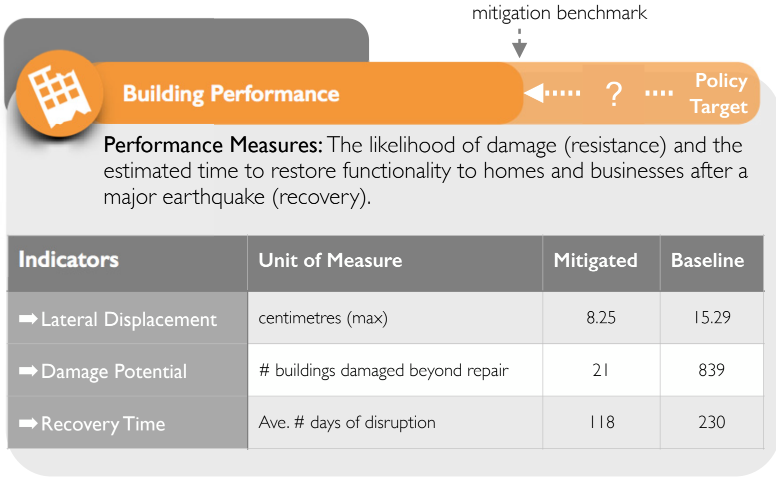
Ground Failure

Liquefaction is expected to occur in areas underlain by water-saturated soils that would loose cohesion during intense ground shaking. Areas of concern include low-lying waterfront developments underlain by saturated glacial outwash sediments and/or landfill deposits (sand, gravel, crushed rock). Lateral displacements in these areas are likely to be 60-90 cm, and in some places greater than 150 cm. Other areas of concern include delta and outwash terrace deposits of sand and gravel in the lower Capilano and Seymour valleys, where lateral displacements are likely to be 30-60 cm.

Earthquake-triggered landslides occur along steep unstable slopes where severe ground shaking results in forces that are strong enough to overwhelm the internal shear strength of surficial materials and the gravitational forces that hold them in place on the hillside. Hotspots of concern coincide with areas of previous landslides, and zones of high landslide potential identified through independent geotechnical studies commissioned by the District of North Vancouver [M Porter et al., 2007]. They include steep valley walls and preserved outwash terraces along the East shore of Capilano Reservoir, upper reaches of the Capilano River, Mackay Creek, Mosquito Creek, Lynn Creek and the Seymour River. The extent and magnitude of ground failure for the Georgia Strait scenario earthquake is similar to that expected for lower probability but more severe earthquake events in the region.

Building Performance

Building performance directly influences the safety and security of individuals, the extent of social disruption following an earthquake, and the longer-term economic security of a community. As such, it is an important measure of disaster resilience and the primary focus for risk reduction through investments in structural mitigation.



Performance Measures: The likelihood of damage (resistance) and the estimated time to restore functionality to homes and businesses after a major earthquake (recovery).

Indicators	Unit of Measure	Mitigated	Baseline
➡ Lateral Displacement	centimetres (max)	8.25	15.29
➡ Damage Potential	# buildings damaged beyond repair	21	839
➡ Recovery Time	Ave. # days of disruption	118	230

Figure 97: Assessment criteria used in establishing policy targets for reduced physical vulnerability and increased building resilience for scenario earthquake.

From the perspective of planning and policy-development, the intent is to maximize the capacity of buildings to withstand and recover from the likely impacts of earthquake damages through strategic investments in land use and/or seismic retrofit measures that reduce physical vulnerabilities and the loss of functionality following a major earthquake (Figure 97). Key performance measures include the effectiveness of these measures in reducing the number of structures likely to sustain extensive and/or complete damage (resistance), and the number of days needed to restore baseline levels of functionality (recovery).

The National Building Code of Canada currently utilizes outputs of probabilistic earthquake hazard assessments carried out by the Geological Survey of Canada to establish seismic safety guidelines for the siting and construction of new buildings and engineered structures. Safety guidelines are focused on ensuring the safety of individuals from building damage during an earthquake event based on the likelihood of exceeding minimum thresholds of ground shaking for a given return period. Safety thresholds in the current building code are based on probable ground shaking intensities for a return period of 1/2475 years (2% in 50-year 'design' threshold). Results of our study extend the scope of analysis to include an overall assessment of damage potential and recovery time for the full inventory of homes and businesses in the community, the majority of which predate the development of modern seismic safety guidelines.

We developed a 'what-if' scenario to model the effectiveness of investing in seismic retrofit measures by first selecting a portfolio of ~1,900 buildings that are exposed to extensive or complete levels of damage associated with known seismic hazards with a return period of 1/2475 years (2% in 50-year 'design' threshold). These are mostly older structures that were never designed or constructed to meet current building code guidelines for seismic safety.

The effects of installing seismic retrofits for each building in the portfolio was modelled by adjusting performance characteristics and corresponding fragility curves in the Hazus AEBM module to simulate increased levels of structural resistance that meet current safety thresholds outlined in the National Building Code of Canada [NBCC, 2010]. We then used the Hazus model to calculate expected impacts and consequences for the Georgia Strait scenario earthquake with mitigation measures in place.

The effectiveness of seismic retrofits for each building was assessed on the basis of reductions in damage potential and recovery time — both of which contribute to increased building performance and overall disaster resilience. Results of our analysis are summarized in Figure 98. Differences between building performance for baseline and mitigated scenarios provide an important benchmark for establishing thresholds of risk tolerance and identifying actions to reduce the physical vulnerability of homes and businesses in the community.

Damage Potential

Eight-hundred and thirty-nine buildings are expected to sustain extensive or complete damage in the Georgia Strait M7.3 scenario earthquake. The majority of these are older concrete and unreinforced masonry structures in business precincts along the waterfront (~600 buildings), More than 215 residential structures and 25 public sector buildings are also likely to be damaged beyond repair in isolated hotspots of severe shaking and ground failure throughout the District.

Specific measures that might be considered to increase building performance include: the strengthening of foundation connections; bracing and/or anchoring of frame, floor and roof systems; the addition of shear walls, and; a variety of other measures to help dissipate seismic energy and resist the effects of shear and lateral drift.

With these mitigation measures in place, all but 21 of the 839 buildings currently exposed to extensive or complete damage from a major earthquake would be preserved from significant damage (Figure 98). Fifteen of the buildings still in danger of collapse are situated along the industrial waterfront with the remaining six in surrounding commercial precincts. Nearly all are larger unreinforced masonry buildings that are likely to collapse from lateral spreading caused by liquefaction.

Recovery Time

Investments in seismic retrofits to the most vulnerable buildings in the District also have the effect of reducing recovery times for homes and businesses. The greatest gains are in the residential sector, where mean recovery times are reduced by almost 95% (See Figure 99). Recovery times are reduced by ~4 months for single family homes and over one year for multi-family residential buildings that have been seismically retrofitted. Recovery times are reduced ~4 months for commercial and industrial buildings, and ~1 week for public sector buildings.

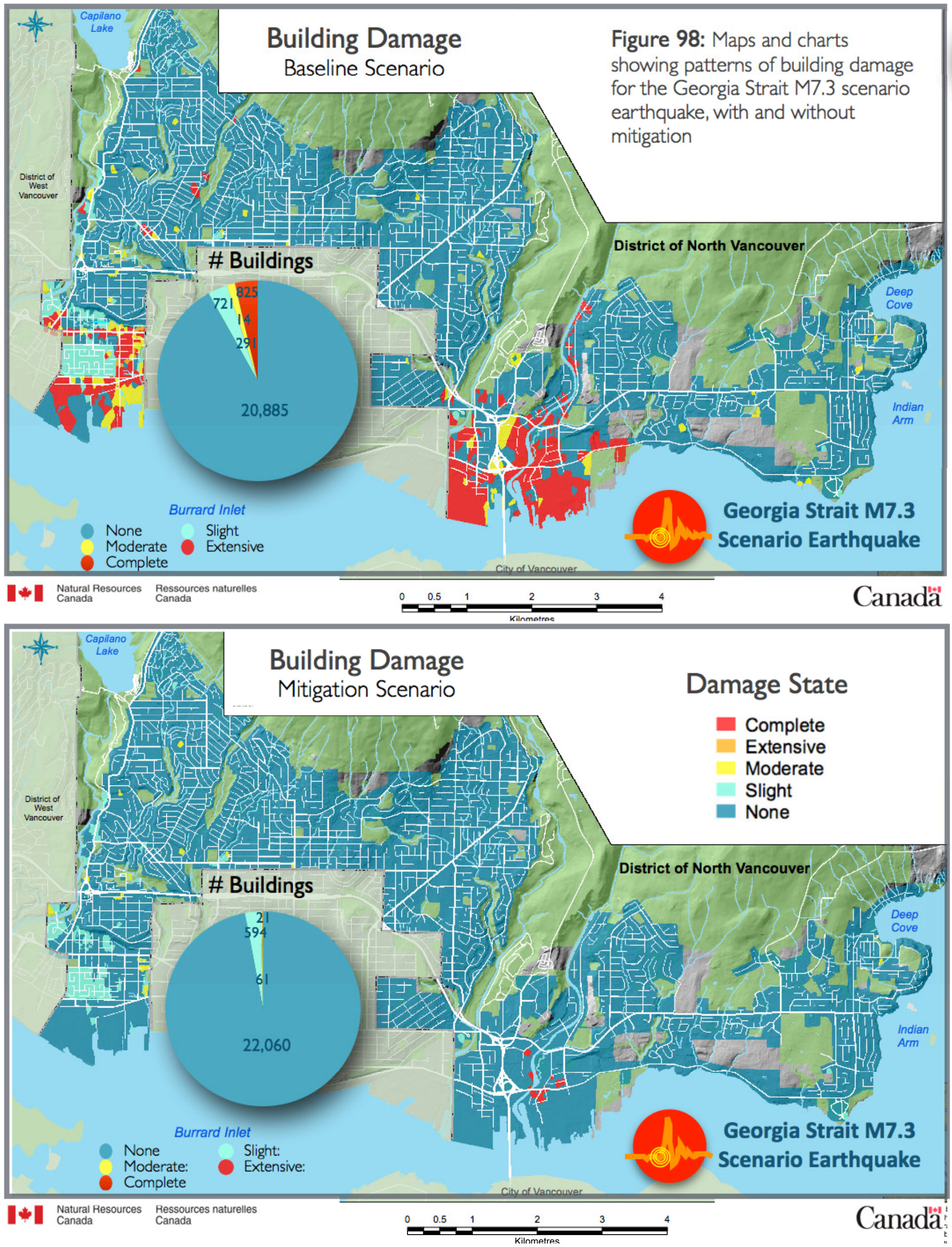


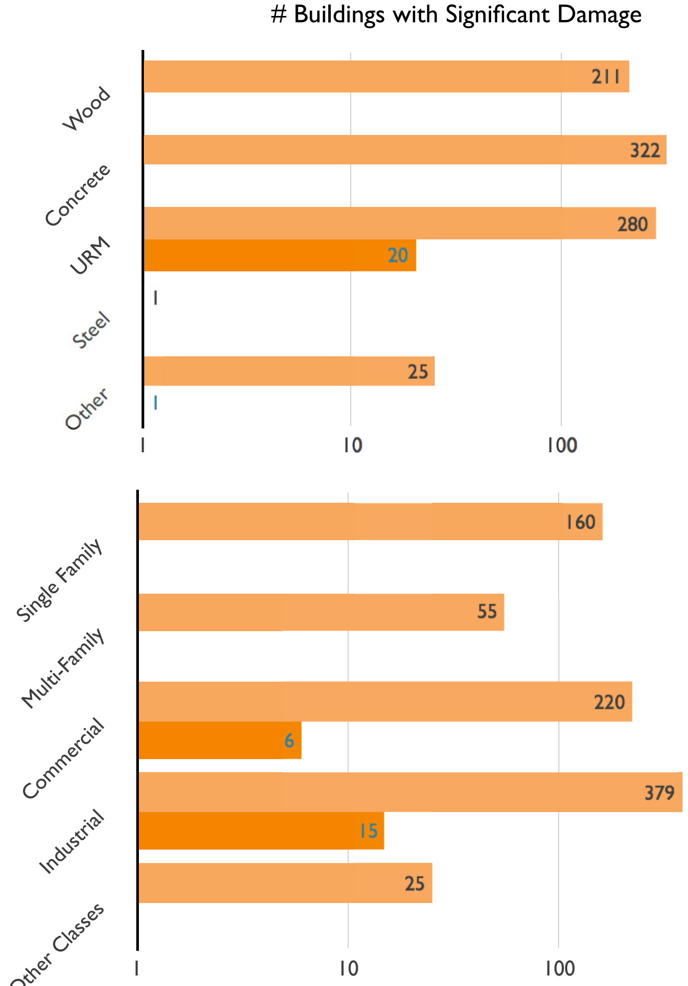
Figure 98: Maps and charts showing patterns of building damage for the Georgia Strait M7.3 scenario earthquake, with and without mitigation

mitigation benchmark

Building Performance - *Damage* ? **Policy Target**

Number of buildings that are likely to sustain extensive or complete damage in the scenario earthquake

Baseline Scenario Mitigation Scenario



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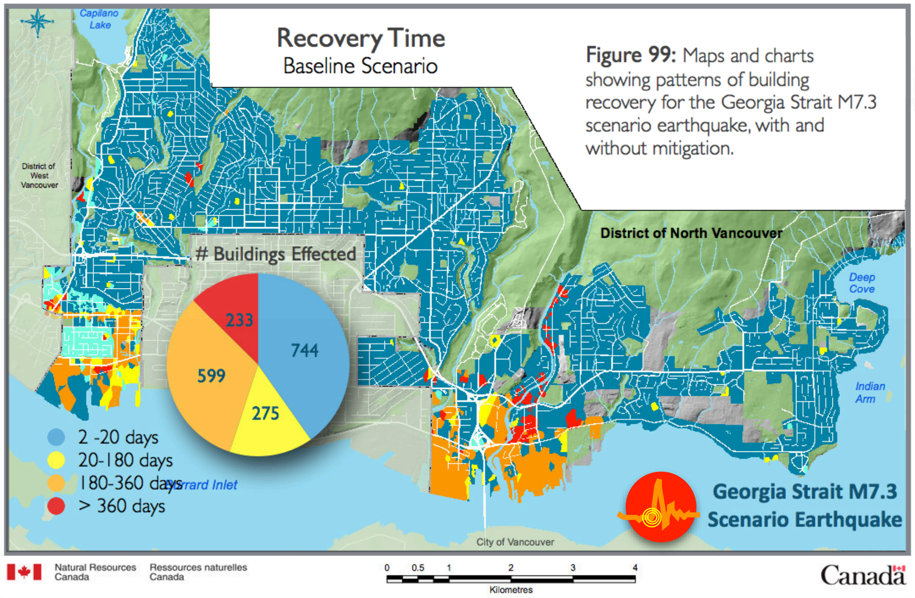
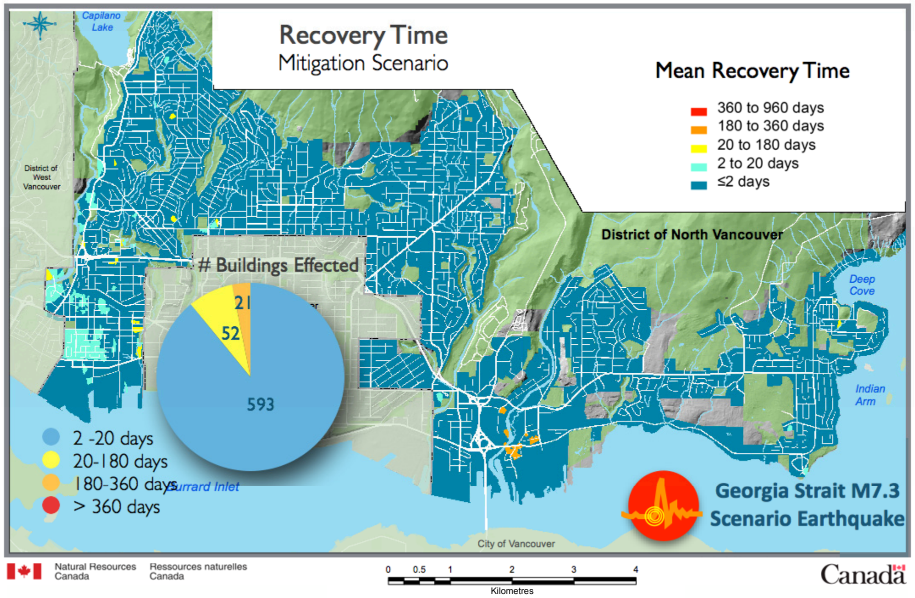


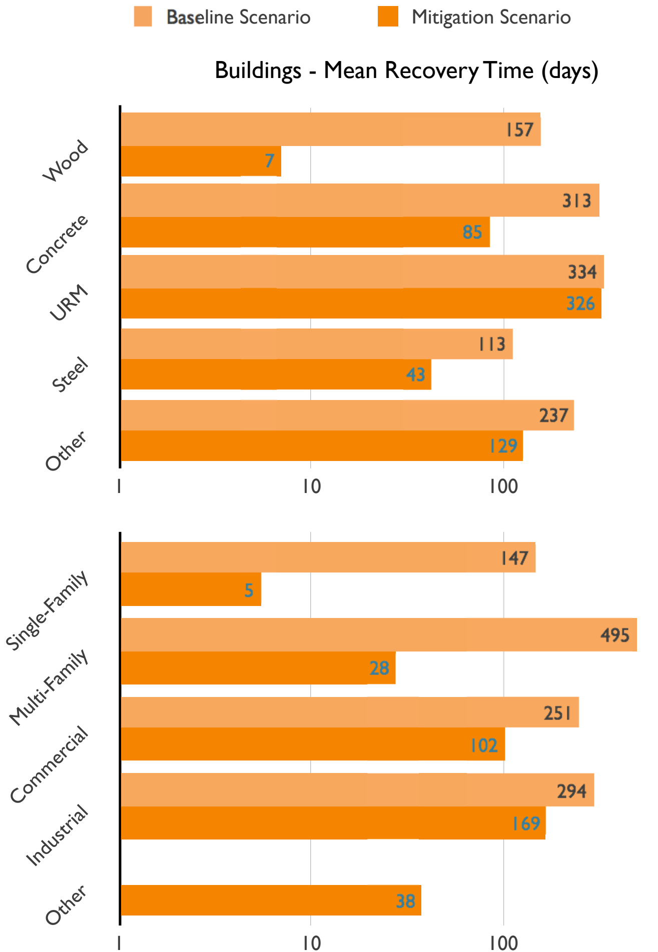
Figure 99: Maps and charts showing patterns of building recovery for the Georgia Strait M7.3 scenario earthquake, with and without mitigation.



mitigation benchmark

Building Performance - *Recovery* ? **Policy Target**

Average number of days required to restore baseline levels of functionality to individual buildings following the scenario earthquake



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Public Safety

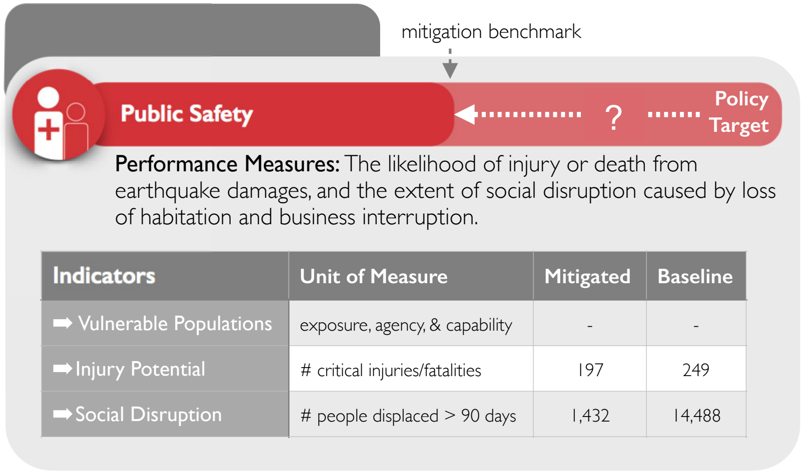
Ensuring the safety of citizens who are exposed to hazard threats beyond their control is perhaps one of the most fundamental public policy mandates for government at all jurisdictional levels. In addition to increasing building performance by encouraging seismic retrofits to vulnerable homes and businesses, local authorities are legislated to provide emergency response services to protect life and limb and to provide short-term assistance to those impacted by an earthquake event.

To this end, we have developed a set of performance measures that track the extent and severity of injuries resulting from building damages with and without mitigation measures in place, and the level of social disruption that can be expected during subsequence phases of response and recovery (Figure 100). Results of our analysis are summarized in Figures 101 and 102.

Injuries

Although seismic retrofits are effective in reducing the number of buildings expected to sustain extensive or complete damage, the likelihood of injuries caused by falling debris and non-structural impacts remains high in both baseline and mitigation scenarios. The number of people expected to sustain or succumb to life-threatening injuries for a daytime earthquake scenario is reduced by 52 with mitigation measures in place (See Figure 101).

The greatest gains are made through investments in seismic retrofits to older concrete and unreinforced masonry buildings, where safety performance levels increase by 17% and 28%, respectively. While this represents a significant reduction in the number of potential fatalities, more than 1,300 people will still sustain injuries that require paramedic care and ~425 will need emergency medical care at a hospital — even with mitigation measures in place.



Performance Measures: The likelihood of injury or death from earthquake damages, and the extent of social disruption caused by loss of habitation and business interruption.

Indicators	Unit of Measure	Mitigated	Baseline
➡ Vulnerable Populations	exposure, agency, & capability	-	-
➡ Injury Potential	# critical injuries/fatalities	197	249
➡ Social Disruption	# people displaced > 90 days	1,432	14,488

Figure 100: Assessment criteria used in establishing policy targets for reduced social vulnerability and increased public .

Social Disruption

Most of the population will shelter in place. However, more than 3,000 residents are expected to be displaced from their homes for up to 20 days after the scenario earthquake to allow time for building inspections and restoration of lifeline services. While the majority of those displaced will seek temporary accommodation with friends and family, several hundred people will seek emergency shelter and social services from local authorities and supporting aid agencies.Seismic retrofit measures are most effective in reducing the extent of social disruption for those displaced three months or more as a result of damages caused by the earthquake (See Figure 102). More than 13,000 people who would otherwise be displaced by the earthquake are expected to return to their homes and places of work with mitigation measures in place. The most significant reductions in social disruption are for residents displaced more than a year (~1,500 people), and for employees displaced for 3 months or more (~16,500 workers).

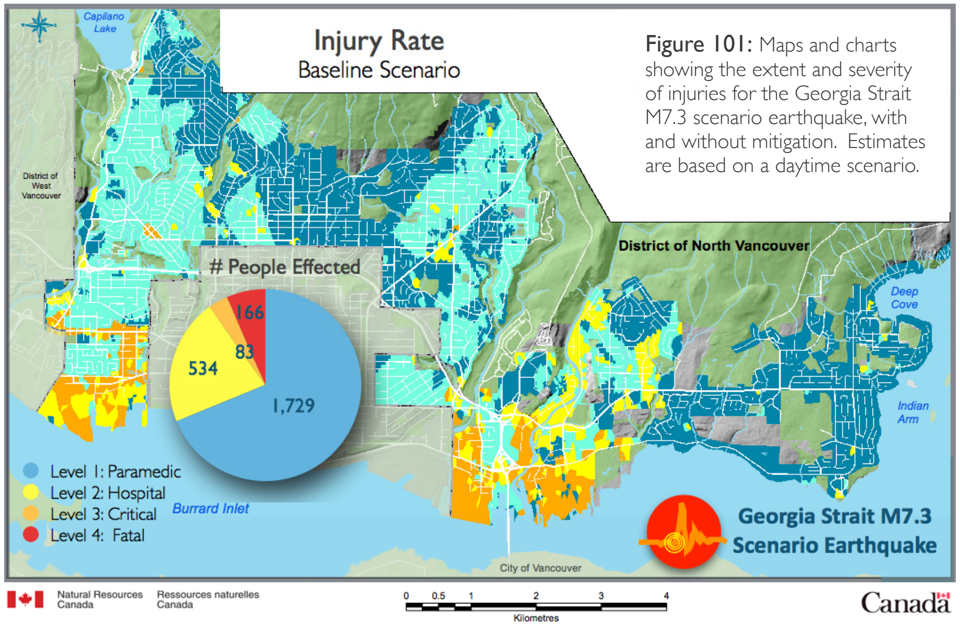
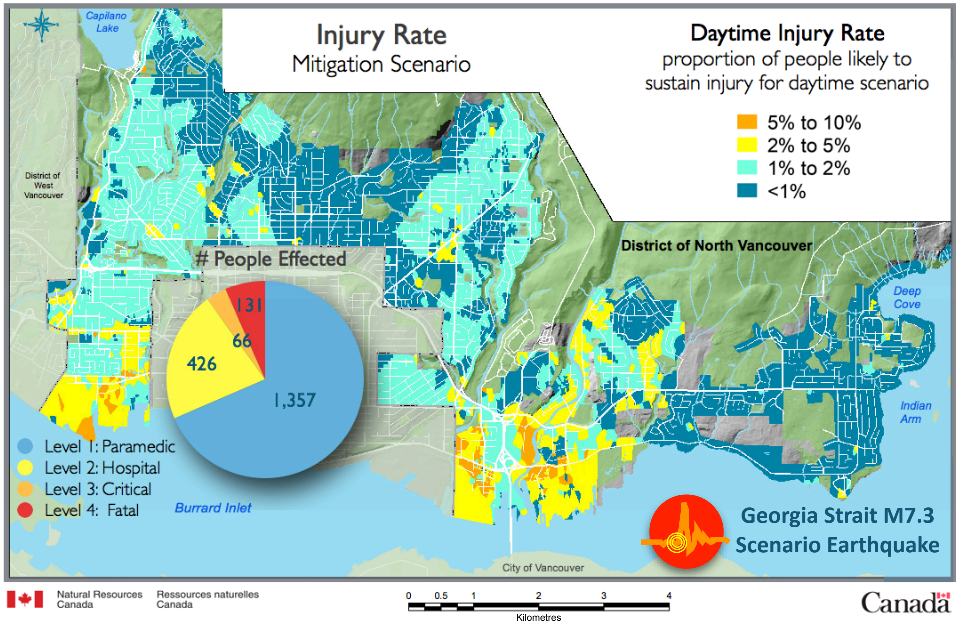
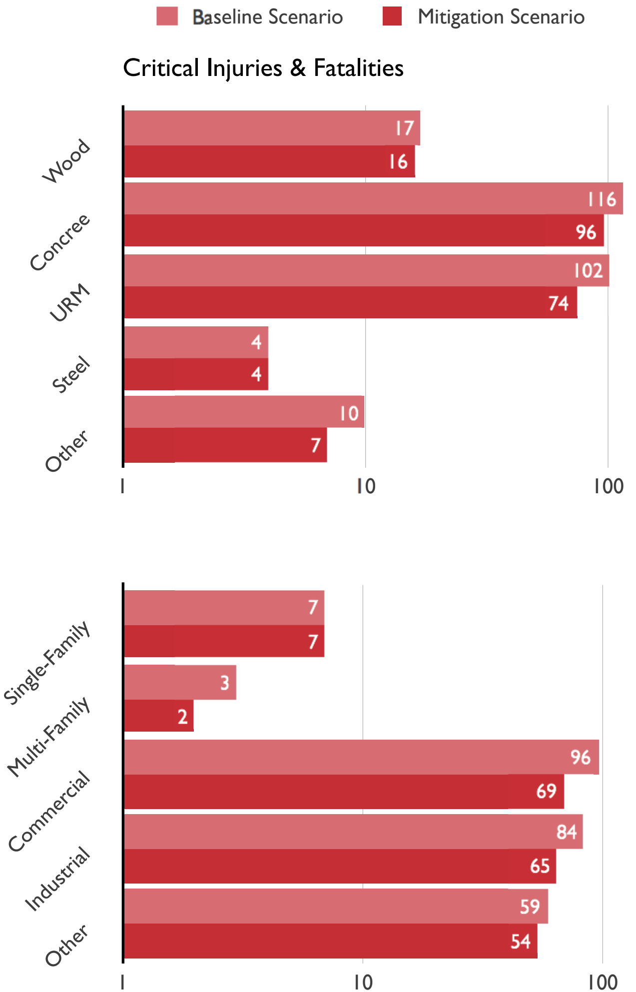


Figure 101: Maps and charts showing the extent and severity of injuries for the Georgia Strait M7.3 scenario earthquake, with and without mitigation. Estimates are based on a daytime scenario.



Number of people likely to sustain life-threatening injuries in the scenario earthquake



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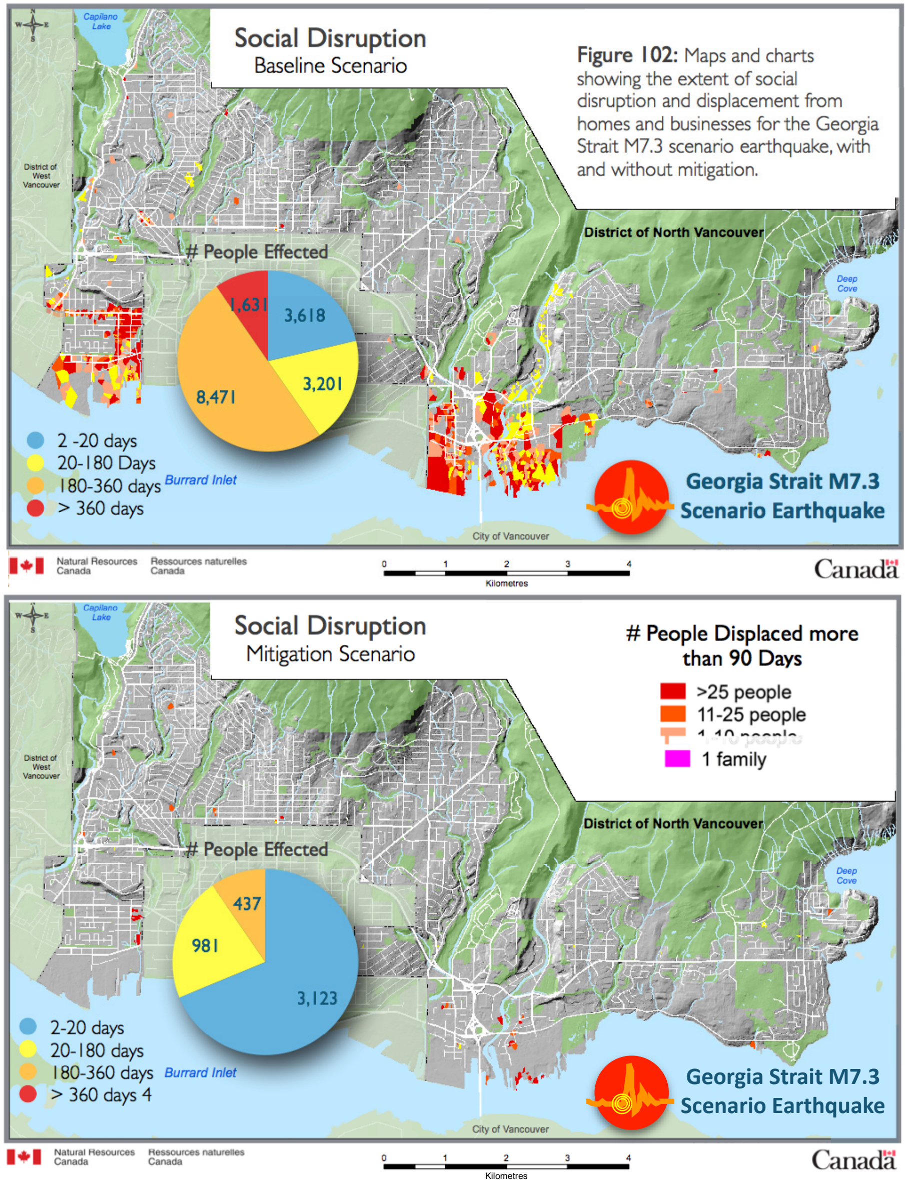
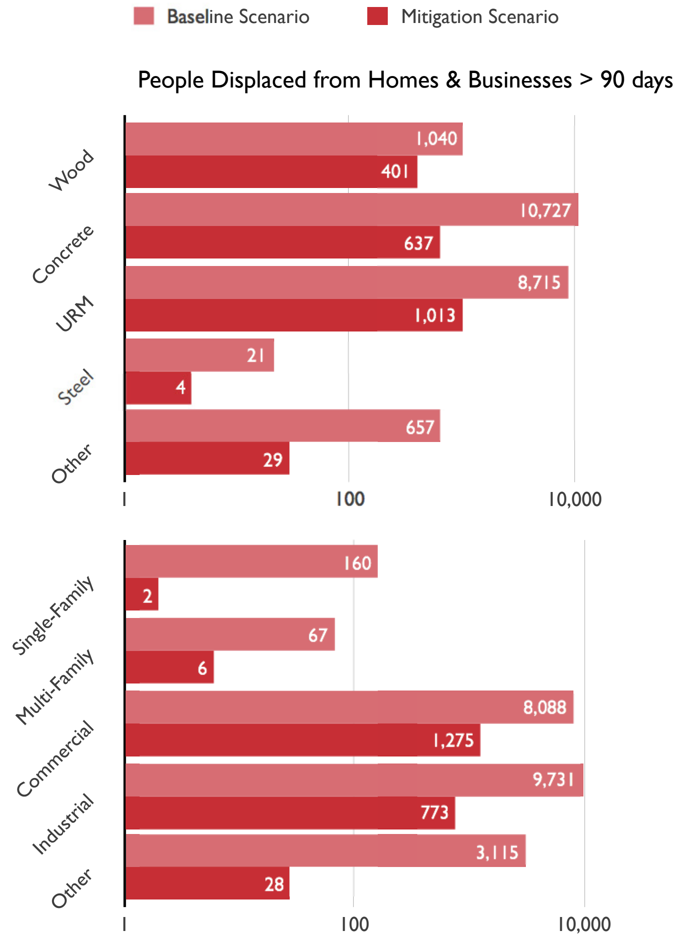


Figure 102: Maps and charts showing the extent of social disruption and displacement from homes and businesses for the Georgia Strait M7.3 scenario earthquake, with and without mitigation.

mitigation benchmark

Public Safety - *Social Disruption* ◄··· ? ········ **Policy Target**

Number of people who are displaced from their home and/or place of work for more than 3 months.



Disclaimer: Results of our analysis are intended to show regional trends and should be used as a guide only. The results do not replace a need for more detailed site-level geotechnical investigations for seismic design, construction and/or engineering purposes.

Lifeline Resilience

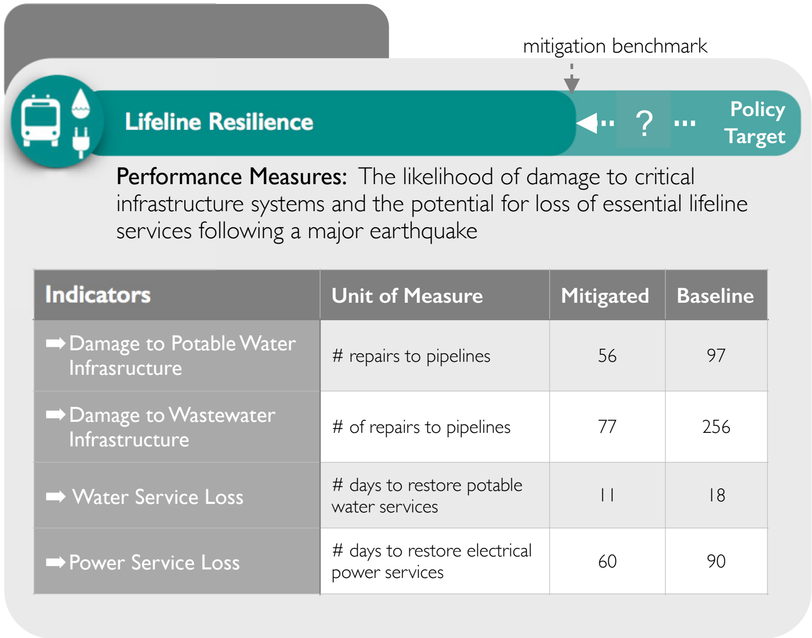
Lifeline resilience measures the extent to which critical infrastructure systems can absorb the impacts of sudden shocks that threaten structural coherence and functional integrity, and the capability of these systems to provide access to essential services during the recovery process. From the perspective of planning and policy development, the goal is to increase the structural resistance of system components through mitigation in order to reduce the amount of time required to restore essential functions and lifeline services to pre-disaster levels.

Target criteria for this study are expressed in terms of performance measures that monitor overall lifeline resilience (See Figure 103). Indicators track the number of system components that are expected to remain functional following a major earthquake (resistance) and the number of days required to restore water and power services to the community (recovery).

The District has already adopted a risk-based approach to managing ongoing maintenance and replacement of critical infrastructure systems based on the likelihood of failure and the potential for loss of lifeline services to the community [Carter, 2012]. We explore opportunities to further increase the resilience of critical lifeline systems by modelling the effects of seismically upgrading water and power facilities that are vulnerable to earthquake damages, and replacing older pipeline components with ductile materials that are more resistant to severe ground shaking and lateral shear. The effectiveness of investing in seismic retrofit measures is evaluated on the basis of increases in overall resistance to pipeline failure and improved service capacity during the recovery period.

Water Utilities

Water utilities and related lifeline services are particularly vulnerable to earthquake damage and loss of functionality in areas of severe ground shaking, and in older neighbourhoods where pipelines are constructed of older brittle materials that are less resistant to settling and lateral displacements caused by earthquake-triggered liquefaction.



Performance Measures: The likelihood of damage to critical infrastructure systems and the potential for loss of essential lifeline services following a major earthquake

Indicators	Unit of Measure	Mitigated	Baseline
➡ Damage to Potable Water Infrasructure	# repairs to pipelines	56	97
➡ Damage to Wastewater Infrastructure	# of repairs to pipelines	77	256
➡ Water Service Loss	# days to restore potable water services	11	18
➡ Power Service Loss	# days to restore electrical power services	60	90

Figure 103: Assessment criteria used in establishing policy targets for reduced vulnerability and increased resilience of lifeline services.

System vulnerabilities are concentrated in two north-south corridors adjacent to the Capilano and Seymour River Valleys (Figures 104). The western corridor includes a potable water pumping station at the Capilano Reservoir, water main and distribution pipelines, and primary trunk lines that connect to regional wastewater management systems. The central corridor includes pumping stations, water mains and distribution pipelines along the Lynn and Seymour Valley escarpment that provide potable water to the Metro Vancouver region, as well as primary trunk lines and sewer infrastructure that is essential for

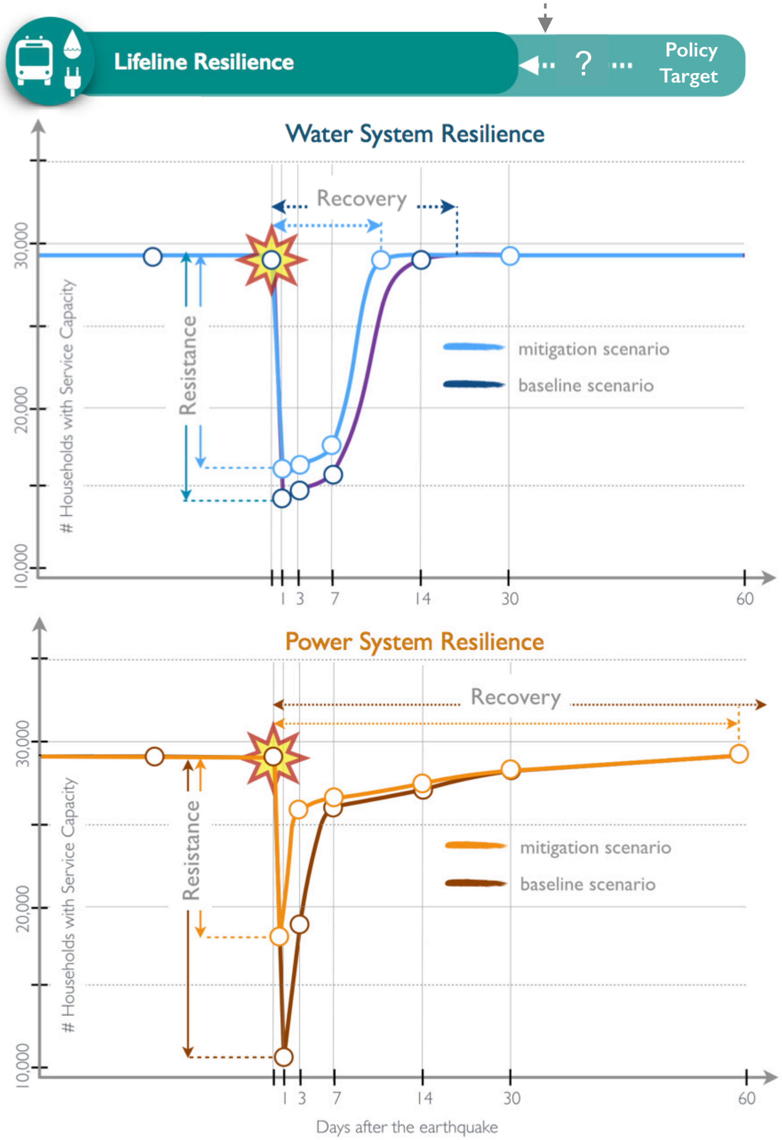


Figure 104: Comparative profiles of potable water and power system resilience for the scenario earthquake both with and without mitigation measures in place.

wastewater management in the District. Earthquake damages are expected to result in leaks and breaks that would require at least 100 repairs to restore potable water service, and ~250 repairs to restore functionality for wastewater infrastructure.

System resilience is measured in terms of the number of homes and businesses without access to water services in the days and weeks following the earthquake, and the number of days required to restore service capacity (Figure 105). For current conditions, it is estimated that more than half of all homes and businesses would be without water for up to 7 days after the earthquake. Depending on the size and capacity of repair crews, it would take up to 18 days to restore full service capacity. Nearly 700 homes and businesses that would otherwise be without services would have access to potable water within 7 days as a result of investments in seismic retrofits to pipelines and water facilities. In addition, the time required to restore full service capacity is likely to be reduced by one week or more. This represents a ~ 40% increase in service capacity for potable water systems and a ~70% increase for wastewater systems.

Power Utilities

Our assessment of power system resilience is limited to an analysis of damages to electrical substations within the District and does not account for upstream dependencies on power generation or distribution. Electrical facilities are expected to sustain a ~50% drop in service capacity with as many as 18,000 homes and businesses without access to power immediately after the earthquake and ~3,500 without power one week later. Investments in seismic retrofits to vulnerable facilities have the potential to increase overall system resistance with ~7,000 fewer service interruptions immediately after the earthquake, and a significantly shorter amount of time to restore full service capacity to the community. Gains in system resilience have important implications on business interruption and overall economic security during the recovery process.

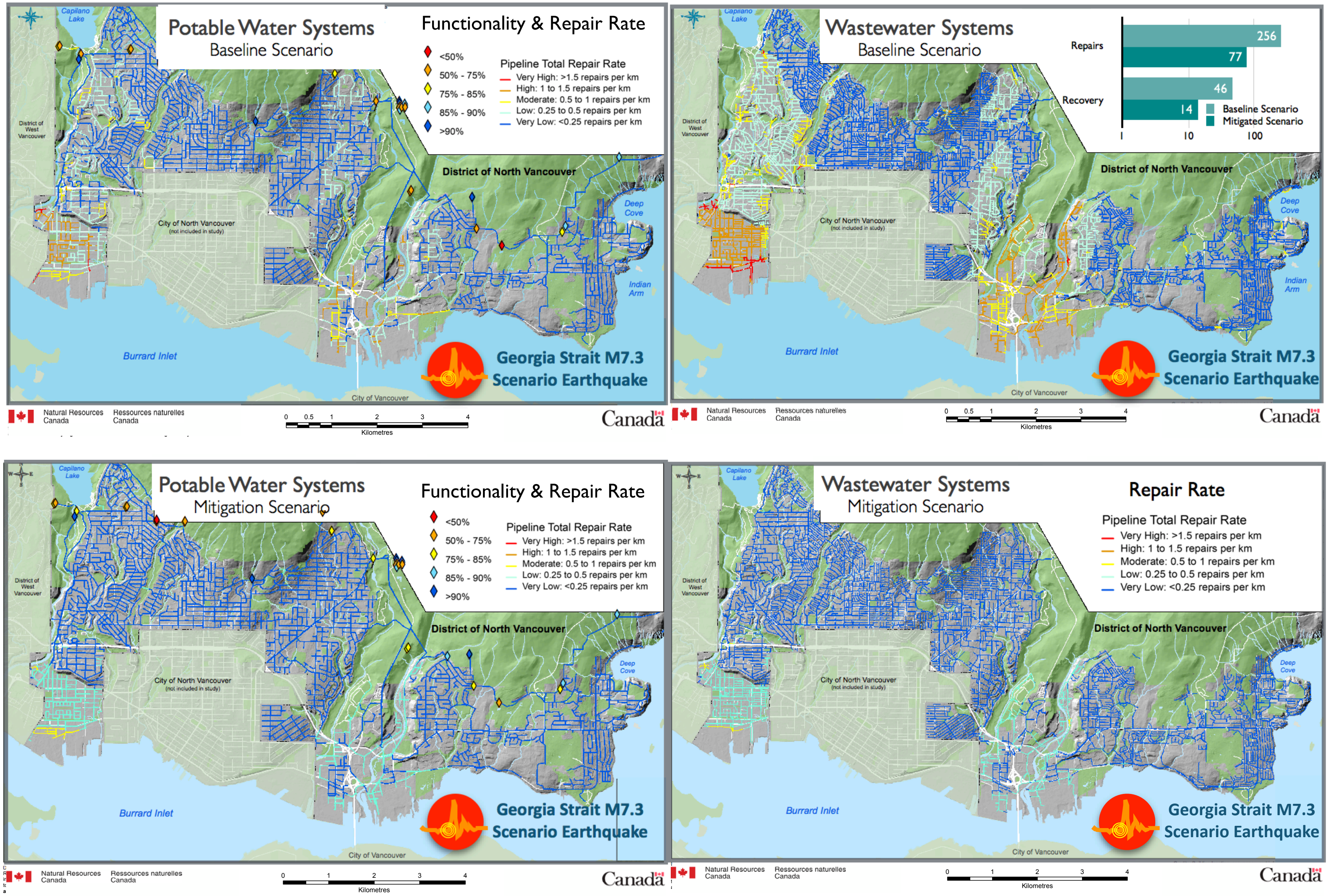


Figure 105: Maps and charts summarizing expected earthquake damages to potable and wastewater systems for baseline and mitigation scenarios.

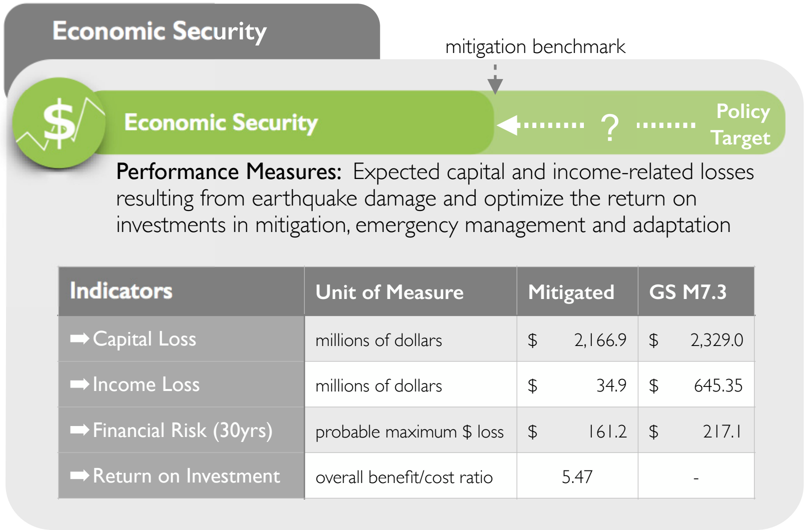
Economic Security

Economic security is a measure of community wealth and the financial integrity of critical assets that may be exposed to the impacts and consequences of a disaster event at some point in the future. It encompasses both direct capital assets that are invested in buildings and related infrastructure, and income-related assets that are driven by employment and the marketing of goods and services on a day-to-day basis. From the perspective of planning and policy development, the goal is to maximize community wealth through strategic investments in mitigation and/or adaptation measures that have a potential to reduce future losses and that yield a positive rate of return over time horizons of interest.

Target criteria include performance measures that track the proportion of capital assets that are vulnerable to earthquake loss (loss rate), the cumulative loss potential (direct economic losses), financial risk for a given time horizon (Probable Maximum Loss; PML), and the expected rate of return for mitigation investments. We have evaluated the potential for reducing earthquake risk in the community by assessing each of these target criteria with and without mitigation measures in place. The results provide important insights on loss potential and opportunities to increase overall economic security in the community following a major earthquake (Figures 106 and 107).

Losses Avoided

The mean loss ratio for residential homes in the scenario earthquake is ~13%, which translates into an average capital loss of ~$66,000 for a single-family residence and ~$345,000 for multi-family apartment and condominium complexes. The mean loss ratio for business assets is significantly higher with expected average capital losses of $360,000 for commercial buildings and up to $500,000 for industrial facilities. Total expected capital losses for the scenario earthquake are $2.33 billion dollars. As expected, the profile of loss is skewed by the vulnerability of older concrete and unreinforced masonry buildings in commercial/industrial zones along the waterfront (See Figure 108). As a result, the business sector is expected to bear the largest burden of financial risk with a potential for up to 90% loss in gross daily revenue. This translates into nearly $645.4 million of total income-related losses for the duration of the recovery process. Prolonged business disruption at this level would have a substantial and lasting impact on the community and economic vitality in the broader Metro Vancouver region



Performance Measures: Expected capital and income-related losses resulting from earthquake damage and optimize the return on investments in mitigation, emergency management and adaptation

Indicators	Unit of Measure	Mitigated	GS M7.3
➡ Capital Loss	millions of dollars	$ 2,166.9	$ 2,329.0
➡ Income Loss	millions of dollars	$ 34.9	$ 645.35
➡ Financial Risk (30yrs)	probable maximum $ loss	$ 161.2	$ 217.1
➡ Return on Investment	overall benefit/cost ratio	5.47	-

Figure 106: Assessment criteria used in establishing policy targets for reduced economic losses and increased return on investment in risk

Investments in seismic retrofits have the potential to reduce capital losses by ~ $160 million dollars and income-related losses by more than $610 million dollars in the District. The greatest efficiencies are gained in retrofitting older concrete, unreinforced masonry and pre-cast structures in commercial/industrial areas along the waterfront. As a result, business disruption and related losses are reduced by 95%, thereby promoting economic security.

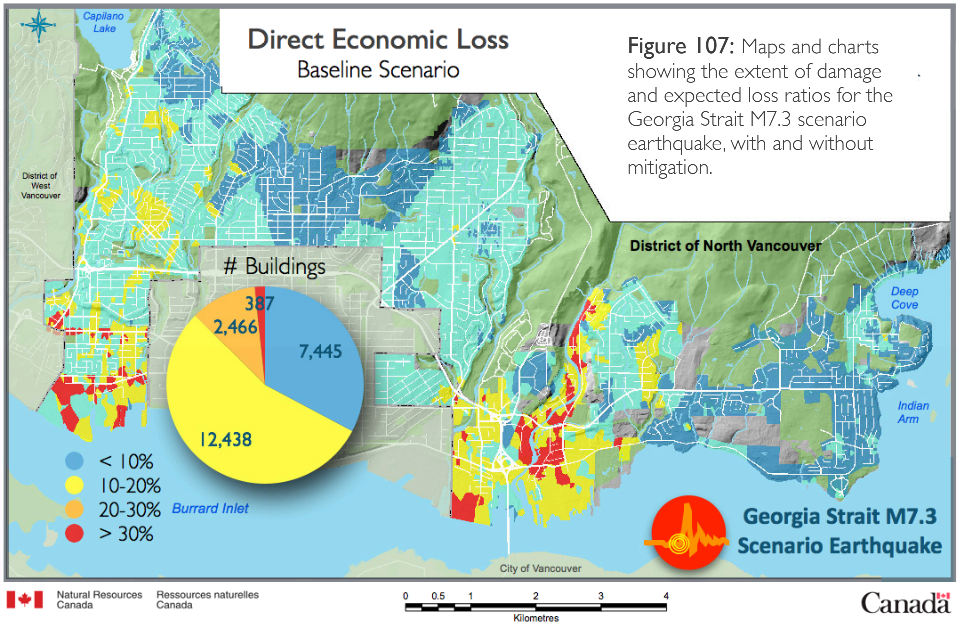
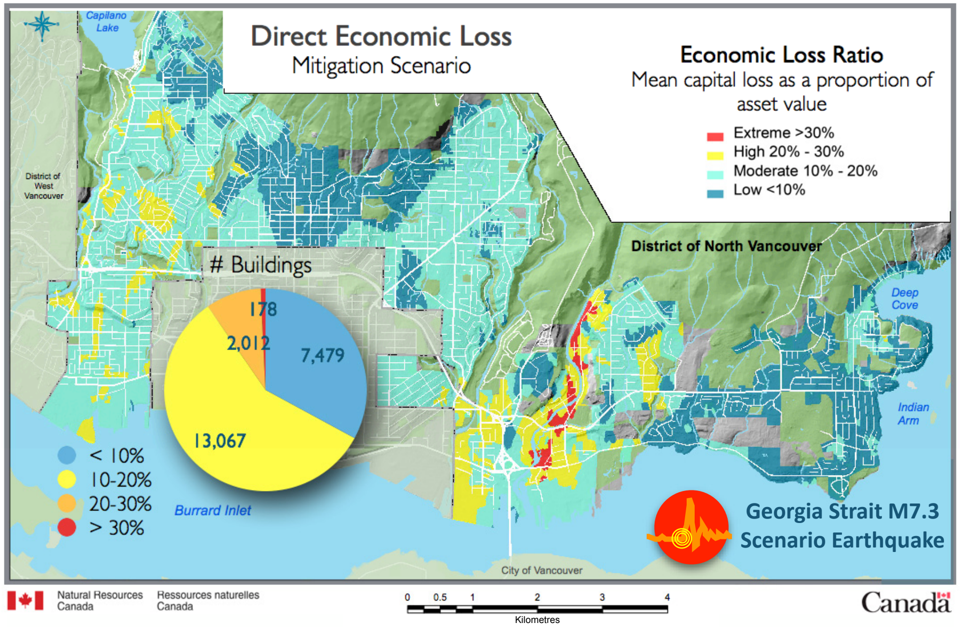


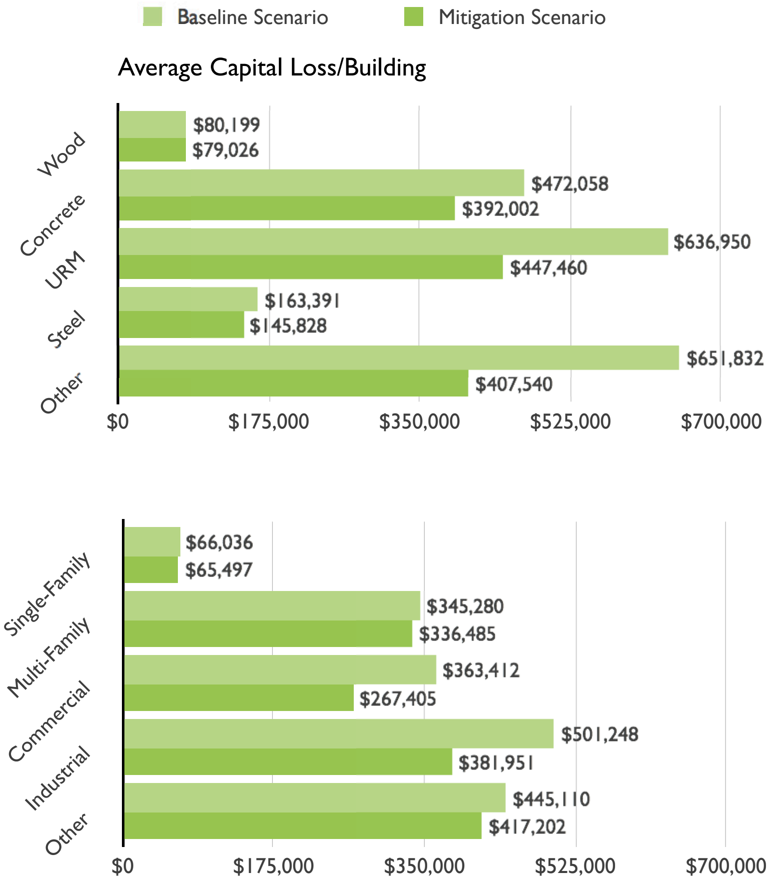
Figure 107: Maps and charts showing the extent of damage and expected loss ratios for the Georgia Strait M7.3 scenario earthquake, with and without mitigation.



mitigation benchmark

$ Economic Security - *Total Loss* ◀··· ? ······· **Policy Target**

Average capital loss per building type. Estimates based on direct economic losses resulting from the scenario earthquake. They do not take into account income-related losses resulting from business disruption.



Disclaimer: Results of our analysis are intended to show regional trends and should be used as a guide only. The results do not replace a need for more detailed site-level geotechnical investigations for seismic design, construction and/or engineering purposes.

Costs and Benefits of Mitigation

Benefit-Cost Analysis (BCA) is a common methodology for assessing the strengths and weaknesses of investing in mitigation measures, and is an essential component of disaster resilience planning. It is a structured and relatively transparent method of evaluating the efficacy of mitigation alternatives that seeks to balance opportunities for growth and development with objective measures of financial risk [Cullen and Small, 2000; Dasgupta and Pearce, 1978; FEMA, 2010; Mechler, 2003; Mechler and et al, 2008].

A BCA requires explicit monetary valuation and accounting of all relevant community assets, mitigation costs and potential losses resulting from a disaster event. The analysis is focused primarily on conventional real estate parameters used to evaluate the feasibility of a development project. For the most part, a BCA is limited to capital investments in buildings and critical infrastructure (stocks) for which monetary values can be assigned. It does not include the broader range of socioeconomic variables and interdependencies that will ultimately determine overall resilience of a community.

The strength of this approach is that it provides an internally consistent and legally defensible metric against which policy alternatives can be compared and evaluated in absolute terms. Asset values can be adjusted against anticipated future costs to derive discount rates that are used to track economic fluctuations over variable planning horizons, thereby providing a means of evaluating trade-offs between short- and long-term policy alternatives. However, the selection of decision criteria and the scope of mitigation choices that might be considered is often limited by performance measures that can be assigned a market value or an equivalent measure that reflects a willingness to pay for non-market goods or services [Gamper et al., 2006].

We have used a simple benefit-cost analysis to explore the effectiveness of investing in seismic retrofit measures aimed at reducing the vulnerability of older buildings in commercial/industrial zones that are susceptible to significant damage and capital losses in the event of a major earthquake. The analysis compares expected losses for baseline conditions and a mitigation scenario in which vulnerable homes and businesses have been seismically retrofitted to current seismic design standards as part of an ongoing community development process (building permits for renovation, business continuity plans, etc.).

The benefits of mitigation were analyzed for each building in the portfolio based on losses avoided across a spectrum of target criteria and related performance measures. In addition to reductions in capital and income-related losses for homes and businesses (Economic Security), we also assessed mitigation benefits in terms of increased structural resistance to earthquake damages and corresponding reductions in the amount of time required to restore baseline levels of functionality (Building Performance); reductions in the number of people likely to sustain life-threatening injuries, and the extent of social disruption in the community (Public Safety). Results of our analysis are summarized in Figure 108).

The costs of mitigation were estimated to be 2-3% of the total replacement value based on empirical data from seismic retrofit programs that have been implemented in California [City and County of San Francisco, 2010; K Porter et al., 2006]. Average mitigation costs range from $12,000 dollars for a typical residential wood frame building to ~$50,000 dollars for concrete and masonry structures that are common in higher density mixed-use town centres and older commercial/industrial precincts along the waterfront.

As expected, the economic benefits of investing in seismic retrofit measures are greatest for older concrete (~$118,000), unreinforced masonry (~$206,000) and other classes of vulnerable buildings (precast, reinforced masonry and manufactured structures, etc.) that do not conform to modern

Summary of Risk Reduciton Potential for Porfilio of Buildings with Seismic Retrofits

Benefit-Cost Analysis	Exposure			Losses Avoided through Mitigation Investments					
	# Buildings Mitigated	Average Asset Value	Average Mitigation Cost	# Buildings Preserved	Reduced Recovery Time/Bldg (Days)	Reduced Social Disruption (People)	Total Injuries Avoided (People)	Losses Avoided/ Bldg	Benefit /Cost Ratio
Construction Type									
Wood	1,090	$721,059	$18,403	211	718	3,019	24	$ 53,225	2.89
Concrete	399	$1,483,863	$41,009	322	308	11,644	168	$ 118,054	2.88
URM	349	$2,411,425	$59,313	261	295	9,448	349	$ 206,497	3.48
Steel	12	$606,647	$15,166	1	101	153	2	$ 48,395	3.19
Other Types (PC,RM,MH)	35	$5,125,040	$115,529	24	794	703	43	$ 560,712	4.85
Occupancy Class									
Single Family	878	$474,173	$12,152	160	131	163	4	$ 25,609	2.11
Multi-Family	82	$1,872,072	$47,486	55	565	73	18	$ 331,320	6.98
Commercial	355	$1,762,937	$44,073	214	238	10,724	274	$ 175,719	3.99
Industrial	492	$2,061,878	$48,905	365	282	10,629	241	$ 178,704	3.65
All Public Facilities	78	$2,019,743	$50,494	25	153	3,378	49	$ 101,681	2.01
Municipal Assets Only	21	$1,579,682	$35,485	21	327	2,532	35	$ 129,362	3.65
Totals/Averages	**1,885**	**$1,638,161**	**$ 40,622**	**819**	**274**	**27,499**	**621**	**$ 162,606**	**4**

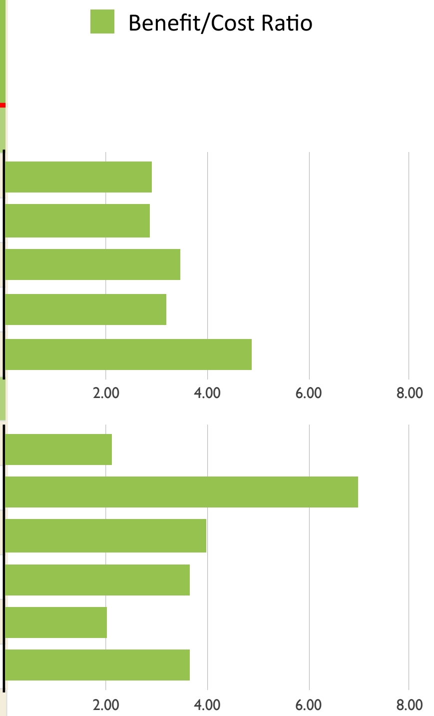
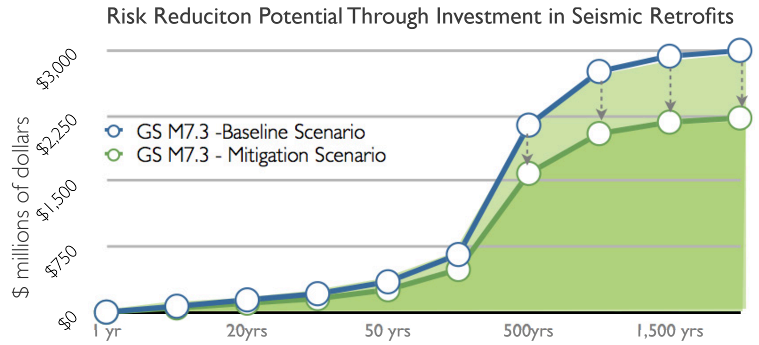


Figure 108: Benefit-Cost Analysis (BCA) of investing in seismic retrofit measures for vulnerable homes and businesses in the District of North Vancouver. Results are based on expected impacts and consequences for the Georgia Strait M7.3 scenario earthquake, with and without mitigation measures in place.

design guidelines for seismic safety (~$560,000). Benefit-cost ratios for each of these building classes are quite variable on a site-by-site basis with mean values that range from a low of 2.9 for wood frame structures to highs of ~4 for more vulnerable concrete and masonry structures. The most significant return on investment is on individual buildings in commercial/industrial centres along the waterfront, where the benefits of mitigation outweigh costs by as much as 11 to 1.

Ancillary benefits include a reduction in the number of people likely to sustain critical injuries in the scenario earthquake, the extent and duration of social disruption, increased business revenue during the recovery period, and a corresponding reduction in socioeconomic vulnerabilities that translate into a higher level of disaster resilience for the community. The greatest efficiencies gained by fully implementing seismic retrofit measures are improvements in overall building performance (resistance and recovery), and increased levels of disaster resilience for the business sector.



Probable Maximum Loss (PML) - $ millions of dollars over planning horizons of interest								
Hazard Event (of specified intensity)	Expected Loss PAA=1	1 yr	10 yrs	30 yrs	50 yrs	100 yrs	500yrs	1,000 yrs
GSM7.3 (B2)	$ 3,000.7	$7.5	$ 74.2	$217.1	$353.0	$ 664.5	$2,142.3	$ 2,755.2
GSM7.3 (M2)	$ 2,228.1	$5.6	$ 55.1	$161.2	$262.1	$ 493.4	$1,590.7	$ 2,045.7
Risk Reduction Potential	$ 772.6	$1.9	$ 19.1	$ 55.9	$ 90.9	$ 171.1	$ 551.6	$ 709.4

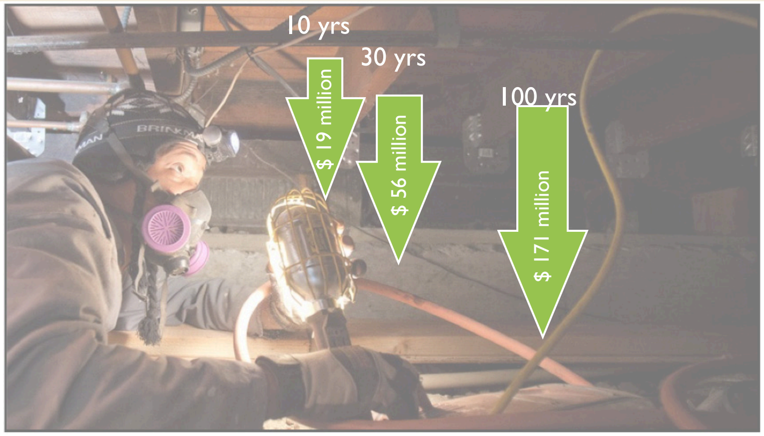


Figure 109: A profile of earthquake risk and the potential to reduce future losses through mitigation investments over planning horizons of interest.

Financial Risk

Financial risk is a function of maximum credible losses resulting from a disaster event (consequences), the likelihood of these losses occurring over a specified time horizon (probability), and the potential to reduce future losses through a combination of mitigation and adaptation (capacity). Balancing the trade-offs between economic growth and the security of financial investments is a subjective judgment that hinges on what is considered a tolerable threshold of risk. There are no specific guidelines on what constitutes a tolerable threshold of financial risk for municipal governments. However, the Canadian Office of the Superintendent for Financial Institutions (OSFI) does provide guidelines to secure collective investments in federally regulated institutions such as banks, pension plans and insurance companies that are exposed to earthquake risk [OSFI, 2013a].

Minimum thresholds of economic risk in Canada are based on Probable Maximum Losses (PML) corresponding to earthquakes with a ~1/500 year likelihood of occurrence [CRESTA, 2003; Kovacs and Seweeting, 2004]. Probable Maximum Loss (PML) is defined as the dollar value above which losses caused by an unexpected financial shock are considered unlikely for a given time interval [OSFI, 2013a]. It is a useful metric in assessing thresholds of financial risk for low probability/high consequence events like earthquakes and for developing strategies that may be needed to manage intolerable levels of risk in the context of ongoing community development.

Figure 109 is a summary of probable maximum losses over planning horizons that are likely to be relevant for community development and infrastructure planning in the District of North Vancouver. Trend lines in the accompanying graph show how probable maximum losses vary as a function of time. Our analysis does not take into account expected depreciation of financial investments in capital assets over time.

A thirty-year time horizon is often used as the planning context for managing growth, land use and development in a community. It is also a familiar time frame for managing individual and collective financial risks associated with capital investments in homes and businesses (mortgages, bank loans, etc.). The 30-year probable maximum loss for the Georgia Strait scenario earthquake is estimated to be ~$220M for baseline conditions and ~$160M with structural mitigation measures in place. Probable maximum losses for longer time horizons that are relevant for strategic land use and infrastructure planning (100 years) are estimated to be ~ $665M for baseline conditions and ~$490M with mitigation measures in place.

EVALUATING CHOICES AND CONSEQUENCES

While the intent of the decision-making process may be clear, the pathway between knowledge about earthquake hazards and those actions with have a potential to reduce future losses is not always evident [Klinke and Renn, 2002; Renn, 2006a; Saner, 2007]. The challenge for emergency managers is to prioritize hazard threats and identify people and community assets of concern in order to develop strategies that optimize public safety and system resilience during response and recovery phases of a disaster. For the community planner, the challenge is to reduce risk and increase resilience in ways that balance trade-offs between public safety, economic security, environmental integrity, and the overall quality of life for existing and future generations.

Scenario-based modelling is an effective way of integrating science into the decision making process. It is effective in establishing a shared understanding of the risk environment between scientists and practitioners, and offers a structured framework for exploring the strengths and weaknesses of policy alternatives. Figure 110 summarizes risk reduction metrics for the Georgia Strait M7.3 scenario earthquake.

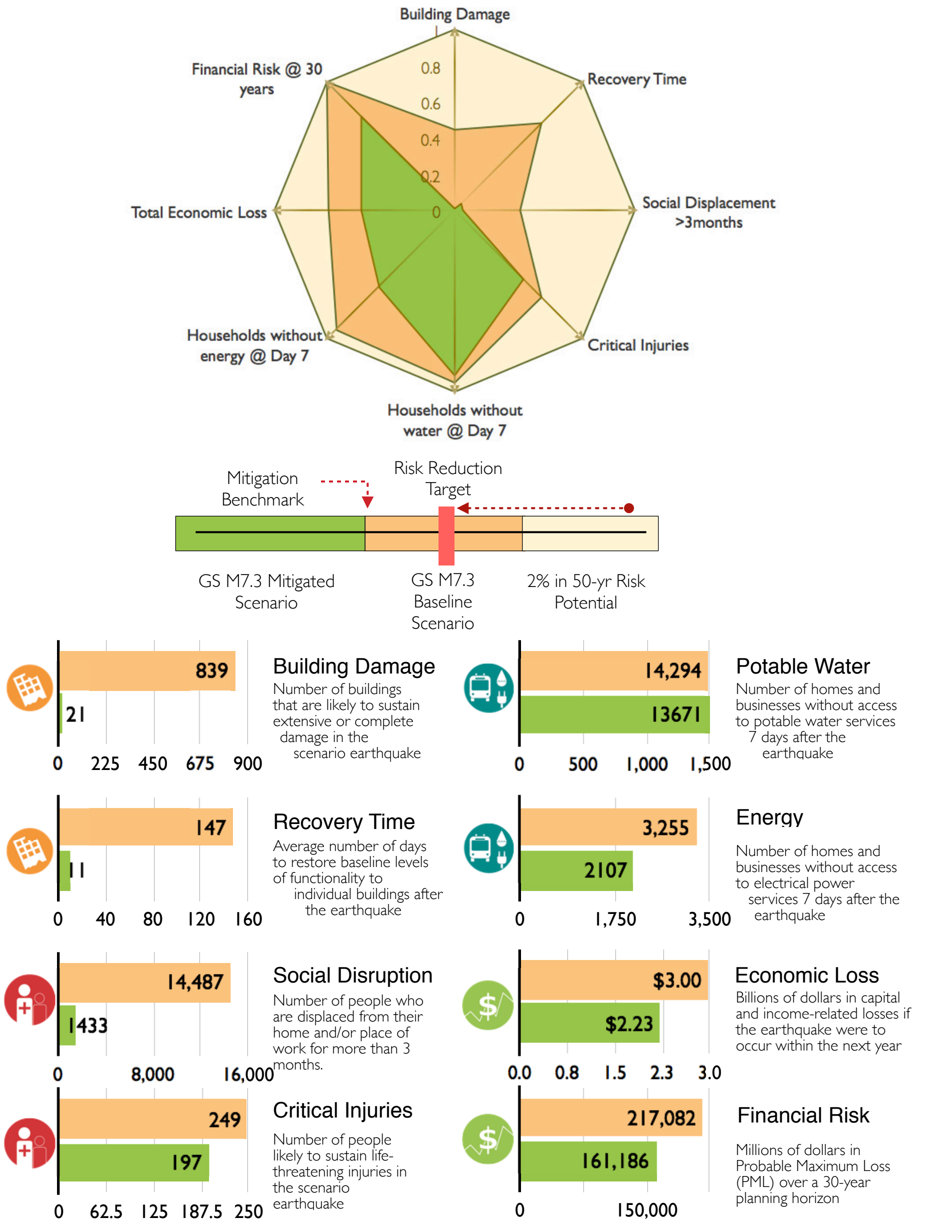


Figure 110: A summary of risk reduction potential for the Georgia Strait M7.3 scenario earthquake, with and without mitigation measures in place.

Target criteria characterize the dimensions of earthquake risk for existing conditions (baseline scenario), and establish mitigation benchmarks that track risk reduction potential with seismic retrofit measures in place (mitigation scenario). Setting of risk tolerance thresholds and associated policy targets will depend on value preferences and capacities of the community to reduce risk levels as low as reasonably possible within the limits of legislative authority and available resources [Renn, 2006b; ALARP; UK Health and Safety Commission, 2001].

There are two fundamental ways of using risk scenarios to structure the decision making process [Linkov et al., 2006; McDaniels et al., 2004; Omann, 2004]. One involves a process of rational analysis to optimize specific policy goals for reducing risk (goal-based decision making). The other takes a more integrative approach that utilizes scientific analysis to explore risk reduction scenarios that balance trade-offs between competing policy goals (evidence-based decision making). 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 management objectives that reflect diverse and often competing value preferences.

Goal-Based Decision Making

Goal-based decision making is focused on optimizing the performance of policy targets based on principles of effectiveness and efficiency (utility). It is well suited to situations in which uncertainties about potential cause-effect relationships are well constrained over short time horizons, and where the goal is to optimize public safety and/or economic security objectives to comply with legislative mandates that are intended to guide ‘common good’ decisions in the public domain [Dietz et al., 2003; Ostrom, 1991].

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]. 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, and are negotiated through ongoing evaluation and deliberation.

Relevant examples for the District might include development permit approvals that require land use activities to be ‘safe for the use intended,‘ and compliance with risk tolerance criteria that have been established for debris flow hazards, which stipulate a 1/10,000 loss of life threshold for existing development [APEGBC, 2010]. Risk reduction benchmarks indicate that investments in seismic retrofit measures have the potential to reduce the number of buildings likely to sustain extensive or complete damage in the scenario earthquake from 839 to 21. Retrofit measures are also effective in reducing recovery times and corresponding levels of social disruption (Figure 110).

Nonetheless, there are still ~20 buildings with a potential for collapse and loss of life. Risk factors for these buildings exceed the current 1/10,000 threshold established for debris flow hazards by a factor of 3. Even with the best of intentions, it may not be possible to achieve policy targets for public safety without considering additional risk avoidance measures, such as altering the use of vulnerable historic buildings in commercial/industrial areas along the waterfront. Changing land use patterns has the potential to minimize the likelihood of critical injuries in the event of structural collapse. However, such a decision would come at a cost as many of these buildings are vital for the economic vitality of commercial/industrial activities that sustain the community.

Evidence-based Decision Making

Evidence-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, economic security, lifeline services, and social equity). In this context, trade-offs are defined as choices that involve giving up one thing to gain another [Yoe, 2002].

Trade-off analysis is the method used to evaluate policy alternatives that result in the greatest overall value across the full spectrum of target 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 outcome, rather than absolute judgments based on the performance of a selected subset of target criteria.

An essential component of evidence-based decision making is the establishment of risk tolerance thresholds that reflect what the community considers of value and need of safeguarding through investments in mitigation and/or adaptation. In some cases, the actions required to meet risk tolerance targets will mean making trade-offs against other policy objectives that reflect equally important value preferences for the community. These are not easy choices, particularly when they involve trade-offs between the short-term benefits of growth and development, and the longer-term benefits of sustainable land use practices that incorporate principles of disaster resilience.

Relevant examples for the District might include the development of land use guidelines that provide economic incentives for seismic retrofitting of vulnerable homes and businesses; and for risk avoidance measures that are effective in keeping people out of harms way through density transfer or revisions to current zoning bylaws. This may provide a capability to meet policy targets for increasing building performance and public safety for the community, while minimizing financial risks to individual homeowners and businesses that may be effected.

Next Steps

While we cannot predict when a devastating earthquake will strike, we do have the ability to anticipate what might happen, and 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 valuable and in need of safeguarding.

Next steps include the development of an earthquake action plan for the community, and the establishment of risk tolerance criteria to guide ongoing planning and policy development. Target criteria provide a basis for exploring thresholds of risk tolerance, and a framework for incorporating principles of disaster resilience into policies for emergency management and sustainable land use in the District. Insights and methodologies developed as part of this study are transferrable to other communities who may face similar earthquake risks in Canada, and contribute to broader efforts by the Canadian Safety and Security Program to promote a culture of risk awareness in Canada, and to build capacities for an all-hazard approach to disaster resilience planning at a national scale.

CHAPTER 10: DNV Earthquake Ready Action Plan

Image Source: FEMA

CHAPTER 10: THE DNV EARTHQUAKE READY ACTION PLAN

Primary Authors: Dercole, F., Westin, M., and Mason, D.

Disaster resilience is a forward-looking process of planning through which knowledge about the risk environment is transformed into actions that have potential to reduce intrinsic vulnerabilities and increase the capacities of a community to withstand, respond to and recover from unexpected hazard events. The aim is to marshal the resources and capabilities needed to realize policy goals for growth and development (opportunities) while minimizing the potential negative impacts of hazards that can undermine the longer-term sustainability of a community or region (risks and liabilities).

Mitigation is focused on measures that can be implemented before a disaster event to reduce the physical vulnerability of people and critical assets and the potential for socioeconomic losses. Structural mitigation involves retrofitting core elements of a building or engineered structure to increase physical resistance to seismic loads and lateral displacements caused by severe shaking and/or ground deformation. Non-structural mitigation includes measures that minimize the exposure of people and physical assets to known earthquake hazards through land use policies, development restrictions (permits, bylaws, etc.), early warning systems, and the physical retrofitting of non-skeletal building elements (facades, internal partitions, contents, machinery and utility systems).

Emergency management embraces the full spectrum of preparedness planning and operational activities that are taken both during and after a disaster to ensure the safety and security of people and critical assets. Emergency preparedness activities are designed to increase awareness, self-reliance, and response capabilities of individuals and communities following a disaster. They include continuity planning for homes and businesses to minimize levels of disruption during the recovery process; risk transfer and disaster relief funding to minimize the longer-term socioeconomic consequences of a disaster; land use policies that direct the re-building and ongoing development of communities in ways that minimize exposure to earthquake hazards; and governance models that build on effective public-private partnerships to streamline the process of recovery and re-building.

Adaptation encompasses a wide range of actions that are planned in advance but implemented after a disaster event to increase the capacities of people, buildings, and engineered systems to respond and recover from the impacts and consequences of a major earthquake. Resilient systems experience relatively small levels of disruption and are likely to recover baseline levels of performance in a relatively short period of time. In some cases these systems may even increase overall performance due to adaptive design and reorganization during the recovery period. Systems characterized by low levels of resilience experience a relatively large drop in performance following a disaster, take a longer period of time to recover, and may never regain pre-event levels of functionality.

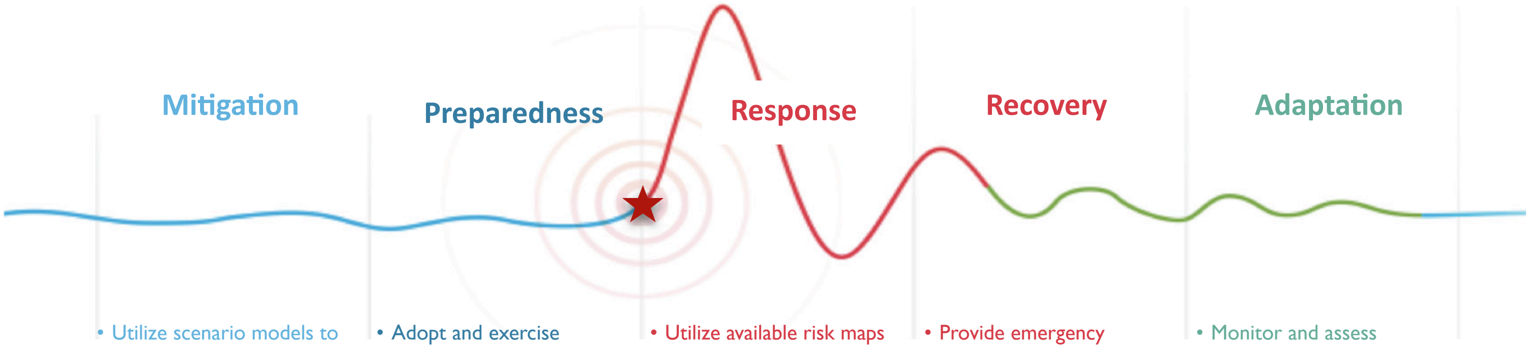
CONTEXT

Outputs of this study have informed an earthquake action ready plan for the District of North Vancouver. The plan was developed by District staff with input from the community Natural Hazard Task Force. It is aligned with risk reduction guidelines of the UN Disaster Resilience Cities Program [UNISDR, 2012], and is intended to help increase capacities to reduce future losses and become more resilient to earthquake hazards through strategic investments in mitigation, emergency management and adaptation planning (Figure 111).

Background and Purpose

Being earthquake resilient is a monumental task for a local government and the community it serves. A risk analysis is an important component of disaster resilience as it clearly illustrates the impacts of credible hazard scenarios and provides an opportunity to take action to reduce risk. The purpose of the Earthquake Ready Action Plan is to strengthen the DNV's capacity to become more resilient to earthquakes in four key domains — mitigation, preparedness, response and recovery — by focusing on the people, buildings, infrastructure and systems that are most vulnerable.

The Earthquake Ready Action Plan is a living document that will expand and shrink as new ideas for resilience emerge or need updating, and as actions are completed. Please consult the District of North Vancouver website for the most current version of the action plan.



Mitigation

- Utilize scenario models to identify people and assets of concern & establish risk tolerance criteria to guide mitigation measures
- Establish guidelines for land use & site planning
- Implement seismic retrofits to District facilties and infrastructure
- Encourage seismic retrofits to vulnerable homes, and businesses
- Explore risk transfer strategies for community assets of concern

Preparedness

- Adopt and exercise earthquake action plan
- Utilize scenario models to develop post-earthquake recovery plan
- Integrate principles of disaster resilience into sustainable community planning & DNV operations
- Build disaster resilience capacity of DNV staff through training
- Promote disaster resilience through community outreach and business continuity planning

Response

- Utilize available risk maps to Identify and prioritize hotspots for emergency response operations
- Deploy rapid damage assessment unit to collect and catalogue earthquake impacts
- Coordinate emergency response across jurisdictional levels
- Implement emergency communication strategy

Recovery

- Provide emergency shelter and relocation support based on Recovery Plan
- Secure hotspots of concern for recovery operations
- Engage mechanisms for disaster relief funding
- Implement post-disaster permit guidelines and procedures to expedite recovery process

Adaptation

- Monitor and assess capacities to withstand, respond and recover from earthquake event
- Refine DNV guidelines and policies for disaster resilience planning based on lessons learned
- Marshall resources needed to meet community thresholds of risk tolerance
- Invest in strategies that build disaster resilience

Figure 111: Elements of an earthquake action plan for the District of North Vancouver. Based on risk reduction guidelines of the UN Disaster Resilience Cities Program (Figure modified from Keller and Schneider, 2014).

Risk Governance - Best Practices

The City of Seattle recognized six factors necessary for an effective earthquake response by local government after the 2001 Seattle earthquake [Earthquake Incident Annex: Seattle Office of Emergency Management, 2012].

1. District employees know their disaster role, are trained and personally prepared
2. A large percentage of the public are prepared to survive without outside assistance for a minimum of three days and possibly several weeks
3. Redundant systems/procedures are in place to ensure continuity of command, control, coordination and communications
4. A unified government response
5. Responders who are prepared to act without delay
6. Timely, accurate public information to assist the public in meeting their own needs

Planning Assumptions

- Modelling indicates limited damage to residential areas, with damage areas concentrated in the commercial/industrial areas due to liquefied soils and building age and composition.
- After an earthquake, the Integrated North Shore Emergency Operations Centre (INSEOC) will be activated. The INSEOC will follow BCERMS goals for priorities and a State of Local Emergency will be declared.
- The INSEOC might not receive assistance and/or support from the Provincial Regional Emergency Operations Center (PREOC) for the first day or two, until regional priorities are established.
- In accordance with BCERMS goals, life safety rescue activities will take priority over other property and service restoration activities during the first operational period.
- Vancouver Fire Department has one of the 5 federal Urban Search and Rescue Teams, the next closest is Calgary Fire Department. The Vancouver team will be used in Vancouver for post-earthquake life rescue; the North Shore will likely not have access to the Vancouver team resource.
- Bridge damage to the Lions Gate and Second Narrows bridges may prevent access to the North Shore for emergency supplies, equipment staff resources.
- While we hope that our staff, their families, and DNV residents are prepared to survive without assistance for a minimum three days to one week; we assume that the majority are not prepared.
- While we hope that businesses have business continuity plans and consider options for emergency backup power and water supplies; we assume that the majority are not prepared.
- Communications networks such as cellular and internet may be limited.

ACTION PLAN

1. Before the Disaster

In advance of the disaster, we need to focus on hazard-mitigation activities. What do we need to be doing now to make sure that our built environment can recover quickly from a major earthquake? Which existing buildings need to be retrofitted — and to what standard of performance? How do we encourage better performance from new buildings? How do we strengthen our lifelines so that our buildings are served by water, sewer and power after an earthquake?

Mitigation

Mitigation is focused on measures that can be implemented before a disaster event to reduce the physical vulnerability of people and critical assets and the potential for socioeconomic losses. Structural mitigation involves retrofitting core elements of a building or engineered structure to increase physical resistance to seismic loads and lateral displacements caused by severe shaking and/or ground deformation. Non-structural mitigation includes measures that minimize the exposure of people and physical assets to known earthquake hazards through land use policies, development restrictions (permits, bylaws, etc.), early warning systems, and the physical retrofitting of non-skeletal building elements (facades, internal partitions, contents, machinery and utility systems).

The DNV Earthquake Ready Action Plan includes a blend of structural and non-structural mitigation measures:

- Utilize scenario models and indicator framework to develop risk tolerance thresholds that will guide municipal planning and decision making. Risk tolerance criteria may be evaluated in terms of building performance, public safety, lifeline resilience and/or socioeconomic security.
- Establish land use policies and seismic safety guidelines to inform development in areas that exceed tolerable thresholds of earthquake risk. Investigate the feasibility of implementing development permit areas that reduce physical vulnerabilities, and encourage the establishment of professional practice guidelines to inform the work of Qualified Professionals in high-risk areas.
- Identify and prioritize municipal assets that exceed risk tolerance thresholds and develop seismic retrofit strategy that can be incorporated into the DNV asset management plan using principles of ALARP.
- Assess vulnerabilities and interdependencies of critical lifeline services (power, potable water, wastewater, etc.) in order to identify restoration priorities, and to develop an integrated recovery plan with Metro Vancouver and private owners/operators.
- Explore risk transfer strategies for municipal assets that exceed minimum thresholds, and that cannot be effectively mitigated using principles of ALARP.
- Research best practices and explore the potential of incentive programs that encourage private investment in seismic retrofits to homes and businesses in areas of high seismic risk.

Adaptation

The window of opportunity for implementing adaptation measures following a disaster event is often small and quickly crowded with diverse and often competing public policy issues. The key is to identify those actions with the greatest potential to effect change during the recovery process, and to marshal resources and capabilities that will be required to implement these measures when the time comes.

Adaptation measures identified in the DNV Earthquake Ready Action Plan are to:

- Monitor and assess capacities to withstand, respond and recover from earthquake event.
- Refine DNV guidelines and policies for disaster resilience planning based on lessons learned.
- Marshall the resources needed to meet community thresholds of risk tolerance for vulnerable populations and critical assets.
- Share lessons learned

2. Disaster Response

In the immediate days and weeks following a catastrophic event, response activities should focus on public health and safety, evacuation, ensuring the safety of responders, restoring vital systems, damage assessment and communication with the public.

We also need to continue focusing on preparedness and planning activities. Continuing to develop emergency plans, train and exercise our municipal staff and volunteers will be a focus so they are prepared and able to respond. How do we best reach out and educate our citizens and businesses on their personal responsibilities to be prepared for any disaster?

Preparedness

Emergency preparedness recommendations developed as part of the DNV Earthquake Ready Plan include the following:

- Seek approval from municipal council to adopt and exercise the earthquake readiness action plan as part of ongoing emergency management operations in the District.
- Utilize scenario models to develop and refine post-earthquake response and recovery plans as new information becomes available.
- Build disaster resilience capacity of DNV staff through ongoing training and professional development in earthquake readiness.
- Integrate principles of earthquake readiness into sustainable community planning & DNV operations using risk tolerance criteria to help guide decision making.
- Promote an awareness and understanding of earthquake readiness through community outreach and business continuity planning.

Response

Recommendations to increase emergency response capabilities for the District include:

- Utilize earthquake risk maps to identify and prioritize emergency response operations based on hotspots of concern (damages & casualties) and available resources.
- Increase capacity of rapid damage assessment unit to collect and catalogue earthquake impacts. Revise emergency response operations as new information and resources become available.
- Coordinate emergency response operations across all levels of government according to EMBC protocols and existing mutual assistance programs developed as part of the Integrated Partnership for Regional Emergency management in Metro Vancouver.
- Implement emergency communication strategy to ensure that information about the disaster event and evolving response/recovery operations is accessible and updated regularly.

3. After the Disaster

In the months and years following the disaster, we will need to focus on long-term recovery. How will we determine what to rebuild the same as it was before the disaster and what to rebuild differently? How do we restore our major pieces of infrastructure?

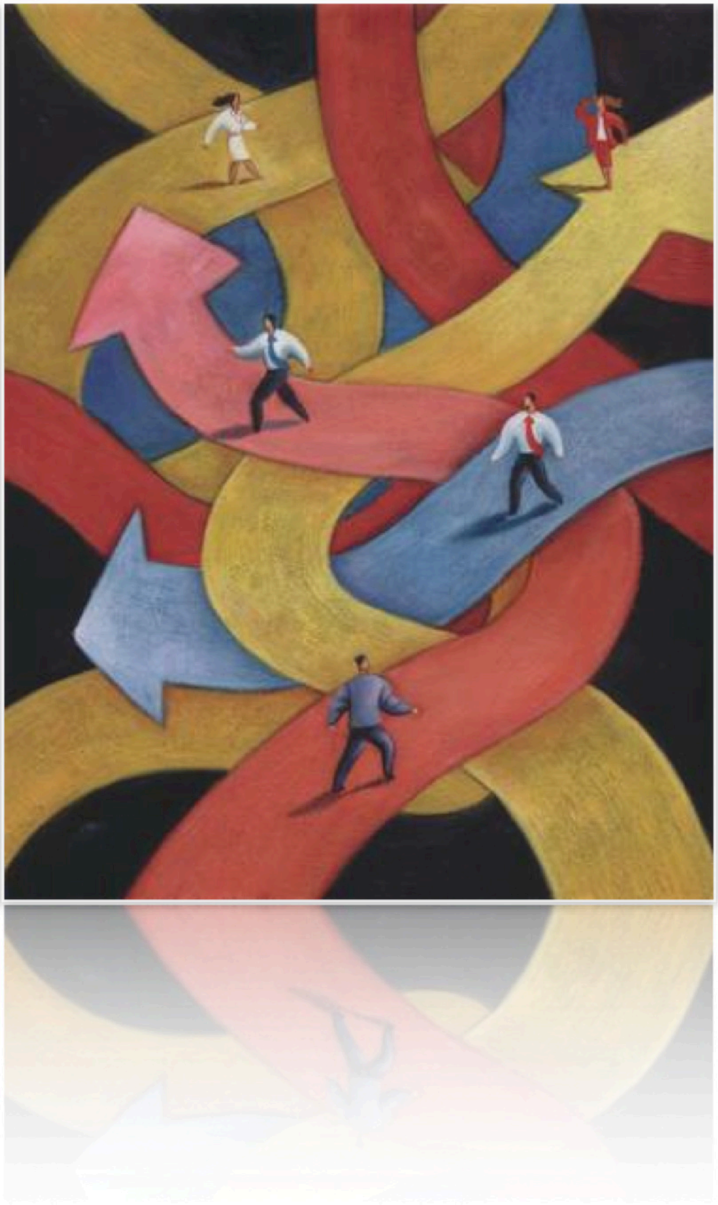
Recovery

Recommendations to increase the effectiveness of recovery operations in the District include:

- Provide short-term emergency shelter and relocation support based on initial damage assessment reports and updates from social assistance operations.
- Secure hotspots of concern for recovery operations and provide estimates for restoration of lifeline services (water, power, etc) and baseline functionality for homes and businesses that are damaged by the earthquake.
- Engage mechanisms of disaster relief funding for homes and businesses that sustain economic losses exceeding minimum thresholds established by Provincial and Federal agencies.
- Implement post-disaster permit guidelines and procedures to expedite recovery process for homes and businesses that are damaged in the earthquake. Rapid Recovery

The window of opportunity for implementing adaptation measures following a disaster event is often small and quickly crowded with diverse and often competing public policy issues. The key is to identify those actions with the greatest potential to effect change during the recovery process, and to marshal resources and capabilities that will be required to implement these measures when the time comes.

While we cannot predict when a devastating earthquake will strike, we do have the ability to anticipate what might happen, and 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. Outputs of this study provide a foundation for ongoing disaster resilience planning and sustainable community development in the District of North Vancouver.



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A Profile of Earthquake Risk for the District of North Vancouver is the basis for a series of companion publications:

- ***RiskMap Atlas for the District of North Vancouver*** *(GSC Open File 7816)*: A collection of maps documenting expected impacts and consequences of earthquake hazards for the community.
- ***When the Ground Shakes*** *(District of North Vancouver)*: is a plain language companion piece to this study. It tells the story of three fictional, but typical, North Vancouverites and their experiences immediately following a major earthquake.
- ***EQ Story Map*** *(District of North Vancouver)*:is an interactive storytelling tool that uses images and GIS maps to highlight important components of this study.