Federal Flood Mapping
Guidelines Series

Federal Hydrologic and Hydraulic Procedures for Flood Hazard Delineation

Version 1.0

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Table of Contents

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CONTEXT

A community achieves an elevated level of resilience when its risks are proactively managed, it is adequately prepared for known and potential disaster events and it demonstrates an ability to recover after such events have taken place. In order to become resilient, a community's mitigation planners must first understand risks and ensure their capacity to manage those risks.

Floods are the most commonly occurring natural hazard in Canada and account for the largest portion of disaster recovery costs on an annual basis. Mitigating flood risks is therefore key to increasing the resilience of affected communities. By proactively investing in flood mitigation activities, a community secures practical investments for its future growth and prosperity, reducing the risk of significant disaster recovery costs, productivity losses, economic losses, destruction of non-monetary cultural assets, environmental damage, injuries and deaths.

Flooding is the temporary inundation by water of normally dry land, and it can occur in coastal and lake areas, along rivers, from stream blockages including ice-jams, from failure of engineering works including dams, from extreme rainfall, rapid snow/ice melt or poor drainage characteristics, and other sources. Flood mapping that accurately delineates flood hazards, including those impacted by future conditions due to anticipated development or projected changes in climate, serves as the precondition for such mitigation activities and is therefore the first step to increasing community resilience with regard to flooding. Establishing a national approach to flood mapping will facilitate a common national best practice and increase the sharing and use of flood hazard information, thereby improving the foundation from which further mitigation efforts can be initiated.

FEDERAL FLOOD MAPPING FRAMEWORK

The Flood Mapping Framework consists of all the components of the flood mitigation process, from flood hazard identification to the implementation of flood mitigation efforts. The following flow chart illustrates the relationship between these different components and links each of them to the relevant *Federal Flood Mapping Guidelines Series* document.

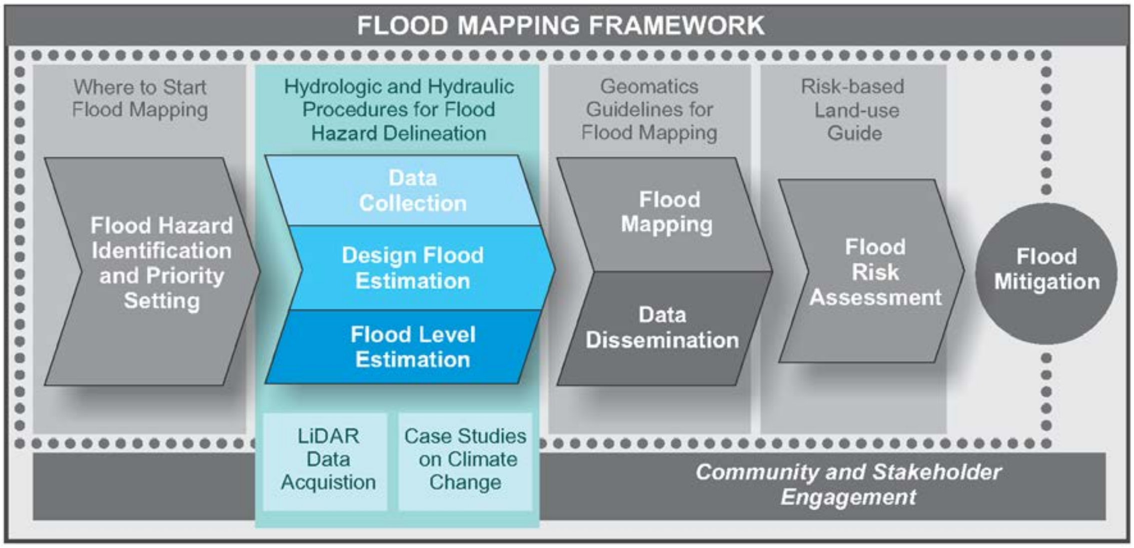


Figure 1: Flood Mapping Framework

FEDERAL FLOOD MAPPING GUIDELINES SERIES

The following documents are intended to inform any individual or organization involved with flood management in Canada:

1. Federal Flood Mapping Framework
2. Flood Hazard Identification and Priority Setting
3. **Federal Hydrologic and Hydraulic Procedures for Flood Hazard Delineation**
4. Federal Airborne LiDAR Data Acquisition Guideline
5. Case Studies on Climate Change in Floodplain Mapping
6. Federal Geomatics Guidelines for Flood Mapping
7. Flood Risk Assessment
8. Risk-based Land-use Guide: Safe use of land based on hazard risk assessment
9. Bibliography of Best Practices and References for Flood Mitigation

GUIDELINE SUMMARIES

1. Federal Flood Mapping Framework

This document provides background and context on flood mapping in Canada, describes a vision and principles for flood guidance, and introduces the *Federal Flood Mapping Guidelines Series.* It provides a summary of each of the documents in the Series and explains how each document fits into the overall framework, including its place in the flood mapping cycle.

2. Flood Hazard Identification and Priority Setting

This document has yet to be developed. It will outline methods for determining where to conduct flood mapping and how to prioritize flood mapping projects.

3. Federal Hydrologic and Hydraulic Procedures for Flood Hazard Delineation

This document provides technical guidance on hydraulic and hydrologic procedures for preparing flood hazard maps in a Canadian jurisdiction, including standard of care, different types of flooding, procedures for hydraulic and hydrologic analyses, and incorporation of non-stationary processes including climate change.

4. Federal Airborne LiDAR Data Acquisition Guideline

This document is to be used as a resource for the acquisition of base elevation data from airborne LiDAR data undertaken across Canada. This guideline aims to provide advice to federal, provincial and territorial departments, as well as individuals and organizations in Canada that need to understand and plan for airborne LiDAR data acquisition.

5. Case Studies on Climate Change in Floodplain Mapping

This collection of documents describes projects from across Canada where climate change has been incorporated into the floodplain mapping process. It will provide examples for practitioners to draw on and learn from others' experiences and will complement the climate change-related information and resources included in the "Federal Hydrologic and Hydraulic Procedures for Flood Hazard Delineation" document.

6. Federal Geomatics Guidelines for Flood Mapping

This document covers the Flood Mapping and Dissemination components of the Flood Mapping Framework. It contains information on the different types of flood maps and outlines methods for acquiring, managing and disseminating these maps and associated geospatial data.

7. Flood Risk Assessment

This document is currently under development and will provide technical guidance on conducting flood risk assessments in Canada.

8. Risk-based Land-use Guide: Safe use of land based on hazard risk assessment

This document provides guidance on using risk-based methodologies for the purpose of land-use planning.

9. Bibliography of Best Practices and References Related to Flood Mitigation

This document contains lists of Canadian and international references and case studies pertaining to hydrology and hydraulics, climate change, risk assessment and flood mapping. The purpose of this document is to provide a consolidated list of reference materials intended as further resources for practitioners involved in flood mapping.

LIST OF ABREVIATIONS AND ACRONYMS

EMFC	Emergency Management Framework for Canada
NDMP	National Disaster Mitigation Program
GOC	Government Operations Centre (Canada)
FFA	Flood Frequency Analysis
RFFA	Regional Flood Frequency Analysis
ECCC	Environment and Climate Change Canada
NGO	Non-governmental Organization
UAV	‘Unmanned’ Aerial Vehicle
NRCan	Natural Resources Canada
NOAA	National Oceanic and Atmospheric Administration (USA)
mPING	Meteorological Phenomena Identification near the Ground
CSA	Canadian Space Agency
AEP	Annual Exceedance Probability
AM	Annual Maximum
POT	Peaks over Threshold
GEV	Generalized Extreme Value
LiDAR	Light Detection and Ranging
IDF	Intensity Duration Frequency
SCS	Soil Conservation Service
AES	Atmospheric Environment Service (Canada)
QA/QC	Quality Assurance / Quality Control
SV	Saint-Venant
1-D	One Dimensional
2-D	Two Dimensional
3-D	Three Dimensional
FEMA	Federal Emergency Management Agency (USA)
CHS	Canadian Hydrographic Service
DFO	Fisheries and Oceans Canada

NS	Navier-Stokes
NLSW	Non-Linear Shallow Water
CFD	Computational Fluid Dynamics
h/L	Ratio of Wave Height to Length
ESM	Earth System Model
GCM	Global Climate Model or General Circulation Model (used interchangeably)
RCM	Regional Climate Model
CORDEX	Coordinated Regional Climate Downscaling Experiment
PCIC	Pacific Climate Impacts Consortium
RCP	Representative Concentration Pathway
SLR	Sea Level Rise
CMIP	Coupled Model Inter-comparison Project
m	metre
m^3	cubic metre
cm	centimetre
km	kilometre
km^2	square kilometre
m^3/s	cubic metres per second
LPIII	Log-Pearson Type 3 Distribution

1.0 INTRODUCTION AND PURPOSE

The *Federal Flood Mapping Guidelines Series* is a set of nine documents published by the Government of Canada to provide technical guidance to individuals and organizations involved in flood mapping activities in Canada. Flood management in Canada is regulated at the provincial, territorial, and municipal levels of government, and technical methods vary between jurisdictions. This document, *Federal Hydrologic and Hydraulic Procedures for Flood Hazard Delineation Version 1.0*, is intended to provide a summary of the current technical practices used by qualified professionals in Canadian jurisdictions, and to provide accepted practices for qualified professionals practicing flood delineation.

These practices are not intended to supersede other federal, provincial, territorial, or local legislation, regulations, by-laws, policies, or technical guidance. The information and perspective in this federal document does not necessarily reflect that of any individual provinces and territories.

The purpose of this document is to provide technical guidance on hydraulic and hydrologic procedures for preparing flood hazard maps in a Canadian jurisdiction. The specific objectives of this document are to:

1. Describe the standard of care that should be expected from qualified professionals providing technical flood mapping services, including quality management and technical review;
2. Describe different types of flooding that occur in Canada, including but not limited to riverine, pluvial, coastal and ice-affected;
3. Provide guidance for qualified professionals to conduct hydrologic and hydraulic analyses as part of the flood mapping process; and,
4. Provide guidance for how future non-stationary processes including climate change should be addressed.

The scope of this document is limited to hydraulic and hydrologic assessments; guidance on mapping and geospatial data dissemination is included in the *Federal Flood Mapping Guidelines Series* document titled *Federal Geomatics Guidelines for Flood Mapping*. Examples of projects incorporating climate change considerations in flood mapping are also provided as a key reference in the *Federal Flood Mapping Guidelines Series* document titled *Case Studies on Climate Change in Floodplain Mapping.*

2.0 NOTE ON TERMINOLOGY

All *Federal Flood Mapping Guidelines Series* documents will apply the following definitions, provided in the Emergency Management Framework for Canada (EMFC 2016) and National Disaster Mitigation Program (NDMP) literature. It is recognized that provinces and territories may define these terms differently, and these definitions are not intended to be prescriptive outside the context of the *Federal Flood Mapping Guidelines Series* documents.

Flooding : The temporary inundation by water of normally dry land.

Flood Mapping : The delineation of flood extents and elevations on a base map. This typically takes the form of flood lines on a map that show the area that will be covered by water, or the elevation that water would reach during a specified flood event. The data shown on the maps, for more complex scenarios, may also include flow velocities, depth, other risk parameters, and vulnerabilities.

Hazard : A potentially damaging physical event, phenomenon or human activity that may cause the loss of life or injury, property damage, social and economic disruption or environmental degradation.

Risk : The combination of the likelihood and the consequence of a specified hazard being realized; refers to the vulnerability, proximity or exposure to hazards, which affects the probability of adverse impact.

Flood maps are used for several different purposes, including identifying hazards and risks, land use planning, emergency planning and response, and public awareness and communication. Under the broad definition of ‘flood map’, different types of geospatial, hydraulic, and hydrologic information can be presented to meet specific assessment requirements. For consistency, four main types of flood maps are defined in the Federal Flood Mapping Framework.

Inundation Maps : Maps that show the floodwater extent of real flood events, or that show potential floodwater coverage for flood events of different magnitudes (e.g. annual exceedance probabilities). They are intended to aid in the management of emergency preparedness plans for communities situated within floodplains and flood hazard zones.

Flood Hazard Maps : Engineering maps that display the results of hydrologic and hydraulic investigations that show areas that could be flooded under different likelihoods. These maps are used for regulatory planning purposes related to land use planning and flood mitigation.

Flood Risk Maps : Maps that indicate the potential adverse consequences associated with floods, including but not limited to social, economic, environmental and cultural consequences to communities during a specific potential flood event and the overall risks to the community from a range of potential flood scenarios.

Flood Awareness Maps : Communication maps that serve to inform members of the public regarding the history of flooding in their communities, as well as the potential for future flooding and the risks that such flooding would pose to residential properties, businesses, cultural assets, infrastructure and human life. These interactive web maps or printed poster-style maps include a range of additional content types, such as photographs, descriptive text and graphics.

For the purposes of this document, the following definitions also apply:

Stream : A general term used to describe watercourses including streams and rivers. Throughout the document, ‘stream’ and ‘river’ are used interchangeably.

Streamflow : Discharge (e.g. in cubic metres per second (m^3/s)) at a specific location on a stream. Throughout the document, ‘flow’ and ‘discharge’ are used interchangeably.

Study Stream : The stream on which flooding is studied.

3.0 STANDARD OF CARE

Flood maps are critical tools for disaster mitigation planning and emergency management, including protection of life and property. In addition, flood maps are essential for land use planning, zoning, insurance, and communication of flood-related risks to the public. The flood mapping process, including hydrologic and hydraulic analyses, must be conducted in accordance with safety and standard of care requirements such as those described by provincial and territorial geoscience and engineering regulatory bodies.

Engineers Canada is the national organization of 12 engineering regulators that licence members of the profession in Canada through provincial or territorial acts, regulations and by-laws. Engineers and geoscientists practicing in a Canadian jurisdiction are required to be registered members of a professional association, and must comply with the requirements of the acts, regulations, by-laws, and the required standards of care. The practices in this document (*Federal Hydrologic and Hydraulic Procedures for Flood Hazard Delineation*) submit to all acts, regulations, by-laws, or any other requirements of provincial or territorial professional engineering and geoscience associations. Engineers and geoscientists are required to provide the standard of care described by professional engineering and geoscientist associations in their province or territory.

Specific requirements of engineers and geoscientists to conduct professional practice preparing flood maps in Canadian provinces and territories include, but are not limited to:

- Holding paramount the safety, health and welfare of the public and protection of the environment;
- Complying with acts, regulations, by-laws, and standards of care (e.g. as outlined in guideline documents published by the relevant provincial or territorial professional engineering and geoscience association);
- Possessing the appropriate level of training and experience to carry out flood mapping in that geographic area;
- Consulting stakeholders and specialists when appropriate; and,
- Establishing a mechanism for internal checking and review, which may include independent peer review.

For the purposes of this document, a ‘qualified professional’ signifies someone who possesses the specialized knowledge and experience required to conduct hydrologic and hydraulic analyses to support flood mapping, including those licenced under a provincial or territorial engineering regulator in Canada.

4.0 REGULATORY REGIMES IN CANADA

In Canada, flood management is primarily the responsibility of the provinces and territories, and is often delegated to municipalities and conservation authorities through legislation. Therefore, most flood management activities including mapping, planning, preparation, response and recovery are executed at the ‘local’ rather than provincial, territorial or federal levels. However, provincial legislation generally includes provisions requiring municipalities to undertake flood mitigation and response actions deemed necessary in the public interest. Municipalities, in partnership with provinces, have established organizations such as Conservation Authorities (in Ontario) and Conservation Districts (in Manitoba) to support flood management.

The federal government has three general areas of responsibility relating to flooding in Canada, each involving coordination with provinces and, in some cases, municipalities:

1. Monitoring of and response to Canadian flood situations through the Government Operations Centre (GOC), which coordinates federal government responses to flood events of national significance;
2. Provision of disaster assistance, including Disaster Financial Assistance Arrangements, for the provinces and territories to address flood-related financial losses; and,
3. Implementation of the National Disaster Mitigation Program (NDMP), including support for flood mapping activities used to mitigate flood risks and costs and to reduce or negate the effects of flood events in Canada.

The NDMP fills a critical gap in Canada’s ability to effectively mitigate, prepare for, respond to, and recover from flood-related events by building a body of knowledge on flood risks in Canada, and investing in foundational flood mitigation activities. Flood mapping information that is current and accessible will help governments, communities and individuals understand flood risks and employ effective mitigation strategies to reduce the impacts of flooding, and will promote the development of a residential flood insurance market in Canada.

5.0 GENERAL PRACTICES

Practices in this document are included in each report section in tabular format. A summary of general practices is included as Table 1.

Table 1: General Practices for Hydrologic and Hydraulic Procedures in Flood Hazard Mapping

Number	General Practices
A.1	Conduct hydrologic and hydraulic analyses using the skills and experience of a qualified professional as defined in this document.
A.2	Include consultation with stakeholders and specialists as part of project activities as appropriate.
A.3	Establish and use a mechanism for internal checking and review for each project.
A.4	Complete a project report that includes a description of the following: 1. Objective of study; 2. Limitations (including uncertainty, risks, disclaimers, and recommendations for future study); 3. Data sources; 4. Methodology; 5. Assumptions; 6. Results; 7. Evaluation of methods and models; and, 8. Technical review, including summary, review author, review description, review purpose, summary of documentation and communications, review methodology, and review findings.
A.5	Incorporate future non-stationary considerations such as climate change where possible or required.
A.6	As part of project activities, include a communications plan for disseminating flood hazard and flood risk information, in conjunction with the updated mapping.

6.0 HYDROLOGIC PROCEDURES

A description of hydrologic procedures supporting flood mapping is included in this section, and a flowchart showing individual tasks is provided in Figure 2. Hydrologic practices are shown in Table 2.

Flood events are usually expressed in terms of a return period or an Annual Exceedance Probability (AEP). For example, a flooding event with an AEP of 0.01 (1%), and a flood event with a return period of 100 years, are equivalent. However, the concept of return periods can be misleading to a non-technical audience who may erroneously infer that two “100 year floods” (100 year return period or 0.01 AEP floods) cannot occur, for example, 25 years apart. Therefore, this document uses the term ‘AEP’ instead of ‘return period’.

Analysis using hydrologic procedures is the first step in the engineering analysis required to define flood levels and extents. The selection of appropriate procedures depends upon the type of hydrologic ‘problem’ under study and the availability of data required to solve it. For example, in some jurisdictions the design flood used is based upon a defined frequency of occurrence, or AEP (e.g. eastern Ontario). In this case, a single streamflow value corresponding to that AEP, is all that is required to “solve” the problem. If data is available, this can be achieved without a hydrologic model using a procedure such as single station Flood Frequency Analysis (FFA). However, in other jurisdictions (e.g. central Ontario) the design flood is defined by the transposition of a historical storm event (e.g. rainfall associated with Hurricane Hazel, Timmins Storm) over the area of interest. In these cases, hydrologic models are used.

The process of identifying and implementing appropriate hydrologic procedures is often iterative. A preferred method may be identified but later discovered to be infeasible due to insufficient data (e.g. for single station FFA) or because the data is non-stationary (e.g. in a gauged watershed that has undergone urban development during the period of record). In such cases, an alternative method may be required.

For cases in which high quality, long-term data is unavailable within proximity of the area of interest, multiple procedures should be applied to validate results from the “preferred” procedure. For example, an AEP flood extent obtained from a hydrologic model can be verified by applying corresponding results from a Regional Flood Frequency Analysis (RFFA).

6.1 Data Requirements

6.1.1 Geospatial Data

Hydrologic procedures require geospatial data including watershed areas, surface water networks, elevation data, watershed slopes, stream slopes, stream cross-sections, lake areas, land use coverage, and other hydrologic features. The accuracy and precision of flood hazard maps are highly dependent on the quality of the geospatial data used. The *Federal Airborne LiDAR Data Acquisition Guideline* and the *Federal Geomatics Guidelines for Flood Mapping* provide guidance on sourcing and using geospatial data for flood hazard mapping.

6.1.2 Hydrometric Data

Hydrometric data include stream discharges and water levels measured at hydrometric stations located on the study stream and on other streams in the region. Hydrometric data availability is fundamental to choosing appropriate hydrologic procedures and to the output of accurate hydrologic design streamflows. Additionally, the boundaries of the region studied are defined by the methods used for hydrologic analysis; for example, studies on ungauged streams will generally include data from neighbouring gauged streams and watersheds.

Hydrometric data in Canada is available from the Water Survey of Canada (ECCC 2017a), the Québec Hydrometric Network (Québec 2017), and other sources such as hydroelectricity generation facilities and private companies (e.g. data made available as part of environmental assessments for large development projects). Potential sources of hydrometric data should be researched and station metadata recorded including the following:

- Location;
- Length of record;
- Regulation type;
- Period of record;
- Datum;
- Data provider;
- Operation schedule (e.g. continuous, daily, etc.);
- Remarks (e.g. records being reviewed); and,
- Drainage area.

Careful evaluation of data quality prior to use is necessary due to the wide variations in data quality that exist depending upon the data source.

In some cases, where the streamflow record length is less than recommended (see Section 6.3.2), the record can be extended by considering other data from either within the study watershed or within the broader region containing the watershed. The following sections describe some possible approaches.

6.1.3 Extension of On-site Instantaneous Flow Record

In many cases, instantaneous peak flow data is required to employ hydrologic procedures such as single station FFA. Often, the period of record for instantaneous peak flows (QP) at a gauge is significantly less than for mean daily peak flows (QD). Using the period of record when the two types of data overlap, the following relationship may be developed in which ‘a’ and ‘b’ are variables describing the relationship between QP and QD:

$$QP = a * QD^b$$

The result can subsequently be applied to the period when only mean daily peak flows exist to estimate the equivalent instantaneous peak flows.

6.1.4 Transposition from the Same or Adjacent Watersheds

The most common method of extending or infilling missing streamflow records for a study stream is achieved by transposing flow records from a gauge within the study watershed or from a nearby gauged watershed with a longer period of record than the study stream. If the periods of record overlap, a site-specific correlation can be derived and applied. If not, a more generic, possibly physiographic, relationship can be employed (e.g. one based upon the ratio of drainage areas).

6.1.5 Pre- Record Floods

Uncertainty in hydrologic analysis can be reduced by inclusion of historic floods, that occurred prior to hydrometric records (pre-record floods), in the data set. These floods may have associated physical, photographic, or other evidence useful to estimate flood magnitude. Resulting estimated water levels can be used to derive flow and applied in hydrologic procedures. The usefulness and accuracy of the derived flow information will depend upon the reliability of the stage-discharge curve at the observation location. For extreme floods, the stage-discharge curve may have to be extended empirically leading to considerable uncertainty in the flow estimate. The benefits of including such estimates must be balanced against its uncertainty.

Evidence of historic and pre-record floods can be found in newspapers, city records, universities, libraries, historic photographs, Indigenous Nations Traditional Knowledge oral history, and other sources. Using pre-record floods in flood frequency analysis may reduce the uncertainty associated with high-magnitude flood events and may better align the data set with the local experience of the community affected by those flood events.

Historical data should be validated to the extent possible and ideally corroborated from multiple sources (e.g. newspaper article description of inundated areas matching a photograph with identifiable landmarks).

Consideration of ‘perception levels’ is important in evaluating pre-record floods. Research should be conducted to determine the minimum threshold flood event that was recorded by people who experienced the flood. Guidance on perception thresholds is included in USGS (2015), Gerard and Karpuk (1979), and NRC (1989).

6.1.6 Extending Streamflow Records

It is possible to gather information on floods that occurred prior to the collection of historical records through collection of physical, geomorphological, and other data.

Paleofloods are flooding events that occurred prior to the collection of hydrologic records, including those that occurred several thousand years ago. Geographical and physical evidence of paleofloods includes rock alcoves with sequences of slack-water deposits, scarring on trees, gravel bar deposits, erosional scars, and excavated soil (Jarrett and England 2002). Specific expertise in geomorphology, geology, or a related science is required to identify and date these features. In addition to identification of paleoflood events, it is possible to identify an *absence* of paleoflood events, which increases the confidence level in the existing hydrometric data set (i.e. a reasonable degree of confidence is gained that the hydrometric record does not erroneously omit significant flood events).

Botanical information is also useful to “extend” streamflow records by examining deposited sediments around tree trunks, examining tree ring patterns, and other methods. Specific expertise is required for these types of analysis.

The direct inclusion of flow estimates based on paleofloods in a hydrologic data set used for frequency analysis should be used with extreme caution. It may be more appropriate to reserve such data for qualitative checking of results.

6.1.7 Meteorological Data

Meteorological data may be required for analysis methods other than flood frequency analysis on gauged streams. Hydrologic modelling will require meteorological data possibly including evaporation, rainfall, snowfall, temperature, and other data. Hydrologic modelling is discussed in Section 6.5.

Historic meteorological data is available for download on a daily or longer time step from Environment and Climate Change Canada (ECCC) for 8737 stations across Canada, including approximately 1566 active stations (ECCC 2017b). For shorter time steps, such as hourly data, specific arrangements must be made with ECCC for data acquisition. Other sources of meteorological data which may not be integrated into the ECCC database can include local and regional municipalities, Conservation Authorities / Districts and other water management entities, environmental NGOs, and citizen scientists.

Radar-rainfall data is useful in identifying the spatial distribution of rainfall events. This can be particularly helpful when calibrating and validating hydrologic models with specific rainfall events. Snowpack data including snow depth, density and water equivalent are frequently required for hydrologic modelling and flood decision support systems. Current measurement networks are relatively sparse due to the expense and complexity of widely used in-situ instruments (Smith et al. 2018; Pirazzini et al. 2018) although this situation may improve with new low cost remote sensing technologies (see Sections 6.11 and 6.13).

6.1.8 Streamflow Regulation

There are over 900 major dams in Canada, and thousands of small dams. Most large dams in Canada are used for hydroelectric power generation, though other uses include water supply, irrigation, flood control, and recreation. Streamflow regulation alters the shape of the streamflow hydrograph, including timing and shape of peaks. This may result in downstream flows being non-stationary, which should be considered for FFA or RFFA analysis (see Section 6.3). One possible technique is de-regulation of the data in which reverse routing estimates ‘natural’ inflows upstream of the regulation. In addition, if regulation is by means of a fixed structure with little storage compared to the flood volume, the data can be considered to be stationary.

Modelling can be applied to understand both unregulated and regulated streams. If operating procedures are clearly defined and quantifiable, they can be applied directly into hydrologic models. Dam breaches and overtopping can be included into hydraulic models (see Section 7.1) but are a specialized case of flood hazard not generally covered by these practices.

Streamflow diversion involves moving water out of streams, and is much less common than dam regulation in Canada. However, any diversions in the modelled stream and in the study area should be identified and data on diverted water obtained, including operating procedures.

6.1.9 Stage-Discharge Relationships

Stage-discharge relationships are required whenever observed water levels are used to obtain flow estimates at a site. Generally, when published streamflow data is obtained, a stage-discharge relationship will be available. Reviewing this relationship is helpful in understanding uncertainties in the flow data.

In the case of a new gauging location or when estimating discharges from miscellaneous water level data (see Sections 6.1.3 through 6.1.9), the development of stage-discharge curves is required. Measurements of flow and depth, and the ‘curve fitting’ required in developing the relationship, are subject to uncertainty. Stage-discharge curves are affected by ice, sediment or debris. High flows are particularly uncertain due to extrapolation, gauge loss or damage, overtopping or breaching of flood defences, and in extreme cases, avulsion that changes flow paths within the stream corridor.

6.1.10 Aerial Photographs

Aerial photographs are valuable tools in preparing data for use in hydrologic modelling (e.g. identifying the extent of different types of land use). They aid in identifying flood extents for actual events to derive water levels and subsequently to estimate discharges for use in model calibration. Morphological changes visible in aerial photographs provides an approximation of the sensitivity of peak flow estimates to sediment aggradation or erosion. Aerial photographs can also be used to identify geomorphological changes in watercourses over time.

6.1.11 Autonomous and Remotely Controlled Aerial Vehicles

Autonomous and Remotely Controlled Aerial Vehicles are either fixed-wing or rotary-wing aircraft that are flown without a pilot present on board, and are also commonly referred to as UAVs (Unmanned Aerial Vehicles) and drones. These aerial vehicles can either be flown using a pre-programmed routine or behaviour, or by a pilot flying the aircraft remotely by sight or instruments. UAVs are excellent tools for monitoring flood conditions and providing high-resolution time-stamped and geo-referenced images for post-flood model calibrations and determining flood extents. They are also useful for other data collection purposes such as identifying watershed land use and creating high spatial resolution maps of depth change (Fernandes et al. 2018).

6.1.12 High Water Marks

High-water marks are physical evidence of flooding extent, including debris, sediment deposits, staining, scars on trees, and water damage. Survey crews can document this physical evidence to determine approximate flood extent and depth; however, it may not be possible to determine the precise time of maximum flooding. This type of data must be translated into accurate discharge data to be useful in hydrologic procedures.

6.1.13 Citizen Science

Mobile phones produce high-resolution photographic images that are time-stamped and geo-referenced. Citizens can photograph and record videos of flooded areas, which can be interpreted by practitioners to determine flood extents. The utility of the data in hydrologic procedures will depend on the ability to translate the observations into accurate discharge estimates. There are currently several initiatives in Canada to engage citizen scientists, primarily by gathering and submitting environmental and ecological data via mobile phones and the internet. Current examples include earthquake reporting through Natural Resources Canada (NRCAN 2017), and the Agroclimate Impact Reporter from Agriculture and Agri-Food Canada (AGR 2017). In the United States, the National Oceanic and Atmospheric Administration (NOAA) mPING Project (NOAA 2017) has produced a mobile app that enables citizen scientists to submit reports on meteorological and physical events, including rain, snow, mudslides, and flooding. The data is then filtered and used to ground-truth satellite observations.

Additional sources of usable data include social media postings and photograph or video sharing about flooding events and other disasters. There are also initiatives to correlate the prevalence of certain words, terms, and tags to the progression of on-ground conditions; however, separating legitimate signals from invalid ones is challenging and robust quality assurance methods are required. Accurate discharge estimates must be derivable for the data to be useful in hydrologic procedures.

Snow depth measurements with comparable accuracy to meteorological station instruments are now routinely derived from remote web-camera imagery of rulers placed in snowpacks. This measurement concept allows for a large number of measurements from remote locations and can leverage camera networks used for other monitoring purposes such as security, habitat, recreation and transportation. Current practices are based visual interpretation of rulers (Parajka et al. 2012; Oakes et al. 2018) but recent developments permit automated estimation of snow depth in both open regions (Hedrick and Marshall, 2014) as well as forest landscapes (Fernandes et al. 2019).

6.1.14 Satellite Imagery

Satellite image analysis is a practical way to determine floodwater extent at different times. Canada's RADARSAT-2 satellite is capable of providing spatial resolution of 1 m and data is available through Macdonald, Dettwiler and Associates Geospatial Services (MDA 2017) for commercial clients and the Canadian Space Agency for federal government clients (CSA 2017).

Satellite images can be acquired, received, processed and delivered based on client requirements. RADARSAT-2 data is excellent for delineating flood extents to provide model calibration points.

6.1.15 Data Evaluation and Quality Assurance / Quality Control

All data must be subject to a quality assurance and quality control (QA/QC) process that includes, at a minimum, screening for:

1. Missing data;
2. Outliers or suspect data;
3. Data jumps or broken lines; and,
4. Data flags.

A description of how missing or unreliable data was managed must be included in the study report. Additional information on QA/QC is included in Section 6.3.3.

6.2 Stationarity

The stationarity level in hydrologic datasets is typically impacted by land use changes, development, erosion, climate change effects, or other factors. Therefore, a visual and statistical assessment for stationarity at the beginning of the flood mapping process is required.

6.2.1 Land Use Changes, Development, and Erosion

Land use changes that can affect runoff, streamflow, and flooding include:

1. Urban development, including piping, paving, and construction;
2. Agricultural drainage network development;
3. Flood mitigation measures, including dikes, berms and conveyances;
4. Changes within the stream channel, including construction of bridges;
5. Anthropogenic changes to land cover, including forest cover, that may alter interception, infiltration, evapotranspiration, flow routing, erosion, and sedimentation; and,
6. Natural processes including the effects of forest fires, parasites, and disease on vegetation.

6.2.2 Climate Change Non-Stationarity

Climate change effects are often undetectable within individual streamflow records due to the relatively short data collection period, and the high degree of noise relative to climate change signals. In some cases, climate signals can be found in annual extreme values or in values above a certain threshold. Hydrologic analyses should make appropriate allowances for climate change non-stationarity where trends are detected. Whether or not a climate trend or signal has been detected, a precautionary allowance may be appropriate (EGBC 2017) and analyses can make use of climate change projections (see Section 10.0). Changes in precipitation patterns may increase the magnitude and frequency of floods, and expose historically low-flood risk areas to flooding (Warren and Lemmen 2014). In addition, climate change effects include melting glaciers and thawing permafrost (Warren and Lemmen 2014).

6.3 Flood Frequency Analysis

Flood frequency analysis uses the statistical properties of a historical flood record to define a relationship between peak flow magnitude and probability of exceedance at a given site. The relationship is used to estimate peak flow for one or more desired flood frequencies.

Floods of interest for flood mapping, such as the 0.01 AEP, are often much greater than any flood recorded in the relatively short period covered by historical records (averaging less than 40 years in Canada). Extrapolating a simple statistical model of a complex physical process can introduce considerable uncertainty into the results. Procedures designed to address and minimize these uncertainties are described in this section.

While this discussion focuses on conventional peak streamflow frequency analysis, many of the concepts are equally applicable to flood-duration-frequency analyses (e.g., Cunderlik et al., 2007) and to analyses of flood volumes, water levels, seasonal peak flows, and other natural phenomena including rainfall. New statistical methods, including the use of copulas, allow for multivariate frequency analysis.

6.3.1 Key Assumptions of Flood Frequency Analysis

Use of FFA assumes that the record of observed floods can be treated as independent random variables drawn from a homogeneous and representative population that remains unchanged over time. A variety of statistical tests exist to help qualified professionals determine how well a peak flow record meets each of these pre-requisite assumptions for FFA. Greater departures from these assumptions require increased caution when evaluating results, and increases the importance of independent checks. In some cases, it is possible to improve the suitability of FFA by undertaking additional data analysis. In other cases, specialists' input may be required.

6.3.2 Record Length

Extrapolation contributes significantly to uncertainty in FFA results. The most effective way to mitigate this uncertainty is by maximizing the record length and representativeness of the available data record.

Single-site flood frequency analysis can be conducted in cases with a period of record greater than 10 years (England et al 2017). However, obtaining reliable results requires a period of record that significantly exceeds the AEP of interest (e.g., Klemeš, 1987). Since this is impractical in the Canadian context, the goal of FFA must be to obtain a reasonable, estimate based on a record length proportional to the desired AEP. A common rule is to avoid extrapolating to AEPs more than double the length of the available record (e.g. limiting extrapolation from a 50-year record to the 100-year AEP flood). Some references have provided specific recommendations; for example, Coulson (1991) proposed specific minimum record lengths for estimating various AEP flood events in British Columbia.

These minimum criteria could be insufficient if the period of record happens to correspond to a period of unusually high or low flood activity. Records of a short period require validation by consulting historical sources of information or data from nearby hydrometric stations with longer records. Sections 6.1.3 to 6.1.6 describe approaches for extending the historical flood record by transposing data from other nearby gauges, incorporating floods that pre-date the systematic record, and incorporating paleoflood data from extreme floods at geologic timescales.

Upon compiling the record, it is necessary to determine whether the analysis will be based on instantaneous or daily-average peak flow data. If the record includes winter floods, the qualified professional must also determine whether the analysis will consider calendar years or hydrologic years. These considerations may affect the amount of data available.

6.3.3 Data Quality and Completeness

Peak flow data is usually subject to high uncertainty. Because FFA are sensitive to a small number of high streamflow observations, care is needed to understand the uncertainties that are implicit in the measurement process. Additionally, data missing from broken and incomplete records should be infilled wherever possible.

Once screened and reviewed for quality, the qualified professional should plot and review the record to determine its likelihood to produce a satisfactory FFA. Outliers, step-changes and slope breaks indicate that different flood-generating processes may be present. Low outliers that could influence the FFA (e.g. zero-flow years) should be screened and removed using a statistical test such as the multiple Grubbs-Beck test (Cohn et al 2013; England et al., 2017).

Extraordinary floods (high outliers) may be identified using a similar process, but are usually retained due to the importance of high flows for design flood prediction. High outliers may be the result of a different flood-generating process, requiring a more complex analysis as discussed in the next section.

Regulation and inter-basin diversions must be accounted for, since FFA should be applied to a “naturalized” peak flow series. The qualified professional must determine whether it is appropriate to re-regulate the resulting peak flow based on anticipated operating procedures and stakeholder risk tolerances.

6.3.4 Analysis Structure

For a single-site FFA, there are three key criteria to consider in terms of analysis structure (each is described below in this section):

1. Annual maximum (AM) versus peaks-over-threshold (POT);
2. Combined population versus mixed population; and,
3. Whether the analysis must account for non-stationarity.

The term AM refers to the creation of a historical flood series that includes only the highest peak flow in each year. In some cases, an AM approach may not capture important information about flood behaviour. For example, some years might have multiple large floods while other years lack even a single significant event. To address this, incorporate all peaks above a selected threshold in a POT analysis, also referred to as a ‘partial duration series’ analysis.

POT analyses are more complex than AM analyses, and identification of an appropriate threshold may be complicated. POT results are comparable to AM results for more extreme events.

Most FFA are based on a ‘mixed population’ analysis of annual maximum with stationary, or assumed stationary, peak flows. The term mixed population implies that all peak flows are driven by the same flood-generating process, or that the effect of different processes is neglected. In some cases, there may be two or more different processes that contribute to flood risk such as freshet, rainfall floods, and ice-jams. In these instances, a combined population analysis is advisable. A combined population analysis creates a separate FFA for each process and combines the results into a single composite magnitude-frequency or stage-frequency relationship. A combined population analysis is more complex than a mixed-population analysis and is usually only considered for situations in which:

- There are distinct processes in the historical record (i.e. observed peak flows show evidence of two or more populations) and there is indication that process differences will be significant for peak flow estimates at the desired AEP;
- There is a need to capture the different implications of climate change or land-use change for different flood processes; and,
- The frequency analysis process is based on different methodologies and data types (e.g. ice-jam versus open water flooding).

Stationarity is assumed in most FFA projects using traditional tools. However, more recent FFA tools provide the option of accounting for non-stationarity (e.g. El Adlouni et al., 2007; Razmi et al., 2017). These newer non-stationary FFA tools are more complex than traditional FFA tools. The practitioner must determine whether the additional complexity is required. For example, it may be more cost-effective to account for climate change by applying a reasonable but conservative factor to the results of a stationary FFA.

6.3.5 Probability Distributions

There is a wide variety of software packages available for conducting FFA. Most offer a choice between multiple probability distributions, though not all programs offer the same options. Specific software packages for FFA should be chosen based on considerations of input data, computational methods, outputs, and the application of results. It is important to document the reasons for model selection.

Some probability distributions are well suited for FFA based on theoretical criteria. For example, the Generalized Extreme Value family of distributions has a strong theoretical basis for AM applications while the related Generalized Pareto distribution is preferred for POT analyses. In other cases, an ‘institutional’ distribution is adopted to define a common standard of practice. Through the US Geological Survey Bulletin 17B (U.S. Interagency Advisory Committee on Water Data, 1982) and forthcoming 17C (England et al., 2017), the US adopted the log-Pearson Type III (LP3) as an institutional distribution. In Canada, many FFA studies consider at least one distribution drawn from each of the normal, GEV, and Pearson distribution families. Other distributions with more parameters (e.g. the five-parameter Wakeby distribution) are better suited for analyses with more data than is usually available for Canadian stations.

However, performance criteria to assess the goodness of fit of a distribution often include a term that favours parsimony (e.g. fewer distribution parameters).

Once a distribution has been selected, it must be "fit" to the observed flood data. The ease, variety, and objective nature of mathematical curve fitting has relegated the once-popular method of graphical fitting to rare extenuating circumstances.

There are numerous mathematical methods for fitting distribution parameters, including least squares, method of moments, probability-weighted moments and L-moments, and maximum likelihood and generalized maximum likelihood methods. Some parameter-fitting methods are better suited to particular distributions than others are. More specialized statistical approaches like Expected Moments Analysis (Cohn et al., 1997) are required when data records are censored, broken, or incomplete, or when incorporating historical flood observations. Comparison of skew coefficients used in three-parameter distributions to theoretical and regional values may also be helpful in the curve-fitting process determining best-fit characteristics. The choice of probability distribution is typically more important than the method of fitting the distribution; however, both should be considered with due regard for the overall uncertainty in the FFA results (Alberta Transportation, 2001).

Some software packages provide Bayesian probability analysis and decision support systems to assist users in determining whether a given distribution is more or less appropriate. While statistical measures of fit are useful, they can also provide biased or misleading conclusions. For example, the Kolmogorov-Smirnoff statistic is still sometimes improperly used to evaluate the suitability of a parametric distribution (e.g., as described in Crutcher, 1975). Expert judgement still plays an important role in determining how to interpret, prioritize, and select the best choice among alternative distributions.

In the absence of a well-defined standard of practice, some approaches used by professionals to select "final" FFA results include:

- Using results from a single 'best-fit' distribution, where 'best fit' is apparent;
- Using an average or weighted average of all reasonable distributions; and,
- Using the most conservative result from a set of 'acceptable' distributions.

6.3.6 Documentation of FFA Results

The following information should be documented for each FFA:

- Software name and version;
- Input data and metadata (including source, date of acquisition, and any subsequent adjustments or corrections;
- Tests for compliance with FFA assumptions (Section 6.3.1);
- The type of analysis (i.e. AM or POT);
- Distribution name, method of fitting, and distribution parameters for each distribution modelled;
- Graphical and numerical results for flood quantiles and confidence limits;

- Commentary on observed behaviour (e.g. assessments of fit to the general population and the highest flood events as well as irregular tail behaviour that limits extrapolation).
- Final peak flow for each desired AEP, and the basis for that selection; and,
- Any allowances for natural and anthropogenic changes that have been applied to account for issues such as climate change, land use, or future development.

It is appropriate to check FFA results against independent peak flow estimates, particularly in analyses that involve significant extrapolation of a short historical record. Sources for independent data could include previous studies, regional estimates (see Section 6.4), or hydrologic model results (see Section 6.5). Results of FFA should be compared to observed flood information for consistency. For example, results should be re-evaluated if the 0.01 AEP flood is exceeded several times within a 100-year record or has a magnitude several times the largest observed event.

The results of any independent checks should be included in the FFA documentation.

6.3.7 Implementation of FFA Results

Classic FFA results provide peak flow values associated with a specific AEP. A more complete hydrodynamic analysis may require more information about the shape, volume and timing of the flood hydrograph. Additional information is obtainable using multivariate frequency analysis or hydrologic modelling (see Section 6.5).

6.4 Regional Flood Frequency Analysis

The preceding section described FFA in the context of application to a single site. However, FFA also plays a key role in regional analyses. A Regional Flood Frequency Analysis (RFFA) is used to estimate peak flows for ungauged locations and for locations where the available flood record cannot support a reliable single-site analysis. RFFA can also provide a valuable independent check on the results of single-site analysis, even where the at-site data is robust.

The RFFA process substitutes “space for time” by grouping data from hydrologically-similar locations. Groups are typically defined based on hydrologic, climatological or physiographic similarities and validated using homogeneity statistics (e.g. Hosking and Wallis, 1997). The incorporation of multiple data sources means that the scope of work and level of effort required for RFFA is considerably higher than for a single-site FFA.

There are similar sources of uncertainty in RFFA and single-site FFA, including statistical assumptions for each flood record, choice and fitting of probability distributions, and extrapolation of short records. With proper assumptions, the additional uncertainty introduced through the regionalization process will usually be offset by the advantages of using data from multiple sites. The two main approaches to RFFA (index flood analysis and multiple regression analysis) are described in the following sections.

6.4.1 Index Flood Analysis

Index flood analyses assume that sites within each hydrologically-similar region will share a common ‘growth curve’ that relates flood frequency to dimensionless flood magnitude. Dimensionless flood magnitudes are obtained by dividing FFA results by a common ‘index flood’.

The index flood is often the mean annual flood, but other representative floods may also be used. The index flood must be estimated independently for each site, often based on multiple regression (see Section 6.4.2).

Peak flow estimates for the site of interest are obtained by combining a site-specific index flood with the regional growth curve.

6.4.2 Regression Analysis

Conducting RFFA regression analysis involves developing direct relationships between peak flow magnitude and watershed characteristics. The results are typically a suite of regression equations (e.g. for different AEPs) unique to each hydrologically-similar region. The multiple regression approach is widely used throughout the United States where standardized equations are widely available.

Independent variables, or predictors, used in the regression equations typically include key physiographic characteristics such as watershed area and channel slope. Other physiographic and climatological characteristics may also be considered such as watershed shape, lake area, and mean annual precipitation, provided the individual characteristics are not correlated with each other. Transformations such as logarithms are often required to meet regression assumptions of normality and linearity. In general, it is preferred to use the minimum number of variables that can provide an acceptable description of behaviour.

6.4.3 Published Regional Flood Data

Comprehensive RFFA studies that span larger jurisdictions are sometimes summarized into a map or atlas (e.g., Coulson and Obedkoff, 1998), or documented in a publicly available regional report. Results from more recent studies may be available through online mapping applications. For example, the Ontario Flow Assessment Tool (Ontario Provincial Mapping Unit, 2017) can provide RFFA peak flow estimates at user-specified locations based on either index flood or multiple regression analyses.

These tools are extremely useful for preliminary screening assessments and for independent checks on project-specific results. The large-scale and comprehensive nature of these studies is generally not well suited for flood mapping applications, and project-specific analyses will typically be required.

6.5 Hydrologic Modelling

Hydrologic modelling involves estimating flow at a specific location using precipitation data (rainfall and snowmelt) for the upstream watershed. Hydrologic models can be simple or complex, ranging from simple water balances calibrated using a runoff coefficient, to detailed computer models with estimates for variables including temperature, soil moisture, land cover, ice effects, stream cross-sections and bathymetry, digital elevation data (e.g. LiDAR), lake storage, evaporation, seasonal runoff coefficients, and others.

Conceptual models are empirical representations of a hydrologic system, and can be visualized using flowcharts and diagrams. Computer models apply mathematical principles and relationships to conceptual models, and are usually created using software programs. In this section, hydrological modelling refers to the use of computer models.

Hydrologic modelling allows for the construction of a system of hydrologic relationships that can then be used to predict flows for a range of input conditions. These models are generally deterministic models that are used to generate specific outputs (e.g. flows) for a defined set of input conditions. This type of model is used to determine the design flows associated with a design storm input (e.g. Hurricane Hazel). Examples include single event models such as Visual OTTHYMO, GAWSER or HEC-HMS and continuous simulation models such as HSPF, Mike SHE, DHSVM, UBCWM and NWSRFS. Some models such as HEC-HMS and GAWSER can also be used in either single event or continuous simulation mode. Probabilistic models or techniques, sometimes referred to as stochastic models, can be used to generate a set of outputs with associated probabilities for a range of possible input conditions. This type of model is often run as a Monte Carlo simulation, in which output probabilities are calculated based on a high number of model runs (e.g. 1000). Probabilistic models can quantify uncertainty in input conditions and are potentially powerful tools for situations in which there is complex and uncertain interaction between input variables; however, these models are not currently as widely used in hydrologic assessments as deterministic models.

6.5.1 Model Selection

Hydrologic models should be chosen based upon an assessment of appropriateness, including considerations of input data, computational methods, and outputs. It may be necessary to use a combination of models for a specific task. Reasons for model selection should be documented.

Hydrologic models should be of appropriate complexity to capture the dominant and sensitive processes in the modelled system. Models that are too simple or too complex may contain high levels of uncertainty.

6.5.2 Continuous Simulation Modelling using Long Duration Climate Records

Continuous simulation hydrologic models are used to generate long duration synthetic streamflow estimates for a watershed using various types of long-term climate records as inputs. Continuous simulation models vary in complexity but all track the state of a watershed over time. When a precipitation or snowmelt event occurs, they can use that state to estimate antecedent moisture conditions and calculate the amount of runoff from the event. Some models such as QUALHYMO use a simple, continuously updated antecedent precipitation index to track watershed state between events. Others such as HSPF use a complex model of interception storage, soil moisture storages, groundwater storage, etc. Similarly, some models require only limited input data such as precipitation and temperature whereas others require many types of input data (e.g. precipitation, temperature, evaporation, wind speed, dew point, cloud cover, solar radiation, etc.).

Assuming the model provides a good representation of the modelled watershed's characteristics and has been satisfactorily verified, calibrated and validated, the synthesized flows can be used in place of observed flows. For example, they can be used in a single station FFA to obtain design flows for various AEPs. However, there is additional uncertainty in these synthetic design flows because the model will never be a perfect representation of the watershed's characteristics.

A more limited use of a simple continuous simulation model is to generate antecedent moisture estimates for a detailed single event model. This can also be referred to as a "quasi-continuous simulation" approach.

In many parts of Canada, processes leading to flood events are complex and correlated. For example, coastal flooding in British Columbia can result from a combination of snowmelt, rainfall, tides, and storm surge. Although tides and snowmelt are independent variables, a single storm event could result in rainfall, rain on snow leading to snowmelt runoff, and storm surge. Therefore, it is critical to consider joint probabilities rather than the product of individual probabilities (which would result in underestimating actual event probabilities). Continuous simulation approaches based on long-term data sets and modelling can provide usable joint probability data for variables including coastal water levels (NHC 2014).

6.5.3 Single Event Modelling using Historic Storms and Design Storms

Single event models generally use a time distributed rainfall input, referred to as a hyetograph, to generate a time distributed discharge output, or hydrograph. The input hyetograph will generally be either an observed historical storm or a synthetic storm using a typical rainfall distribution with a volume corresponding to a probability and duration.

Historic storms are recorded extreme storms used as inputs to hydrologic models, and are dynamic events that move across watersheds. The areal extent of historic storms, and their movement, are important considerations in modelling.

Historic storms often exceed the minimum design criteria (e.g. 0.01 AEP flood) in a particular jurisdiction and for which precipitation data is available. In some Canadian jurisdictions, historic storms are used for regulatory purposes instead of design floods; examples are Hurricane Hazel in the Toronto area and the Timmins Storm in parts of Northern Ontario.

Design storms have precipitation hyetographs generated by analysis of historical climate data, and are generally applied across an entire study area without spatial variation. Design storms can be synthesized for specific watersheds and areas using local Intensity-Duration-Frequency (IDF) curves. The most common example would be the 'Chicago Storm', which combines intensities at all durations for a common frequency. Other synthetic storm distributions are available for different regions of Canada. Common examples include the 'SCS Storm' series and the Canadian 'AES Storm' series. These storms are based on historical observations indexed to a particular duration (e.g. 24-hour rainfall for the SCS storms) and may not match the IDF curve at all durations. Caution is required to ensure that precipitation intensity at critical durations is represented appropriately.

A design storm with a particular AEP will not necessarily produce a flood hydrograph with the same AEP because different initial or antecedent conditions (e.g. soil moisture and water levels) will produce different flood responses. It can be difficult to confirm and replicate those initial or antecedent conditions when conducting modelling.

6.5.4 Modelling Considerations

Considerations in model construction include:

1. Land use, including impervious areas and effects of urbanization. Land cover significantly impacts infiltration rates and hydrologic response time;
2. Appropriate discretization of the watershed into sub-watersheds to capture the variations of land use, soil types, slopes, etc. and the number of flow computation points desired;
3. Losses and gains from the modelled system, including groundwater inflows and outflows. These should be modelled to the level of complexity necessary for model calibration, but high-complexity groundwater models may not be required;
4. Inputs from upstream routing (e.g. channels and sewers carrying flows from upstream watersheds);
5. Storage areas including volumes, inflow and outflow rating curves; and,
6. Model time-steps, which are chosen to allow for reasonably smooth progression of streamflows and should be short enough to capture peaks. For channel routing and reservoir routing, time-steps must be short enough to meet criteria for numerical stability. However, time-steps that are too short will increase computational time without appreciably increasing accuracy or precision.

When selecting the appropriate hydrologic model, data availability is an important overriding consideration.

6.5.5 Model Evaluation

A hydrologic model is a simplified mathematical representation of physical processes that can be used to predict the magnitude and rate of flow of water through a system. To be useful, a hydrologic model should produce results that are acceptable based on an evaluation procedure that should include the following elements:

1. Verification: a computer model is deemed verified for its intended purpose if it accurately represents the intended conceptual model, and if it is capable of producing reasonable and stable results. Models that are verified are not necessarily the best or most useful models; rather, they are judged to be applicable for the intended modelling purpose.
2. Calibration: models are calibrated using known input and output data. For example, if precipitation inputs and downstream streamflows are known, internal model parameters such as runoff coefficients and snowmelt factors can be adjusted to achieve model calibration. Not all input and output data should be used for calibration; a sub-set of data should be set-aside for validation. The World Meteorological Organization (WMO) has provided guidance on the amount of data that should be used for calibration of continuous simulation models versus that which should be reserved for validation (WMO 2011). Other organizations such as the Toronto and Region Conservation Authority

have refined those guidelines to define the number of events to be used for calibration and validation for event-based models.

3. Validation: the calibrated model is validated for its intended purpose by running the calibrated model using the set-aside input data to compare modelled versus measured output data.
4. Sensitivity analysis: internal model parameters including runoff coefficients, snowmelt factors, and other variables are modified through an input range of reasonable values to determine the sensitivity of the model to these parameters. Parameters that show a high level of sensitivity are chosen using robust and documented methods or assigned conservative values in the absence of such methods.
5. Uncertainty analysis: the uncertainty analysis should include an assessment of potential sources of error including uncertainty associated with parameter values, hydrologic constants, input data, and methods. This analysis can be performed using numerical modelling or more qualitatively by considering the results of sensitivity analysis, input data representativeness and goodness-of-fit for model calibration and validation.

Evaluated models that show good performance using these steps are considered ‘useful’ for conducting hydrologic analysis. This evaluation requires good professional judgement and a robust approach.

6.6 Summary of Hydrologic Procedures

Figure 1: Hydrologic Procedures Flowchart

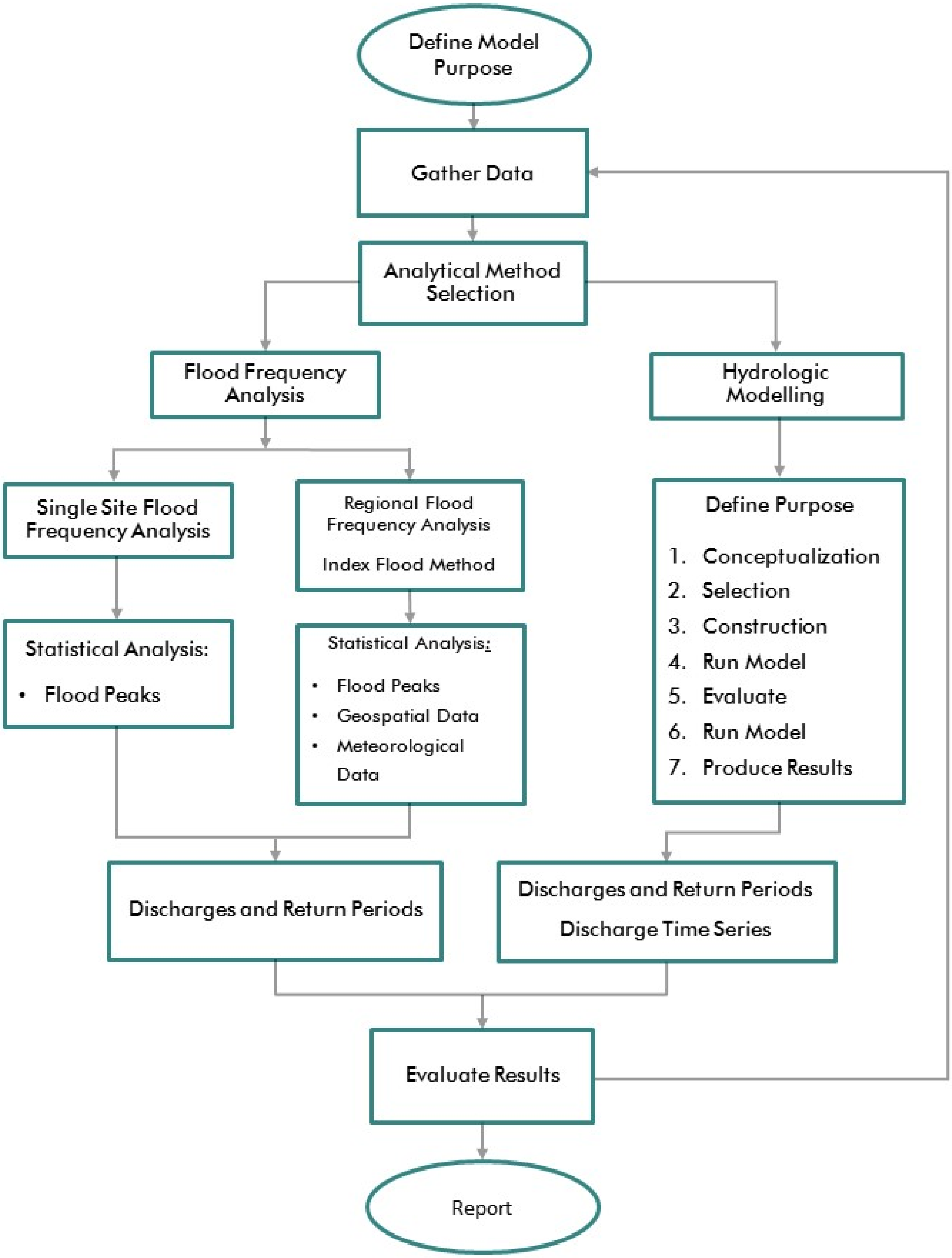


Table 2: Hydrologic Practices

Number	Hydrologic Practices
B.1	Identify all sources of data in the defined hydrologic region. Include hydrologic data that meet key data requirements. Document sources of data selected. If necessary, ensure hydrologic data is extended to maximize the available flood record. Conduct a QA/QC check on the hydrologic data including verification of stationarity. Identify the effects of flow regulation and diversion on hydrologic data to ensure it is appropriately addressed by the selected hydrologic procedure.
B.2	Where data is available, conduct single station Flood Frequency Analysis (FFA) to select appropriate method(s) and distribution(s) based on the available data. Practitioners must be aware of the uncertainties of this approach and confirm that the data meets the underlying assumptions. Techniques that are more complex are required to account for multiple flood-generating processes, non-stationarity in the observed flood series, and historical floods that pre-date the systematic record.
B.3	Where data is not available to support single station FFA, conduct Regional Flood Frequency Analysis (RFFA) for a hydrologically homogeneous region with a sufficient number of streamflow records with adequate periods of record. RFFA typically involves either estimating an index flood for the study stream and applying a dimensionless regional growth curve, or using multiple linear regression to estimate flood quantiles directly from watershed physiographic data. Results from wide-area regional peak flow studies (e.g. provincial maps or GIS layers) are not usually considered sufficient for flood mapping studies.
B.4	Conduct hydrologic modelling when appropriate or required. Hydrologic modelling is the preferred approach for situations in which design flows are based on a historic storm or synthetic design storm, a flood hydrograph is required, or where the watershed has experienced land use changes. As a minimum, hydrologic modelling involves the following stages: 1. Define Purpose; 2. Conceptualization; 3. Select Model; 4. Construct Model; 5. Test Model; 6. Evaluate and Modify Model; 7. Run Model for Design Cases; and,

	8. Produce Results.
B.5	Evaluate the hydrologic modelling results. Model evaluation involves the following stages: 1. Verification; 2. Calibration; 3. Validation; 4. Sensitivity Analysis; and, 5. Uncertainty Analysis.
B.6	Document model complexity by capturing the dominant and sensitive processes of the system to the degree required to satisfactorily reproduce the characteristics of observed flows.
B.7	Investigate the impact on design flows of future non-stationarity caused by factors such as climate change. Continuous simulation deterministic models are used where long-term climate data is available to generate long-term discharge series. FFA methods can be applied to the output to calculate design flows for specific AEPs. Single event deterministic models can be used for regions that use historic storms or synthetic design storms as inputs to hydrologic models or in cases where there is insufficient data to support continuous simulation modelling.
B.8	Verify and document study results. Whenever possible, verify results of a chosen hydrologic procedure (FFA, RFFA, or hydrologic modelling) by comparing to results from one or more alternative procedures. Document all aspects of the selection, implementation, testing, verification, results, sensitivity and uncertainty associated with the selected procedure.

7.0 HYDRAULIC ANALYSIS

A description of hydraulic procedures supporting flood mapping is included in this section, and a flowchart showing individual tasks is provided in Figure 3. Hydraulic modelling applications are shown in Table 3 and hydraulic practices are included in Table 4.

The purpose of hydraulic analyses in flood modelling is to convert estimated flows to representative water levels along a river or stream. This has the capability to be a more sophisticated process than was possible during flood mapping programs conducted in the 1970's and 1980's because computers and computer models have become more powerful and able to compute more complex aspects of flow dynamics. There have also been significant advancements in survey data collection whereby the collection of bathymetry by sonar-based technologies and land surface information using LiDAR and other forms of remote sensing can provide a much more detailed picture of the ground surface. The complexity of the hydraulic analysis should be commensurate with the data available and the project needs. A more complex modelling platform will not necessarily increase the accuracy of results if there are limitations in the flow estimate or the topographic data used to construct the model.

An important concept that has been adopted as part of the land use planning in areas that may be subject to flooding is the division of the flooded area into the floodway and flood fringe. In general, the floodway conveys the majority of the flow and it is the area where flows are deepest, fastest and most destructive; the flood fringe is generally shallower and has slower velocities than in the floodway. The flood fringe may be inundated under the flood of interest but would not be subject to hydraulic conditions that make mitigation measures impractical nor cause significant negative impacts on adjacent flood levels and velocities. New development in the flood fringe may be permitted in some municipalities depending on local guidelines, which vary by jurisdiction. Some jurisdictions in Canada define the flood fringe as the area of conveyance that can be encroached upon and not increase the floodway water levels by more than 30 centimetres (cm). In other jurisdictions, the flood fringe may be defined as a combination of water depth and velocity (e.g. areas of the active flow path where the water depth is less than 1 metre (m) and velocities are less than 1 metre per second (m/s) for the design event). This definition does not take into account the potential impact of encroachment or flood protection measures on water levels and the change in inundation in unprotected areas of the floodplain or flood hazard area.

Configuration of the hydraulic models used to produce inundation maps is required to produce the parameters required to define the floodway and flood fringe according to the applicable regulations or guidelines.

7.1 Model Purpose and Model Selection

Most hydraulic models are based on the finite difference solution of the Saint-Venant (SV) equations for either one-dimensional (1-D) or two-dimensional (2-D) flow. These equations define the principles of conservation of mass and momentum balance in a fluid. They are sometimes simplified in hydraulic models to exclude various terms in the equations.

For the purposes of this section, hydraulic models refer to computer models. A summary of model applications is provided in Table 3. In general, hydraulic models for flood mapping include modelling the main channel and the more complex flood hazard area. Modelling approaches include steady and unsteady 1-D, 2-D, combined 1-D and 2-D, quasi-2-D, and, in specialized cases, three-dimensional (3-D) models.

The application of hydraulic modelling generally follows a stepwise procedure including:

1. Determine modelling objectives, extents, and accuracy requirements;
2. Review existing hydrometric and topographic data;
3. Select modelling platform;
4. Identify data gaps and required data collection;
5. Select data periods for model calibration and validation;
6. Conceptualize, calibrate, run, and validate model; and,
7. Simulate design event based on hydrologic analysis.

7.1.1 1-D Steady-State Flow Modelling

Use of 1-D steady-state modelling is widespread and intended for calculating water surface profiles for steady state flow where it is assumed that flow rates change gradually and the hydraulic profile is computed using flows that change spatially but not temporally.

The basic computational procedure for this type of model is based on the solution of the 1-D energy equation. Energy losses are evaluated as the sum of friction, contraction and expansion losses. The momentum equation may also be used in situations where the water surface profile is rapidly varied such as at bridge openings and when evaluating profiles at stream confluences.

A 1-D numerical solution of the SV equations is based on several assumptions (Cunge et al., 1980) including:

- Flow is confined and 1-D;
- Water level across the section is horizontal;
- Vertical accelerations are negligible;
- Effects of boundary friction and turbulence can be accounted for using resistance laws analogous to those for steady flow conditions;
- Average channel bed slope is small; and,
- Flow velocities are perpendicular to channel cross-sections.

This type of model is relatively simple to set up and run, does not require powerful computer processors, and can generate quick, accurate results for streams that meet the listed criteria when applied by an experienced practitioner. They do not require full stream bathymetry, and are good at modelling in-stream features including culverts, bridges, weirs, dams, and other hydraulic structures.

In general, 1-D steady flow modelling requires the following inputs:

- Stream cross-sections;
- Hydraulic structure information;
- Hydraulic coefficients;
- Channel resistance coefficients such as Manning's "n" values; and,
- Boundary conditions.

7.1.2 1-D Unsteady Flow Modelling

Applications for 1-D unsteady flow modelling, also known as 1-D hydrodynamic modelling, include model situations with significant storage, flow reversals, variable boundary conditions, rapidly varying flow and waves, and the need to understand the interaction with time varied flows from tributaries. This type of modelling has been less common than steady state 1-D modelling but has increased in popularity due to faster computational speeds and the need to model more complex phenomenon such as variable flow rates along a channel that result from channel storage and flood wave attenuation.

The data requirements for most 1-D hydrodynamic models are similar to 1-D steady state models, with the exception of the need for appropriate time-varying boundary conditions and hydrographs.

7.1.3 2-D Modelling

In many practical situations, the interaction of channel and floodplain flow fields is quite complex, including situations where the flow is poorly confined, flow attenuation and floodplain storage is important, and flows are complex along streets and between developments. For these applications, 2-D hydraulic models are generally preferred (Horritt and Bates, 2002; Hunter et al., 2008). Due to continuous improvements in computing resources, the time and cost requirements of 2-D modelling are decreasing.

The 2-D models employ depth-averaged Navier-Stokes equations, commonly called the Saint-Venant shallow water equations (SV-SWE), and can produce more realistic results for complex flood situations if properly configured with sufficient data. However, these models require much longer simulation times than 1-D models and are particularly suitable when detailed information about flow velocities and depths are required, flow-depth hazard to people is important, and lateral variation in water surface elevations need to be accounted for. Detailed digital elevation models, such as LiDAR data, and full bathymetry (rather than stream cross-sections) for stream channels, is generally required to support 2-D modelling.

7.1.4 Combined 1-D and 2-D Modelling

A partial solution to the high computational demands of 2-D modelling involves the use of combined 1-D and 2-D modelling. This usually involves using 1-D models for the defined flow channel coupled with a 2-D model in the complex overbank areas. There are a number of hydraulic modelling software packages that allow the coupling of 1-D and 2-D models. The advantage of using a combined 1-D and 2-D model is that the model is simpler, faster to run, and employs the advantages of both 1-D and 2-D modelling. However, this comes at the cost of increased data management, increased model complexity, and longer simulation times compared to 1-D modelling.

7.1.5 Quasi 2-D Modelling

Quasi 2-D modelling involves linking multiple 1-D models together to account for overland flow separately from the main flows. Although this method can involve setting up several distinct models, the individual models are generally simple and model outputs from upstream segments are used as inputs for downstream segments. This method has been shown to require less computing power and have similar accuracy to 2-D modelling when properly configured.

7.1.6 3-D Modelling and Physical Models

In addition to the horizontal velocity component achieved using a 2-D model, 3-D models include a vertical velocity component. Applications of 3-D modelling include complex hydraulic modelling of rapidly variable flow such as in the forebay of a hydroelectric dam.

These models are not generally used for flood modelling purposes, except in highly specialized cases such as modelling flow around a specific, complex structure, or where the hydrodynamics are impacted by density stratification (e.g. due to salinity, temperature or suspended sediment concentration gradients).

Physical models are generally used by organizations with specific technical needs to evaluate conditions that may not be well represented by computer models, and to use simulations to obtain empirical data about real-world processes. A high level of expertise is required to design experiments that properly account for scaling.

Table 3: Hydraulic Model Applications

Hydraulic Model Type	Application
1-D Steady State Modelling	Channelized flow. Primarily Gravity-driven flow. Streams where topographic and hydrographic data is limited. Streams with culverts, bridges, weirs, dams, and other in-stream structures. Situations where computational power is limited. Streams with limited hydrologic data. Preliminary assessments where only a general indication of flood level is required and significant uncertainty is acceptable.

1-D Unsteady Flow (Hydrodynamic) Models	Primarily gravity-driven flow. Streams with culverts, bridges, weirs, dams, and other in-stream structures. Low gradient streams with significant hydraulic differences in rising and falling limb characteristics. Streams with significant storage effects. Tidally influenced boundary conditions. Time varied flow conditions. Situations in which failure scenarios are being modelled and significant horizontal dissipation of the flood wave is not expected (e.g. dam breach in confined valleys).
2-D Steady and Unsteady Flow Models	Complex flow patterns outside main flow channel. Structure overtopping (e.g. dikes). Braided or multi-channel streams. Relatively flat floodplains with variable velocity components across floodplain. Tidal, wind and wave influenced flow. Urban flooding when there is sufficient high quality topographic data. Situations in which failure scenarios are being modelled and significant horizontal dissipation of the flood wave is expected (e.g. dike failure). Frequently used in combination with 1-D models.
Combined 1-D and 2-D	Uses the advantages of 1-D and 2-D modelling (e.g. 1-D modelling for main channel; 2-D modelling for overbank areas). Situations requiring optimization to reduce computational power requirements. Enhancing existing 1-D models for specific areas.
Quasi 2-D	Uses the advantages of 1-D and 2-D modelling; however, may not capture tidal, wind and wave influences as well as 2-D modelling. Situations with models requiring high computational power. Generally used for complex streams, but not modelling complex areas outside channel.

7.2 Data Requirements

7.2.1 Geospatial Data

The accuracy and precision of hydraulic analyses and flood hazard maps is highly dependent on the quality of geospatial input data used. The *Federal Airborne LiDAR Data Acquisition Guideline* and the *Federal Geomatics Guidelines for Flood Mapping* provide guidance on sourcing and using geospatial data for flood mapping.

Geospatial data may include stream cross-sections (generally to support 1-D modelling) or detailed digital elevation models and bathymetry (generally to support 2-D modelling).

7.2.2 Stream Cross-Sections

Stream cross-sections are the basic input to 1-D models. They are usually gathered from ground-based and bathymetric surveys and should be representative of the typical topography and cross-sectional area available for a particular reach. In general, cross-sections should be taken perpendicular to the direction of flow. Some models suggest the cross-sections be bent in the over-bank areas to maintain the cross-section perpendicular to the flow. This approach must be used appropriately to prevent an overestimate of the flow area and to maintain stream channel length.

Cross-sections should be spaced to capture significant changes in channel characteristics such as channel width and bed slope and to define abrupt changes that result from weirs, bridges, culverts, and other hydraulic structures.

7.2.3 Resistance Coefficients

Most hydraulic models require the selection of coefficients that help describe the energy losses due to the channel resistance. Various researchers have developed a number of these coefficients. One of the most common is referred to as Manning's '*n*'. Manning's *n* allows for modelled stream conveyance to be altered based on the physical characteristics of the stream channel, overland flow area, and other features that are in contact with flow. In practice, several different Manning's *n* values can be used in a single hydraulic model, including different Manning's *n* values across a single stream cross-section.

Manning's *n* is an empirical value that not only varies with the physical stream roughness, but also with its relationship to stage and flow. Selecting the appropriate resistance values requires an understanding of stream hydraulics, and care should be taken to select reasonable initial values for a hydraulic model. It is likely that resistance coefficients values will be altered during the calibration process, but calibration should not be forced by choosing values outside a reasonable range of values.

Increasing channel resistance for a stream reach will decrease the flow velocity and therefore locally increase the stage while increasing flood wave travel time. The relationship between flow rate and flow stages is somewhat sensitive to changes in channel resistance and the appropriate values should be selected based on a thorough understanding of the model and how the coefficient is used, a review of the pertinent literature, and hydraulic expertise.

Initial resistance coefficients values are selected using one of the following methods:

1. Consultation with published Manning's *n* values (e.g. Chow 1959);
2. Comparison to similar streams with calculated Manning's *n* values (e.g. USGS 2017);
3. Equations specifically intended to relate Manning's *n* to physical stream properties (e.g. Limerinos 1970); and,
4. Using technical expertise from hydraulic experts familiar with the studied stream.

In all cases, the selected Manning's *n* values should be adjusted as necessary based on calibration and validation procedures, but within the limits set forth in the preceding references.

7.2.4 Hydraulic Structures

Hydraulic structures include weirs, dams, bridges, culverts, and other in-stream features. These structures can significantly alter streamflow characteristics and every effort should be made to model them accurately. Generally, design information on hydraulic structures are entered into a hydraulic modelling software program, and loss coefficients are chosen based on published values and professional judgement. If possible, losses at hydraulic structures should be checked using a second computation method. Calibration and validation should be completed over a wide range of flows. Generally, 1-D models are best for modelling hydraulic structures and losses.

7.2.5 Dikes and Other Flood Mitigation Measures

Hydraulic analysis should include an assessment of the impact of dikes and other flood mitigation measures on flood stages. A river or stream that contains significant overland flow paths where large flow quantities leave the river at one point and re-enter downstream is another example requiring careful analysis. Due to the local impact on water levels, these features should be accounted for in the model conceptualization (e.g. urban flooding on a river that meanders through a city).

7.2.6 Boundary Conditions

The boundary conditions for the model should be representative and not adversely affect the simulation process. For example, the downstream boundary of study should be chosen so that the study area water level is not sensitive to the downstream water level, where possible. This can be achieved by selecting a location sufficiently far downstream to have low sensitivity to upstream flows (evaluated by conducting a sensitivity analysis) or by selecting a control point at which the upstream reach is hydraulically independent. Alternatively, a model should be selected that allows the boundary conditions to be altered during the simulation to produce a representative hydraulic profile. An example of this is simulating the influence of tides on water levels using a hydrodynamic model where the downstream water level boundary can change to represent ocean levels.

In the case where the downstream boundary condition is controlled by the ocean or by a much larger river (i.e. where flooding is governed by independent processes), boundary conditions should reflect conditions that are reasonably likely to occur concurrently with the design flood on the study stream. There may be an intermediate section (e.g. coastal estuaries) where the influence of boundary conditions on flood levels becomes significant. Joint probability analysis or long-term simulation using continuous data records may be necessary to establish flood levels in transitional reaches.

7.2.7 Stage-Discharge Relationships

Stage-discharge rating curves describe the relationship between water level and discharge at a specific stream location (e.g. hydrometric station), and are generally used to calculate discharge from a measured water level. These relationships are usually derived by either:

1. Conducting field discharge measurements at a range of water levels, and plotting the relationship curve and associated equation; or,
2. Conducting stream cross-section measurements to determine stream profiles at specific locations, and conducting hydraulic modelling using a software program.

Estimating stream discharge at a hydrometric station based on measured stage allows a flow hydrograph to be developed that can be used as an input to a hydraulic model.

7.3 Summary of Hydraulic Procedures

Figure 2: Hydraulic Procedures Flowchart

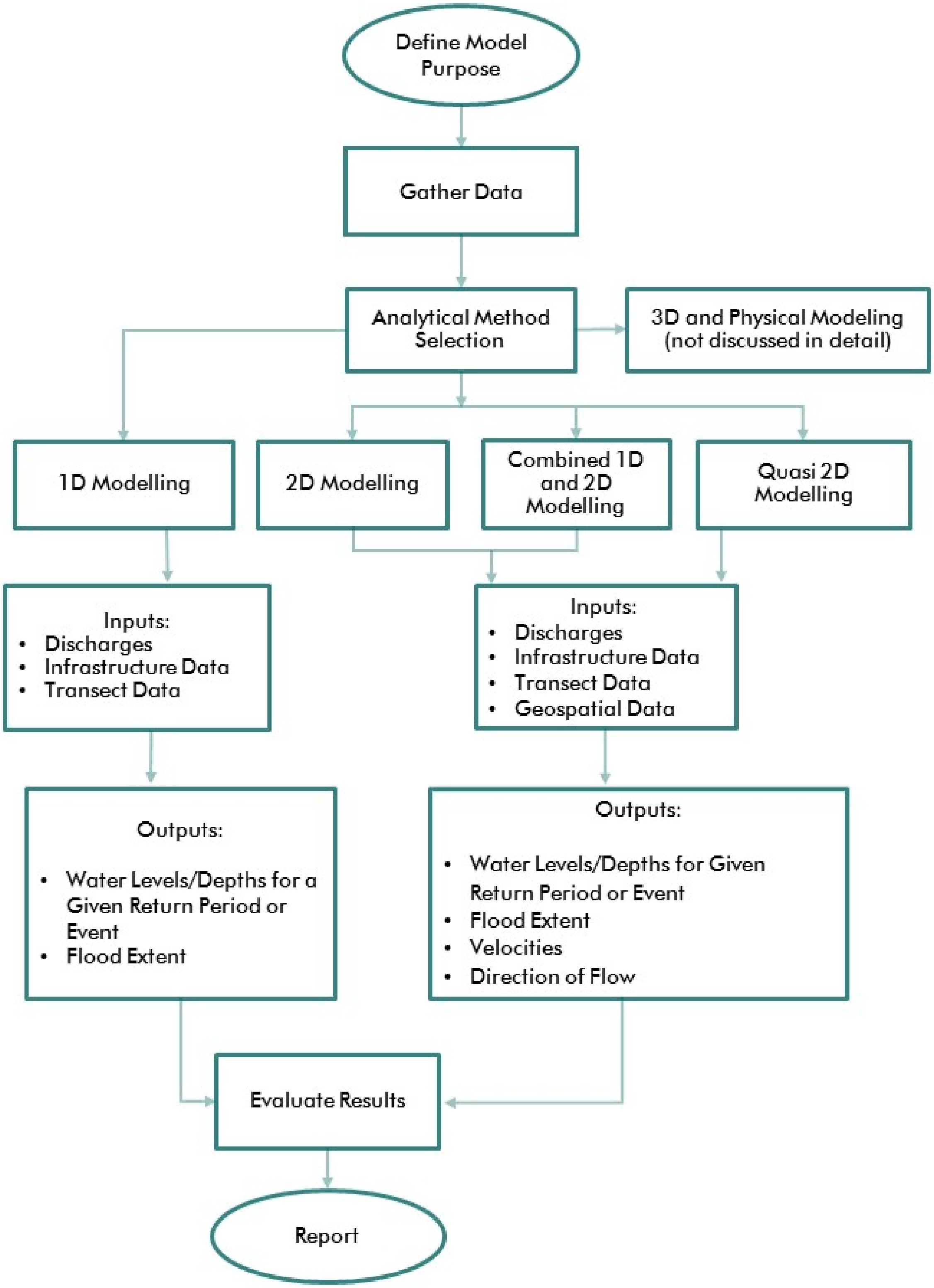


Table 4: Hydraulic Practices

Number	Hydraulic Practices
C.1	Identify hydraulic data from all sources in the defined study area that meet key data requirements. Document data sources. Conduct a QA/QC check on all hydraulic data used in the analysis.
C.2	Conduct the hydraulic analysis to determine the flood elevation over a range of AEPs, including but not limited to the design flood event as defined by provincial or territorial guidelines.
C.3	Define the floodway and flood fringe using the appropriate guidelines in each jurisdiction. This can be based on velocity, depth, or the water level increase if the flood fringe was removed from the active flow area.
C.4	Select analytical methods and models using professional judgement based on the input data available, the analysis to be conducted, and the output data required.
C.5	Employ 1-D steady flow modelling combined with 2-D modelling, where appropriate.
C.6	Use 1-D models when channel and overland flow are relatively simple and velocity can be reasonably assumed to be perpendicular to stream cross-sections.
C.7	Use 2-D, combined 1-D and 2-D, or quasi-2-D models when channel flow is relatively complex, and velocities are not assumed to be perpendicular to stream cross-sections.
C.8	Use 2-D modelling to model overbank areas whenever possible, including urban areas, areas with dikes and other flood protection measures, and areas where different scenarios will be modelled (e.g. dike breach).
C.9	Select the appropriate resistance coefficients such as Manning's *n* values using hydraulic expertise, published values, or similarity to streams with calculated values. Values should remain reasonable to avoid model calibration at specific locations that provide unrealistic results in other locations.
C.10	Calibrate resistance coefficients values to at least two known flood events and further validate by at least one additional event.
C.11	Select boundary conditions and locations such that they do not cause an unrealistic influence on the simulated water levels, where possible.

C.12	Ensure initial conditions are physically realistic and allow the flow rates to be gradually varied to prevent model instabilities.
C.13	Develop cross-sections for 1-D models perpendicular to streamflow across the full width of the 1-D modelling area and where they never cross or intersect.
C.14	Space cross-sections to capture changes in streamflow, either abrupt (e.g. from hydraulic structures) or gradual but significant changes (e.g. changes in bedslope or channel width). Take cross-sections above and below hydraulic structures and significant inputs (e.g. tributaries, storm sewer outflow, etc.).

8.0 ICE EFFECTS

A description of procedures for considering ice effects in hydraulic analysis is included in this section, and a summary of processes leading to ice-jams is provided in Figure 4. Figure 5 is a flowchart showing individual tasks for ice-effect analysis. Ice-effect practices are included in Table 5.

8.1 Ice-Related Flooding

Ice-related floods are complex physical processes that occur in many parts of Canada, and ice effects should be considered when conducting hydrologic and hydraulic assessments to support flood mapping. The primary cause of ice-related flooding in Canada is ice-jams, which can occur at freeze-up, at breakup, or during a mid-winter thaw. Modelling ice-related flooding is a specific technical discipline, and requires involvement of experts (Kovachis et al. 2017; Lindenschmidt et al. 2018).

There are currently two standard methods for incorporating ice effects into flood frequency analysis:

1. Conventional Analysis, using direct incorporation of ice-affected flooding using stage-frequency analysis with long-term data sets that include several well-documented ice-affected flooding events; and,
2. Synthetic Frequency Curve Generation, based on an understanding of ice mechanics and running Monte Carlo simulations for different defined ice-jam events.

Although ice-jams tend to recur on specific reaches of specific rivers, the probability of an ice-jam occurring, the timing of the ice-jam, and the effect of the ice-jam are difficult to determine. If possible, hydrometric data for ice-jam events should be used directly to create an ice-affected flood frequency curve. When there is not sufficient ice jam data to directly extrapolate AEPs, synthetic frequency curve generation methods are possible. In the cases where a less detailed analysis is appropriate, a high-level preliminary assessment can provide a coarse estimate of the maximum expected ice-related levels.

8.2 High-Level Preliminary Assessment

In many cases, a simplified analysis of ice-related levels is undertaken to provide a reasonable estimate of the maximum expected ice-related levels because it is not deemed to be important, open-water conditions are believed to govern, or there is insufficient data available to warrant an extensive analysis. In these situations, a suitable procedure (NRC, 1989) would be as follows.

- Assess the potential for the development of ice-jams or severe ice accumulations based on geomorphic features (slope changes, channel constrictions, sharp bends, etc.) evident on maps and aerial photographs;
- Consult satellite imagery and other remotely-sensed data to track ice conditions on a seasonal basis to characterize dominant processes locally and on a reach-scale;
- From site inspections, identify vegetal and morphologic features that would indicate the height of ice action;

- Collect anecdotal evidence about ice conditions from residents and authorities and correlate with the vegetal and morphological indicators;
- Assess the mitigation potential of floodplains and relief channels to limit the height of ice action;
- Estimate the severity of ice-related flows from a regional perspective, if necessary; and,
- Estimate the channel slope and channel dimensions at bankfull (map slope and a rectangular representation of the channel would be appropriate) and calculate the expected height of an ice accumulation using appropriate hydromechanical relationships or their graphical approximation (Beltaos, 1983).

8.3 Ice-jam Flooding

Certain rivers in Canada are more susceptible to ice-related flooding than others. Analyses of rivers that have a documented history of ice-related flooding should include an assessment of the impacts of ice-jams on water levels and AEPs. Rivers that may not have a documented history of ice-related flooding, but have characteristics that may lead to ice-jams, should be evaluated for ice-jam risk.

The conditions that influence the formation of ice-jams include:

1. Water levels at freeze-up;
2. Channel characteristics;
3. Characteristics of ice cover;
4. Melting regime (thermal or mechanical);
5. Characteristics of flowing ice; and,
6. Carrier flow (river discharge).

There are three main stages in the life-cycle of river ice: ice formation, ice thickening, and ice breakup. Figure 4 identifies the ice-jam potential during each of the three different stages.

8.3.1 Ice Formation and Thickening

Ice cover that forms at freeze-up in the absence of shore ice can be treated as ice-jams or ice accumulations, of which there are two types: juxtaposed and consolidated. A juxtaposed accumulation forms by the superposition of ice floes, one layer thick, when the approach velocity is low enough to prevent their entrainment under the leading edge of the ice cover. In this case, internal stability is developed from interstitial freezing (Andres, 1999), and the internal strength of the thin accumulation is sufficient to withstand the increasing shear and gravity forces on the lengthening accumulation.

A consolidated ice cover forms if a juxtaposed ice cover cannot form, either because ice floes are entrained under the leading edge, or there is insufficient interstitial freezing to maintain stability (Beltoas 2013). Consolidated ice covers can be viewed as granular structures (Beltaos, 1996) in which internal stability is defined in one of two ways:

1. Hydraulically by the ’narrow channel’ jam stability criterion (Pariset et al., 1966) wherein the accumulation is thick enough that its leading edge is not submerged; or,
2. Hydromechanically by the ‘wide channel’ jam stability criterion where accumulation thickness is defined by its internal strength derived from intergranular friction.

Generally, the ‘wide channel’ stability criterion will produce the highest water levels, followed by the ‘narrow channel’ criterion, and the juxtaposing ice cover will produce the lowest water levels. Should either a juxtaposed or consolidated ice cover become destabilized and collapse, the ice cover can further thicken. These freeze-up ice-jams can cause dramatic rise in water levels, particularly on regulated rivers that have increased winter discharges.

Additionally, ‘hanging dams’ can form by transport and accumulation of frazil ice under an already-formed sheet ice cover. This type of ice-jam is not encountered frequently, but can lead to flooding because the deposited ice can attain extreme dimensions under certain circumstances. Details can be found in Beltaos (2013b).

8.3.2 Ice Breakup

Increases in temperature, either during warmer winter periods or during springtime, affect the degradation or breakup of ice cover in two ways:

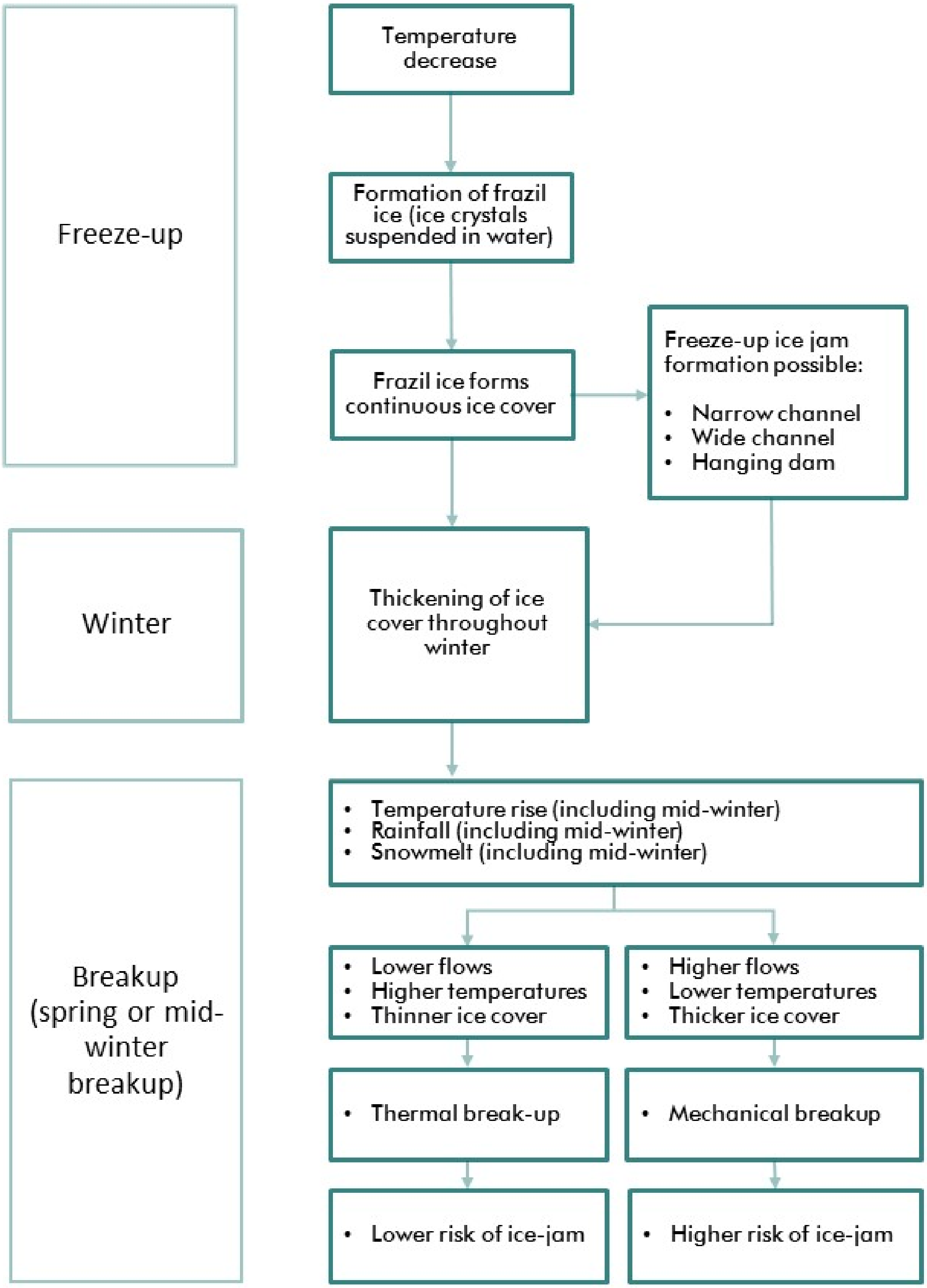
1. Direct thermal degradation of the ice cover; and,
2. Mechanical degradation via increased streamflows associated with higher runoff (rainfall and snowmelt) and groundwater inputs.

Generally, when thermal degradation dominates breakup, the risk of ice-jams is low. This is common for cases when streamflows do not substantially increase during breakup. However, in cases where streamflows substantially increase and mechanical degradation dominates, the risk of ice-jams is relatively higher. In the latter case, ice-jams can form and release, releasing surges of ice and water (referred to as ‘javes’) downstream and possibly creating new ice-jams.

Javes are complicated hydrologic phenomena that are created by the formation and release of ice-jams, and are an important feature of the breakup process. Larger ice-jams lead to larger javes traveling downstream. Unsteady flow (including javes) may produce higher water levels and thicker ice jam accumulations than may be modelled using equilibrium jam theory. Considerable research is being carried out to understand the characteristics of javes (Jasek, 2003; She and Hicks, 2005; Beltaos, 2013a).

Notably, warmer winters resulting from climate change have the potential to result in thinner ice covers, which affect ice-jam severity. Warmer winters and greater amounts of precipitation may also increase the likelihood of midwinter thaws leading to ice-jams (Beltoas et al. 2003).

Figure 3: Processes Leading to Ice-jams



8.4 Ice-jam Analysis

8.4.1 Data Requirements

Ice-jam data includes hydrometric records, information on recorded ice-jam events, and information on ice characteristics during ice-jam events. Hydrometric records may be incomplete during ice-related flooding events because ice often damages in-stream gauging equipment. Further, discharges derived from rating curves are highly unreliable under ice conditions due to backwater effects. Therefore, careful expert examination of the hydrometric record is necessary. If the record is composed of highly censored ice-related water levels such as resident recollections and archival materials, techniques are required to minimize the inherent bias introduced by including only the remarkable (severe) events in the record and omitting the unremarkable ones.

Perception-level types of analyses described in Section 6.1.3 can be applied to ice-related flooding as demonstrated by Winhold (AEP 1993) at Fort McMurray, Alberta. Once the data series is established, conventional analysis can be undertaken, as above, to define a stage-frequency curve.

Data on ice-jam floods can be gathered from a number of sources, including:

- Hydrometric records including from government agencies;
- Community members;
- Videos (including online video sharing websites);
- Newspaper articles; and,
- Physical evidence including tree scars, high-water marks, and disturbed vegetation and bank sediments.

8.4.2 Reach-Based Extrapolation

Since most historical information consists of ice-related water levels at one location – typically at a hydrometric gauge or at a unique location of interest or access point – there is a need to generalize water levels throughout the reach of interest by extrapolation upstream and downstream from the locations of known water levels. This can be done in a variety of ways, which range in complexity from a simple uniform slope calculation using a known open water slope, to a non-uniform hydraulic modelling analysis (Carson et al., 2011; Brunner, 2016) that can account for changes in cross-section shape and a non-uniform channel slope. In either case, measured ice-jam profiles (Andres and Doyle, 1984) and observations of general ice conditions provide confidence in both the uniform flow extrapolation and in the calibration the non-uniform water level simulations. To assist with this analysis, it would be good practice to carry out at least one set of winter observations to monitor freeze-up and breakup conditions if there are known ice issues at a location where a flood hazard study is to be undertaken.

8.4.3 Conventional Analysis (Direct Method)

Conventional analysis refers to deriving an ice-affected stage-frequency distribution from a data set that generally spans 25 (FEMA 2003) to 30 (Beltaos 2012) years, and has at least three discernible ice-jam flooding events (FEMA 2003). The steps for conducting a conventional analysis are:

1. Conduct evaluation of data set;
2. Select plotting formula;
3. Plot ice-affected stage-frequency distribution;
4. Extract ice-jam flooding probability distribution.

The main advantage of conventional analysis is that it is data-driven and requires fewer assumptions than other methods.

8.4.4 Synthetic Frequency Curve Analysis (Indirect Method)

Synthetic frequency curves can be used to generate estimates of ice-jam flood stages for cases where ice-jams are a known or anticipated flood hazard, but where the existing ice-jam data is not of appropriate length or quality to extrapolate to low AEPs. However, use of synthetic frequency curves involves a high level of judgement and expertise, and can be an inherently uncertain process. The general process for generating synthetic frequency curves is described in Trillium (2000a) and (2000b). Alternative methodology can be found in Beltaos (2012) and Lindenschmidt (2016).

8.5 Effects of Regulation

Regulation that can alter the winter flow regime can affect ice processes in numerous ways, and should be considered depending on its proximity to the site of interest (Huokuna et al., 2017). High winter flows, fluctuations, and thermal effects can contribute to a regulated ice regime that is quite different from the natural one. This includes an increased potential for ice concerns throughout the ice season. Assessing flood hazards due to regulation prior to the construction of a facility is a complex, multi-faceted task that is best undertaken using a well-calibrated ice model that simulates the full range of hydrothermal and hydromechanical processes (Shen et al., 1995). For situations where regulation has been in place for several years and ice-related water level outcomes have been measured, operating procedures usually have been established to limit the severity of the impacts. However, ice-related hazards still can occur (Trillium, 1997) despite every effort to control outcomes. In these situations, the challenge is to combine the effects of random events and imposed conditions in the probability analysis.

8.6 Summary of Procedures for Consideration of Ice Effects

Figure 4: Ice-jam Analysis Flowchart

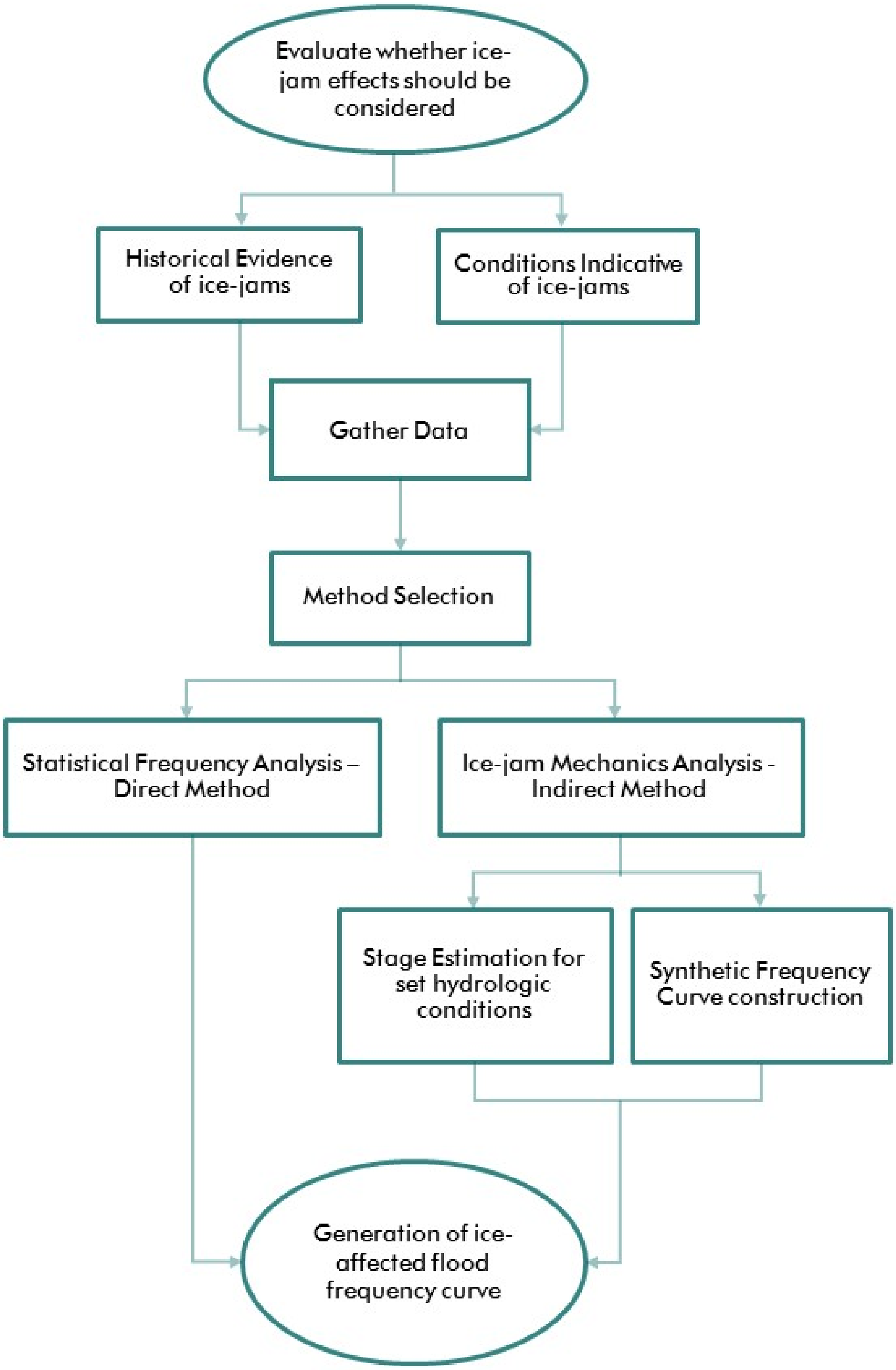


Table 5: Ice-jam Flood Practices

Number	**Ice-Jam Flood Practices**
F.1	Analysis should include consideration of ice-jams in locations that have experienced historic ice-jamming.
F.2	Analysis should include consideration of ice-jams in locations that exhibit characteristics typical of ice-jamming.
F.3	Consider backwater effects when analyzing for ice-jams.
F.4	If sufficient data is available, conduct a conventional analysis using the data set to develop an ice-affected stage-frequency distribution.
F.5	If sufficient data is not available for direct determination, conduct a synthetic ice-stage frequency analysis.
F.6	Incorporating ice effects in hydrologic and hydraulic analysis is complex and should involve an experienced practitioner with relevant expertise.

9.0 COASTAL AND LARGE LAKE AREAS

This chapter first summarizes prevailing physical processes in extreme coastal water levels, including storm surge, in Section 9.1. Data sources are summarized in Section 9.2, to support statistical analyses as described in Section 9.3. Additional considerations on wave run-up and overtopping are included in Section 9.4. Finally, a summary of coastal and large lake area practices is included in Table 6. For information on climate change effects on sea level change and coastal flood mapping see Section 10.

9.1 Physical Processes

9.1.1 Overview

Extreme water levels along large lakes and coastal areas may come from a combination of the following factors:

- Astronomical tides;
- Storm surge: the difference between the observed water level during a storm and the predicted astronomical tide. Storm surge is generally the largest contributor to extreme water levels above normal tidal elevations, and general methods for its estimation are listed in Section 9.3.1. It is due to meteorological effects on sea level, such as:
    - Wind set-up : the downwind increase in water level occurring as a result of shear stress exerted by the wind on the water surface, with possible influence by local bathymetry;
    - Barometric set-up: the increase in water level due to changes in atmospheric pressure during storm events;
- Wave run-up: the vertical distance a wave travels up the shoreline above the still water level. Guidance on wave run-up estimation is given in Section 9.5;
- Seiching: a dynamic effect whereby perturbations in water level are amplified by bathymetry or coastlines (e.g. standing waves or oscillations in harbours or semi-enclosed basins);
- Wave set-up: the increase in mean water level near the shoreline, which occurs as a result of a slope in the water level required to balance the onshore flux of wave momentum (radiation stress), usually associated with wave breaking. Beach areas with a wide surf zone are most prone to wave set-up. Wave set-up contributes to wave run-up, discussed in Section 9.5. Wave set-up is by convention (but not always) excluded in the definition of storm surge. When analysing tide gauge data with the intent of potentially using it for a site nearby, the practitioner should investigate whether measured storm surges would include wave set-up or seiching, which are best addressed with numerical modelling;
- Tsunami; and,
- River discharges.

Long-term, large scale influences arising from slow changes to mean relative sea-level. Changes to relative sea-level are due to a combination of:

- Changes to global sea-level arising from ocean water thermal expansion, glacier and ice-sheet discharge to the oceans, and other factors; and,

- Vertical land motion. Land uplift contributes to relative sea-level fall, while land subsidence adds to relative sea-level rise. In Canada, a dominant source of vertical land motion is the delayed response of the solid Earth to weight of the ice sheets, a process called glacial isostatic adjustment or postglacial rebound. Other processes, such as tectonics and sediment compaction also contribute to vertical land motion.

In addition to these long- term changes, ocean climate cycles (El Nino/Southern Oscillation, Pacific Decadal Oscillation, and others) and seasonal effects cause changes to mean sea-level that vary from season to season and over years to decades and that can have an amplitudes of centimeters to tens of centimeters.

A variety of methods may be used to estimate extreme water levels for coastal and large lake sites in Canada. Selection of the appropriate method depends on a number of considerations, including:

1. Site characteristics, including the availability of long-term water records, potential interactions between storm surge and bathymetry, or other processes;
2. Application of analysis, including preliminary planning or detailed design;
3. Desired level of certainty; and,
4. Level of complexity involved in analysis.

9.2 Data Sources

9.2.1 Historical Water Level Observations

The Canadian Hydrographic Service (CHS) maintains a tide gauge network of approximately 87 permanent operating stations throughout Canada (15 in the Atlantic Region, 39 in the Central and Arctic Region, 13 in the Pacific Region and 21 in Quebec), some providing more than a century of sea level records. Data is generally available at hourly (or more frequent) sampling intervals. The data is freely available to download from the Fisheries and Oceans Canada (DFO) Tide and Water Levels Data Archive (DFO 2017).

Monthly mean water levels are also available for the Great Lakes (Lake Superior, Lake Michigan-Huron, Lake St. Clair, Lake Erie and Lake Ontario) from 1918 to 2013. The water levels for each lake are averages based on a network of gauging stations in Canada and the United States. Monthly mean water levels for Montreal Harbour are available for the period 1967 to 2013.

In many cases, it is unlikely that long-term water level gauges will be located directly within an area of interest. However, data may be available for neighbouring or comparable sites. For these cases, correlation techniques, interpolation or extrapolation can be used to estimate water levels at the site of interest (e.g. Rogers et al., 2010). Although these methods are generally quicker to apply and less costly than numerical modelling or field measurement campaigns (described below), they should be applied with care, especially over long distances or along complex coastlines due to site-specific differences including in the phase or timing of high water levels. Supporting data collection should include:

- Proximity of the gauge to the site;
- Relative exposure to waves and meteorological effects;
- Potential influences of bathymetry and topography; and,
- Potential influences of river discharges.

9.2.2 Tide Gauge Deployment

Where representative long-term water level records are not available, water level gauges can be deployed to collect data for comparison to long-term records at adjacent sites, and to support numerical modelling. Comprehensive guidance on selecting tide gauge sites, installation, survey control, data processing and quality control is provided in the “Manual on Sea Level Measurement and Interpretation” (Intergovernmental Oceanographic Commission, 2016). Standards, guidelines and manuals developed by provincial and local governments or professional associations may also stipulate requirements for data acquisition and surveys (e.g. British Columbia Ministry of Environment, 2009). Generally, meteorological and hydrometric data will also be required.

9.2.3 Historical Wave Buoy Data

Historical wave buoy data (and ancillary meteorological data) are freely available through DFO (2017) website and can provide a useful basis for supporting wave effects assessments, typically in conjunction with numerical wave modelling. Historical meteorological measurements are available through Environment Canada archives (ECCC, 2017b) for more than 8,000 stations across Canada.

9.2.4 Wave Model Hindcasts

Most areas do not have wave buoy data available. Studies must then rely on offshore wind and wave model hindcasts, which should be transformed to nearshore locations using a numerical wave model. Canadian waters now have extensive coverage from offshore wind and wave hindcast products developed by Oceanweather Inc., calibrated to meteorological and wave buoy measurements, and available by request from ECCC. These include MSC50 Atlantic (Swail et al. 2006), Northeast Pacific GROW-Fine and Beaufort GROW-Fine (Swail et al. 2007).

9.2.5 Satellite Altimetry

Satellite altimetry data can provide a useful basis for supporting storm surge and wave effects assessments in open water, subject to certain limitations (e.g. Walker et al., 2014). Altimetry data is freely available online for a number of historical and ongoing satellite missions, such as ERS-1, JASON-1, JASON-2, and TOPEX/Poseidon. It important to note that satellite altimetry data is generally relevant for open water areas, and coastal flood studies should generally rely on higher resolution local information instead.

9.2.6 Numerical Models

Numerical models provide useful tools to support establishment of extreme water levels at coastal and large lake sites, where available data is scarce, or where available data does not support direct analysis and prediction of future water levels.

9.3 Typical Methods for Storm Surge Estimation

Three widely used approaches to evaluating or predicting extreme storm surges in coastal and large lake areas are described in the following sections, with guidance on key considerations and the application of each method.

9.3.1 Simplified Methods

The simplified methods typically involve the use of analytical models or empirical formulae to predict contributions by wind and atmospheric pressure effects to water levels (e.g. methods provided in Chapter 4 of the Rock Manual (CIRIA, CUR, and CETMEF, 2007)). These methods are generally appropriate for preliminary assessments, for sites where simplifying assumptions are valid (e.g. straight and parallel bottom contours), or where high levels of uncertainty in the estimates can be tolerated.

9.3.2 Analysis of Long-term Water Level Gauge Records

These approaches typically involve a harmonic analysis of gauge data to extract residuals or skew surges, for input to joint probability or statistical frequency analysis. Details are provided in Section 9.4.3. The analysis is only possible where long-term water level records exist for the site of interest. The need for alternative methods should be considered where water levels are potentially influenced by processes other than tides and surge (e.g. seiches, wave effects, tide-surge interactions, large-scale climate variability patterns) because it may not be possible to distinguish between contributions from these processes based on a direct analysis of measurements.

9.3.3 Numerical Modelling

Numerical modelling predictions of storm surges generally involve the use of 2-D or 3-D hydrodynamic models that allow for prescription of temporally and spatially varying wind fields, pressure fields and tidal boundary conditions (for coastal models) to generate storm surge predictions near the shore. The modelling is generally appropriate:

- Where long-term records are not available;
- Where necessary to gain in-depth understanding of the spatial distribution of storm surges;
- To determine interactions with bathymetry and other processes (most importantly tides, and to a much lesser extent temperature and salinity stratification);
- To investigate hypothetical or future storm scenarios;

- To examine the effects of changes and development in the coastal zone on storm surges;
- To support analysis of flood-generating pathways (e.g. overtopping and erosion); and,
- To provide input to overland flood hazard modelling and mapping.

Field measurements, which may also include historical tide gauge records, should be used to calibrate and evaluate numerical models to provide confidence in model projections and to quantify uncertainty.

9.4 Frequency Analysis

9.4.1 Extreme Value Analysis

Extreme water levels are generally calculated using one of two methods for coastal areas where observed or hindcast data is available:

1. Annual Maximum (AM); and,
2. Peaks over Threshold (POT).

While the AM method is simpler, POT has the advantage of allowing for incorporation of storm surge events, tides, and other factors that may produce multiple significant high water events over the course of a calendar year. The POT method also allows more data points to be used for the extreme value analysis, and therefore higher confidence in the results (provided the extrapolated AEP is not excessively long relative to the sample duration). The sample should be large enough to represent the local climate and meteorological mechanisms associated with extreme water levels and should not just cover the calm or stronger period of activity. Ideally, for stationary processes, the sample size duration should represent at least half of the extreme AEP being extrapolated (e.g. a sample of at least 50 years is recommended for estimating a 100-year return value).

Extreme value analysis methods rely on the assumption of stationarity, which may not be valid for areas that have experienced historical change, such as sea level rise. Careful trend analyses are recommended prior to conducting extreme values analyses. In the case of historical sea level rise, the practitioner may choose to de-trend the time-series of historical peaks and correct it to present-day water levels prior to calculating present-day return values. The issue of future sea level rise must then be accounted for in projecting future extreme water levels (see Section 8.6).

Practitioners should keep the ultimate goals (e.g. public safety) in mind when conducting extreme value analysis and recognize that the objective should not necessarily be to obtain the best statistical fit of a distribution. Additional practices for extreme value analyses are provided in Section 6.3.

9.4.2 Independent and Dependent Variables

Software packages can be used to separate tidal, storm surge, and skew surge effects from each other and conduct frequency analyses on each process. In general, it may be reasonable to assume that tidal effects are independent of storm surge effects, and that the extreme high water level for a given AEP is the marginal probability of each variable. However, wind set-up, wave run-up height, and storm surge are all dependent variables because the processes generating them (e.g. storms) have the same cause (the underlying storm), and the processes are partially correlated. Analysis of these variables is therefore more complex.

Superimposing tide, surge, and wave effects (i.e. by treating them as independent variables) can provide an efficient but conservative preliminary estimate of extreme water levels for an ungauged site. More accurate evaluation of dependent variables can be conducted using joint probability analysis (discussed in Section 9.4.3) and Monte Carlo simulation (discussed in Section 9.4.4).

9.4.3 Joint Probability Analysis

Joint probability analyses should be conducted on related variables that are driven by storm events, most notably storm surges, wave heights, and precipitation where applicable. The joint probability of tide and surge should be investigated as well, particularly for sites where the tide has a large influence on other processes (e.g. in the Bay of Fundy). The analyses should identify a reasonable approach for pairing AEPs of dependent variables without being unduly conservative. For example, a ‘design storm’ using coincident N-year return storm surge with both N-year return wave heights and N-year return precipitation may result in a AEP that is much lower than 1/N years.

In addition, in coastal cases where a given flood probability is to be estimated over a long period into the future, the practitioner may use cumulative probabilistic techniques to account for the probability increasing each year due to gradually increasing sea level.

9.4.4 Stochastic Methods (Monte Carlo Simulation)

Due to the complexity of dependent variables in calculating extreme still water levels, storm surge and wave effects, stochastic methods may also be used. Following separation of tidal, skew surge, and storm surge, these effects can be built into the model and combined with precipitation and stream flow data to generate joint probabilities of stream elevations and coastal water levels and storm surges. The principles of hydrologic modelling described in Section 6.0 should be followed.

9.5 Wave Run-up and Overtopping

Wave run-up is the maximum elevation of wave uprush on the shore above the still water level. As explained in the Coastal Engineering Manual (US Army Corps of Engineers, 2002), wave uprush consists of two components: super-elevation of the mean water level due to wave action (set-up) and fluctuations about that mean (swash).

Wave run-up is a complex phenomenon that depends on the local water level (including surf beat or infragravity wave effects), the incident wave conditions (height, period, steepness, direction), and the nature of the beach or structure at the coast (e.g. slope, reflectivity, height, permeability, roughness) (FEMA 2005).

When wave run-up exceeds the crest elevation of a beach or coastal structure, water flows over the crest. This is referred to as “green water” overtopping. Another form of wave overtopping can occur when waves break on the seaward face of a structure, causing splash droplets to be carried over the crest by their own momentum or wind (EurOtop, 2007).

9.5.1 Wave Effect Considerations

Wave run-up and overtopping should be included for flood studies in most coastal areas, including (but not limited to) areas exposed to open water wind fetch (i.e. with distance for wind waves to grow), and areas where property or infrastructure is located close to the shoreline with limited natural buffers.

The impact of future sea level rise on wave heights must also be examined. Since breaking wave heights are a function of the water depth, in some areas sea level rise will allow larger waves to break close to shore, potentially increasing wave run-up and overtopping. In most cases however, the largest contribution to the increase in flooding risk would generally be due to the higher still water level.

9.5.2 Empirical Formulae

Empirical methods use a simplified representation of the physics of the wave run-up and overtopping process presented in (usually dimensionless) equations to relate the main response parameters (e.g. 2% wave run-up elevation, mean overtopping discharge, etc.) to key wave and structure parameters (EurOtop II, 2017). Empirical coefficients and constants used in the formulae have typically been derived from physical model testing or field measurements.

There are numerous empirical formulae available for calculating wave run-up and overtopping. FEMA (2005) outline a number of relevant issues to evaluate and consider when selecting the appropriate method:

- Each method or model is based on certain assumptions and empirical data, and each is valid over a range of morphologic, hydraulic, and sometimes geographic conditions;
- Some use deep water wave conditions as input; others use local (i.e., transformed) wave conditions at the toe of the barrier;
- Some methods or models are applicable to beaches and others to coastal structures;
- Some are applicable to cross-section type analyses while others are appropriate to grid or element based analyses; and,
- Each requires trade-offs among simplicity, accuracy, data requirements, ease of use, and economy.

EurOtop (2007) and EurOtop II (2017) provide the most recently updated guidance and calculation tools for evaluating wave run-up and overtopping of coastal structures. Methods for evaluating wave run-up and overtopping of beaches are provided in the Coastal Engineering Manual (US Army Corps of Engineers, 2002) and FEMA (2005).

Empirical formulae are prone to uncertainty and inaccuracy if used to extrapolate beyond the limits of parameters and conditions for which they have been developed (EurOtop II, 2017; FEMA, 2005; US Army Corps of Engineers, 2002). They should be thought of as providing order of magnitude approximations only (EurOtop, 2007). It is therefore recommended that they be used with extreme caution by experienced practitioners with knowledge of the origins, limitations and applicability of the formulae. The uncertainty should be weighed against the consequences of errors in estimates for a particular application, to support decision-making on whether more advanced techniques such as numerical or physical model testing are required.

9.5.3 Numerical Modelling

The FEMA guidance identifies drawbacks and barriers for the use of numerical modelling. The barriers include increased requirements for data, expertise and higher costs compared to simple procedures. However, FEMA states that “ultimately, FEMA’s methods will be overtaken and replaced by numerical models”, pointing to the advantages of numerical models in areas with complex shorelines and processes. No references to physical modelling techniques are made in the FEMA guidance document.

A range of numerical models can be used to simulate the processes of wave run-up and overtopping on structures and beaches. Unlike the empirical formulae described in Section 7.5.2, numerical models can be developed for most types of shoreline treatments and geometries, and can be used to provide estimates of wave run-up and overtopping on time scales of individual waves. However, all numerical models require some simplification or parameterization of physical processes, and generally require more skill and time to use successfully. Numerical models may need to be coupled with nearshore wave and hydrodynamic models, and overland flooding models.

Some of the key relevant physical processes to consider when evaluating numerical models for selection include (EurOtop II, 2017):

- Wave breaking and wave run-up on or over the structure, resulting in complex free surface configurations;
- Violent wave breaking with air entrainment or impulsive wave breaking on the structure, resulting in 3-D turbulent flow;
- Flow through interstices within the structure (e.g. voids between rocks) or beach material;
- Entrainment of sediment in the flow; and,
- Dynamic response of beaches, dunes and sea defences including structure motion, scour, breaching and erosion.

Summaries of different types of numerical models used to assess wave run-up and overtopping are provided in FEMA (2005) and EurOtop II (2017). Most numerical models used for this purpose require wave information to be specified at the seaward boundary, e.g. based on output from a wave transformation model. Five categories of numerical models used to simulate wave run-up and overtopping are defined as follows:

- Non-Linear Shallow Water (NLSW) equations models;
- Boussinesq equations models;
- Non-hydrostatic models;
- Navier-Stokes (NS) equations models; and,

- Smoothed particle hydrodynamics (SPH) models.

9.5.4 Equations

Both the NLSW and Boussinesq equations are simplified forms of the NS equations that describe fluid dynamics. The NLSW equations are usually simplified from the NS equations by averaging over depth, assuming flow is horizontal, assuming a hydrostatic pressure distribution in the vertical, and ignoring frequency dispersion of waves. They are therefore only applicable in shallow water (where the ratio of water depth to wave length, h/L, is less than 0.05).

The Boussinesq equations allow for frequency dispersion of waves, which extends their applicability to intermediate water depths (h/L < 0.5). However, this comes at increased computational cost.

9.5.5 Non-hydrostatic Models

Non-hydrostatic models use the NLSW equations with the addition of a vertical momentum equation and a non-hydrostatic pressure term in the horizontal momentum equations. Unlike Boussinesq models, the vertical structure of the flow is resolved. Non-hydrostatic models also account for frequency dispersion of waves.

9.5.6 Navier-Stokes Equations Models

NS equations models are sometimes referred to as computational fluid dynamics (CFD) models and numerically solve the equations of fluid flow in an Eulerian framework. They are sophisticated, non-linear models that offer the most flexibility in numerically simulating wave run-up and overtopping, but typically require significant skill and effort to use successfully. Due to the large number of variables and options for simulation, and the skill required to use these models, calibration and validation using field or physical model data is usually strongly preferred. These models are typically run using high performance computing hardware.

9.5.7 Smoothed Particle Hydrodynamics Models

SPH models take a Lagrangian (i.e. particle-following) approach to solving the NS equations. Due to the large number of particles required to accurately simulate fluid behaviour, the computational cost of these models is high. These types of models are therefore mainly used only in a research context at present (EurOtop II, 2017). DualSPHysics is an example of an open-source SPH code developed to solve free-surface flow problems.

9.5.8 Physical Modelling

Physical model testing is an established and reliable method for estimating wave run-up and overtopping on beaches and coastal structures. Scale models of the prototype structure or beach and nearshore bathymetry are typically constructed in 2-D wave flumes or 3-D wave basins. A range of wave, water levels and currents can be generated, to investigate the response and interactions with the structure or beach.

Care and experience is required when designing physical model test programmes to make sure the important hydrodynamic model parameters are scaled and assessed correctly. Guidance on scale effects, model effects and other considerations for physical model testing are provided in Hughes (1993). Due to the present limitations of existing empirical and numerical methods for assessing wave run-up and overtopping, and the complexity of the physical processes involved, physical modelling often remains the most reliable option. In particular, physical model testing is recommended where the risks or consequences of wave run-up and overtopping are high. In some cases, selective physical model testing can be used to calibrate or validate empirical formulae and numerical models.

9.6 Summary of Practices for Coastal and Large Lake Areas

Table 6: Coastal and Large Lake Area Practices

Number	Coastal and Large Lake Area Procedures
G.1	Gather data on all sources of extreme coastal and lake water levels including annual maxima and storm peaks above normal (e.g. tidal) thresholds, tidal effects, storm surges, wind and wave effects, seiches and sea level rise.
G.2	Use the extreme value analyses using peaks-over-threshold (POT) method for large lake and coastal areas. This allows for use of a greater number of extreme values than annual maximum (AM) method.
G.3	Estimate joint probabilities of high water from the relevant physical processes using probabilistic modelling methods. The probabilities must consider future sea level change for coastal areas.
G.4	Estimate the site-specific effects of high water on coastal and large lake structures using numerical modelling and physical modelling.

10.0 CLIMATE CHANGE CONSIDERATIONS

Future climate patterns are projected to differ significantly from the historical record. Two recent publications, “Canada in a Changing Climate: Sector Perspectives on Impacts and Adaptation” (Warren and Lemmen, 2014) and “Canada's Marine Coasts in a Changing Climate” (Lemmen et al. 2016) indicate that changing precipitation patterns under climate change may expose new areas to the effects of floods, and may increase the magnitude and frequency of flooding in areas already impacted by flooding. Coastal areas are likely to experience changes in the frequency and intensity of extreme water levels; future flooding events will be driven by changes in mean sea level, combined with the effects of tides, sea ice, storm surges and waves. Therefore, assessments of flood risks to property, and human life or safety would benefit from considering the impacts of future flooding conditions under a changing climate both in coastal and inland situations.

Integrating future climate conditions into flood mapping is an emerging area which has been applied in multiple jurisdictions across Canada and in other countries using different qualitative (e.g. adding ‘freeboard’, a vertical distance applied to account for uncertainty) and quantitative (e.g. modelling) approaches. A document titled *Case Studies on Climate Change in Flood Mapping* is part of the Federal Flood Mapping Guidelines Series. This document includes three approaches used in different jurisdictions in Canada to incorporate climate change projections into flood mapping. However, at this time, there is no broadly recognized standard methodology or approach.

Some methods are becoming more broadly used, including coastal flooding which incorporates sea level rise, and others have less consensus, including riverine flooding. The science associated with climate change projections is continually being updated, revised, and strengthened. The level of certainty that can be achieved with the impact of climate change on flood levels will increase over time. Uncertainty associated with various climate change scenarios and models can be partly quantified probabilistically by using an ensemble forecast approach. The development of guidance on options for addressing climate change in flood mapping will need to recognize different flood types, site conditions, availability of data as well as the regional context.

Environment and Climate Change Canada (ECCC) has maintained a climate monitoring network for several decades and has conducted climate modelling that has enabled the production of climate change scenarios for Canada and at the global scale. Recently, ECCC established the Canadian Centre for Climate Services to conduct research and provide access to climate information and tools which can be used to support flood mapping exercises.

The purpose of this section is to provide information on considerations for incorporating climate change projections into flood mapping. This section provides a description of the components needed to incorporate climate change considerations either qualitatively or quantitatively. The information provided is not intended to allow practitioners to select, analyze and use projected climate information, but rather to be more informed of the process. Climate information should be selected, analyzed and used on the advice of a qualified professional. A summary of a process for incorporating climate change is shown in Figure 6. Climate change practices are included in Table 7.

10.1 Climate Change Information and Data

10.1.1 Global Climate Models and General Circulation Models

The terms Global Climate Model and General Circulation Model are both abbreviated to GCM and are generally used interchangeably to describe numerical models that represent coupled physical processes in the atmosphere, ocean, cryosphere, and land surface. Development of the most recent generation of GCMs has emphasized the representation of biogeochemical cycles, particularly explicit representation of the carbon cycle; hence, these global models are often referred to as Earth System Models (ESMs). GCMs and ESMs are currently the most advanced tools employed to simulate the response of the global climate system to increasing greenhouse gas concentrations. They generally have a horizontal resolution of 100 to 250 square kilometres (km^2) with periods of simulation that can reach thousands of years (Charron, 2014).

10.1.2 Ensembles

GCMs are sophisticated but imperfect representations of reality and contain different assumptions about how to best represent complex physical processes, especially those that operate at spatial and temporal scales that are not explicitly resolved in the model. There are dozens of GCMs that have made projections of future climate, each with different assumptions and analytical methods. Due to the high level of uncertainty associated with using any particular GCM, it is generally recommended to use an ensemble of GCMs to project future climate variables. The Pacific Climate Impacts Consortium (PCIC 2017) uses an ensemble of 12 different GCMs to conduct statistical downscaling for projecting future climate variables. Other scenarios are available in Canada (e.g. through the Canadian Centre for Climate Services (at ECCC) and the Ouranos consortium) and internationally (e.g. Coupled Model Inter-comparison Project (CMIP)). In addition, most providers have model ensembles driven by different GHG emission scenarios (see Section 10.1.4).

10.1.3 Downscaling GCMs

Dynamical Downscaling by Regional Climate Models

Dynamical downscaling involves running a physically-based climate model, referred to as a Regional Climate Model (RCM), which operates at higher resolution, typically from 10-50 km, over a limited-area domain. For future climate simulations, the RCM is driven at its lateral boundaries by output from a GCM. This approach captures more local variability in land cover, water surface area, topography, and other physical features, including local feedbacks, but the RCM will also inherit errors and biases that may be present in the GCM. In some cases, the results of dynamical downscaling may not be more accurate than using data at the resolution of GCMs. The benefits and costs (including potentially high computing power) of dynamical downscaling should be assessed at the initial stage of climate change assessment. Like GCMs, RCMs are developed at numerous institutions around the world, and most participate in the Coordinated Regional Climate Downscaling Experiment (CORDEX).

Statistical Post-Processing and Downscaling

Usually, GCMs and RCMs are known to have systematic biases at local or basin scales. Consequently, GCM and RCM projected data requires post-processing to produce reliable estimations. Many de-biasing methods exist, including the ‘delta approach’ and quantile mapping. Further downscaling of GCM or RCM outputs to higher spatial resolution may also be required, in which case statistical downscaling methods can be applied either separately or in combination with bias correction.

Statistical downscaling involves the combination of climate model projections and local or regional observations to provide climate information with more spatial detail. Different approaches can be used, including regressions, stochastic weather generators and machine learning algorithms. In addition to helping with resolution, downscaling allows derivation of other variables needed for flood mapping. The Pacific Climate Impacts Consortium (PCIC 2017) has produced a publicly available, statistically downscaled ensemble of GCMs to an approximate grid size of 10 kilometres (km). A number of publicly available statistical downscaling tools exist (e.g. SDSM, Wilby et al. 2002 and ASD, Hessami et al. 2008). This approach is generally quicker and requires less computing power than dynamical downscaling. However, it does not attempt to reproduce atmospheric physical processes, instead relying on statistical relationships between climate model outputs and local or regional observations. Statistical downscaling approaches (e.g. regression-based methods) assume stationarity of statistical relationships as well as credible simulation of larger-scale variability by the climate model.

Although statistical downscaling provides more spatial detail, it is not certain for many locations whether the results of downscaling will be more accurate than using data at the resolution of the climate models. The benefits and costs of statistical downscaling should be assessed at the initial stage of climate change assessment.

10.1.4 Representative Concentration Pathways

Projections of future climate change require projections of external drivers of change such as greenhouse gas and aerosol concentrations that are used as inputs to GCMs. Representative Concentration Pathways (RCPs) are standardized scenarios of radiative forcing and accompanying greenhouse gas, atmospheric aerosol, and land use change time series referred to as RCP2.6 (low radiative forcing pathway), RCP4.5 and RCP6.0 (moderate radiative forcing pathways), and RCP8.5 (high radiative forcing pathway).

10.2 Coastal Considerations

Projections for sea level change are relatively simple to incorporate into future coastal flooding projections. However, coastal flooding is due to several different factors (briefly described in Section 9.0), and an assessment of projected changes in climate variables may be completed using GCM outputs (directly or downscaled) as described in previous sections.

In coastal cases, where a given flood probability is estimated over a long period into the future, the practitioner may use cumulative probabilistic techniques to account for increasing flood probabilities due to gradually increasing sea level. In addition, as indicated in the Section 7.0, sea level rise may allow larger waves to break close to shore, potentially increasing wave impacts.

10.2.1 Sea-Level Rise Projections

Relative sea level (RSL) refers to the relative sea-level change that is experienced on the coastline, and is a combination of global sea-level rise and vertical land motion. Incorporating projections of RSL change in flood mapping is essential for developing long-term adaptation strategies. Flood mapping that accounts for RSL should use up-to-date scenarios from national and international scientific reports. At the time of writing, relevant Canadian publications were available from NRCan (James et al., 2014; 2015; Lemmen et al., 2016) and DFO (Han et al. 2016). Land uplift contributes to relative sea-level fall, while land subsidence adds to relative sea-level rise. In Canada, a dominant source of vertical land motion is the delayed response of the solid Earth to weight of the ice sheets, a process called glacial isostatic adjustment (GIA) or postglacial rebound. Although GIA generates land uplift across much of Canada, it causes land subsidence in parts of the Maritimes and the Beaufort coastline.

10.3 Summary of Practices for Consideration of Climate Change

Figure 5: Climate Change Analysis Procedures

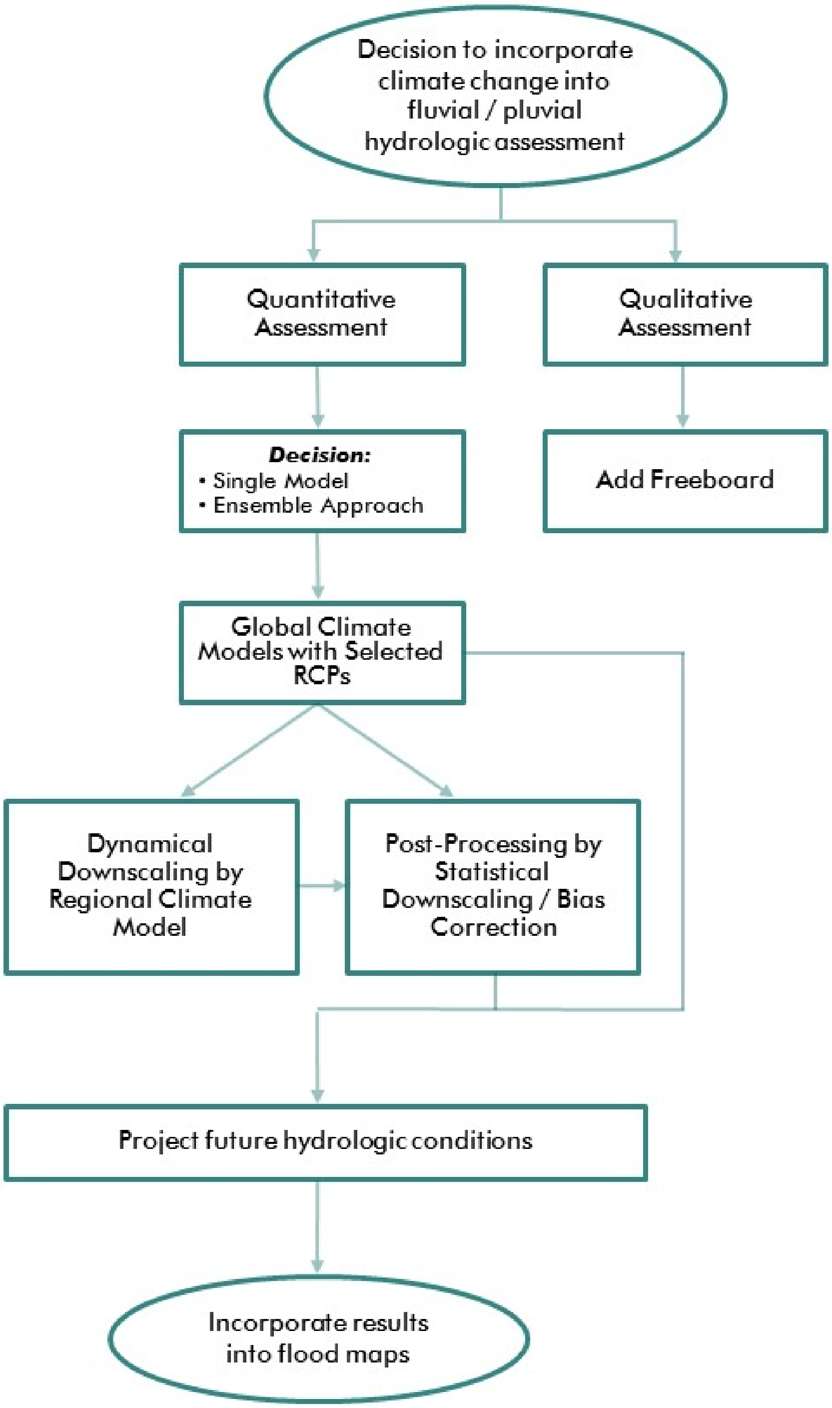


Table 7: Climate Change Consideration Practices

Number	Climate Change Consideration Practices
H.1	Involve the advice of a qualified professional when selecting, analyzing and using climate information for flood mapping.
H.2	Freeboard may be used as a qualitative method for accounting for climate change uncertainty.
H.3	Conduct downscaling for cases in which this approach will reduce the uncertainty associated with using a Global Climate Model.
H.4	Consider changes in sea level as well as hydrologic processes, climate processes, tides, and storm effects when analysing coastal flooding.
H.5	Update climate change projections as regularly as is reasonable and incorporate recent scientific developments.

11.0 RISK-BASED DECISION MAKING

The Federal Government has acknowledged, through the NDMP, and as a signatory to the Sendai Framework on Disaster Risk Reduction, that flood and other natural hazards should be managed based on the principles of risk, where hazard is considered along with the negative consequences of the events occurring. Understanding the hazard is a cornerstone of this, and is the focus of this document. A companion document in the *Federal Flood Mapping Guidelines Series* titled *Flood Risk Assessment* is planned to further guidance on the other components of risk (exposure, vulnerability and resilience). In the meantime, additional information on risk-based approaches to flood hazard can be found in the *Risk-Based Land-Use Guide: Safe use of land based on hazard risk assessment* (NRCan Geological Survey of Canada Open File 7772) and *Way forward for risk assessment tools in Canada* (NRCan Geological Survey of Canada Open File 8255).

12.0 UNCERTAINTY IN FLOOD RISK ASSESSMENT

The physical processes involved in flooding are inherently complex and uncertain, and therefore, flood maps are subject to uncertainty. This is in addition to uncertainty associated with the methods and limits associated with the estimation of flood extents and depths. Uncertainty should be acknowledged, and where appropriate, quantified and managed.

12.1 Uncertainty in Hydrologic and Hydraulic Assessments

Changes in climate and land use can cause hydrologic and hydraulic assessments (and the flood maps they support) to become obsolete. Periodic review of modelling assumptions is particularly important where flood maps form the basis for flood planning and regulation.

When a review shows that a flood map has become obsolete, updates are required so that map users can appropriately understand and manage risk. Careful planning can avoid the need for frequent updates that increase cost and can create a 'moving target' for municipal planning, growth and development.

As part of each flood mapping study, a qualified professional should review the intended scope and use of the flood mapping products in the context of ongoing and expected changes within the watershed and along the river corridor. Where possible, studies should identify an appropriate planning horizon for flood risk management, and take into account any climate and land use changes that are expected within that planning horizon (e.g. sea level rise, changes in precipitation, and urbanization of natural areas). Precautionary allowances may be appropriate in situations where uncertainty is high. Consideration should also be given to planned flood mitigation works that may affect inundation extents, depths, or velocities.

12.2 Uncertainty in Climate Change Projections

Climate change uncertainty is the result of a cascade of uncertainties coming from various sources: emission scenarios, climate models, downscaling and bias-correction methods, natural variability, statistical parameter estimation, and the applications methods that are being used to incorporate climate information as inputs. Regarding climate indicators for example, an uncertainty range of -5% to +200% is not uncommon when performing a sensitivity analysis on infrastructure design (Roy et al., 2017). Inter-comparison of applications methods, including hydrologic models, may be useful in ensuring that scenario-based impacts are assessed in a consistent manner, as previous studies have shown differences in hydrologic model representation of evaporation and snowmelt processes (Cohen et al., 2015).

The decision-making process can become much more complex in the context of these uncertainties. Users of flood maps can consider climate uncertainty with (a) safety factors, (b) by carrying out sensitivity analyses, (c) using a risk-based approach, (d) planning for adaptive designs, and (e) managing residual risks during infrastructure operation (Roy et al. 2017).

13.0 CONCLUSION

This document provides guidance for conducting hydrologic and hydraulic analyses for flood delineation in Canada. It is not intended to supersede other federal, provincial, territorial, or local legislation, regulations or by-laws. Publication of Version 1.0 of this document provides a basis for flood delineation, and future updates are anticipated to expand the scope and detail of the document.

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