Coastal flood risk assessment guidelines for building and infrastructure design: supporting flood resilience on Canada's coasts

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https://doi.org/10.4224/40002045

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COASTAL FLOOD RISK ASSESSMENT GUIDELINES FOR BUILDING AND INFRASTRUCTURE DESIGN

Supporting flood resilience on Canada's coasts

National Research Council Canada
Conseil national de recherches Canada

Canada

Paper: Cat. N° NR16-333/2020E · ISBN 978-0-660-37617-2
PDF: Cat. N° NR16-333/2020E-PDF · ISBN 978-0-660-36745-3

NRC.CANADA.CA

Coastal Flood Risk Assessment Guidelines for Building and Infrastructure Design

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Preface

This is the first (draft) edition of *Coastal Flood Risk Assessment Guidelines for Building and Infrastructure Design*.

Buildings and infrastructure situated on Canada's marine coasts and large lakes, and the communities that they serve, are vulnerable to flood hazards caused by the combined effects of tides, storm surges, waves, and tsunamis. In many coastal locations, the risks associated with flood hazards are projected to increase over the coming decades due to development and population growth, rising sea levels, land subsidence, declining sea ice cover, and possibly shifting weather patterns associated with climate change. This escalating risk profile will necessitate more sophisticated approaches to coastal flood risk management that leverage a broader range of options and techniques, including building- and infrastructure-level design measures.

This document was developed as a step toward addressing gaps in guidance on how to assess flood risk to buildings and infrastructure in coastal areas of Canada for design (and retrofitting) applications. Coastal flood risk assessments (CFRAs) provide a means to determine the risk (likelihood and consequences) of flooding, as a vital first step in guiding decision making for flood-resilient building and infrastructure design. The guidelines are intended to inform designers of buildings and infrastructure, and other interested parties (including owners), on best practices for conducting CFRAs to support resilient design. This is intended to complement existing and emerging national guidance that addresses other aspects and applications of flood risk assessment (e.g., the Federal Floodplain Mapping Guidelines Series), and establish linkages to building and infrastructure design, to support more holistic approaches to flood risk reduction. It is envisaged that, over time, the guidelines will enable the development of new provisions in Canadian building codes and infrastructure design standards to enhance flood resilience, and help to clarify the potential role of building and infrastructure design within the portfolio of flood risk management tools available.

In 2018, an advisory committee was established to provide (on a voluntary basis) technical review and advice in support of the guideline development, and to coordinate with other relevant initiatives and stakeholders. Collectively, members have broad expertise in various fields relevant to coastal flood risk assessment (risk analysis, coastal engineering, oceanography, climate science, natural hazards, municipal engineering and emergency response), knowledge of the distinct challenges faced in each of Canada's four coastal regions (Arctic, Atlantic, Great Lakes-St. Lawrence System, and Pacific), and building/infrastructure design practice. The committee includes representatives from various levels of government, academia, and the private sector.

These draft guidelines are intended to promote discussion and an exchange of ideas on striving for best practices to assess and address coastal flood risks to buildings and infrastructure, and ultimately communities, across Canada. This will require the involvement of a broader number of interested groups and professionals than could be engaged within a practical timeframe to develop this draft. It is expected that the document will evolve over time, be periodically updated, and/or be integrated into more holistic guidelines, codes or standards for flood risk management and building/infrastructure design.

The development of this guideline document was made possible, in part, by the financial support of Infrastructure Canada and the National Research Council of Canada, as part of the Climate-Resilient Buildings and Core Public Infrastructure project under the Pan-Canadian Framework on Clean Growth and Climate Change.

Summary

More than 15 million people live within 20 km of Canada's marine and Great Lakes coasts. The buildings and infrastructure that they rely on are vulnerable to coastal flood hazards resulting from extreme water levels, waves, tsunamis and other contributing factors. The risks associated with coastal flood hazards are escalating over time, due to development and population growth in coastal zones, and climate-driven effects, such as global sea-level rise. These growing concerns are prompting a broad re-think of how coastal flood risks can be better managed in Canada, including how building and infrastructure design practice can be enhanced to support resilience objectives.

These guidelines apply to coastal flood risk assessments for building and infrastructure design (including retrofit design) applications in Canada. The document is intended to inform, and provide a technical reference for, a wide variety of users interested in building and infrastructure design in areas potentially exposed to coastal flood hazards under present-day and/or future conditions. The guidelines advocate a move toward risk-based approaches to analysis and design for flood resilience, and identify the following:

- Key concepts and terminology relevant to understanding and performing coastal flood risk assessments to support building and infrastructure design.
- A possible framework and methodology for conducting coastal flood hazard and risk assessments to inform the design and rehabilitation of buildings and infrastructure in areas potentially exposed to coastal flood hazards.
- The different levels or tiers of analysis that can be used as the basis for risk assessments, and the circumstances in which they should be applied.
- Suggestions for effective stakeholder, partner and public engagement in the coastal flood risk assessment process.
- Recommendations for establishing risk-based design criteria for buildings and infrastructure.
- Data requirements, and sources of data and information, to support coastal flood risk assessments.
- Methodologies and key considerations for assessing coastal flood hazards.
- The role of building and infrastructure design practice within the portfolio of tools and strategies available to address coastal flood risks in a changing climate.

Though not the focus of the guidelines, some background information on strategic approaches to coastal flood risk management is provided. This information is provided to illustrate how the information derived from a coastal flood risk assessment can be used to support building and infrastructure design within the broader context of managing, mitigating and adapting to flood risks. Efforts have also been made to identify gaps and future needs to support coastal flood risk assessments for design applications, which include:

- Expanded hazard datasets (including enhanced spatial and temporal coverage of water level, wave and other parameter measurements).
- Improved vulnerability-hazard function datasets, which would enable proper consideration in risk assessments of (i) the benefits and performance of difference structural features, materials, and construction techniques; and (ii) regional differences in hazards and construction types.
- New provisions in building codes and infrastructure design standards to address flood resilience objectives, and to enable integration of flood (and eventually multi-hazard) risk management practices with codes and standards.

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Glossary

Term	Definition
Adaptation	The practice of adjusting or taking actions to limit or reduce vulnerability to changing hazard risk. In the context of climate change impacts on coastal flood hazard risk, specific adaptation actions might include improved coastal zone management, changes to planning, permitting and codes and standards, design of buildings/infrastructure, and social preparedness.
All Hazards	Referring to the entire spectrum of hazards, whether they are natural or human-induced. For example, hazards can stem from natural (e.g., geological or meteorological) events, industrial accidents, national security events, or cyber events.
All-Hazards Approach	An emergency management approach that recognizes that the actions required to mitigate the effects of different types of emergencies can be similar, irrespective of the nature of the incident/hazards, thereby permitting an optimization of planning, response, and support resources.
Annual Exceedance Probability (AEP)	The probability or chance that a hazard event of a given magnitude will occur or be exceeded in any given year, usually expressed as a percentage.
Assets-At-Risk	Refers to those things that may be harmed by a hazard (e.g., houses, buildings, infrastructure, cultural assets, or the environment).
Average Annual Damages	A risk metric expressing, in monetary terms, the average damages expected in a year (e.g., due to coastal flooding), considering all possible AEP events and associated damages.
Barometric Set-Up (Set-Down)	Also referred to as Atmospheric Set-Up (Set-Down). The rise (or fall) in water level due to changes in atmospheric pressure during the passage of storm events. A component of storm surge.
Coast	In these guidelines, coastal areas are generally taken to mean Canada’s marine coasts (Arctic, Atlantic, and Pacific) and the Great Lakes. The guidelines may also be useful for informing risk assessments on the shores of other lakes in Canada; particularly larger lakes where some physical processes are similar to oceanic processes.
Coastal Flood Hazard	A potentially damaging flood event (or multiple events), that may cause damage to buildings and infrastructure in coastal regions, and/or the loss of life, injury, property damage, social and economic disruption, or environmental degradation. Coastal flood hazards are characterized by location, intensity, duration, frequency, and probability. The focus of these guidelines is on coastal flood hazard and risk arising from ocean/sea and lake processes, including the effects of tides, extreme water levels, relative sea-level rise, and waves. Contributions from fluvial (riverine), pluvial (intense rainfall), elevated groundwater levels, river ice and erosion hazards are not

	addressed in detail, except to highlight circumstances and exceptions where such processes may have an important influence on coastal flood risks to buildings and infrastructure.
Coastal Flood Risk	The combination of the probability (likelihood) of a coastal flood hazard event (or multiple events) and the associated negative consequences.
Contents Damages	The damages to the contents within a building, such as appliances, furniture, electronics, etc.
Critical Infrastructure (CI)	Processes, systems, facilities, technologies, networks, assets, and services essential to the health, safety, security, or economic well-being of Canadians and the effective functioning of government.
Damages	The financial and non-financial impacts/consequences of a hazard event. For buildings and infrastructure, this may include structural damage or loss of performance, or damages due to loss of serviceability/operability.
Design Criteria	The explicit objectives that must be met by a building or infrastructure asset or system, defining what success looks like for a new build or retrofit.
Digital Elevation Model	A digital representation of relief composed of an array of elevation values referenced to a common vertical datum and corresponding to a regular grid of points on the earth's surface. These elevations can be either ground or reflective-surface elevations.
Digital Surface Model (DSM)	A representation of the earth's surface including vegetation and human-made structures. The Digital Surface Model (DSM) provides the height of the vegetation, canopies and structures relative to the vertical datum.
Digital Terrain Model (DTM)	A representation of the bare ground surface without any objects, such as vegetation and buildings. The Digital Terrain Model (DTM) provides the height of the ground relative to the vertical datum.
Direct Damages	The financial costs to repair or replace an asset to its pre-flood condition. Direct damages include structure and contents damages. Direct damages, per unit floor area, are estimated based on the structure classification and water depth. Adjustment factors may be used to account for flood duration, sediment content, etc.
Disaster	A serious disruption of the functioning of a community or a society at any scale due to hazardous events interacting with conditions of exposure, vulnerability and capacity, leading to one or more of the following: human, material, economic and environmental losses and impacts.
Disaster Risk Management	The application of disaster risk reduction policies and strategies to prevent new disaster risk, reduce existing disaster risk and manage residual risk, contributing to the strengthening of resilience and reduction of disaster losses.

Disaster Risk Reduction	The concept and practice of reducing disaster risks through systematic efforts to analyze and reduce the causal factors of disasters. Disaster risk reduction includes disciplines like disaster mitigation and preparedness.
Encounter Probability	The likelihood of an event with a defined AEP being encountered (or exceeded) over a prescribed time horizon, such as the design life of a building or infrastructure asset.
Erosion	The removal of sediment by, for example, wind or moving water.
Exposure	The presence of people, infrastructure, housing, or other assets-at-risk (or parts thereof) in places that could be adversely affected by hazards. Exposure occurs when an asset-at-risk lies within a region that may experience a hazard. Therefore, just as there are different hazard levels (different AEPs) there are different levels of exposure. Exposure does not necessarily imply an adverse impact. Example: parts or all of houses, schools, and livestock in an area that is prone to flood hazards.
Flooding	The presence of surface water on land that is normally dry.
Floodproofing	Any combination of structural or non-structural additions, changes, or adjustments to structures that reduce or eliminate flood damage to buildings, infrastructure, and their contents. Dry floodproofing measures prevent water ingress to a building or infrastructure envelope. Wet floodproofing measures prevent or provide resistance to damage from flooding while allowing floodwaters to enter the building or infrastructure envelope.
Frequency of Flooding	The number of occurrences of flood events over a defined period of time. Often expressed as the Annual Exceedance Probability or Likelihood.
Hazard	A potentially damaging physical event, phenomenon, or human activity that may cause the loss of life, injury, property damage, social and economic disruption, or environmental degradation. Hazards can include latent conditions that may represent future threats, and can have different origins: natural (geological, hydrometeorological, and biological) or be induced by human processes.
Hazard Assessment	Acquiring knowledge of the nature, extent, intensity, duration, frequency, and probability of a hazard occurring.
Higher High Water Large Tide	The average of the highest high tide elevations, one from each year of a 19-year tidal epoch.
Indirect Damages	The financial costs incurred as a result of a flood event. Indirect damages include flood fighting/mitigation, evacuation, temporary housing, employment and productivity losses, post-flood clean-up, etc. Areas outside the flood hazard may also experience indirect damages, such as business disruption.

Intangible Damages	The non-financial or otherwise non-quantifiable impacts due to a flood event including social, health, and environmental impacts. Areas outside the flood hazard may also experience intangible damages, such as due to the spill and transport of a deleterious material.
Inundation	Flooding or immersion of land resulting from water levels exceeding local ground elevations.
Likelihood	A general concept relating to the chance of an event occurring. Likelihood is generally expressed as a probability or a frequency of a hazard of a given magnitude or severity occurring or being exceeded in any given year. It is based on the average frequency estimated, measured, or extrapolated from records over a large number of years, and is usually expressed as the chance of a particular hazard magnitude being equaled or exceeded in any given year (e.g., Annual Exceedance Probability).
Light Detection and Ranging (LiDAR)	A remote sensing method that uses light in the form of a pulsed laser to measure ranges (variable distances) to the earth.
Losses	Equivalent to damages that occur as a result of a flood event, both direct and indirect, tangible and intangible.
Maladaptation	Actions, or inaction, that may lead to increased vulnerability or risk, or reduce capacity to adapt to changing hazard risk.
Mitigation	The practice of taking actions or implementing measures to control or limit flood risk, typically by reducing vulnerability. Note: This definition differs from “Climate Change Mitigation”, which is typically used to refer to efforts to reduce or prevent carbon emissions.
Natural Hazard	Natural process or phenomenon that may cause loss of life, injury, other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage.
Probability	In statistics, a measure of the chance of an event or an incident happening. This is directly related to likelihood.
Quantitative Risk Assessment	A risk assessment that is completed using quantified or calculated measures of risk.
Residual Risk	The risk that remains even when effective risk reduction measures are in place.
Residual Water Level	The difference between the absolute or total water level (as measured by a tide gauge) and the astronomical (tidal) component. As storm surge often represents the greatest contribution to the residual water level at a coastal site, the terms “storm surge” and “residual water level” are sometimes used interchangeably.
Resilience	The ability of a system (such as individual or multiple buildings or infrastructure assets), community, or society exposed to hazards to resist, absorb, accommodate and recover from the effects of a hazard

	in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions.
Risk	The combination of the probability of a hazard event and its negative consequences.
Risk Assessment	A method to determine the nature and extent of risk by analyzing potential hazards and evaluating existing conditions of vulnerability that together could potentially harm exposed buildings, infrastructure, people, property, services, livelihoods, and the environment on which they depend. Risk assessments (and associated risk mapping) include: a review of the technical characteristics of hazards, such as their location, intensity, duration, frequency, and probability; the analysis of exposure and vulnerability, including the physical, social, health, economic and environmental dimensions; and the evaluation of the effectiveness of prevailing and alternative coping capacities, with respect to likely risk scenarios. This series of activities is sometimes known as a risk analysis process.
Risk Management	The systematic approach and practice of managing uncertainty to minimize potential harm and loss.
Risk Tolerance	The readiness to bear risk. This is variable across different hazards, people and time.
Scour	Erosion of sediment (e.g., by floods or waves), usually in the vicinity of a structure or building.
Storm Surge	The increase (or decrease) in still water level at a coastal site due to meteorological conditions. Storm surge may include wind set-up (or set-down) and barometric set-up (or set-down).
Physical Damages	Damages to the physical systems of a building or infrastructure, such as walls, floors, heating and cooling systems, etc.
Swash	See “wave runup”.
Tangible Damages	Measurable impacts due to a flood event.
Tsunami	A series of waves caused by a rapid, large-scale disturbance of water. Tsunamis can be triggered by earthquakes, landslides, volcanic eruptions, meteor impacts, human activities (e.g., explosions), and meteorological/atmospheric phenomena (meteotsunamis).
Vulnerability	The characteristics and circumstances of a community, system, or asset that make it susceptible to the damaging effects of a hazard.
Wave Overtopping	When wave runup 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.

Wave Runup	The maximum elevation of wave uprush on the shore above the still water level. Wave uprush consists of two components: superelevation of the mean water level due to wave action (wave set-up) and fluctuations about that mean (swash). Typically not included in the definition of storm surge.
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. Wave set-up contributes to wave runup. Typically not included in the definition of storm surge.
Wind Set-Up (Set-Down)	The downwind (or upwind) increase (or decrease) in water level occurring as a result of shear stress exerted by the wind on the water surface. A component of storm surge.

Acronyms

AAD	Average Annual Damages
AEP	Annual Exceedance Probability
AIDR	Australian Institute for Disaster Resilience
ASCE	American Society of Civil Engineers
BSI	British Standards Institution
CAN-EWLAT	Canadian Extreme Water Level Adaptation Tool
CDEM	Canadian Digital Elevation Model
CDF	Cumulative Distribution Function
CFD	Computational Fluid Dynamics
CFRA	Coastal Flood Risk Assessment
CFSR	Climate Forecast System Reanalysis
CGVD	Canadian Geodetic Vertical Datum
CHS	Canadian Hydrographic Service
CI	Critical Infrastructure
CIRIA	Construction Industry Research and Information Association
CORDEX	Coordinated Regional Downscaling Experiment
DEM	Digital Elevation Model
DFO	Fisheries and Oceans Canada
DSM	Digital Surface Model
DTM	Digital Terrain Model
FEMA	(U.S.) Federal Emergency Management Agency
FPIC	Free, Prior and Informed Consent
GEV	Generalized Extreme Value
GFDRR	Global Facility for Disaster Risk Reduction
GLERL	Great Lakes Environmental Research Laboratory
GPS	Global Positioning System
HAT	Highest Astronomical Tide

HHWLT	Higher High Water Large Tides
HRDEM	High-Resolution Digital Elevation Model
HyVSepS	Hydrographic Vertical Separation Surfaces
IDF	Intensity-Duration-Frequency
IGLD	International Great Lakes Datum
IHO	International Hydrographic Organization
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
JPM	Joint Probability Method
LiDAR	Light Detection and Ranging
LNG	Liquified Natural Gas
MCT	Maximum Considered Tsunami
MSL	Mean Sea Level
NARCCAP	North American Regional Climate Change Assessment Program
NAVD88	North American Vertical Datum of 1988
NFIP	(U.S.) National Flood Insurance Program
NLSW	Non-Linear Shallow Water
NOAA	(U.S.) National Oceanic and Atmospheric Administration
NRC	National Research Council of Canada
NRCan	Natural Resources Canada
OMNRF	Ontario Ministry of Natural Resources and Forestry
PTHA	Probabilistic Tsunami Hazard Assessment
RCP	Representative Concentration Pathway
RSLR	Relative Sea-Level Rise
SDB	Satellite-Derived Bathymetry
SEI	Structural Engineering Institute
SfM	Structure-from-Motion
SLR	Sea-Level Rise
TOR	Terms of Reference
UAV	Unmanned Aerial Vehicle

UN	United Nations
UNDRIP	United Nations Declaration on the Rights of Indigenous Peoples
UNDRR	United Nations Office for Disaster Risk Reduction
UNISDR	Former acronym for United Nations Office for Disaster Risk Reduction (see UNDRR)
USACE	United States Army Corps of Engineers
WIS	Wave Information Study
WSC	Water Survey of Canada

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Acknowledgements

The authors thank all contributors for their input, support and advice during the development of these guidelines. The Climate-Resilient Buildings and Core Public Infrastructure (CRBCPI) project management team and the technical teams at the National Research Council's Construction Research Centre are thanked for their support of the guideline effort in various ways, particularly Marianne Armstrong, Sarah Gagne, Fiona Hill, Johanne Lavictoire and Ahmed Attar. Karen Hagar, Mallory Kroker, and Maryse Proulx from the National Research Council's Ocean, Coastal and River Engineering Research Centre are thanked for administrative support. Useful comments, edits and suggestions to improve various sections of the guidelines were provided by Anne Barker, Seth Bryant, David Didier, Mike Currie, Donald Forbes, Bob Frederking, Mitchell Hahn, Carolyn Mann, Irvin Marucelj, Diane Meehan, Karen Savage, John Sommerville, Denise Sudom and Jackie Yip. Nicole Couture at Natural Resources Canada provided useful input to early phases of the guideline development. Support received from the National Research Council's Marine Infrastructure, Energy and Water Resources Program is gratefully acknowledged. The guidelines were copy edited by Sarah MacKinnon of Interwoven Editing.

1 Introduction

1.1 Scope and Purpose

1.1.1 General

These guidelines apply to coastal flood risk assessments for building and infrastructure design applications in Canada. The guidelines identify:

- A possible framework and methodology for conducting coastal flood hazard and risk assessments to inform the design and rehabilitation of buildings and infrastructure in areas potentially exposed to coastal flood hazards.
- Data requirements, and sources of data and information, to support coastal flood risk assessments.
- Suggestions for stakeholder and partner engagement.
- Recommendations for establishing design criteria for buildings and infrastructure to address coastal flood risks.

1.1.2 Users/Audience

These guidelines are intended for use by:

- Designers of buildings and infrastructure in coastal regions of Canada (e.g., users or adopters of the National Building Code of Canada).
- Professionals involved in design for retrofitting of buildings and infrastructures for coastal flood resilience.
- Provincial and municipal authorities or others interested in coastal flood resilience measures for buildings and infrastructure (e.g., through regional implementation of the National Building Code).
- Owners and operators of buildings and infrastructure in coastal regions of Canada.
- Educators, for the purposes of knowledge transfer.
- Others with a vested interest in understanding or managing coastal flood hazards and risks to buildings and infrastructure.

1.1.3 Applicability

These guidelines apply to the assessment of coastal flood risks to buildings and certain types of infrastructure. The outcomes of such assessments are intended to inform the design of new buildings and infrastructure, and retrofitting measures for existing buildings and infrastructure.

The primary focus of this guideline document is on assessing coastal flood risks to buildings and certain types of "Core Public Infrastructure", specifically:

- Bridges
- Roads
- Water and Wastewater Infrastructure
- Transit

In these guidelines, coastal areas are generally taken to mean Canada's marine coasts (Arctic, Atlantic, and Pacific) and the Great Lakes. The guidelines may also be useful for informing risk assessments on the shores of other lakes in Canada; particularly larger lakes where some physical processes are similar to oceanic processes.

1.1.4 Exclusions

Although some high-level strategies for mitigation of coastal flood risks and adaptation to future changes in coastal flood risks are presented in this document, the primary focus is on best practices for assessing coastal flood risks to inform mitigation and adaptation. It is anticipated that mitigation and adaptation measures will be more comprehensively addressed in other guidance, including land use planning regulations, local bylaws, infrastructure design standards and building codes. Nevertheless, the guidance provided herein may inform the development or updating of existing regulations and guidance on mitigation and adaptation measures.

Specific considerations for infrastructure not described as "Core Public Infrastructure" in Section 1.1.3, such as community flood protection works (e.g., sea dikes), stormwater systems and ports, are excluded. However, the information presented in these guidelines may still be useful for stakeholders interested in the planning and design of those types of infrastructure.

The Sendai Framework for Disaster Risk Reduction (UNISDR, 2015), to which Canada is a signatory, emphasizes multi-hazard approaches to assessing and managing disaster risks. The scope of these guidelines is limited to presenting best practice approaches for assessing coastal flood hazards and risks to buildings and infrastructure, and therefore does not consider multi-hazard approaches (e.g., including wildfires, earthquakes, landslides), beyond the fact that coastal flood hazards originate from multiple sources. Nevertheless, it is anticipated that the information presented herein will provide valuable background information on how coastal flood hazards can be characterized as part of multi-hazard risk assessments.

The focus of these guidelines is on coastal flood hazards and risks arising from ocean/sea and lake processes, including the effects of tides, extreme water levels, sea-level rise, waves and tsunamis. Contributions from fluvial (riverine), pluvial (intense rainfall), debris, river/lake/sea ice, groundwater, hydrogeology, meteotsunamis and erosion hazards are not addressed in detail, except to highlight some circumstances and exceptions where such processes may have an important influence on coastal flood risks to buildings and infrastructure.

1.2 Suggestions for How to Use this Document

Based on the target users/audiences identified in Section 1.1.2, it is assumed that users of these guidelines have some basic prior knowledge and understanding of coastal flood hazards and risk assessment processes. The guidelines are therefore unlikely to be read from "cover to cover" but are intended to provide a useful reference for technical information and best practice approaches to coastal flood risk assessment. While the guidance is intended to identify general best practices, it is recognized that there is no "one-size-fits-all" approach. Indeed, there are a multitude of region- and site-specific issues and stakeholder needs that may warrant consideration during a coastal flood risk assessment, and it is not feasible to comprehensively address them all here. An attempt has therefore been made to strike a balance between: (i) providing sufficient detail to satisfy the needs of designers and practitioners who may be more familiar with the underling subject matter, and (ii) making high-level processes and information accessible to non-specialist users or interested audiences in a reasonably user-friendly way. References to best practices and data sources are therefore provided, without delving too deeply into technical details and specifics that are explained in other guidance and reference documents. To aid user-friendliness, the overall framework for coastal flood risk assessment is provided in Figure 1 (see also Section 3), with hyperlinks to sections addressing the main steps in the process. It is anticipated that this framework will provide a useful starting point and reference for users of the guidelines, directing them to relevant sections of the document.

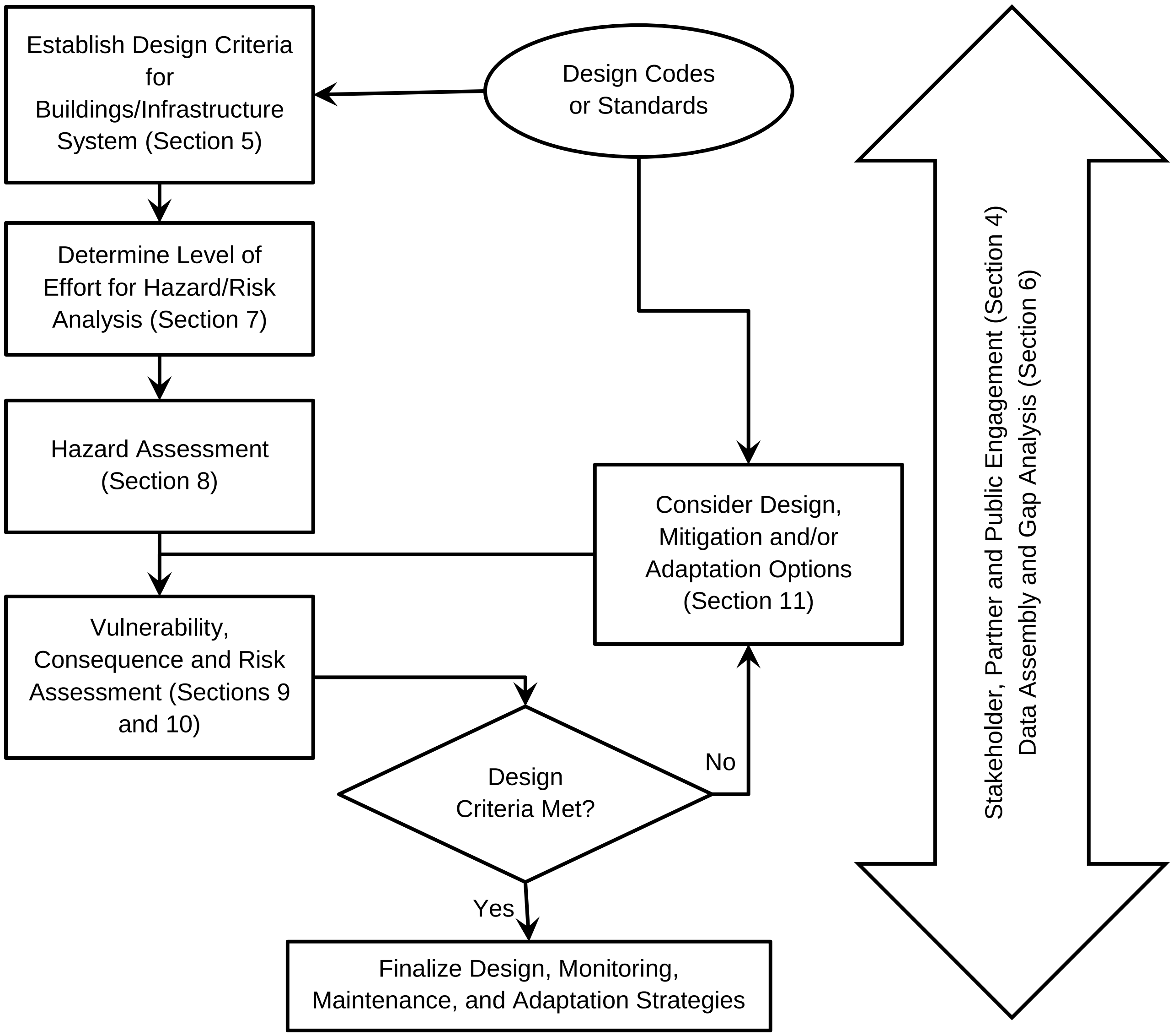

Figure 1. Coastal flood risk assessment framework.

1.3 Related Guidance

The guidelines provided in this document are intended to supplement and complement existing guidance developed by provinces, territories and municipalities, as well as the Federal Floodplain Mapping Guidelines Series being developed by Natural Resources Canada (2019), by providing additional information relevant to assessing coastal flood risks specifically for building and infrastructure design (or retrofitting) purposes. As such, it is anticipated that, going forward, the guidelines may be referenced or replaced by new or updated provisions for addressing flood loads and effects in infrastructure design standards, the National Building Code of Canada, and provincial/territorial building codes.

2 What is Flood Hazard Risk?

2.1 Risk

A solid grounding in the understanding of the term *risk* is key to understanding the components of a risk assessment. *Risk* is a function of both the *likelihood* of an event occurring, and the *consequences* if that event occurs (Figure 2). C*onsequence* is defined as a function of the *hazard* (where and how severe is the event?), *exposure* (what's in the way of the hazard?) and *vulnerability* (how susceptible is the asset?). *Vulnerability* can be further described as a function of *resilience* (how will the system—for example, a building, infrastructure asset, its users or inhabitants, and interconnected systems—resist and recover?), and *damage mitigation* (what measures are in place to reduce damage?).

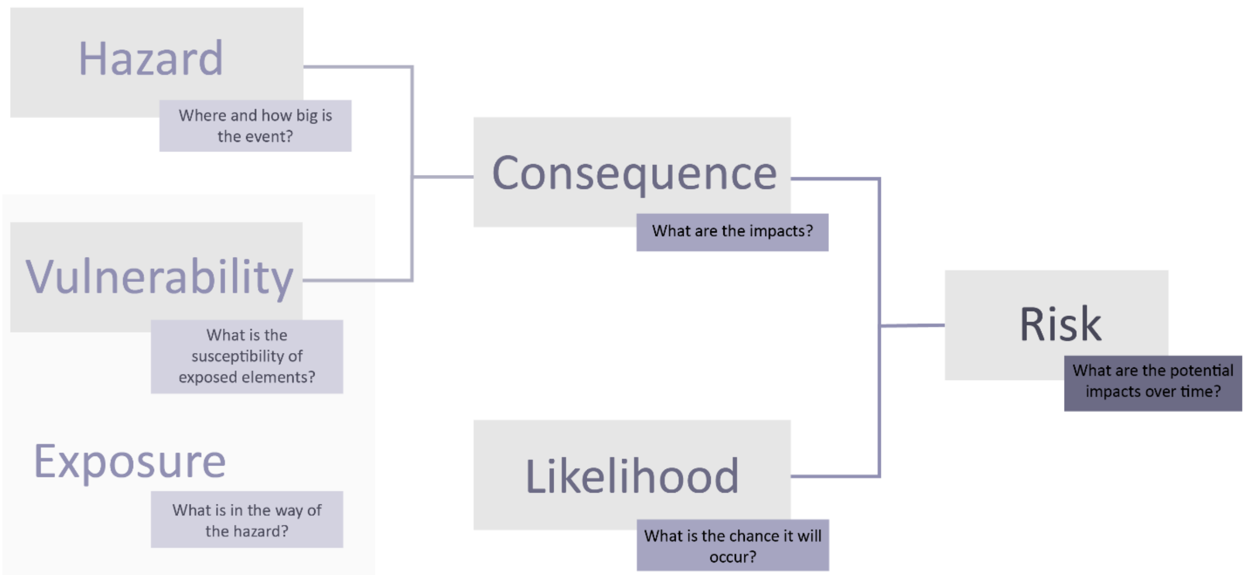

Figure 2. Risk as a function of consequence and likelihood (Ebbwater Consulting Inc., 2019).

Risk increases with likelihood and consequence (Figure 3). A virtually certain, low-consequence event can have a similar level of risk as a catastrophic but rare event. This becomes particularly important as we look across the long (i.e., multidecadal) time-horizons applicable to the design lifetimes of buildings and infrastructure. For example, a nuisance hazard that occurs annually over several decades and accumulates losses may in fact be more impactful than a catastrophic hazard that occurs just once. A risk assessment can be used to compare both the impacts and the potential benefits of design and mitigation options for the whole spectrum of nuisance to catastrophic events. Risk assessments therefore provide a rigorous, logical, and defensible basis on which to make informed investment, planning and design decisions. Consequently, risk-based assessment methodologies play an important role in building resilience to the effects of coastal flooding and climate change around the world (e.g., Bowker et al., 2007; FEMA, 2016b; Jongejan & Maaskant, 2015; Nicholls et al., 2005; van Alphen et al., 2011).

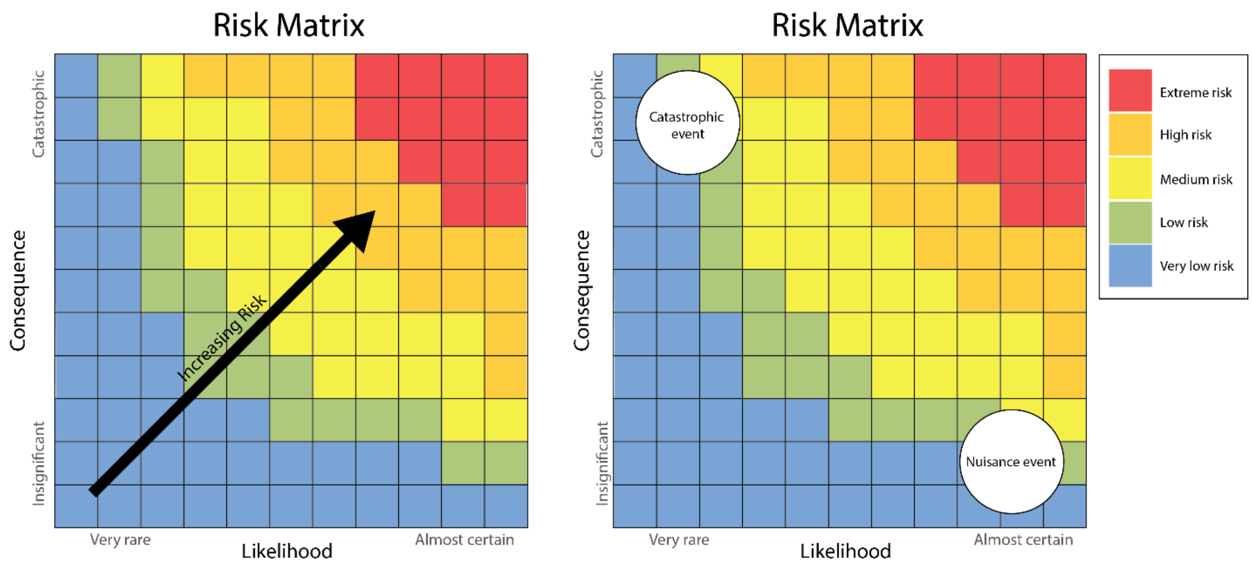

Figure 3. Risk as a function of likelihood and consequence – nuisance and catastrophic risk (Ebbwater Consulting Inc., 2019).

2.2 Coastal Flood Hazard Risk

Coastal flood hazards originate from a variety of sources and combinations of sources; including tides, storm surges, waves, seiches, rainfall, river flows and tsunamis. The likelihoods associated with each type of event are different, and site-specific, and the type and combinations of hazard sources can significantly affect the scale and severity of the impacts (consequences) (e.g., Figure 4[1]). For example, coastal flood risks can be associated with low likelihood events, such as tsunamis, which can have minimal or catastrophic impacts, or more frequently occurring storm events. There are many different pathways that can lead to coastal communities, buildings or infrastructure becoming exposed to flood hazards (e.g., breaching or overtopping of coastal defences, direct inundation, erosion, etc.). Furthermore, as explained in Section 2.1, there are multiple factors that affect vulnerability. Natural hazards are also characterized by the speed at which they are triggered and propagate. For instance, proximal earthquake-generated tsunamis (i.e., where the seismic source is close to the area of interest) are generally considered to be sudden (as opposed to slow-onset) hazard events, which has considerable implications for warning times and response capacity. The duration of a coastal flood hazard event (hours or days) will also affect risk. Understanding the scale and specific nature of hazard risk is key to planning and design for mitigation, management, and response.

[1] Likelihood and consequence designations in Figure 4 are for illustrative purposes only and are indicative. The likelihood and consequences of different types of events is highly site-specific.

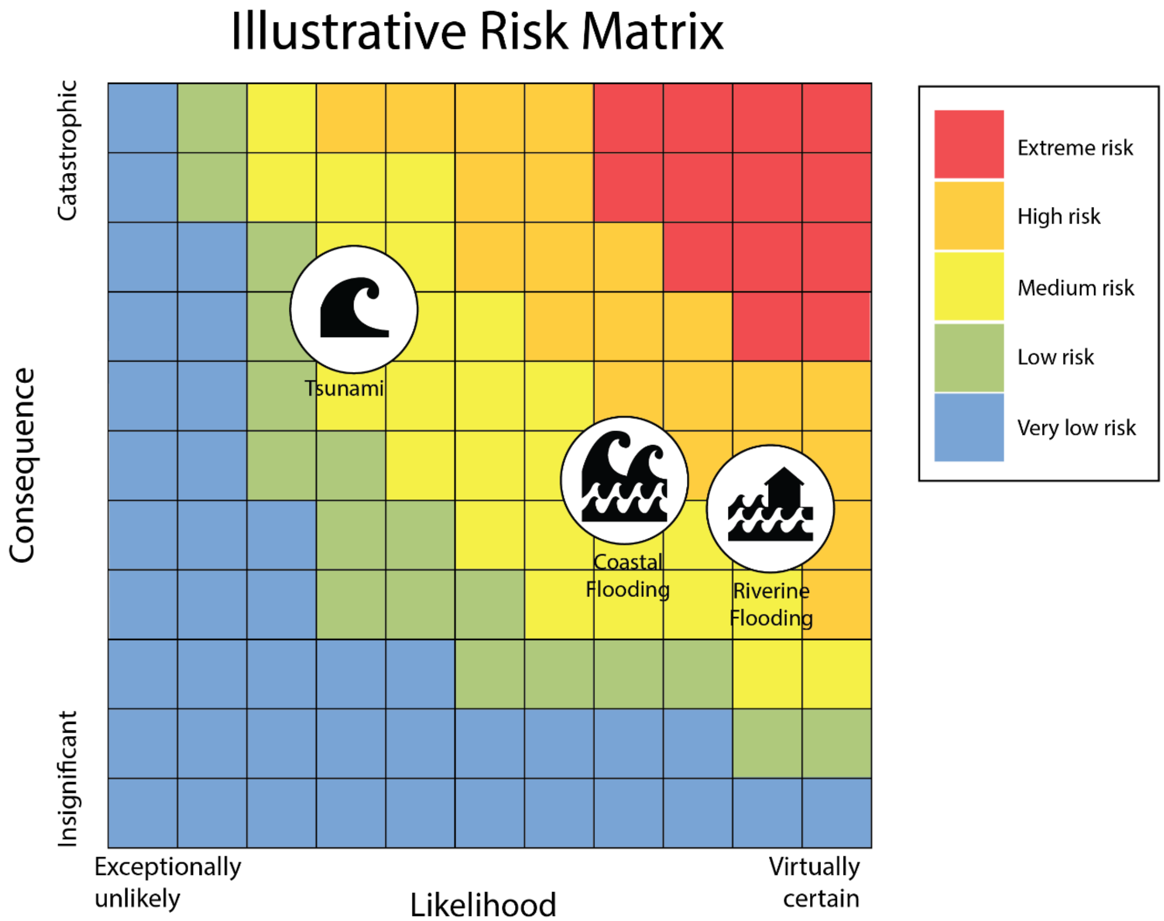

Figure 4. Illustrative risk matrix for selected natural hazards (Ebbwater Consulting Inc., 2019).

2.3 Risk as a Dynamic Concept

Risk is not static. The variables that affect risk (i.e., hazard likelihood and severity, exposure, and vulnerability) are all prone to change over time. These changes may be a result of global-scale issues, such as climate change, which can impact local hazard profiles (e.g., through sea-level rise), or local issues (e.g., land use decisions) which may affect exposure and vulnerability. Figure 5 demonstrates schematically how risk can increase over time. For many natural hazards it is expected that climate change will lead to increases in event likelihoods (it may also lead to increases in event severity and therefore consequences), resulting in increased risk (i.e., shifting the risk bubble from left to right along the likelihood axis in Figure 5). The consequences associated with hazard events can also change over time. Where development is permitted in hazard areas, negative consequences will be exacerbated, corresponding to a shift from the bottom to the top of Figure 5 along the consequence axis and an increase in risk. These effects can be compounded, and increased event likelihoods combined with increased consequences will result in significantly increased risk (as illustrated by the bubble in the top right of the graphic).

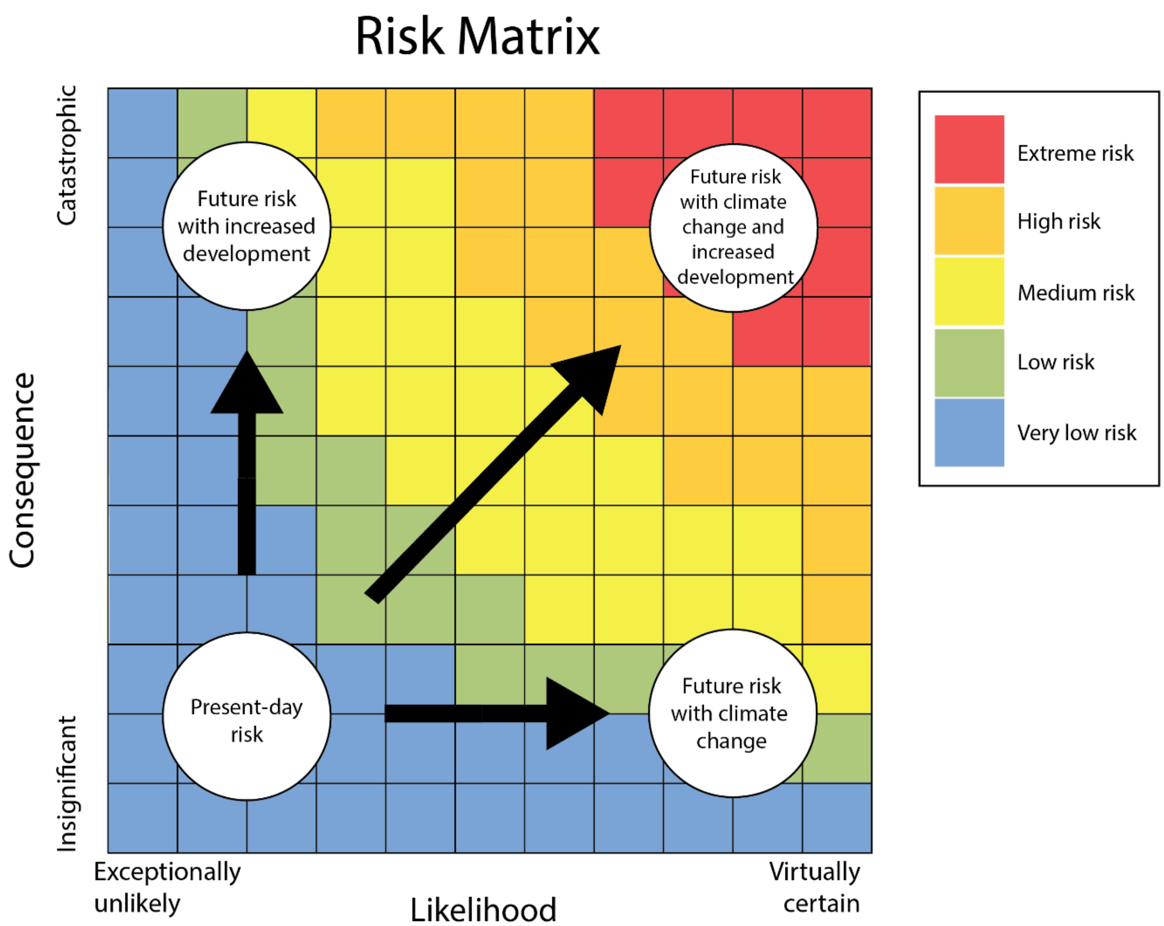

Figure 5. Dynamic risk with climate change and increased development (Ebbwater Consulting Inc., 2019).

Given the dynamic nature of risk, it is important to consider both present-day and future risk, spanning or extending beyond the full lifecycle of buildings and infrastructure, especially when seeking to maintain or reduce risk over time. These ideas, in the context of coastal flood risk, are explored in more detail later in these guidelines.

2.4 Hazard Likelihood Concepts

The likelihood (or probability) of hazard occurrence is a key descriptor contributing to understanding of the hazard. The frequency of a particular event is tied to its severity. Minor hazard events tend to occur more frequently, and larger magnitude ones occur less frequently.

2.4.1 Annual Exceedance Probabilities

In this report, hazard likelihood is expressed as an Annual Exceedance Probability (AEP). AEP refers to the probability of a coastal flood hazard event occurring or being exceeded in any year, expressed as a percentage.[2] For example, an extreme coastal flood hazard that has a calculated probability of 0.2% of occurring or being exceeded in this or any given year is described as the 0.2% AEP coastal flood hazard. The return value (i.e., the magnitude of the hazard) for a defined AEP is typically determined by fitting an extreme value statistical distribution to historical data (Figure 6). Further details of techniques to evaluate AEPs associated with coastal flood hazards, or components thereof, are provided in Section 8.4.

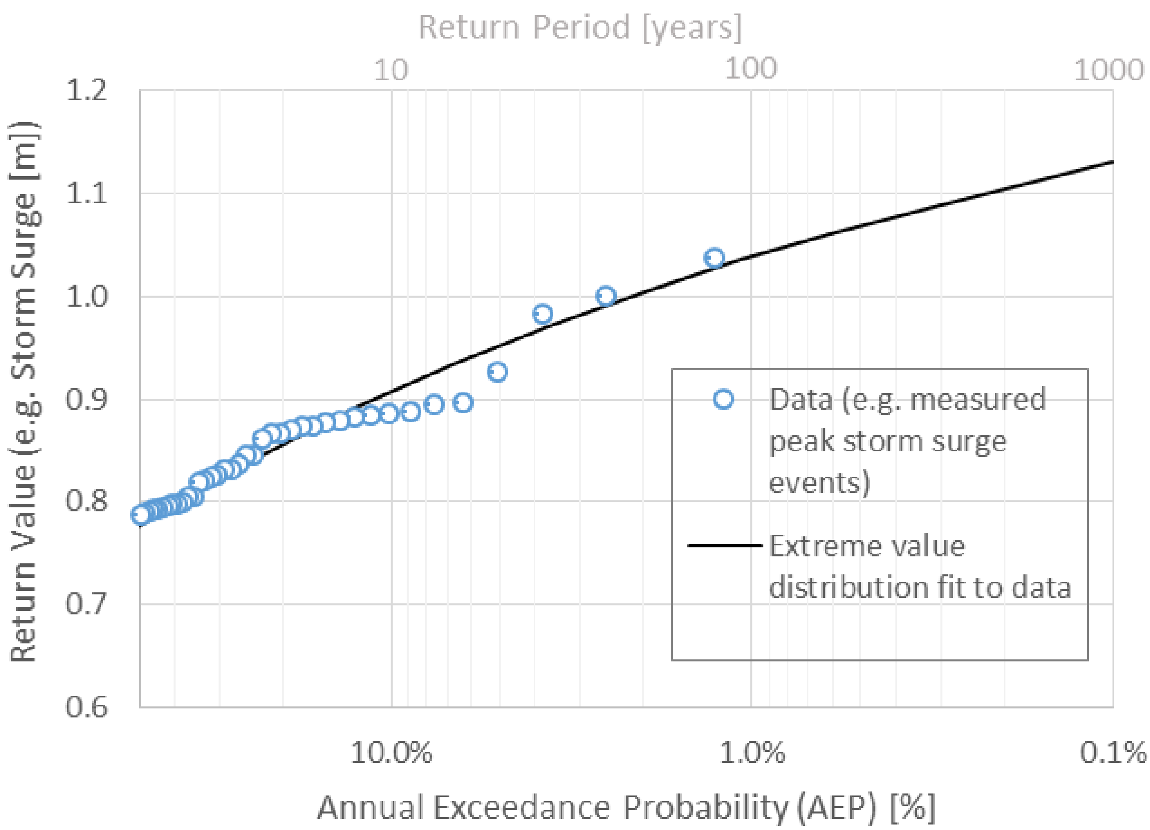

Figure 6. Example extreme value distribution fit (solid black curve) to historical storm surge events (blue dots).

2.4.2 Encounter Probabilities

In the context of buildings and infrastructure design, it may be more useful to think about hazard likelihood in terms of the probability of encountering an event of a given magnitude over a defined period of time, such as the design life of a building or infrastructure asset (e.g., 75 years for bridges covered by the Canadian Highway Bridge Design Code). For a 1% AEP event, there is a 53% chance that an event of this magnitude or greater will occur over a 75-year period (Table 1 and Figure 7). Understanding the likelihood of an event as well as the encounter probability over the design life can support design decisions related to building- and infrastructure-level measures for enhancing resilience based on stakeholder risk tolerances, as well as decisions related to broader coastal flood risk management strategy. For the same encounter

[2] It is emerging best practice to represent hazard likelihoods with an AEP. In the past, hazard likelihood was commonly represented as a 1 in X-year return period. However, this tends to cause confusion regarding the frequency of an event with the lay public. For example, it is commonly believed that if a 100-year event has occurred, it will not re-occur for another 99 years, which is incorrect. AEP in % = (1/X) x 100.

probability, higher AEPs can be adopted for the design of a structure with a design life of 25 years than for one with a design life of 50 years. Encounter probabilities can be linked to target design criteria for buildings or infrastructure. For example, a design code or standard may require structural integrity (or building integrity) to be maintained for very low encounter probabilities (e.g., to meet life safety objectives), whereas serviceability criteria may be based on higher encounter probabilities, assuming some occasional loss of function can be accepted over the service life. Such criteria may take into account capital and maintenance or whole lifecycle costs and associated trade-offs.

Table 1. Encounter probabilities for various AEPs and design/service life.[3]

Annual Exceedance Probability (AEP)	Design or Service Life of Building/Infrastructure			
	25 years	**50 years**	**75 years**	**100 years**
10%	93%	99%	100%	100%
3%	53%	78%	90%	95%
2%	40%	64%	78%	87%
1%	22%	39%	53%	63%
0.5%	12%	22%	31%	39%
0.2%	5%	10%	14%	18%
0.1%	2%	5%	7%	10%

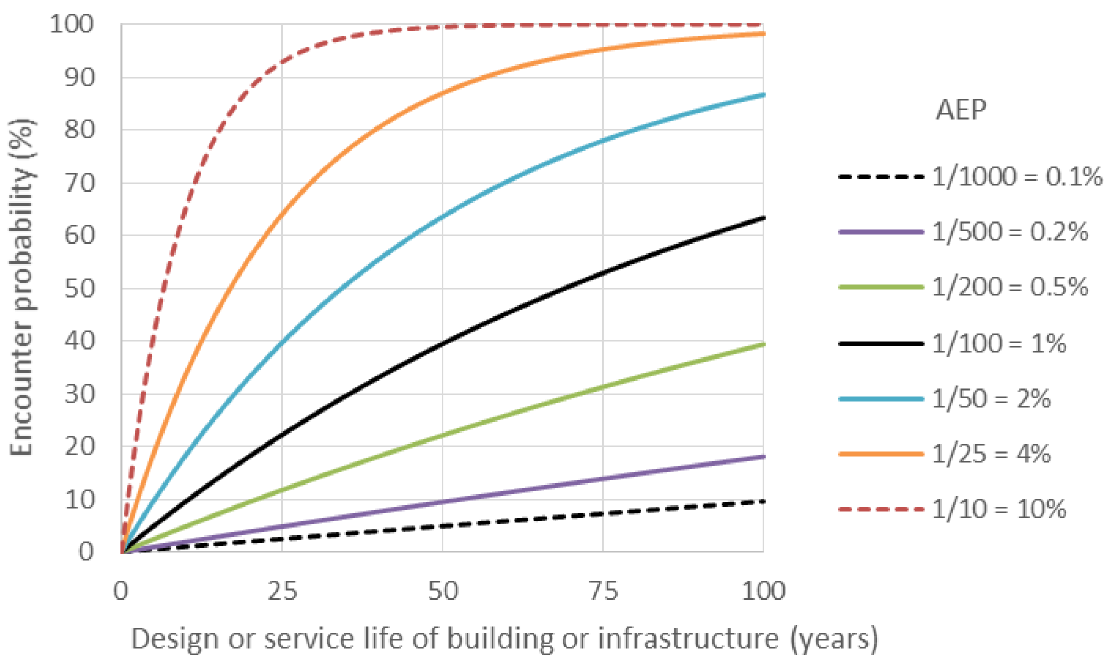

Figure 7. Encounter probabilities for various AEPs and design/service life.

[3] Encounter probabilities are calculated as $Pe = 1 - (1 - AEP)^n$, where Pe is Encounter Probability, AEP is Annual Exceedance Probability and n is design or service life (years).

3 Framework for Coastal Flood Risk Assessment (CFRA)

A suggested framework for conducting coastal flood risk assessments (CFRAs) for the purpose of informing the design or retrofitting of buildings and infrastructure is shown in Figure 8 below, and is broadly consistent with established methodologies for hazard risk assessment (e.g., Journeay et al., 2015). The framework is intended to illustrate the potential linkages with building and infrastructure design codes and standards. Codes and standards typically identify mandatory minimum (but not necessarily all) design criteria, and may specify certain types of mitigation and adaptation measures that can be implemented by design or retrofitting. The sections describing each task or component of the framework are shown in Figure 8.

The CFRA framework (Figure 8) involves the following key steps:

1. **Stakeholder, partner and public engagement** (Section 4), which occurs throughout the process. This activity ensures that stakeholder perspectives and needs are captured by the assessment, and that risks are properly understood.
2. **Establishing risk-based design criteria** for the building(s) and/or infrastructure system(s) (Section 5), which include, but need not be limited to, requirements identified in codes and standards. This step essentially defines the intended outcomes of the risk assessment and will therefore inform data needs and decisions surrounding the appropriate level of analysis.
3. **Data assembly and gap analysis** (Section 6), generally commencing with the initiation of the risk assessment to identify data acquisition needs for later stages of the process.
4. **Determining the appropriate levels of analysis** (Section 7) needed for the risk assessment, which can depend on: objectives of the assessment, the phase of the design process, the spatial scale of the system/asset and affected areas, the criticality of buildings and infrastructure exposed to flood hazards, and the availability of data and other resources to conduct the assessment.
5. **Hazard assessment** (Section 8), to characterize the probability and intensity of flood hazards.
6. **Vulnerability and consequence assessment** (Section 9), which combines information derived from the hazard assessment with information on the susceptibility of buildings and infrastructure, and the people or systems that rely on them, to determine the consequences of flooding.
7. **Risk assessment** (Section 10), which multiplies the probability of coastal flood hazard events by the consequences of each event.

Depending on the outcome of the CFRA; risk management strategies, mitigation measures, and/or adaptation planning may be required to ensure risk tolerance criteria are met (Section 11). An iterative approach will often be required where various options are generated, developed and appraised (i.e., re-evaluating risks associated with each option) to arrive at a strategy or solution that meets the design criteria.

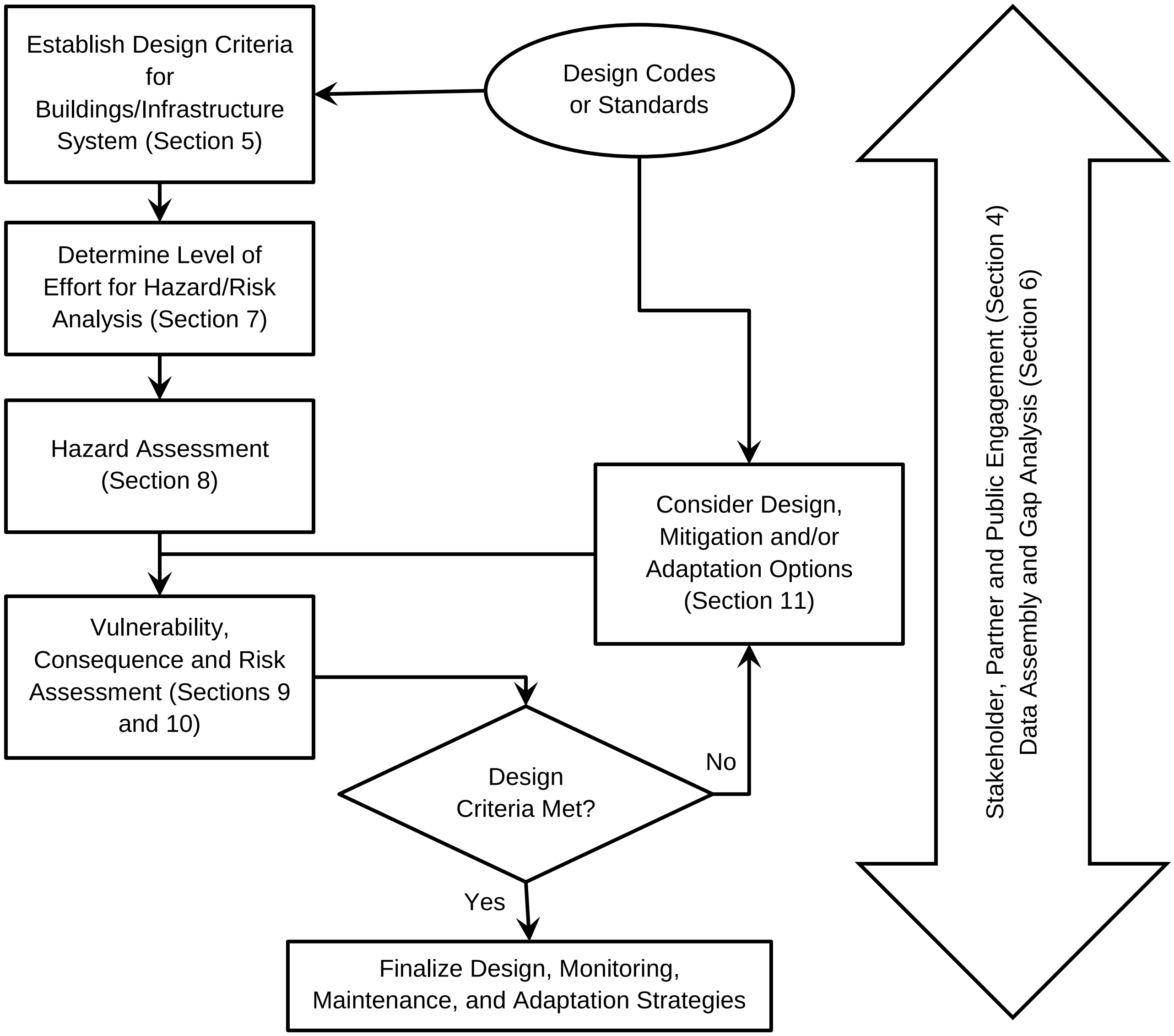

Figure 8. Framework for CFRA.

4 Stakeholder, Partner and Public Engagement

Any new building or infrastructure project (or retrofit) has the potential to impact or affect the interests of a variety of stakeholders, partners and the general public. Interested and affected parties may include owners, decision makers, government, regulators, neighbours, neighbouring communities, campaign or public interest groups, private sector organizations and members of the general public. Where there are coastal flood risks, there is almost inevitably some human exposure (either direct, such as pertaining to life safety; or indirect, through potential impacts on, or disruption of, assets that serve the community). It follows that a well-planned process of engagement is a critical component of any coastal flood risk assessment, and more generally needed to ensure the success of a building or infrastructure project.

It is broadly accepted that coastal flood risks are most effectively managed through system-based approaches, which consider the breadth, interconnectedness, and feedbacks of the system exposed to flood hazards. Understanding the role of buildings and infrastructure within the system is crucial for identifying parties that may have an interest in, or be affected by, new builds or retrofits. For example, implementation of local (building-level) flood risk reduction measures has the potential to adversely (if inadvertently) impact surrounding communities, infrastructure or the natural system (environment). Interruptions of critical infrastructure services due to coastal flood hazards can lead, due to interdependencies, to cascading effects across many sectors, affecting many stakeholders. Understanding the standard and longevity of community-scale flood protection measures (e.g., sea dikes) can have a critical bearing on coastal flood risk at a site, and typically requires some engagement with local municipalities or authorities responsible for managing and maintaining this infrastructure. In the context of design to reduce or mitigate coastal flood risk, broader engagement can help to identify co-benefits and opportunities to pool resources for maximal benefits.

The following section outlines the value and process of engaging stakeholders, partners and the general public in a risk assessment process. Material discussed below is drawn from international best practice approaches (Cornell, 2006; Australian Institute for Disaster Resilience, 2014, 2015; Edelenbos et al., 2017; FLOODsite, 2009; Sayers et al., 2014; UNISDR, 2017; FEMA, 2016). This section is not meant to be a comprehensive guide to engagement, but provides an overview of general components. Readers are encouraged to do further research, and to work with communication and engagement specialists to develop appropriate processes for their project.

4.1 The Value of Engaging Stakeholders, Partners and the Public

Stakeholders, partners, the general public and other interested or affected parties (stakeholders) should be considered an important part of any risk assessment process. Stakeholders, and society as a whole, need to understand the risks they are exposed to and have a legitimate interest in the decisions that relate to flood risk reduction (Cornell, 2006; UNISDR, 2017). Further, meaningful engagement of stakeholders will enable risk assessors to better understand the diversity and the breadth of the problem. The goal therefore of a stakeholder engagement process within a risk assessment process is to ensure that broader societal goals, interests and challenges are ideally reflected in the assessment, or in some cases are noted as a gap. Also, given the data-intensive nature of risk assessment, there are potential advantages to engaging stakeholders from whom data and local knowledge might be leveraged. Although the emphasis of this section is specifically on stakeholder, partner and public engagement as part of the flood risk assessment process, it is recognized that in the broader context of flood risk management, there is a need for continuous engagement and communication.

4.2 Levels of Engagement

Engagement describes a broad spectrum of concepts related to the involvement of, and interactions with, stakeholders in decision-making processes. In the context of coastal flood risk assessment for building and infrastructure design applications, this can range from informing stakeholders about the process, to ‘checking in’ to determine if the process is on the right track, to fully inclusive processes where stakeholders have a say in how they are engaged, how often they are engaged and how they affect decision making. The level of engagement should be dependent of the scope of the risk assessment process, and related to that, to the criticality of the building or infrastructure or its role within broader systems. The criticality of buildings/infrastructure is discussed and defined in more detail in Section 5.3, and levels of risk assessment analysis in general are discussed in Section 7.

Most coastal risk assessment processes, specifically those focussed on infrastructure, will likely fall somewhere in the middle of the spectrum of engagement, where stakeholders are engaged to support the risk assessment and to ensure that the results are accurate and relevant.

Regulatory and legislative requirements for engagement are also important considerations for buildings and infrastructure projects, such as the requirement to consult with Indigenous Peoples (see following section).

In addition to the technical expertise related to coastal flood hazards, exposure/vulnerability and risk needed to support the risk assessment process, it may be desirable or beneficial to engage specialist facilitation/engagement expertise to steer the process.

4.3 Indigenous Engagement

Canada is a signatory to the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP) (UN General Assembly, 2007). A tenet of UNDRIP is the duty for government to obtain free, prior and informed consent (FPIC) from Indigenous Peoples on issues that might affect their interest. Furthermore, Canada is in a time of reconciliation with Indigenous Peoples (First Nations, Métis and Inuit).

There are many circumstances in which it is essential that Indigenous Peoples be appropriately involved in a risk assessment for coastal infrastructure planning. Besides the systemic drivers mentioned above, the integration of Indigenous worldviews adds richness to an assessment, whether or not the assessment is being led by an Indigenous organization. Through a process of weaving together Indigenous and western science perspectives, a more holistic understanding of risk can inform comprehensive risk reduction actions. For example, an Indigenous worldview can provide ecosystem-based perspectives on hazards, identifying the role and potential benefits of such natural phenomena. Indigenous knowledge can also highlight vulnerabilities and consequences (e.g., forced location of reserves in hazard areas, conversion of coastal land used for Indigenous community sustenance to build flood control works protecting settler communities) and the shortcomings of existing datasets (e.g., census data that does not integrate hunting and fishing locations, thus does not accurately define where people spend their time).

The need for expert advice on local-specific Indigenous engagement practices should be considered when developing the scope of a coastal flood risk assessment.

4.4 Steps to Engage Stakeholders

4.4.1 Set Context and Purpose

Prior to identifying stakeholders to involve in the risk assessment process, the context and purpose of their involvement should be clearly defined. In the context of a coastal flood risk assessment for a building or infrastructure asset, the goals of engagement will likely be to ensure that vulnerability is well understood, to establish risk tolerances and design criteria, to ensure compliance with legislative and regulatory requirements (including obtaining permits), and to assess potential impacts on surrounding areas (if any). For a risk assessment with a larger geographic focus (e.g., where risks to multiple infrastructure assets are being assessed, or where community-scale flood risk management measures are being considered), the focus of the engagement may be to better understand the broader impacts of the coastal infrastructure (e.g., dikes or pumping stations) existing or failing.

4.4.2 Identify Stakeholders and Decision Makers

The identification of appropriate stakeholders is key to success in flood management initiatives (Edelenbos et al., 2017). Clearly, the voices around the table will affect the outcome of the process. Some examples of potential stakeholders for risk assessment processes are listed in Table 2; this list is provided as an example and is not exhaustive for specific local conditions. The table indicates that the number of stakeholders typically (although not necessarily always) reflects the scale and footprint of the infrastructure project(s).

Table 2. Potential stakeholders for coastal flood risk assessment processes.

Individual Structure (Generally fewer stakeholders)	Community or Infrastructure System (Generally more stakeholders)
• Asset owner or proponent • Neighboring landowners • Asset users (e.g., for a power station, consider primary power users) • Indigenous Peoples (First Nations, Métis and Inuit) • Local government officials (engineers/operators, biologists, planners, regulators) • Regional government officials (engineers/operators, etc.) • Federal government officials (engineers/scientists, etc.) • Professional associations (e.g., engineers)	• Asset owners or proponents • Indigenous Peoples (First Nations, Métis and Inuit) • Local government officials (engineering and planning) • Regional government officials (engineering and planning) • Provincial/territorial officials (engineering and planning) • Federal government officials (engineers/planners/scientists) • Professional associations (engineers/planners) • Other affected partners • The public

A further consideration in the identification of stakeholders is the role they play within their respective organizations. In most instances for coastal flood risk assessment, it will be important to engage with staff-level experts (who can comment on risk exposure and vulnerability). However, in some instances, where the outcome of the process may require high-level buy-in, it may be important to engage decision makers and, in rare instances, elected officials. Each of these groups can be engaged together or separately depending on the scope of the project and the stakeholder management plan.

4.4.3 Work with Stakeholders

Stakeholders should be engaged at an early stage in the risk assessment process, and in a meaningful way. Some basic principles include:

1. Clear, accurate and timely communications.

2. Accessible and inclusive activities.
3. Transparent processes.
4. Measurable targets.

One means of ensuring that engagement processes are clear, and that roles and responsibilities are delineated, is to develop specific Terms of Reference (TOR) for the stakeholders/advisory committee. Some basic components of TORs include:

- Committee name
- Committee goals and objectives (see above)
- Scope of work (e.g., provide expertise, input and advice to support the risk assessment)
- Governance and decision-making roles and responsibilities
- Meeting schedule and expectations
- Decision process (e.g., majority, consensus)
- Approach to dialogue (e.g., supportive, collaborative, etc.)
- Committee members and roles

Engagement activities should span the entire risk assessment project lifecycle (as indicated in Figure 8 in Section 3), to ensure all parties are kept appropriately informed, aware of others' perspectives, and to steer decision making. Engagement strategies need to be monitored and sometimes changed as the project progresses.

4.4.4 Document Activities and Report Back

Stakeholder activities should be recorded, and meaningfully included in the risk assessment process. This may include minuted meeting notes at a minimum or could include more detailed reports that describe the process, the input from the stakeholders, and how the input was used in the overall risk assessment process.

4.5 Implementation of Engagement

Stakeholder engagement processes are extremely valuable and can greatly enhance the end result of a risk assessment process. However, stakeholder engagement can be a resource-intensive and costly endeavour, particularly for large infrastructure projects, or for projects with a large footprint or a large number of stakeholders. One means of reducing effort and taking advantage of existing social and knowledge capital is to leverage existing networks and processes (Sayers et al., 2014). For example, existing strategic planning processes in coastal areas could be leveraged to support risk assessments for new buildings or infrastructure, or retrofits.

5 Risk-Based Design Criteria for Buildings and Infrastructure in Coastal Flood Hazard Areas

Establishing design criteria is usually one of the first steps in the design process for buildings and infrastructure. Design criteria are the explicit objectives that must be met by a building or infrastructure asset, and therefore define what success looks like for a new build or retrofit. Design criteria may be subdivided into essential (mandatory or minimum) criteria that must be met, and desirable (but not necessarily essential) criteria. Design criteria may be identified as a result of stakeholder engagement (e.g., owner or end-user needs), legislative requirements (e.g., building codes or municipal bylaws, or regulatory compliance), and strategic planning frameworks.

In Canada, minimum (mandatory) design criteria for buildings and infrastructure are established and enforced through codes and standards adopted by the relevant jurisdiction. These are usually (such as in the case of the National Building Code) aimed at establishing minimum requirements to satisfy objectives related to safety, health, accessibility, fire and structural protection, and the environment. These minimum requirements can include specifications for the design life (e.g., 75 years for structures covered by the Canadian Highway Bridge Design Code), serviceability, function, resistance to hazards or acceptable levels of damage, or maintenance; which may dictate some requirements for a coastal flood risk assessment. For example, the design life of a building or infrastructure asset has implications for the flood hazard encounter probability (Section 2.4) and therefore may affect decisions on the range of events to be considered by the risk assessment.

Beyond minimum design criteria for buildings and infrastructure, there may be a range of criteria that are established based on owner or stakeholder needs or desires (see Section 4), which can impact coastal flood risk assessment approaches and methods. These may include criteria determined to be based on, for example:

- Lifecycle objectives (e.g., the building/infrastructure owner may have a preference for capital expenditure to enhance structural resistance/resilience and minimize the costs of routine maintenance or adaptive management over the design life).
- Risk tolerances (e.g., the owner of the building or infrastructure may have different tolerances for flood risk depending on the intended use, contents, and/or insurance coverage).
- Criticality of infrastructure (e.g., whether failure or loss of function could lead to loss of life, or impede emergency response).
- Performance requirements (e.g.. critical infrastructure may need to remain functional during or immediately after extreme events).
- Hazard information needed to support design (e.g., water depths, velocities, wave conditions).

The following sections aim to frame existing building and infrastructure design codes and standards from Canada, as key references for minimum (mandatory) design criteria. Some provincial and territorial guidelines and regulations, as well as international examples of codes, standards and guidelines, are presented to illustrate contrasts and similarities in how flood risk to buildings and infrastructure is considered in different jurisdictions. The focus is on storm-driven coastal hazards; limited information is provided on tsunami hazards. This is a non-exhaustive review.

Finally, this section includes some guidance on moving toward risk-based design criteria. Specifically, it highlights considerations surrounding the criticality of the buildings/infrastructure, and provides notes and guidance on managing uncertainty, changing risk over time, and multiple hazards.

5.1 Canadian Codes, Standards, Regulations and Guidelines

5.1.1 Codes

National Building Code of Canada

The current National Building Code of Canada 2015, which is a model code adopted and enforced by some provinces and territories, is focused primarily on life safety issues and does not address potential flood risk to buildings. Although work is presently underway to develop recommended provisions for flooding, the code does not yet include any design requirements to make buildings more resilient to coastal flooding, nor does it consider potential tsunami hazards or climate change effects, such as sea-level rise. Recently, however, some Canadian Standards Association (CSA) standards for building and infrastructure design have been developed, or are currently under draft review, that address some aspects of flooding (CSA Z800-18, and CSA W204; CSA Group 2018, 2019). They are briefly described in the sections below, however, they are mostly directed at urban drainage design, and do not address coastal flood hazards to buildings and infrastructure. An express document related to LNG facilities (CSA EXP276.1-2015) provides some guidance on addressing tsunami hazards, but again, is not directly related to all other building and infrastructure types within the scope of these guidelines. Some national and provincial guidelines are also briefly discussed in the following sections, as far as they relate to design for coastal flood hazard, or can provide additional information on risk-based design standards.

CAN/CSA S6-19 Canadian Highway Bridge Design Code

With the exception of Manitoba, all provinces and territories have mandated the use of the Canadian Highway Bridge Design Code to establish design criteria for highway bridges, in some cases with amendments or additions. CAN/CSA S6-19 applies to the design, evaluation and structural rehabilitation of highway bridges, and includes provisions for hydraulic design (including floods and scour), water loads, and ice loads (CSA Group, 2019). However, the code does not include provisions for coastal flood hazards, such as those related to storm surges, waves and tsunamis (Murphy et al., 2018).

5.1.2 Standards

CSA W204 Flood-Resilient Design for New Residential Communities

A new flood design standard for new residential communities was published in December 2019 (CSA Group, 2019). The standard is specifically targeted at new neighbourhood-level developments of detached/semi-detached homes and row houses, and mixed-use residential developments (also including small commercial and institutional use). The scope of the standard includes the flood hazards of riverine flooding, overland flooding, storm and sanitary sewer surcharge, drainage system failures and groundwater seepage. However, no coastal flood hazards related to storm surges, sea-level rise or tsunamis are addressed.

The standard aims to increase the flood resilience of new neighbourhood developments. Flood resilience is hereby defined as “the ability of the system (both natural and built infrastructure) to recover from an extreme event with minimal damages, functionality disruptions, and socio-economic impacts during and after an extreme flooding event”. As part of flood resilience, the standard recommends to site new residential developments outside flood hazard areas, and to use floodproofing house design for developments in flood hazard areas. Four characteristics of a resilient community are defined: resistance ("protection of built and natural assets from hazards"), reliability ("design of assets such that they can operate under a range of conditions"), redundancy ("availability of spare capacity or ability for services to be provided through other parts of a network), and response and recovery ("planning, preparation and practice in the field for the response to both specific and more general tasks"). The standard includes an appendix on theoretical approaches to resilience and resilient design for drainage infrastructure. In the standard, design details are provided for storm sewer system design, street design (overland drainage system considerations), sanitary sewer design, and wastewater pumping station design. The standard also highlights "considerations for preservation of natural infrastructure and low-impact development measures".

The standard generally requires design to a "regulatory flood" for each province/territory; the 1% AEP (1:100 years indicative return period) flood for most jurisdictions, with exceptions including 0.5% AEP (1:200 years) for most of British Columbia, and 0.2% AEP (1:500 years) for Saskatchewan (CSA Group, 2019).

While consideration of critical infrastructure is briefly mentioned in CSA W204, no details are provided. It is also suggested to use data that "anticipates future climate changes", but as it "is not yet available with adequate confidence", it is recommended to apply adjustments to current Intensity-Duration-Frequency (IDF) curves. No mentioning of hydrologic and hydraulic modelling for riverine flooding incorporating climate change effects is included; the standard focuses on design to manage urban stormwater.

CSA W205:19 Erosion and Sedimentation Management for Northern Community Infrastructure

As part of the Northern Infrastructure Standardization Initiative,[4] the first edition of a standard to address requirements for managing erosion and sedimentation risks in northern coastal and lakeshore environments, open-channel environments, and terrestrial environments was published in November 2019 (CSA Group, 2019b). Although the primary focus of the standard is erosion and sedimentation hazards, the document recognizes that flooding is often a related hazard, particularly in coastal areas. As such, CSA W205 contains information and guidance of particular relevance to identifying distinct factors contributing to flood hazard risk in northern regions (e.g., erosion driven by permafrost thaw, changing sea ice cover and ice season duration), and risk management strategies. The risk assessment steps and procedures described in CSA W205 are broadly consistent with those presented in these guidelines.

5.1.3 Regulations

Ontario

In Ontario, the Provincial Policy Statement (PPS; Ministry of Municipal Affairs and Housing, 2014) and its associated technical guides (Ontario Ministry of Natural Resources, 2001, 2001b, 2002) identify the flood hazard limit of river systems as the greater of the 1% AEP flood, a flood resulting from rainfall experienced under a "Regional Storm" scenario, or an actual flood event in a watershed. For lakes greater than 100 km^2, additional wind allowance is added. The PPS emphasizes "avoidance", that is, directing development away from hazardous areas, including flood-prone areas. Under the *Conservation Authorities Act*, a series of regulations empower each conservation authority to regulate development and activities in flood hazard areas within their jurisdiction. The Ontario Building Code captures minimal requirements for floodproofing buildings in flood hazard areas, stating that buildings need to be designed to "withstand anticipated vertical and horizontal hydrostatic pressures acting on the structure" and "incorporate floodproofing measures". Local bylaws and standards for floodproofing buildings are established by municipalities. A recent review

[4] https://www.scc.ca/en/nisi

of provincial standards (McNeil, 2019) identified that little guidance exists for developing future climate-informed flood standards, and that standards for floodproofing are outdated (from the 1980s).

Québec

Québec's *Politique de protection des rives, du littoral et des plaines inondables* (Gouvernement du Québec 2019) under section 2.1 of the *Environment Quality Act* (1987) provides a minimal prescriptive framework with objectives including: safety of people and property in flood hazard areas; prevention of erosion and degradation of lakeshores, littoral zones and floodplains; protection of the environment; promotion of sustainability and environmental quality; and promotion of rehabilitation of degraded areas. The document provides guidance to regulate the locations and characteristics of structures, undertakings and works on lakeshores, littoral zones and floodplains. However, there is little reference to coastal flood hazard-generating processes, such as tides, storm surges, and waves. Generally, municipalities are responsible for adopting and enforcing bylaws to implement the principles of the policy. The document includes basic requirements for floodproofing and other considerations for structures, undertakings and works permitted in areas of high flood hazard. Floodproofing measures referred to in annexes to the policy include: elevating openings (doors, windows, etc.) and ground flood levels above the 1% AEP flood level; installation of non-return valves on drains; studies of flood resistance (defined in terms of waterproofing, structural stability, reinforcement needs, seepage water pumping capacity, and resistance of concrete to compression and tension) for parts of any structure below the 1% AEP flood level; restrictions on filling of land around the structure; and taking into account characteristics of the building materials.

New Brunswick

New Brunswick's Coastal Areas Protection Policy (Government of New Brunswick, 2019) identifies activities (including projects, infrastructure and buildings) permissible in different zones. The document stipulates requirements for habitable portions of new or rebuilt structures in coastal lands to be at least 2 metres above the higher high water large tide (HHWLT) elevation or other elevation determined by the local government or regional service commission. Otherwise, no building or infrastructure design guidance for flood resilience is provided.

Nova Scotia

Within the Nova Scotia *Municipal Government Act* (amended in 2019), the flood hazard area is defined as the 1% AEP flood extents, and development restrictions are based on the location within the flood hazard area. The authority of regulating this development sits with municipalities. To our knowledge, no province-wide building and infrastructure design regulations regarding flood-resilient design exist.

5.1.4 Guidelines

Federal Floodplain Mapping Guidelines Series

The Federal Flood Mapping Framework by Natural Resources Canada (NRCan) provides a series of national guideline documents on hazard mapping (NRCan, 2019), but the documents developed so far focus mostly on hazard while a flood risk assessment guide is still under development. Within this series, the Federal Hydrologic and Hydraulic Procedures for Flood Hazard Delineation provides some information on characterizing flood hazards in coastal and large lake areas. A risk-based land use guide by NRCan also provides some guidance on land use and management of flood hazards (Struik et al., 2015), but is directed at all hazards and not specifically focused on buildings and infrastructure. A draft, unpublished report on "Canadian Guidelines and Database of Flood Vulnerability Functions" was prepared as part of this series (NRCan, 2017). The document is currently undergoing revision, prior to release/publication.

CSA Z800-18 Guideline on Basement Flood Protection and Risk Reduction

The CSA Z800-18 guideline focuses on preventing basement floods and foundation damage caused by storm and sanitary sewer back-up (CSA Group, 2018). It is therefore not directly relevant to the coastal flood hazards discussed in these guidelines.

CSA EXP276.1 Express Document for LNG facilities – Tsunami Consideration

This Express Document (CSA Group, 2015) provides guidance and minimum design requirements for marine structures related to liquified natural gas (LNG) facilities. It is however not a standard that has been formally reviewed or approved by a CSA Technical Committee. The CSA EXP276.1 recommends a general assessment of the tsunami hazard during the early stage of project development to consider tsunami hazard in site selection and layout development, and a more detailed tsunami hazard assessment and quantification during the design stage to include appropriate mitigation in facility design and in facility operations procedures for emergency response plans (CSA Group, 2015).

British Columbia Provincial Guidelines

Some provincial and international (Section 5.2) guidance that focuses on managing coastal flood hazard risk, such as the British Columbia (BC) Flood Hazard Area Land Use Management Guidelines (BC Ministry of Environment, 2012; BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development, 2018), include recommendations for the location or elevation of buildings. These are frequently in the form of a prescribed minimum elevation for elements of new buildings that incorporates information about the hazard (i.e., high water levels and wave run-up with prescribed AEP, allowances for erosion if applicable, relative sea-level rise, and freeboard[5] allowances). In BC, this minimum elevation is referred to as a "flood construction level" and represents the level of the design flood, wave effects, relative sea-level rise (RSLR) and freeboard, which is used to determine the elevation of the underside of a wooden floor system or top of concrete slab for habitable buildings. BC Professional Practice Guidelines recommend for coastal zones (that are not subject to significant tsunami hazard) to plan for flood construction levels that consider 1 m sea-level rise (indicative of 2100), a 0.5% or 0.2% AEP total water level (including storm surge, tide, and wave effects, determined either through joint-probability or combined methodology), as well as a minimum freeboard of 0.6 m (Engineers and Geoscientists British Columbia, 2016). The more recent version of these guidelines (Engineers and Geoscientists British Columbia, 2018) is less prescriptive.

Riverine Flood Management Guidelines, Alberta Infrastructure

Although not directly applicable to coastal flooding, Alberta Infrastructure developed flood management guidelines with a risk-based approach to building classifications for new developments that they are funding (Alberta Infrastructure, 2017). While these design categories are not addressing coastal flooding, they do provide some insight on design criteria that are based on the criticality of buildings.

The first principle highlighted in the guidelines is avoidance of building in flood hazard areas, but in case this is not feasible, different design flood levels are defined based on intended use of the building (Alberta Infrastructure, 2017):

[5] The term "freeboard" is defined differently in various guidance documents but is generally taken to mean a vertical allowance, or "buffer", added to the elevation of predicted flood hazards (including water levels, wave runup, relative sea-level rise, etc.). It provides a measure of safety and compensates for uncertainty in flood hazard estimates, as well as leaving some capacity to adapt in the face of changing hazards (e.g., in response to relative sea-level rise).

- The highest design flood of 0.1% AEP (1:1000 year indicative return period) is required for vital lifeline facilities critical to “the ability to save and avoid loss of human life” and to “rescue and treat the injured and to prevent secondary hazards”. The highest design flood of 0.1% AEP is also required for facilities that can endanger human life and environment, as well as facilities that are important to the retention of documented historical data and artifacts.
- The second design flood level of 0.2% AEP (1:500 year indicative return period) is intended for other lifeline facilities that are “critical to the maintenance of public order and welfare”, “critical to the ongoing housing of substantial populations”, and “critical to the orderly return to long-term social and economic welfare”.
- A minimum design flood level of 1% AEP (1:100 year indicative return period) is defined for remaining (non-lifeline) facilities.

5.2 International Examples

Risk-based Building Classes for Flood Design (United States)

In the United States, building codes and standards include minimum requirements for buildings and infrastructure in flood hazard areas that are scaled to the criticality of the building (prescribed in the ASCE 7-16 standard on “Minimum Design Loads and Associated Criteria for Buildings and Other Structures” (ASCE/SEI, 2016), and specifically for floods, in ASCE 24-14 “Flood Resistant Design and Construction) (ASCE, 2015). The same risked-based building categorizations are also used for prescribing minimum requirements for wind, snow, earthquake and ice loads. In total, four building classes are defined “based on the risk to human life, health, and welfare associated with their damage or failure by nature of their occupancy or use” (ASCE/SEI, 2016):

- Class 1 includes buildings and structures that are typically unoccupied and pose minimal risk and disruption to the public should they fail (e.g., temporary structures).
- Class 2 includes buildings that pose moderate risk to the public and moderate disruption to the community should they fail (i.e., most residential, commercial and industrial buildings).
- Class 3 describes buildings and structures that pose a high risk to the public or significant disruptions to the community should they be damaged or fail due to flooding. This class includes buildings where large numbers of people assemble, utilities (power, water and sewage treatment, telecommunications, etc.), as well as buildings that store hazardous and toxic substances.
- Class 4 buildings and structures pose a substantial risk to the public in case of failure due to high amounts of hazardous materials or because they are essential for emergency operations.

Minimum design requirements become more restrictive with increasing risk to public in case of building failure (i.e., from building class 1 to 4). For instance, the required minimum elevation of the lowest floor is increased for building classes 2 and 3, and for building class 4, a more extreme design flood is required. Similarly, the minimum elevation for flood-resistant material or wet and dry floodproofing increases with the criticality of the building. According to the building class, design loads for snow, ice, wind and seismic are also scaled using an “importance factor” that gets higher with the criticality of the building (ASCE/SEI, 2016).

For coastal flood hazard specifically, two coastal zone types are defined in the ASCE 7-16 (ASCE/SEI, 2016):

- Coastal High Hazard Area (V-Zone), which is “an area within a special flood hazard area, extending from offshore to the inland limit of a primary frontal dune along an open coast, and any other area that is subject to high-velocity wave action from storm or seismic sources”.
- Coastal A-Zone, which is “an area within a special flood hazard area, landward of a V-Zone or landward of an open coast without mapped V-Zones, where the principal sources of flooding must be astronomical tides, storm surges, seiches, or tsunamis, not riverine flooding, and the potential for breaking wave heights greater than or equal to 0.46 m must exist during the base flood.”

Any buildings or structures within the flood hazard areas need to meet or exceed the minimum flood design requirements set out in the ASCE 24-14 standard, which is also required by the National Flood Insurance Program (NFIP) from the U.S. Federal Emergency Management Agency (FEMA).

Delta Programme (Netherlands)

In the Netherlands, a decision was taken in 2015 to adopt a risk-based approach to flood risk management policy. Specifically, new design standards for dikes were defined based on both the probability and impacts, including potential socio-economic consequences, of flooding due to dike failure (van der Most et al., 2011). Specifically, public safety (including operability of emergency procedures), the potential scale of societal disruption due to flooding (casualties and/or economic damages), and the protection of vital and vulnerable infrastructure were considered. Higher standards of protection are applied in areas where flooding may cause major damage (in terms of large numbers of victims, economic loss, and/or vital infrastructure of national significance). The new design standards were expressed through the required designated flood probability for different dikes, which were scaled logarithmically (for instance, the lowest risk area requires a dike design to a 1% AEP design flood, whereas the highest risk area requires a dike designed to a 0.001% AEP flood (van der Most et al., 2014).

Tsunami Design Standards for Buildings and Infrastructure (United States)

In the U.S., critical infrastructure (and buildings containing large amounts of hazardous materials) needs to be designed to stringent tsunami standards, if they are located within a tsunami design zone. A tsunami design zone is defined as the area between the shoreline and the maximum extent of flooding of the “Maximum Considered Tsunami”, which is a “probabilistic tsunami having a 2% probability of being exceeded in a 50-year period or a 2,475-year mean recurrence interval” (ASCE/SEI, 2016). A detailed chapter of the ASCE 7 standard, which was added in the 2016 standard update, describes the requirements for tsunami design loads (ASCE/SEI, 2016). Tsunami Risk Categories for buildings are similar to the general building classes described above, with some slight modifications and additions (for instance, tsunami vertical evacuation refuge structures are added to Class 4).

Tsunami design requirements in ASCE 7 apply to a limited class of buildings and structures that provide critical services or pose high risk to the public when failing. Specifically, provisions for tsunami resistance and community resilience in ASCE 7 apply to the following building categories:

- Tsunami Risk Category 4 (buildings that pose substantial risk to public through hazardous materials or are needed for emergency response).
- Tsunami Risk Category 3 (buildings where large numbers of people gather, or that can pose a risk to public) if the tsunami inundation depths of the Maximum Considered Tsunami is greater than 3 feet (0.914 m).
- Tsunami Risk Category 2 (most residential and commercial buildings and infrastructure for buildings with tsunami depths greater than 3 feet, if required by state or local building codes.

If tsunami design is required for buildings/infrastructure as detailed above, tsunami depths and velocities need to be determined by site-specific analysis, for which detailed requirements are given in the standard. An online ASCE Tsunami Design Geodatabase (ASCE, 2018) provides geocoded reference points of Offshore Tsunami Amplitude and other related information, which can serve as input into an inundation model for the site, otherwise, an integrated tsunami generation, propagation and inundation model needs to be used that considers tsunamigenic sources prescribed in the standard, depending on the site location.

Importantly, the standard also prescribes that relative sea-level rise needs to be considered when determining the maximum tsunami inundation depth over the project lifecycle (ASCE/SEI, 2016). For the project lifecycle, a minimum of 50 years needs to be used, and the relative sea-level rise over this period needs to be added to the tsunami runup elevation.

Lastly, the standard also provides structural design procedures that define the required tsunami loads that buildings and infrastructure need to be designed to. Again, tsunami hydrodynamic and impact loads are multiplied with an importance factor, which is higher for Tsunami Risk Category 3 and 4 buildings.

Hierarchy of Building Protection Options (United Kingdom)

The British Standards Institution (BSI) developed standard BC 85500:2015 for flood resistant and resilient construction, with the goal to improve the flood performance of buildings (BSI, 2015). The standard strongly discourages inappropriate development in flood hazard areas, but provides guidance on how to reduce residual risk of buildings that are, after implementing other measures, such as avoidance, still located in a flood hazard area. It recommends a hierarchy of building protection options, that are associated with a decreasing residual flood risk as options are implemented, with “avoidance” as the preferred option, followed by three options that target design at the building level: “resistance”, “resilience” and “repairability” (BSI, 2015; Tagg, 2017; Tagg et al., 2016; Bowker et al., 2007).[6] Definitions of the building-level strategies, and further details of this approach are provided in Section 5.3.6.

The building-level design strategies are recommended only where the depth of floodwaters for the design flood is limited, that is, resistance measures are recommended for flood depths lower than 300 mm, and resistance and resilience measures are recommended for depths of 300 to 600 mm (BSI, 2015).

5.3 Risk-Based Design Recommendations

Considering that there are so far no design codes or standards that specifically address coastal flood risk to buildings and infrastructure in Canada, this section provides recommendations for establishing design criteria, which will influence both the risk assessment and design processes. These recommendations are based on international best practice approaches, and importantly, advocate for a risk-based design approach, which is also integrated within a broader flood risk management strategy. The following 9 key recommendations are detailed in the sections below:

1. Design to achieve strategic planning and risk management goals.
2. Move toward a risk-based design approach.
3. Design considering the criticality of buildings/infrastructure.
4. Design considering environmental impacts.
5. Design according to risk tolerance.

[6] It is understood that the revision of the guidelines in the United Kingdom will include a new definition of the term “resilience”, which will comprise both “resistance” and “recoverability”.

6. Design to mitigate residual risk at the building level.
7. Design for dynamic future risk (including sea-level rise).
8. Design for multiple hazards.
9. Integrate design within broader flood risk management.

5.3.1 Design to Achieve Strategic Planning and Risk Management Goals

Building and infrastructure design measures to reduce coastal flood risks are most effective when applied within the context of broader strategic planning initiatives that weigh a variety of societal and environmental needs and risks. The need for, and prioritization of, new buildings and infrastructure should be driven by planning strategy, which may also help to define clear objectives for risk assessments. With effective strategic planning frameworks in place, the circumstances where building and infrastructure design measures are required to manage coastal flood risk may be limited. The flood risk assessment process will help to determine the need for, and scope of, building and infrastructure design measures to manage risk, which may validate or reject strategic planning decisions. As such, the flood risk assessment process provides an opportunity to step back and consider if a particular building or infrastructure system best meets societal needs. For example, understanding the true risk (i.e., inclusive of potential failure) of a pump station in a coastal hazard zone might warrant further consideration of demand-side infrastructure and actions (e.g., reducing loads through education or green infrastructure) that would have a lower risk profile.

5.3.2 Move Toward a Risk-Based Approach

Historically, a fixed standards-based approach has been used to promote avoidance of coastal flood hazards in Canada, where, for instance, prescribed minimum elevations or setback distances are recommended for buildings for one specific design flood (typically for the 1%, 0.5%, 0.2% or 0.1% AEP). However, the challenge is that this standards-based approach focuses only on one single scenario. It therefore does not include the full range of potential flood events, where high-frequency/low-impact flooding may lead to cumulative impacts on buildings and infrastructure, or where rare but severe floods may lead to worse impacts than captured through the design flood. Standards-based approaches also lack the flexibility needed to address the dynamic nature of coastal flood risk in a changing climate (Section 2.3), and can create barriers to adaptation when significant changes occur (e.g., by perpetuating development close to the "regulatory" flood hazard area), and false perceptions of risk (i.e., false sense of security for owners/operators of buildings and infrastructure just outside the regulatory flood hazard area).

International best practice advocates a shift away from a fixed standards-based approach toward a risk-based approach that considers both local hazard and consequences of flooding (Sayers et al., 2013, 2014). The idea is to no longer design solely for a single event focusing on safety and using engineered flood defences, but to use a more holistic approach that considers what is at risk, and maximizes social, economic and environmental benefits (Sayers et al., 2013). Typically, this would involve implementing a wide range of integrated flood measures and instruments.

5.3.3 Design Considering the Criticality of Buildings/Infrastructure

The location/siting and design of individual buildings and infrastructure, or infrastructure systems, play an important role in determining coastal flood risks to communities and systems more broadly. Appropriate and flood-resilient design is particularly essential for critical infrastructure where failure due to flooding could have significant social and economic consequences, or for buildings with storage of toxic materials where failure could lead to significant public health and natural environment impacts (see also Section 5.3.4).

The need for critical infrastructure resilience to current and emerging hazards is also highlighted in the National Strategy for Critical Infrastructure, which advocates for an all-hazards and risk-based approach (Government of Canada, 2009).

One way to approach a risk-based design, which considers potential consequences of building damage or failure, is to adjust design criteria according to the criticality and the potential for public and natural ecosystem harm. We define four criticality categories for buildings and infrastructure below, and for each of these building categories, provide design recommendations for both coastal storms and tsunamis (see Table 3; the criticality categories and design recommendations were developed based on the ASCE 7-16 standard in the U.S. and the Alberta Infrastructure guidelines). Note that in some cases, both tsunami and coastal storm hazard will exist, and design should consider both hazards. Details on building and infrastructure types included in each of the four categories are provided in the respective footnotes.

The risk-based categories defined in Table 3 refer to "minimum", "moderate", "high" and "substantial" design coastal storm floods and tsunami risk categories. However, no specific AEPs (or tsunami scenarios) are prescribed, as these should be selected based on the **risk tolerance** of stakeholders (see Section 5.3.5 on risk tolerance and Section 4 on stakeholder engagement).

For **coastal storms**, it is recommended that all building and infrastructure types within the flood hazard area be designed to resist the appropriate design flood (see Section 11 for discussion of resistance, resilience and repairability). However, avoidance is usually the most effective strategy for flood risk management (Section 11), and therefore, locating buildings and infrastructure in high flood hazard areas should always be avoided where possible.

For **tsunamis**, it is not feasible to design all buildings or infrastructure within a tsunami inundation zone to withstand tsunami impact. Some tsunamis will be preceded by, or coincide with earthquakes, making it even more difficult to design structures to withstand both hazards. We therefore recommend that all buildings of category 4, and buildings of category 3 above a defined tsunami hazard threshold,[7] be designed to tsunami criteria (buildings of category 2 can be added if desired by regional/local codes). Most importantly for tsunamis, it is crucial that that there are enough tsunami-resistant buildings within a tsunami inundation zone to host and provide emergency services for the population in the inundation zone, should higher ground evacuation centres not reasonably be reachable within the tsunami warning time. Again, avoidance is strongly recommended.

Further, at a minimum, **relative sea-level rise** over the anticipated building lifecycle period should be included (see also Section 5.3.7 for designing for dynamic future risk). Potential changes in storm frequency and intensity over time, and other non-stationarity, should also be considered when defining the design flood. However, the uncertainty and inter-model variability in future projections of extreme winds makes this practically challenging, and understanding future climate impacts on coastal storm conditions remains the subject of ongoing research (Casas-Prat & Wang, 2019; Murphy et al., 2020). In many cases, changes in sea level are the predominant factor affecting the increased frequency of extreme water levels, but a simple sensitivity analysis by Bernier et al. (2007) demonstrated "that changes in storminess should not be overlooked."

[7] In ASCE 7-16, tsunami hazard thresholds may be determined by state or local governments and may depend on the community's tsunami hazard, tsunami response procedures, evacuation egress times, and whole community disaster resilience goals. At the time of writing these guidelines, detailed probabilistic tsunamic hazard assessments are not available for Canadian coastal regions, which would inform the development of such thresholds.

Table 3. Risk-based categories for building and infrastructure design for coastal storm flood and tsunami hazard, based on ASCE/SEI (2016) and Alberta Infrastructure (2017).

Category	Potential Disruption and Risk	Building and Structure Types Included	Coastal Storm Flood		Tsunami	
			Design Event	Design Measures	Design Event	Design Measures
1	**Minimal disruption** to community, or **Minimal risk** to people or natural environment	Temporary structures, storage buildings (not commercial storage), and some agricultural structures	**Minimum** design coastal storm flood + RSLR* over lifecycle	Based on flood hazard thresholds and cumulative flood impacts. Avoidance preferred.	**Minimum** Tsunami Risk Category Tsunamic Hazard + RSLR over lifecycle	Not usually feasible, but ensure no new hazard (e.g., debris) is created. Avoidance preferred.
2	**Moderate disruption** to community, or **Moderate risk** to people or natural environment	Most residential, commercial and industrial buildings	**Moderate** design coastal storm flood + RSLR over lifecycle	Based on flood hazard thresholds and cumulative flood impacts. Avoidance preferred.	**Moderate** Tsunami Risk Category Tsunami Hazard + RSLR over lifecycle	Not feasible for all, but ensure no new hazard (e.g., debris) is created. Avoidance preferred.
3	**Significant disruption** to community, or **High risk** to people or natural environment, or **High loss** of historical data and artifacts	Critical infrastructure; buildings where many people assemble; buildings with hazardous materials (not included in Category 4); and museum/archives [8]	**High** design coastal storm flood + RSLR over lifecycle	Avoidance recommended. If not possible, design measures based on flood hazard thresholds and cumulative flood impacts	**High** Tsunami Risk Category Tsunami Hazard + RSLR over lifecycle	Avoidance recommended. If not possible, design measures based on defined tsunami hazard threshold.
4	**Critical for emergency response and recovery** of community, or **Substantial risk** to people or natural environment	Emergency response and recovery critical infrastructure and buildings with hazardous materials [9]	**Substantial** design coastal storm flood + RSLR over lifecycle	Avoidance strongly recommended. If not possible, design measures based on flood hazard thresholds and cumulative flood impacts.	**Substantial** Tsunami Risk Category Tsunami Hazard + RSLR over lifecycle	Avoidance strongly recommended (apart from vertical evacuation structures). If not possible, design measures based on defined tsunami hazard threshold.

*Note: RSLR = Relative Sea-Level Rise.

[8] Category 3: Buildings where many people assemble (community centres, schools, cultural centres, etc.), and critical infrastructure not included in Category 4 that would cause disruption and economic losses. Buildings not included in Category 4 that contain toxic or explosive substances with threat to public or natural environment (e.g., some agricultural supplies). Museums, archives, historic buildings and cultural sites, etc.

[9] Category 4: Hospitals and other emergency treatment facilities; Fire, rescue, ambulance and police stations; Designated emergency shelters; Designated emergency operations centres; Power generation, water and wastewater facilities, and other utilities critical for emergency operations, emergency response related aviation, telecommunications, fuel or water storage facilities; Buildings and structures that store high quantities of hazardous materials (fuels, chemicals, waste) that are toxic or explosive and pose threat to public or natural environment when released.

Based on flood hazard thresholds (including flood depth, velocity, debris loading, etc.) for the specified coastal storm design flood, different measures of **flood resilient building and infrastructure design** can be employed, similar to the design approach in the United Kingdom (Section 5.2). Specific flood hazard thresholds are based on risk tolerance (and the evolving field of wet and dry floodproofing). First and foremost, efforts should be made to avoid new development (and in particular, no buildings/infrastructure from category 3 and 4) in areas of high flood hazard. If buildings or infrastructure must be situated in these areas (or are already located there), resistant, resilient and repairable design measures should be employed. When designing measures for flood-resilient buildings and infrastructure, the cumulative effects of low-impact but frequent flood events should also be considered. Mitigating residual risk at the building level is discussed in more detail in Section 5.3.6.

5.3.4 Design Considering Environmental Criteria

It is essential to consider the potential public health and natural ecosystem impacts a flood-related release of hazardous or toxic material could have. Both the ASCE 7-16 and the Alberta Infrastructure Guidelines prescribe highest design levels to buildings that store substantial amounts of hazardous, toxic or explosive material (Table 3). Furthermore, negative environmental consequences of other design decisions (such as building materials and fill), or the ecosystem consequences of engineered flood defences should be minimized. Where appropriate, nature-based design features (coastal green infrastructure), such as dynamic coastal landforms (beaches, dunes) and coastal vegetation (salt marshes, kelp forests, dune and riparian vegetation) (World Bank, 2017; Conger, 2018; Bridges et al., 2015) should be considered as part of the design process to reduce coastal flood hazard risk. More broadly (i.e., beyond considerations for design of buildings and infrastructure), strategic land use and urban planning approaches (including flood risk avoidance measures) that consider whole system health and sustainability should be utilized to manage coastal flood risk.

5.3.5 Design According to Risk Tolerance

Design criteria should establish the flood event likelihoods (and corresponding flood hazards) for which different performance objectives must be satisfied. Ideally, a range of flood scenarios should be considered (i.e., moving beyond the traditional standards-based approach). Some of the decisions surrounding design criteria will be determined by the risk tolerance of stakeholders. For new builds, the minimum level of acceptable risk for communities and municipalities is, to some extent, set by land use planning regulations and bylaws, and infrastructure design standards. However, in cases where those standards cannot be met (e.g., critical infrastructure within areas of high hazard risk), or where proponents wish to go beyond minimum requirements to protect their interests, judgments must be made on what risk of flooding is acceptable and what is not. Risk tolerance is defined as an "organization's (or jurisdiction's) or stakeholder's readiness to bear the risk after risk treatment to achieve its objectives" (Australian Institute for Disaster Resilience, 2015, adapted after ISO 2009). Risk tolerances are typically connected to the criticality of the buildings or infrastructure, such that critical infrastructure will have a much lower risk tolerance than other types of infrastructure.

Different risk tolerances are reflected in the four risk categories defined in Table 3, where risk category 4 (buildings or infrastructure critical for emergency response, or with high amounts of toxic substances) has a much lower risk threshold, resulting in more stringent design requirements.

Developing Risk Tolerance Profiles for the City of Vancouver

An example of how risk tolerance criteria can be established for a community is provided in the City of Vancouver Sea-Level Rise Planning Framework (Ebbwater Consulting and Compass Resource Management, 2018). In this study, assets throughout the city were classified into 5 main categories: residential property, commercial property, institutional buildings, critical infrastructure (including power supply and telecommunications, water supply, wastewater, and roads/transportation), and parks. This classification was based on UNDRR documents (UNISDR, 2015, 2016), as well as City government requirements. In workshops, City staff and decision makers were asked to indicate their risk tolerance, in terms of the tolerable probability of flooding, for three flood scenarios: minor/nuisance flooding with flood depth 0–10 cm, moderate flooding (~30 cm depth), and severe flooding (~1 m depth). Risk tolerances were typically much lower for critical infrastructure and institutional buildings.

5.3.6 Design to Mitigate Residual Risk at the Building/Infrastructure Level

Unless the exposure to coastal flood hazards can be completely avoided for all event likelihoods, some residual risk of flood impacts will remain. The residual risk of flooding can be reduced using avoidance measures (e.g., increasing setback distances or freeboard allowances), usually as a first preference, or by implementing building- and infrastructure-level design measures. One model consistent with this approach identifies a hierarchy of four principles or strategies for reducing residual flood risks, described as avoidance, resistance, resilience and repairability (BSI, 2015; Tagg, 2017; Tagg et al., 2016; Bowker et al., 2007):

- **Avoidance:** includes the use of land use planning tools or minimum elevations for construction to restrict development in areas of flood hazard risk.
- **Resistance:** includes measures to stop floodwaters from entering a building or infrastructure components (barriers, flood doors, resistant material, such as waterproof renders).
- **Resilience:**[10] aims to reduce the impact of floodwaters by incorporating measures that enable faster and more economical recovery following a flood event (e.g., materials that allow for easier and faster drying and cleaning).
- **Repairability:** similar to resilience but focuses more on incorporating components (e.g., materials) that make replacement and repairs easier or more economical following a flood event.

5.3.7 Design for Dynamic Future Risk (including Sea-Level Rise)

Flood risk is dynamic, due to ever-changing environmental and social conditions (GFDRR, 2016). Coastal flood hazards are influenced by climate change effects (e.g., sea-level change, potential changes in the frequency and intensity of storms, changing ice conditions) as well as other environmental changes that are not necessarily attributable to climate change, or occur over different time frames (e.g., coastal erosion and isostatic adjustment). Exposure to coastal flood hazards also changes over time. For instance, seaside neighbourhoods that are not exposed to significant coastal flood risk under present-day conditions may become exposed in the future as a result of relative sea-level rise or coastal erosion. Rising population

[10] Somewhat different from the conventional use of “resilience” to mean “the ability of a system, community, or society exposed to hazards to resist, absorb, accommodate and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions.”
It is understood that the revision of the guidelines in the United Kingdom will include a new definition of the term “resilience”, which will comprise both “resistance” and “recoverability”.

densities in coastal communities, and the associated development of buildings and critical infrastructure services, may also result in increased exposure to coastal flood hazards (GFDRR, 2016).

In the context of dynamic (changing) risk, it is essential to consider the anticipated building or infrastructure lifecycle period, and ensure buildings and infrastructure are located and designed in anticipation of future changes—or are designed flexibly enough to allow adjustments to a changing future. Furthermore, it is essential to plan ahead and anticipate the timing when future risk may exceed risk tolerance thresholds (e.g., due to rising sea levels). This may require planning for risk profile changes over multiple decades, and identifying required lead times or trigger points for decision making, since most major infrastructure projects or design adaptations may require many years to implement. The planning and design process for adaptation typically must begin years ahead of the required in-service dates (Figure 9).

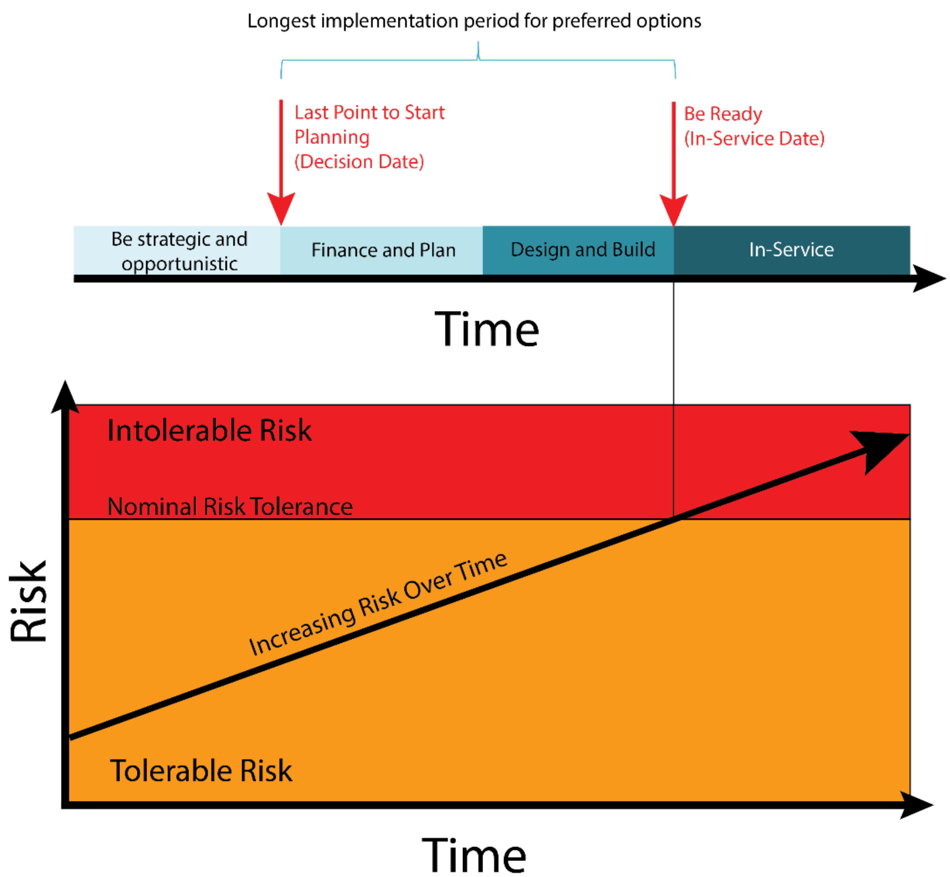

Figure 9. Example timeline for adapting to coastal flooding with sea-level rise. Figure adapted from Ebbwater Consulting and Compass Resource Management (2018), permission obtained for reprint.

The frequency and severity of floods may change over time. For example, climate change may impact the frequency of coastal storms, and relative sea-level rise will lead to increases in the frequency and magnitude of high water level events over time in some parts of Canada. This implies that return level magnitudes may change over time (i.e., the 1% AEP high water level at a future time horizon may be higher than the 1% AEP high water level based on the present-day or historical climate), or conversely, the frequency of extreme events may change (e.g., the 1% AEP high water level event may become a 2% AEP event at some future time horizon). For further discussion, refer to Section 6.8 (Climate Change Projections) and Section 8.4.1.2 (Sea-Level Rise). An important component of design for dynamic risk is maintaining adaptive capacity and flexibility to respond to a changing environment. Considering that there are many uncertainties surrounding projections of climate change, demographic change and land use change, it is essential to use a design framework that is flexible to respond to changing circumstances and that supports a selection of robust adaptation options. For instance, this could include a building design that can be easily upgraded in response to increasing climate-related hazards.

To identify points in time when risk (through a combination of changes in hazards and consequences) may become unacceptable, triggers for adaptation should be identified. Climate change triggers can be tied to specific thresholds (e.g., when sea levels rise above a certain level) and can reflect observed data, as well as changes in future projections. To ensure changes and approaching triggers for intervention are considered, it is recommended to review flood design and planning approaches every five years, consistent with recommendations by FEMA in the U.S. (FEMA, 2003).

An important benefit of maintaining flexibility and designing for dynamic risk is that maladaptation can be avoided. Large infrastructure projects (e.g., flood defences), which are often associated with significant capital costs and sometimes with adverse impacts on the natural environment, often do not incorporate adequate adaptive capacity. “Poor decisions can ‘lock in’ maladaptation that would poorly serve a changed future society, and are very expensive to reverse” (Sayers et al., 2013). Thus, best practice in flood risk management recognizes the importance of monitoring, reviewing and adapting, which requires a fundamental shift from traditional “construct and maintain” approaches (Sayers et al., 2013).

5.3.8 Design for Multiple Natural Hazards

Another important component of resilient building and infrastructure design is to consider impacts of multiple natural hazards, and combinations thereof, at the site. This helps to ensure that flood-resilient building and infrastructure design does not compromise resilience to other natural hazards. Instead, the goal is to ensure buildings and infrastructure are designed to be resilient to the array of hazards dominant at a given site. For example, for coastal regions within active earthquake zones, such as in British Columbia, it might be necessary to design for seismic hazards, in addition to coastal flood hazards. Other natural hazards relevant to buildings and infrastructure on Canadian coasts include erosion, wildfires, extreme winds and precipitation (rain, snow, ice, hail), ice and frazil effects, extreme temperatures, landslides, debris loads and impacts, and permafrost thaw. For some of these hazards, the frequency and intensity of hazardous events may be altered by climate change (Radić et al., 2015; Cheng et al., 2014; Jeong & Sushama, 2018; Flannigan et al., 2015; Wotton et al., 2017; Jeong et al., 2018). The ASCE 7-16 standard in the U.S. defines risk categories for multiple natural hazards, similar to the approach for flooding and tsunamis (Section 5.2); where, for instance, seismic, wind, snow and ice design loads are increased for buildings or infrastructure with higher criticality.

5.3.9 Integrate Design within Broader Coastal Flood Risk Management Strategies

With a shift toward a risk-based approach, building and infrastructure design criteria should align with and be incorporated as part of a broader flood risk management approach, where land use, environmental and socio-economic constraints are considered. This would include holistic building and infrastructure design approaches, where environmental aspects of building and construction materials are also considered. Flood-resilient design can incorporate many aspects, ranging from coastal green infrastructure, such as dynamic coastal landforms and coastal vegetation, to flood-resilient building design, such as elevated buildings or wet and dry floodproofing. The longer time horizons of adapting to sea-level rise also offer many opportunities for strategic and opportunistic planning. Communities are constantly changing, as neighbourhoods are being newly developed, older buildings are replaced with new ones, or renovations are taking place. These renewals can be used to make buildings more resilient to the flooding that they may face in the future with climate change. Especially for large critical infrastructure projects, which may have long lifespans, it makes sense to design today for potential future impacts.

6 Data Assembly and Gap Analysis

Comprehensive coastal flood risk assessments to support building and infrastructure design (and retrofitting) are data-intensive exercises. Data needed to support a coastal flood risk assessment should be identified, acquired and reviewed as early as possible in the process, to identify data gaps and develop a strategy to resolve them. Metocean (meteorological and oceanographic) data, aerial imagery, topography, bathymetry, and building and infrastructure inventories are available from federal, provincial/territorial, and municipal government sources; with varying spatial and temporal coverages, resolution, and levels of quality assurance. Metocean data tends to be freely available whereas high-resolution imagery, terrain, and building and infrastructure data may require a licensing agreement (often free or for a nominal fee). Regional datasets may also be available from universities and private companies (e.g., short-term instrument deployments, wave hindcast datasets, satellite imagery, satellite-derived bathymetry).

It is rare that all necessary data are readily available at or close enough to a project site to be directly applicable to the site. Site-specific, short-term instrument deployments may be required to characterize environmental conditions (e.g., waves and water levels) at the project site. These short-duration datasets may be used as input to, or to calibrate and validate, numerical models that are aimed at generating data for the longer time periods required to understand extremes and long-term processes. Field data acquisition (e.g., topographic or bathymetric data) can require significant lead times for planning and permitting, and may be restricted to certain times of year (depending on seasonal water levels, waves, ice cover, vegetation cover, regulatory or harvesting windows, etc.). The following types of data may be required to evaluate the coastal flood hazard, vulnerability and risk at a site:

1. **Data Supporting Hazard Characterization**
    - **Existing hazard maps:** existing coastal flood, erosion, and dynamic beach hazard maps.
    - **Water levels:** long-term measurements that capture the seasonal range of water levels, tides, and short-term variations, such as storm surges and seiches.
    - **Meteorological data:** long-term measurements of wind speed, wind direction, and atmospheric pressure. Meteorological data is often used to drive predictive models to estimate storm surge and wave conditions when direct measurements are not available.
    - **Ice:** wave generation and potential dampening of waves and storm surge at the coastline is affected by sea/lake ice extent and the presence of shore-fast ice.
    - **Waves:** direct measurements of wave height, period and direction or hindcast (modelled) wave conditions, developed using meteorological data.
    - **Tsunamis:** tsunamis are very long-period waves triggered by earthquakes, landslides, volcanic eruptions, meteorological effects or other events. Predictive models, geophysical, geological and/or paleotsunami data are often used to estimate tsunami characteristics.
    - **Bathymetry:** nearshore wave processes, storm surge, and tsunamis are influenced by the below water terrain.
    - **Topography:** wave runup and overtopping (both potential pathways to coastal flooding), and the extent and severity of flooding are influenced by the above water terrain.
    - **Aerial imagery:** aerial imagery may be used to identify shoreline structures, evaluate long-term changes in shoreline position, and classify the shoreline into reaches for analysis.
    - **Climate change impacts:** guidance on relative sea-level change (including uplift/subsidence of the ground surface), hydrology (e.g., inland lakes), storm intensity, and ice cover should be reviewed for the study area.

2. **Exposure and Vulnerability Data**
   - **Building and infrastructure inventories:** the vulnerability of a building or infrastructure asset depends on its location, elevation, and type/classification. An inventory of at-risk assets may include location, ground elevation, first floor elevation, building classification (based on type or use, number of storeys, etc.), floor area, value, and critical water levels (e.g., levels at which electrical/mechanical equipment would be exposed to floodwaters).
   - **Holistic exposure and vulnerability data:**
     - **Affected People:** census data, socio-vulnerability data.
     - **Economy:** data on cascading consequences of flooding for economy (e.g., number of businesses in affected area).
     - **Critical Infrastructure and Disruption of Basic Services Data**
     - **Environment:** data on sensitive ecosystems in area, hazardous material data.
     - **Culture:** cultural and (Indigenous/non-Indigenous) archaeological sites in area that may be affected.

This section identifies and reviews sources of available data, options for field data acquisition (if required), required length of data records for analysis, data gap analysis, and quality control for the types of data necessary to complete a coastal flood hazard, vulnerability and risk assessment. All data should be screened for gaps, outliers or suspected errors/inaccuracies before use in a coastal flood risk assessment. Data quality and all related uncertainties and assumptions should be recorded and included in the risk assessment report.

6.1 Water Level Data

Water level data is a critical prerequisite for assessing coastal flood hazards. Ideally, long-term measurements are available at or near the site where risks are being assessed, providing insight to short-term (e.g., tides, storm surges and seiches), seasonal (e.g., in response to hydrological cycles), interannual (e.g., driven by climate variability) and long-term (relative sea-level change) fluctuations in water levels. Semi-qualitative data, such as photographs, high-water marks on buildings, log and debris lines, and anecdotal information on the extent and severity of past storm events are useful (e.g., Daigle, 2006; Forbes et al., 2013).

6.1.1 Available Water Level Data

6.1.1.1 Water Level Measurements

The Canadian Hydrographic Service (CHS) of Fisheries and Oceans Canada maintains a network of permanent water level gauges along Canada's maritime and Great Lakes coasts (Figure 10). Real-time and archived water level data is accessible at waterlevels.gc.ca[11]. The network consists of 88 permanent water level stations plus data for a further 806 temporary stations that have been active at one time or another. More than 50 years of measured data is available for 60 of the stations. Hourly water level data is generally available from the 1960s, with higher frequency measurements from about the 1980s (15 min) and 2000s (3 min or 1 min). Hourly data is sufficient for most extreme water level analyses. Preliminary (non-quality controlled) water levels may be available from Canadian Hydrographic Service regional offices. For example, CHS Pacific has preliminary data for 35 gauges (www.pac.dfo-mpo.gc.ca).

[11] This archive and many other Government of Canada data archives are also accessible through the Open Government portal (https://open.canada.ca/).

Despite the large inventory of temporary and short-term stations described above, there are relatively few continuously operating tide gauges in Canadian waters with long records suitable for analyzing the probability distributions of storm surges or extreme water levels. Long-term measurements, such as those at Halifax, Charlottetown, Vancouver and Victoria are excellent sources of extreme water level data. However, vast areas of Canadian waters have only short-term, and/or intermittent water level datasets.

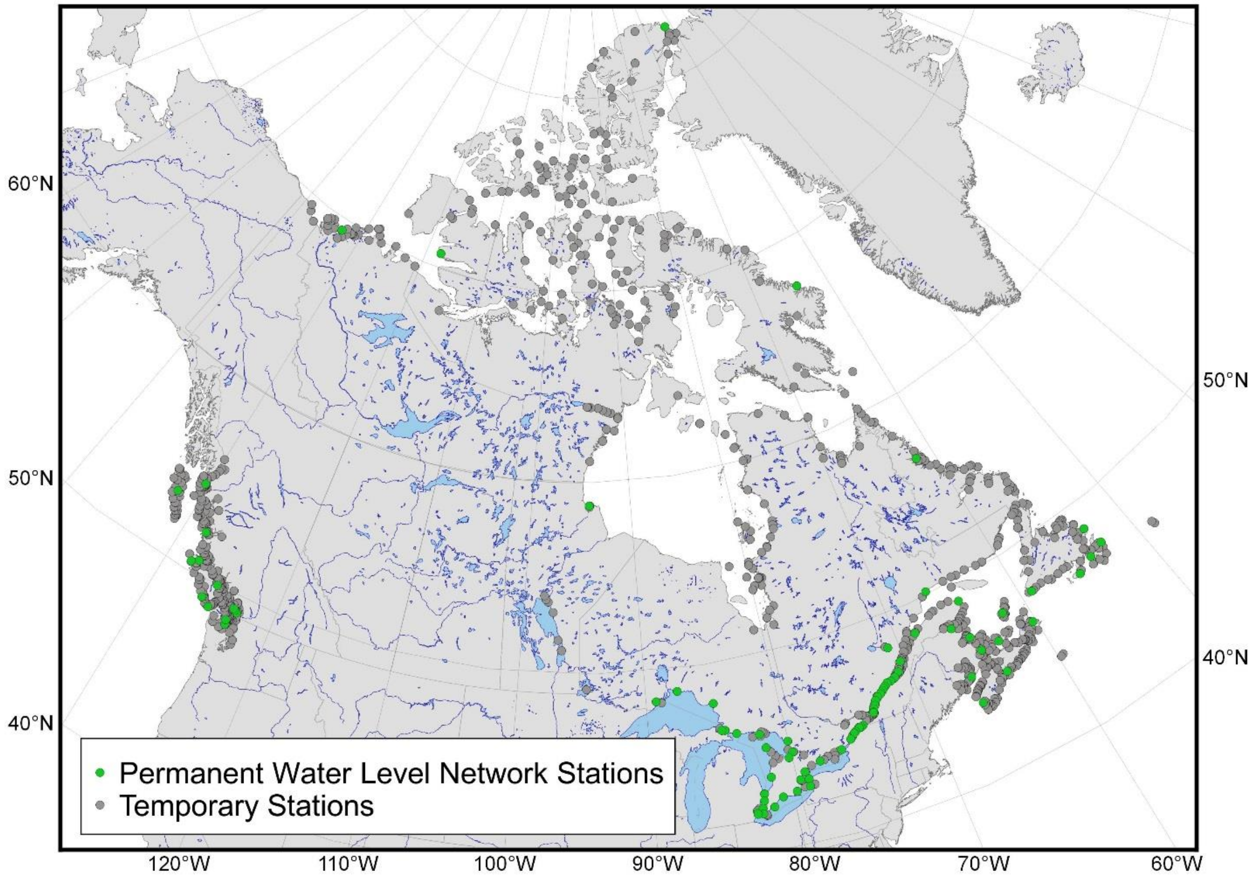

Figure 10. Inventory of water level stations on Canada's marine and St. Lawrence-Great Lakes coasts.

In addition to the CHS water level stations along the St. Lawrence-Great Lakes system, water level data for lakes (and rivers) are available from many different organizations depending on the jurisdiction. The Water Survey of Canada (WSC) provides national coverage and is often the primary source for obtaining water level data. Quality-controlled daily water level and/or river flow data for over 1,900 active stations and over 7,700 discontinued stations is available from wateroffice.ec.gc.ca (Figure 11). Station data may be downloaded individually or as a database. Hourly or more frequent data can be licenced from the WSC for a nominal fee.

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 present (waterlevels.gc.ca/C&A/historical-eng.html). The water levels for each lake are averages based on a network of gauging stations in Canada and the United States.

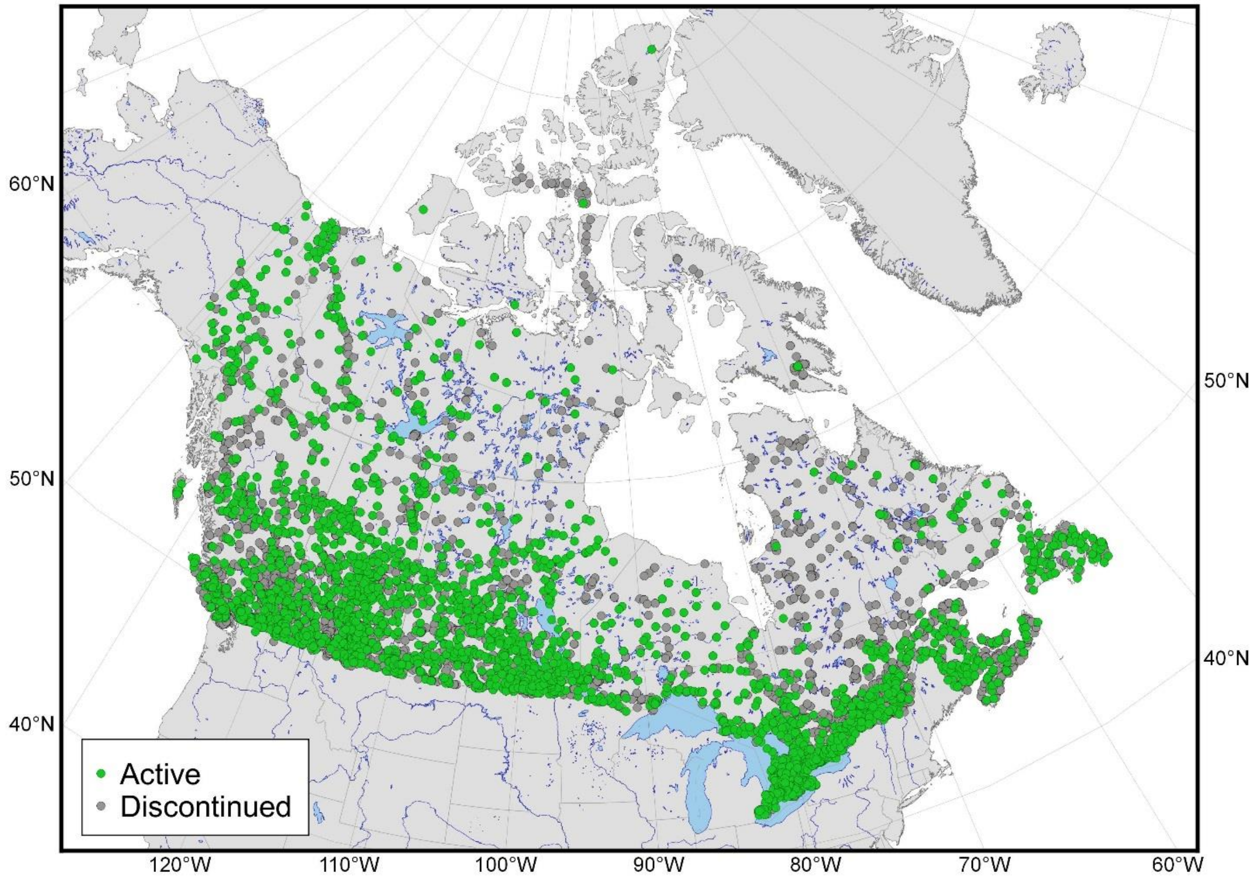

Figure 11. Inventory of Canadian inland water level stations.

Other sources of water level data for inland lakes and reservoirs include provincial authorities, such as the Quebec Ministry of Environment (cehq.gouv.qc.ca), Ontario Conservation Authorities, hydropower operators (e.g., Manitoba Hydro, hydro.mb.ca), and regulation or control boards (e.g., Lake of the Woods Control Board). Recently, the province of Prince Edward Island has implemented their own network of tide gauges to provide improved spatial resolution of storm surge statistics (the province presently has only one long-term tide gauge operated by CHS, at Charlottetown). Many of these secondary sources are more difficult to obtain and may require contacting the relevant data holder in the region of interest.

6.1.1.2 Tidal Constituents

Analysis of a water level record can provide tidal constituents (e.g., Pugh, 1987; Foreman, 1977; Pawlowicz et al., 2002), which are then used to predict the astronomical tide level in the past or future, assuming static mean sea level and bathymetric conditions. The length of the record affects the number of tidal constituents that can be determined through analysis. A period of one lunar month provides a basic understanding of the tidal conditions, while a longer period of many years provides a better representation.

Tidal predictions based on analyzed constituents are estimates of the astronomical tidal contribution to coastal water levels only. The accuracy of tidal predictions is limited by the length and quality of the input data, the methods of analysis/prediction, as well as how representative the measured data are. Atmospheric events, nearby river discharges, sea-level anomalies (e.g., El Niño-Southern Oscillation), and tide-surge interactions can all be reflected in the measurements and can affect the results of the tidal harmonic analysis. Water level predictions generated using tidal constituents provide an estimate of the astronomical contributions to the total water level, and do not represent the meteorological forcings and other components that also contribute to water levels.

Tidal constituents are generally available from the following sources:

- **Canadian Hydrographic Service (CHS):** Official tidal constituents for Canadian ports can be obtained from CHS for a nominal license fee.
- **Databases:** Tidal constituent databases are also available from regional or global models, which may assimilate, or be calibrated/validated using observations (including satellite altimetry data). Examples include WebTide Tidal Prediction Model (bio.gc.ca), which provides tidal predictions for Canadian waters, and TPXO (volkov.oce.orst.edu/tides), a series of global models (Egbert and Erofeeva, 2002). These databases can provide reasonable representations of water levels using a limited number of constituents over the extent of the model. In shallow regions and regions with complex coastal bathymetry, the data may have significant limitations.
- **Tidal analysis:** Tidal constituents may be derived from measured water levels. Fisheries and Oceans Canada's' IOS Tidal Package (Foreman, 1977), and modern implementations of the algorithms, such as the MIKE21 Toolbox (www.mikepoweredbydhi.com), T_TIDE (Pawlowicz et al., 2002), and UTide (Codiga, 2011) are commonly used for tidal harmonic analysis.

6.1.1.3 Modelled Storm Surge Data

There are several computational models in operation that provide storm surge data. Most of these models are typically applied for short-term (i.e., operational) forecasting purposes, and therefore are limited in their usefulness to support risk assessments. However, some long-term hindcasts are now becoming available (Zhai et al., 2019). Bernier (2005) undertook a 40-year hindcast of storm surge in the Northwest Atlantic. Bernier's work has formed the basis for a widely adopted set of storm surge and total water level statistics for Canadian maritime waters developed by Richards & Daigle (2011).

On the Great Lakes, storm water levels arise from a combination of wind-driven set-up, surge and seiching. The Ontario Ministry of Natural Resources and Forestry has compiled extreme water levels for all Ontario waters of the Great Lakes and their connecting channels (OMNRF, 2001). These water levels are based on a joint-probability analysis of annual maximum monthly mean water levels and annual maximum surge levels. Surge predictions are based on the SURGE model, a 2-dimensional free-surface circulation model developed jointly by Environment Canada and the Great Lakes Environmental Research Lab (GLERL) of NOAA. This analysis was last updated in 1989.

6.1.2 Water Level Data Acquisition

Field data acquisition may be required in tidal and inland lake areas if existing water level data is not available. Proximity to existing gauge stations, shoreline configuration, bathymetric data, and other information should be reviewed to assess whether water levels (such as tides, seiches, and storm surges) are likely to be similar, amplified or attenuated relative to those at a nearby station.

Short-term field deployments of one or two months may be adequate to develop a water level relationship between two nearby sites. Multi-year deployments may be required to evaluate extreme water levels.

Submersible pressure transducers are the most common field instruments for water level measurements. Non-vented pressure transducers record the total pressure the instrument is under (hydrostatic and atmospheric pressure). The atmospheric pressure needs to be subtracted from the total pressure measurement to accurately estimate the water level.

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).

Where direct water level measurements are not readily available (e.g., remote locations), post-event survey data or “proxies”, such as deposited driftwood or wrack elevations, can provide useful insight to past high water level conditions (Harper et al., 1988; Leonard & Bednarski, 2014; Didier et al., 2015; Kim et al., in press).

6.1.3 Quality Control of Water Level Data

Quality control of water level data has many considerations ranging from measurement error to how the data are presented and referenced. A summary of some of the common issues is provided below:

- **Data review:** Large, rapid fluctuations in water level can naturally occur or may be the result of an instrument malfunction. Water level measurements in adjacent time steps or corroborating data (such as meteorological events) can often be used to accept or eliminate suspect data. It is important not to filter out all of the legitimate extreme values, which makes data review, filtering and removal of false outliers a delicate process.
- **Data gaps:** Water level data should be reviewed to identify gaps in the temporal coverage. It is not uncommon for instruments to fail during extreme events and examining other datasets (such as wind data and water levels at nearby gauges) is helpful to understand if an extreme event was missed. It is also important to check if there are seasonal gaps (e.g., winter), and if there are, to develop a plan to address them.
- **Location:**
    - The gauge site may or may not be representative of the region of interest. For example, water level records from a gauge in a deeply dredged port area would potentially show a reduced influence by wind and waves compared to a shallow coastal area.
    - The gauge could be influenced by adjacent river flow.
    - Data may have been collected at a slightly different location as gauges often have historical location changes.
- **Datum:** Water levels are measured relative to a vertical reference elevation, which could be local chart datum, another sea-level- or tide-based plane, a land-based datum or benchmark, a geoid-based vertical datum (e.g., Canadian Geodetic Vertical Datum of 2013) or some other definition.
    - The reference plane (such as mean low water or mean sea level) must be considered.
    - Some datum planes are not horizontal, and data must be corrected for modelling/analysis purposes.
    - Gauges are referenced to a vertical datum that may change in time. Datum planes are periodically updated to be more accurate or representative of the present.
    - Recorded levels may require adjustment to account for local relative sea-level change, including vertical land motion, arising from isostatic uplift or subsidence, sediment compaction, and other factors.
    - NRCan’s Passive Control Networks website and/or NRCan’s GPS-H tool should be consulted to convert between vertical datums. The Passive Control Networks provides the elevation of over 80,000 vertical control benchmarks in the common vertical datums for that region (e.g., CGVD2013, CGVD28, and IGLD85).

- **Length of record:** The length of record is important when assessing any measured data, as shorter datasets will limit the possibility to understand long-term statistics and trends, or capture the extreme events that lead to coastal flooding. The following issues need to be considered:
  - Natural vs. regulated water levels: In some lakeshore regions (e.g., Lake Ontario) water level records may incorporate some influences of regulation. Periods where different regulation scenarios or strategies may have been applied should therefore be identified, as water level fluctuations during those periods may exhibit distinct statistical behaviour from present-day or future behaviour.
  - Non-stationarity: Whether due to climate change or other factors, a sample of a few years of data may not be representative of long-term statistical distributions.
  - For tidal regions, longer records allow for more constituents to be identified using a tidal harmonic analysis. At a minimum, approximately one month of data is needed to distinguish the frequency differences between the primary diurnal and semidiurnal constituents in accordance with the Rayleigh criterion. Longer period constituents, such as the fortnightly, monthly, semi-annual and annual may require one year of data or longer to distinguish the tidal signals from the meteorological background noise (e.g., Crawford, 1982).

6.2 Meteorological Data

Meteorological data, including wind speed, wind direction, and atmospheric pressure, are often used to estimate storm surge and wave conditions for coastal flood hazard assessments. In coastal analyses, atmospheric pressure data is most commonly used in conjunction with wind data to understand the atmospheric forcing, or it may be applied to a model when assessing storm surge. Atmospheric pressure data typically does not exhibit the same degree of spatial and temporal variability that is prevalent in wind data. However, intense storms (especially hurricanes) can exhibit large pressure gradients.

On inland lakes, variations in atmospheric pressure typically have limited impact on water levels due to the confined lake area and the smaller scale (relative to coastal waters). Pressure can have an influence on water levels on large lakes, such as the Great Lakes, Great Bear Lake, Great Slave Lake, and Lake Winnipeg, but can often be ignored as a driving force for water levels on most other lakes. In coastal areas, a one-millibar decrease in pressure results in approximately a one-centimetre increase in water level.

6.2.1 Available Meteorological Data

Long-term hourly meteorological data is available from Environment Canada (http://climate.weather.gc.ca/) for nearly 2,000 stations across the country.

Model-derived (hindcast, reanalysis, forecast/nowcast or ensemble) wind and atmospheric pressure datasets are becoming more frequently used as inputs to wave and storm surge modelling due to their availability, broad temporal and spatial coverage, resolution and accuracy, which continue to be improved. However, modelled data are mathematical representations of complex processes and are subject to uncertainty, particularly in the vicinity of land-water interfaces. The modelled datasets are often calibrated/validated using measurements but may vary from conditions on the ground. As such, modelled data should be validated using measured data.

There are fundamentally three types of modelled data:

- **Forecast/nowcast data:** Developed each time the model is simulated, and an archive of the present run time from each simulation can be used to develop a time series. These models represent the model resolution/physics and the data that were available at the time of the simulation, and are not consistent through the years.
- **Hindcast data:** Involves a full simulation of historical conditions using consistent model physics and input data but typically not assimilating any observational data.
- **Reanalysis data:** Uses consistent model physics and (as much as possible) consistent input datasets, and assimilates observational datasets.

Of the three, only reanalysis or hindcast data should be used for developing long-term statistics, since forecast/nowcast datasets are not based on consistent model physics or input datasets and therefore do not necessarily capture long-term statistics. Examples of reanalysis datasets include: NOAA's Climate Forecast System Reanalysis (CFSR) (Saha et al., 2010) and the European Centre for Medium-Range Weather Forecasts' ERA5 Reanalysis (Copernicus Climate Change Service, 2017).

6.2.2 Meteorological Data Acquisition

Due to the availability of meteorological data from nearby weather stations (e.g., airports, wave buoys, etc.) and reanalysis models, it is often not necessary to collect wind and atmospheric pressure data for coastal flood risk assessment projects. However, short-term instrument deployments may be used for remote or greenfield sites, particularly if local topographic influences are deemed important.

Atmospheric pressure data are often collected or obtained to correct water level measurements obtained using non-vented pressure gauges. Having data from close to the pressure gauge installation site is preferable; however, in all but very rare events where pressure gradients are severe (e.g., tropical storms or hurricanes), a pressure reading that is tens of kilometres from the area of interest may still be acceptable.

6.2.3 Quality Control of Meteorological Data

There are many considerations how meteorological data is measured and processed and used for coastal analyses. Some of the fundamental aspects of measured data include:

- **Elevation:** Wind speeds generally increase with elevation and this must be accounted for in analyzing wind data. Ten metres above the ground is the standard elevation, and is typically the measurement height for land-based measurements, such as those recorded at airport meteorological stations. Ocean-based meteorological buoys often take measurements at lower elevations (5 or 6 m above the water surface).
- **Averaging period:** A wind speed averaged over one hour will be less than the one-minute average wind speed (for example). Structural assessments are often based on the three-second gust wind speed, which is higher still. It is important to consider both the averaging period of the measurement (often 10 minutes at the top of the hour) relative to the parameters that are being simulated or assessed. Many coastal models are derived based on the 10-minute average wind speed; however, some agencies (notably NOAA in the U.S.) publish the one-minute wind speed for hurricane conditions.
- **Overland vs. overwater:** Wind speeds over land are typically lower than those over water, due to surface roughness effects. Winds on land can also be strongly influenced by local topography. Measurements on land therefore need to be adjusted to better represent overwater conditions.
- **Air-sea temperature difference:** The difference between the water temperature and the air temperature over the water can have a large impact on the winds close to the surface of the water. This process is strongly evident in the spring over the Great Lakes, where the surface winds over the water may be very light, but low clouds are seen moving quickly overhead. The cold water creates a dense

layer of air that remains stable and does not allow the warmer winds aloft to affect the lake in the usual manner. Conversely, warm lake water in the fall and a cold day will result in vertical mixing of the winds over the lake, bringing stronger winds to the lake surface. Properly considering the impact of the air/water temperature structure can have a large impact on the resulting coastal conditions.

- **Exposure:** Winds should be measured in well-exposed areas, free of the influence of buildings and other structures, trees and topographic relief. Overwater winds are often the most complicated to measure, but can provide the best data as they indicate the conditions over the water, which is typically the area of interest.
- **Atmospheric pressure**: is often converted to "sea-level pressure", which represents the pressure that would be measured if the station were at sea level. This adjustment is necessary to be able to compare the pressure readings from adjacent stations that may be at different elevations. For assessing marine environments, this adjustment is only required if measured data on land are also used, or if interpolating global or regional atmospheric model data near the coast. For inland lakes, it is almost always preferable to use sea-level pressure.

For modelled data, additional considerations include:

- **Spatial and temporal resolution:** Until recently, many global and even regional datasets lacked the high spatial and temporal resolutions necessary to properly resolve tropical cyclone or hurricane wind and atmospheric pressure fields. In some cases, there may be a need to develop parametric wind and pressure fields and assimilate them in hindcast/reanalysis data to accurately characterize the most extreme events. However, newer, high-resolution datasets, such as ERA5, do a much better job of capturing the intense wind and atmospheric pressure fields associated with such events.
- **Quality and resolution of observational data:** Most models are calibrated and validated using, or assimilate (in the case of reanalyses), observational data. The model output is therefore dependent on the quality and resolution of the observational data on which they rely. Model performance also varies spatially. Local verification using field measurements is always prudent, if possible.

6.3 Sea/Lake Ice Data

Ice is an important consideration in many coastal areas as it can:

- Reduce or eliminate the generation and propagation of wind waves, thereby reducing wave runup and associated flooding.
- Run up or pile up onshore under the action of wind, contributing to hazards.
- Affect air-sea momentum transfer, therefore altering (usually attenuating) storm surges (Provan et al., in press; Kim et al., in press).
- Be present in floodwaters and waves, contributing to hazards.

Ice jamming in rivers can cause severe flooding but is outside the scope of this document.

Ice coverage can be extremely variable from one year to another in response to many processes beyond air temperature. Winds, waves, snow cover, rainfall, current wind speeds and the timing of these processes are just some of the factors that can influence ice coverage. For this reason, ice cover should be examined over many years or decades. It is also important to consider that a changing climate could impact the ice coverage and the duration of the open-water season (Section 6.8). This is especially true in Arctic regions, where greater warming is taking place and regions may see an increase in the length of open-water season, increasing exposure to waves, storm surges and other coastal flood hazards.

6.3.1 Available Ice Data

Historical ice observation data are available from the Canadian Ice Service. Great Lakes ice cover is also compiled by the Great Lakes Environmental Research Laboratory (GLERL) at NOAA. The purpose of collecting and archiving these data is primarily in support of navigation.

Ice data are typically collected from satellite or aerial measurement programs and provide maps of coverage on a daily, weekly or other time period. There are many years of historical ice data that have now been converted from paper charts to gridded digital representations of ice cover. Ice data can include concentration (percentage of ice cover), stage of development (thickness), and floe size.

Ice data are generally collected over large regional areas and can have limited coverage in small geographic areas. For example, ice that is only 10 or 20 m wide along a Great Lakes shoreline could provide protection to the shore but is unlikely to be represented in basin or lake-wide datasets. Limited aerial photos along the Great Lakes St. Lawrence Seaway System are also available from the Canadian Ice Service and can provide indications of local ice conditions.

The Canadian Ice Service also maintains an archive of ice thickness and snow depth measurements at 195 sites across Canada (https://www.canada.ca/en/environment-climate-change/). These measurements are conducted on shorefast ice, so are particularly representative of conditions at coastal sites. This program was mainly discontinued in 2002, and data is currently collected at only 10 Arctic sites.

SmartICE (https://www.smartice.org/) is an incorporated non-profit social enterprise corporation dedicated to empowering northern communities to co-produce their own ice mapping data combining field profiles of ice thickness and roughness, in-situ instrumentation, and satellite imagery (Bell et al., 2014; Safer, 2016). SmartICE is operational in multiple communities across the Canadian Arctic and sub-Arctic.

6.3.2 Ice Data Acquisition

Sea or lake ice data is rarely collected for coastal flood risk assessment projects, but project-specific sea or lake ice data collection is advised. Methodologies used by the Canadian Ice Service to measure ice thickness (special auger kit or hot wire gauge) could be implemented to gather site-specific data. Photographs of shorefast ice coverage and ice thickness measurements may be collected for some project sites to better understand the site conditions. Solar-powered camera systems are available and provide a means for collecting season-long records. Local knowledge can provide valuable insight to ice conditions and the potential for, and frequency of, extreme events.

6.3.3 Quality Control of Ice Data

Sea or lake ice cover data may be used for wave or storm surge modelling. In general, the gridded ice cover datasets from the Canadian Ice Service and NOAA are of high quality and do not require additional quality control. The ice thickness data from many of the non-Arctic sites is not continuous and may be for only a relatively small number of years. Freezing degree day determinations from air temperature data can provide a means for extending limited ice thickness data.

6.4 Wave Data

Wave data can generally be classified as measured or modelled.

- **Measured wave data** can come from a variety of sources, including satellite altimetry, wave buoys that use accelerometers or GPS, submerged pressure/acoustic gauges (typically in 25 m of water depth or less), submerged pressure gauges (non-directional and in approximately 10 m of water depth or less), Voluntary Observing Ship (VOS) data, and in rare circumstances, direct measurements of the water surface. Wave measurements are often subject to considerable uncertainty. Wave parameters (e.g., wave heights and periods) are usually derived from measured pressures and velocities. It is imperative to understand potential sources of uncertainty and limitations of measured wave data, depending on the method of acquisition.

- **Modelled wave data** typically consists of predicted (historical or forecast) wave conditions, usually generated using physics-based models (simple empirical formulae or numerical models) driven by wind data. The quality of modelled wave data is directly dependent on the quality of the input wind data, bathymetry, model physics and spatial representation. It is important to understand the capabilities and limitations of a wave model in terms of capturing the important wave generation, propagation, transformation and dissipation processes. Modelled data should be verified using measurements where possible.

Wave heights in a sea state are often characterized by the “significant wave height”, which represents the average of the highest one-third of the waves. The wave period (time between successive crests) and the wave direction (conventionally expressed in terms of the direction from where waves propagate, in degrees clockwise from true north) are also commonly provided from measured or modelled data. There are many variants of these parameters, with different definitions, and a full description is beyond the scope of this document (e.g., U.S. Army Corps of Engineers, 2002; Goda, 2010; CIRIA et al., 2007). The most common wave data variables are significant wave height, peak period and mean wave direction.

Parametric descriptors of sea states (height, period, direction) provide a general description of wave conditions but do not fully characterize the sea state at a given location. For protected coastal and lake regions, these three variables may provide an acceptable approximation of the wave conditions. For more exposed coastal (marine) regions, waves may approach from multiple directions simultaneously, with different periods and wave heights. Under such circumstances, a full description of the wave energy spectrum may be required to adequately characterize the sea state.

More detailed descriptions of wave conditions are conveyed through wave energy spectra that define the amount of wave energy at each frequency (reciprocal of wave period). Spectral representations can be non-directional or directional and provide the ability to define complex multidirectional wave fields. Wave spectra can be derived from wave measurements or as output from certain types of wave models.

Waves in nature are irregular, in that there is variability from one wave to the next in height, period and direction. It is therefore important when measuring waves to obtain a long enough dataset to gather the appropriate statistical information. It is common to measure a sample of approximately 18 minutes (1024 seconds at 2 Hz yields 2048 readings) or longer if long-period waves are of interest. The ability of measurements to properly characterize a sea state will be impacted by the sample length, particularly in terms of capturing parameters such as H_{max} (the maximum wave height within a certain time period).

6.4.1 Available Wave Data

6.4.1.1 Measured Wave Data

Canada has 53 active buoys operated by Environment Canada: 17 of the buoys are located on the Pacific coast, 16 in Ontario (Great Lakes, Lake Nipissing and Lake of the Woods), 13 on the Atlantic coast and Gulf of St. Lawrence, 3 on Lake Winnipeg, 2 on Great Slave Lake, and 1 each at Churchill (Manitoba) and Tuktoyaktuk (Northwest Territories). In addition, data from over 500 historical wave buoy deployments is also available online (http://www.meds-sdmm.dfo-mpo.gc.ca/). Regional wave buoy data may also be available from universities, such as the University of Victoria, Université du Québec à Rimouski, and others.

Adjacent buoys in U.S. waters provide data that are available through the National Data Buoy Center (https://www.ndbc.noaa.gov/), which is part of the U.S. National Oceanic and Atmospheric Administration (NOAA).

Many of the Canadian and U.S. wave buoys are removed in the winter due to sea and lake ice and may have significant gaps depending on operational issues. Most buoys provide sea state parameters (wave height and period) while some also provide full wave spectra.

6.4.1.2 Hindcast Wave Data

Environment and Climate Change Canada has developed long-term (multi-decadal) hindcasts of offshore wave conditions for most Canadian coastal waters (Swail et al., 2007). Data from this model are available as time series of spectral parameters (e.g., significant wave height, peak wave period, dominant direction) at model grid points and full wave spectra at selected grid points (Figure 12). These include the MSC-50 Atlantic hindcast for the northwest Atlantic, which covers coastal waters from the Gulf of Maine north to the Arctic Circle and provides hourly wind and wave conditions from 1954 through 2015 (Swail et al., 2007) (Table 4). The northeast (NE) Pacific GROW-FINE model provides offshore wind and wave hindcasts for British Columbia coastal waters, excluding the Straits of Juan de Fuca and Georgia. For the Great Lakes, the U.S. Army Corps of Engineers (USACE) and Environment Canada have collaborated to generate long-term hindcasts for all shores of the Great Lakes, known as the Wave Information Study (WIS) (wis.usace.army.mil). The most recent version of the WIS dataset used the CFSR wind data, and covers the time period of 1979 to 2014. Unfortunately, the WIS study does not provide data at the wave buoy locations, making validation of this wave study very difficult. Long-term wave hindcast datasets may also be available from private companies and university sources.

Table 4. Summary of wave hindcast data applicable to Canadian coastal waters.

Region	Hindcast	Geographic Extent	Spatial Resolution	Temporal Extent	Temporal Frequency
Northwest Atlantic	MSC50 Atlantic	40.00°N–75.00°N 43.00°W–80.00°W	0.1-degree grid (approx. 10 km)	1954-01 to 2018-12	hourly
Northeast Pacific	NE Pacific GROW-FINE	47.19°N–56.56°N 124.38°W–45.00°W	35-km grid	1980-01 to 2015-12	3-hourly
Beaufort Sea	Beaufort MSCB	68.75°N–71.75°N 126.00°W–42.50°W	0.05 degrees latitude by 0.15 degrees longitude (approx. 5 km)	1970-01 to 2015-12	hourly
Great Lakes	WIS Hindcasts (USACE)	All Great Lakes waters	n/a	1979-01 to 2014-12	hourly

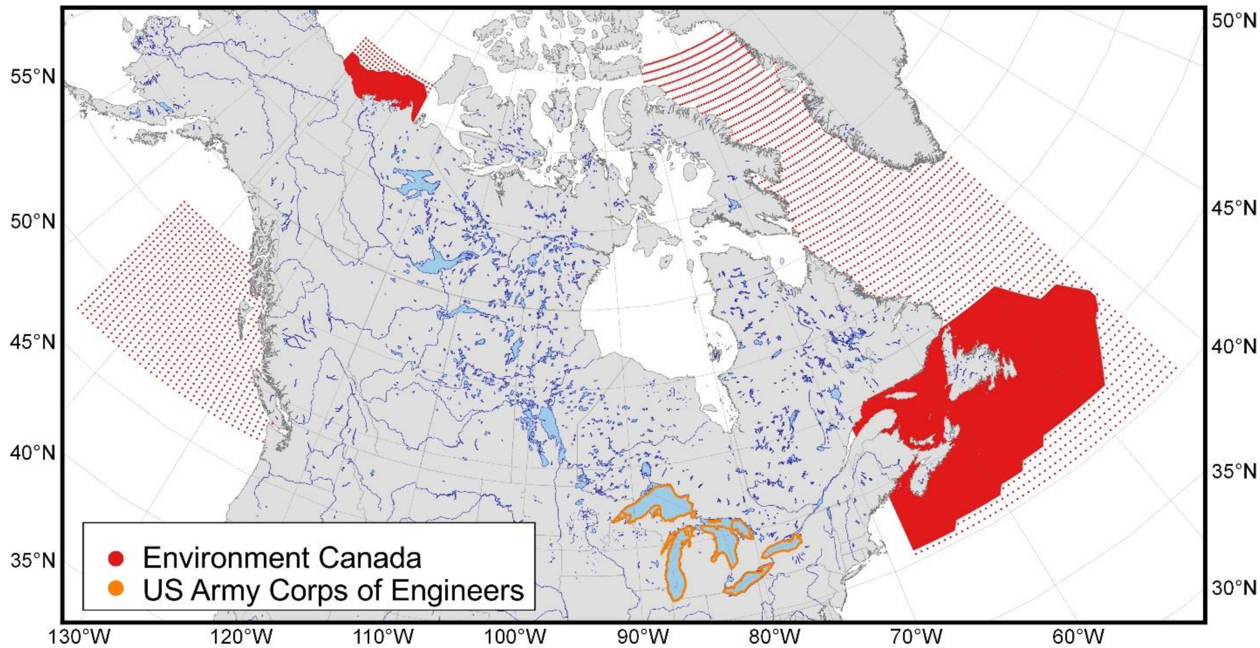

Figure 12. Wave hindcast grid points.

Other organizations also run operational wave forecasts/nowcasts, however, these data are generally not as reliable as the reanalysis type of data. Older hindcast data products may be available in some areas but have generally been superseded by the newer products described above.

Data from regional hindcasts can be downloaded for offshore waters. The data should be reviewed for their underlying spatial resolution, reliance on remotely sensed data for validation, and representation of the physics of wave transformation in coastal waters. Data available in coastal waters, or in confined seas (such as the Gulf of St. Lawrence or Bay of Fundy) may exhibit significant uncertainty, due to the proximity of land, islands, shoals and other features that are not properly captured by coarse-resolution regional or global models. Wave hindcast/reanalysis models are often calibrated using, or assimilate, satellite altimeter data—the temporal and spatial resolution of which introduces limitations for applications in confined seas (Walker et al., 2014). Data should be extracted in deep-water open areas and used as input to nearshore modelling for more confined areas. Consideration must then be given to locally generated wind waves in sheltered areas and the transformation of offshore wave conditions to the nearshore, considering the effects of tides, currents, refraction, diffraction, frictional dissipation, wave breaking and wave-wave interactions.

6.4.2 Wave Data Acquisition

Wave instruments may be installed near a project site to gain a better understanding of the wave climate and calibrate numerical wave models. The length of the instrument deployment may depend on the sampling interval, battery life and project schedule. One to three months of measured wave data is often sufficient to calibrate numerical wave models. Ideally, wave instruments will be deployed during the storm season with at least one storm event recorded for calibration purposes.

6.4.3 Quality Control of Wave Data

In almost all Canadian large lakes (e.g., Great Lakes, Great Slave Lake), wave buoys are removed in the fall and redeployed in spring. As a consequence, wave buoy records may omit some severe storms. Wave data should be reviewed to ensure that the instruments were not recording while on land (e.g., storage yards). Relational checks can be performed (e.g., comparing data to wind records, duplicate wave sensor records, or data from adjacent sites) to provide insight to data plausibility and quality. Extensive guidance on quality control of measured wave data is provided by, for example, IOOS (2015) and Meindl (1996).

Wave measuring instruments usually come with software to calibrate the instrument and process the raw data (pressure, velocity, acceleration, etc.) into derived-wave quantities. Field data should be processed using the manufacturer's software, performing quality control checks as recommended by the manufacturer.

6.5 Tsunami Data

6.5.1 Available Tsunami Data

A preliminary assessment of tsunami hazard for the Canadian coastline was conducted by Leonard et al. (2012, 2014). This assessment presented a first attempt to quantify the tsunami hazard on the Pacific, Arctic and Atlantic coasts of Canada arising from both near- and far-field sources. The study used a simplified probabilistic assessment methodology to estimate probabilities of runup at two levels (≥1.5 m and 3.0 m). Recommendations for an improved probabilistic assessment were provided, including needs to quantify a wider range of source scenarios and to conduct numerical modelling of tsunami propagation incorporating high-resolution bathymetry and overland topography.

A high-level review of tsunami risk, and a description of past damaging tsunami events impacting Canadian coasts, is provided by Clague et al. (2003).

As large tsunami events impacting Canadian coasts may be separated by hundreds of years (Clague et al., 2000), there are limited direct measurements or written historical records available. One of the larger tsunami events captured by tide gauges in Canadian waters is the 1964 Alaskan earthquake-generated event, which was detected by several gauges in British Columbia. Evidence of prehistoric tsunami is often found in sediment deposits and the oral histories of Indigenous Peoples (Clague et al., 2000; Gosse et al., 2020).

The preliminary hazard assessment by Leonard et al. (2012, 2014) estimated that the cumulative estimated tsunami hazard for potentially damaging runup events on the outer Pacific coast of Canada is orders of magnitude higher than for the Atlantic and Arctic, due in part to the dominance of local (Cascadia subduction zone) megathrust sources. Information on potential megathrust tsunami source scenarios for the northernmost Cascadia subduction zone is provided by Gao et al. (2018).

The Canadian North-East Pacific Underwater Networked Experiments (NEPTUNE-Canada) ocean observatory includes a network of bottom-mounted pressure sensors that have recorded tsunamis in Pacific ocean waters off Canada's coast (Thomson et al., 2011; Fine et al., 2015).

6.5.2 Tsunami Data Acquisition

There are a variety of systems and methods available for detecting tsunamis (Thomson et al., 2011; Grilli et al., 2017), many of which can be integrated in operational tsunami forecasting or early warning systems. However, the long intervals between damaging historical tsunami events compared to the length of available records, and the variety of potential tsunamigenic sources (e.g., near- and far-field) make using this information to support risk assessments challenging, beyond supporting calibration and validation of numerical models.

Due to the capacity of tsunamis to transport sediments and debris over large distances and deposit them on land, geologic surveys can provide valuable evidence of pre-historic tsunami events, and are a key component to the recognition and mitigation of tsunami hazards in the Pacific Northwest (Peters et al., 2003; Clague et al., 2003; Leonard et al., 2012).

Post-tsunami forensic surveys of erosion, debris movement patterns and damage have provided valuable insight to tsunami runup, inundation depths, flow patterns and damage (Leonard & Bednarski, 2014; Nistor et al., 2017).

High-resolution topographic, bathymetric and geophysical survey data can be used to identify and reconstruct historical subaerial and submarine landslide-generated tsunami events (Lintern et al., 2019).

Numerical modelling can be used to investigate tsunami wave propagation and interactions with complex shorelines and topography/bathymetry (Cherniawsky et al., 2007; Fine et al., 2008; AECOM, 2013; Thomson et al., 2011; Fine et al., 2015; Grilli et al., 2017) and to characterize hazards associated with potential or hypothetical tsunami scenarios.

6.5.3 Quality Control of Tsunami Data

Due to the long intervals between past large tsunami events impacting Canadian coasts, the lack of direct measurements is a significant source of uncertainty in characterizing tsunami hazards. Identification and accurate characterization of both far- and near-field tsunamigenic sources remains a significant challenge (Venturato et al., 2007; Leonard et al., 2014). Specialist expertise is generally required to conduct geologic or geophysical surveys, identify and characterize potential tsunamigenic sources, numerically simulate tsunami propagation and transformation processes, and interpret field data for the purpose of characterizing tsunami hazards.

6.6 Bathymetric and Topographic Data

Bathymetric and topographic data are key inputs to coastal flood hazard studies. The elevation and shape of the ground surface strongly influences nearshore wave processes, wave runup and overtopping, storm surges, seiches, tsunamis, velocities and depth of flooding.

6.6.1 Available Bathymetric and Topographic Data

The Canadian Hydrographic Service (CHS) is the primary source for bathymetric data in Canada (http://www.charts.gc.ca/). Data is available as digital and paper navigation charts, digital scans of hardcopy field sheets, digital field data (e.g., single or multibeam echosounder, bathymetric LiDAR, etc.), and as a 100-m gridded non-navigational bathymetric dataset (NONNA-100).

Navigation charts, field sheets and field data are provided under licence by CHS. The CHS Digital Data Portal – Licence Application Portal is an online mapping tool that allows users to view the spatial coverage, date, survey technique and other information prior to filing a data licence request. Fees may be required for charts, soundings and some gridded datasets. The NONNA-100 dataset is freely available.

Bathymetric data may also be available from the Geological Survey of Canada, provincial authorities and other government sources. For example, a 3 arc-second (approximately 90-m resolution) bathymetric dataset of the Great Lakes is available from the U.S. National Oceanographic and Atmospheric Administration's National Geophysical Data Center. Specialty products, such as Satellite-Derived Bathymetry (SBD), may be available from commercial providers. SDB is best suited for clear and shallow waters (< 20 m) and may be subject to some uncertainty, so should be ground-truthed using conventional or quality-assured survey data.

Topographic data is available from federal, provincial and municipal sources. Data are usually provided as gridded datasets, but may also be available as contours or points. Airborne Light Detection and Ranging (LiDAR) and photogrammetry are the two main technologies used to develop high-resolution topographic datasets over large areas. For example, Service New Brunswick makes LiDAR data freely available online for most of the province (http://geonb.snb.ca/li/). Advances in bathymetric LiDAR sensors have made this technology more common for bathymetry data capture in shallow waters. Bathymetric LiDAR uses shorter light wavelengths than topographic LiDAR to penetrate the water column. Bathymetric LiDAR is limited by environmental conditions, such as weather, sea states, and turbidity, but is capable of efficiently capturing bathymetric data in nearshore regions where conventional survey techniques are challenging to implement.

Many municipalities have acquired high-resolution topographic datasets to support various planning and engineering studies. As such, datasets with a horizontal resolution of 0.5 m (or better) are often available. In rural areas, data may be available from provincial or federal sources. NRCan is currently compiling LiDAR and photogrammetry datasets into a high-resolution gridded topographic dataset for the country. The High-Resolution Digital Elevation Model (HRDEM) includes a Digital Terrain Model (DTM), a Digital Surface Model (DSM) and other derived data. In southern Canada (south of the productive forest line), the datasets are generated from LiDAR data and are available at 1-m or 2-m resolution. In northern Canada, only a DSM is provided due to the low density of vegetation and infrastructure. The northern dataset is being developed from optical imagery (photogrammetry) and is available at 5-m resolution. Although current coverage in southern Canada is sparse, coverage will continue to improve as LiDAR data is acquired and integrated into the dataset. NRCan's Canadian Digital Elevation Model (CDEM) offers complete coverage of the Canadian landmass at a base resolution of 0.75 arc-seconds (north-south) by 0.75 to 3 arc-seconds (east-west). The horizontal resolution and vertical accuracy of the CDEM dataset is too coarse for most coastal flood inundation studies.

6.6.2 Bathymetric and Topographic Data Acquisition

Nearshore bathymetric and topographic surveys are often carried out to support CFRA studies. Surveys may be carried out using land-based surveying equipment, such as total stations and RTK-GPS systems; vessel-mounted equipment, such as single or multibeam echosounders; and Unmanned Aerial Vehicle (UAV) systems. Aerial LiDAR surveys are generally cost-prohibitive for small-scale coastal flood risk assessment studies, but existing data may be available from government sources (e.g., CHS bathymetric LiDAR). Accurate elevation profiles through the surf zone from the point of wave breaking to the limit of wave runup/overtopping are a key requirement for estimating wave overtopping volumes and associated flooding. However, the surf zone is often characterized by hazardous sea states and currents, mobile sediments, and shallow water depths, which can make surveying in these areas challenging or dangerous. Moreover, the primary objective of most bathymetric surveys is to provide data for marine navigation purposes, and tends to avoid shallow waters. A variety of technologies and techniques have been deployed to address these challenges, such as jetski-mounted surveying equipment (Dugan et al., 2001), amphibious vehicles, remotely operated or autonomous vehicles, survey sleds, shore-based optical imagery, radar, and bathymetric LiDAR (Wilson et al., 2014). All of these systems have associated drawbacks, limitations and uncertainty. Guidance on bathymetric surveys is provided by the International Hydrographic Organization's Standards for Hydrographic Surveys (IHO, 2008), which is presently under review.

6.6.3 Quality Control of Bathymetric and Topographic Data

Bathymetric and topographic datasets are often merged to create a seamless coastal DEM. Issues to be aware of include:

- **Overlap between datasets:** Often there is little or no overlap between topographic and bathymetric datasets, with gaps in data coverage near the water line. Ideally, the bathymetric survey should be conducted at high tide (or high seasonal lake level) and the land survey at low tide (or low seasonal lake level).
- **Interpolation:** Care must be taken when merging bathymetric and topographic datasets (LiDAR, echosounder, etc.) to ensure that interpolations at the interface between the two datasets are representative of the shoreline profile. Linear interpolations, especially over large distances, may not be representative of the foreshore slope.
- **Spatial resolution:** Topographic LiDAR is usually provided at a horizontal resolution of 1 m (or finer) whereas bathymetric LiDAR is usually provided at a coarser resolution (e.g., 5 m). The required resolution varies depending on the intended use/application. For example, high-resolution bathymetric data may not be necessary to support wind-wave modelling in deeper waters but becomes important in shallow coastal waters where wave transformation processes are more significant. For numerical simulation of the propagation of oceanic tsunamis (or other long waves), higher spatial resolution of the seafloor in offshore waters may be required.
- **DTM vs. DSM:** Topographic LiDAR is usually provided as bare-earth terrain (derived from classified point clouds), whereas bathymetric LiDAR is usually provided as a surface (first return from unclassified point clouds). LiDAR surface returns include the height of vegetation as well as wharves and floating structures. Both topographic and bathymetric LiDAR datasets should be clipped at the elevation of the water surface on the date of the surveys so that the topographic LiDAR only includes terrain above the water surface and the bathymetric LiDAR only contains the terrain below the water surface.
- **Morphological and/or human changes to the shoreline or ground surface:** Historical aerial imagery and other information should be reviewed to determine whether the data is appropriate for the study. For example, bathymetry collected decades ago may be quite different from current conditions along retreating shorelines and near coastal structures.
- **Vertical datums:** Vertical datums should be reviewed to ensure that data are referenced to a common vertical datum. NRCan's Passive Control Networks website (http://webapp.geod.nrcan.gc.ca/geod/data-donnees/passive-passif.php) and/or NRCan's GPS-H tool should be consulted to convert between vertical datums. The Passive Control Networks website provides the elevation of over 80,000 vertical control benchmarks in the common vertical datums for that region (e.g., CGVD2013, CGVD28 and IGLD85). For larger regions, conversion between local Chart Datum and orthometric elevation may be completed using the Hydrographic Vertical Separation Surfaces (HyVSePs) developed by CHS and NRCan (Robin et al., 2016), recognizing that there may be local differences relative to control points (such as tide gauges). HyVSePs are available for all tidal waters in Canada. Developing digital elevation models in transboundary waters (e.g., the Salish Sea and the Great Lakes) can introduce additional complexities, such as integrating datasets referenced to different datums, and may require specialist expertise.

6.7 Aerial Imagery

Aerial imagery may be used to identify shoreline structures, evaluate long-term changes in shoreline position, and classify the shoreline into reaches for analysis.

6.7.1 Available Aerial Imagery

High-resolution orthophotographs and satellite imagery may be useful for CFRA applications. Orthophotos are aerial photographs that have been corrected for camera lens and terrain distortions so that each pixel is at the same scale and the image appears to have been taken from directly above. Orthophotos are often provided as seamless mosaic tiles (e.g., 1 km x 1 km) at a horizontal resolution typically between 0.1 and 0.5 m. The photographs are free of clouds and cloud shadows and are usually taken during the spring or fall when there are no leaves, ice and snow.

Orthophotographs are generally available from municipal and provincial web sources, such as GeoBC, Land Information Ontario, GeoNB and GeoNOVA. High-resolution satellite imagery (typically 0.3- to 0.5-m resolution) is also available from commercial providers.

Historical aerial photographs dating back to the 1920s are available from NRCan's National Air Photo Library. Digital scans of the photographs are available for a fee. Historical aerial photographs may be available from provincial and municipal governments, universities and other archive sources.

6.7.2 Aerial Imagery Data Acquisition

Unmanned Aerial Vehicle (UAV) systems are frequently used to capture oblique and nadir (downward-facing) photographs for CFRA studies. Oblique photographs are often used for documentation and communication purposes while nadir photographs are usually processed using Structure-from-Motion (SfM) photogrammetry software to develop mapping products (orthophotos, DEMs, point clouds, etc.). Very high-resolution orthomosaic images (e.g., 5-cm ground resolution) are possible with UAV systems due to the low flight elevations (generally 20 to 100 m above ground).

6.7.3 Quality Control of Aerial Imagery

Modern orthophotographs from government sources rarely require additional quality control checks and processing. However, all aerial imagery (e.g., recent satellite imagery) should be reviewed for horizontal shifts and other distortions prior to use. Historical aerial imagery from the National Air Photo Library and other sources does not contain spatial reference information and must be adjusted and distorted using known control points (e.g., buildings, road intersections, etc.). Historical aerial photographs are often used for shoreline change and other analyses. The spatial accuracy of the georeferenced air photos will depend on the scale and resolution of the photographs, quality and locations of control points common to both images, the camera lens and terrain distortion, and other factors.

6.8 Climate Change Projections

Some insight to projected climate change impacts on coastal flood hazards in Canada is provided by Lemmen et al. (2016) and Bush & Lemmen (2019). The high-level conclusions from the *Canada's Marine Coasts in a Changing Climate* report are (Lemmen et al., 2016):

- *Changing climate is increasingly affecting the rate and nature of change along Canada's highly dynamic coasts, with widespread impacts on natural and human systems.*

- *Recent extreme weather events demonstrate the vulnerability of coastal infrastructure.*
- *Changes in the extent, thickness and duration of sea ice, both in the North and in some areas of the East Coast region, are already impacting coasts, ecosystems, coastal communities and transportation.*
- *Sea-level changes will vary significantly across Canada during this century and beyond. Where relative sea level is rising, the frequency and magnitude of storm-surge flooding will increase in the future.*
- *Knowledge of climate risks and the need for adaptation in coastal areas is increasing, with many examples of local and regional governments in Canada taking action on adaptation.*
- *A range of adaptation measures will be needed in most settings to address the complex array of changes. Alternatives to hard coastal-protection structures can be effective in addressing coastal erosion and flooding in many areas.*
- *It is imperative that future development be undertaken with an understanding of the dynamic nature of the coast and changing coastal risks. Monitoring and assessment of the effectiveness of actions taken to date, as well as research to fill data and knowledge gaps, would help inform sustainable planning and development.*

A headline message from the more recent *Canada's Changing Climate Report* also relates to coastal flood hazard risk (Bush & Lemmen, 2019):

> *Coastal flooding is expected to increase in many areas of Canada due to local sea-level rise. Changes in local sea level are a combination of global sea-level rise and local land subsidence or uplift. Local sea level is projected to rise, and increase flooding, along most of the Atlantic and Pacific coasts of Canada and the Beaufort coast in the Arctic where the land is subsiding or slowly uplifting. The loss of sea ice in the Arctic and Atlantic Canada further increases the risk of damage to coastal infrastructure and ecosystems as a result of larger storm surges and waves.*

There are a variety of recently launched online portals for climate data for Canada,[12] developed by various government and academic institutions and consortiums, including the Canadian Centre for Climate Services. The following sections identify specific sources of data that may be useful to support quantification of climate change effects on coastal flood hazards.

6.8.1 Sea and Lake Levels

Relative sea-level projections (incorporating contributions from global sea-level rise, vertical land motion and other effects) for Canadian coastal locations in the 21st century and for various representative concentration pathway (RCP) scenarios are provided by James et al. (2014, 2015), and summarized in Lemmen et al. (2016) and Bush & Lemmen (2019). The projections were developed for 59 Global Positioning System (GPS) sites located near the coast in Canada. The projections are based on projected global sea-level rise, spatial variations arising from ocean currents and gravitational effects, and GPS-measured rates of vertical land motion. The largest amounts of relative sea-level rise are projected where

[12] https://climatedata.ca
https://www.canada.ca/en/environment-climate-change/services/climate-change/canadian-centre-climate-services.html

the land is currently sinking due to glacial isostatic adjustment in Atlantic Canada (James et al., 2014). Other areas where relative sea level is projected to rise include the Beaufort Sea coastline, parts of southern Newfoundland and Québec, and the British Columbia coast. In other parts of the Arctic, including Hudson Bay and the central Arctic Archipelago, land uplift and the effects of present-day ice-mass changes counteract projected global sea-level rise, resulting in projections of relative sea-level fall or small amounts of sea-level rise.

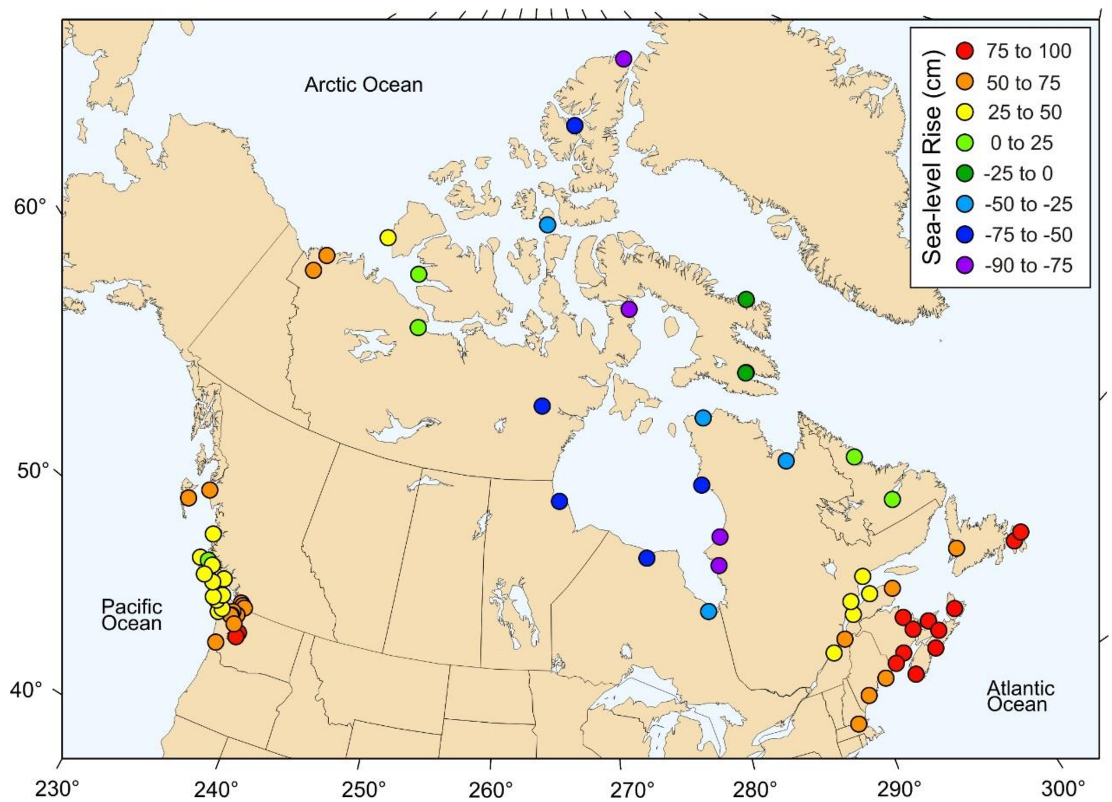

Figure 13. Projected median relative sea-level change by 2100, relative to 1986–2005, for high-emissions scenario RCP8.5 (from Atkinson et al., 2016).

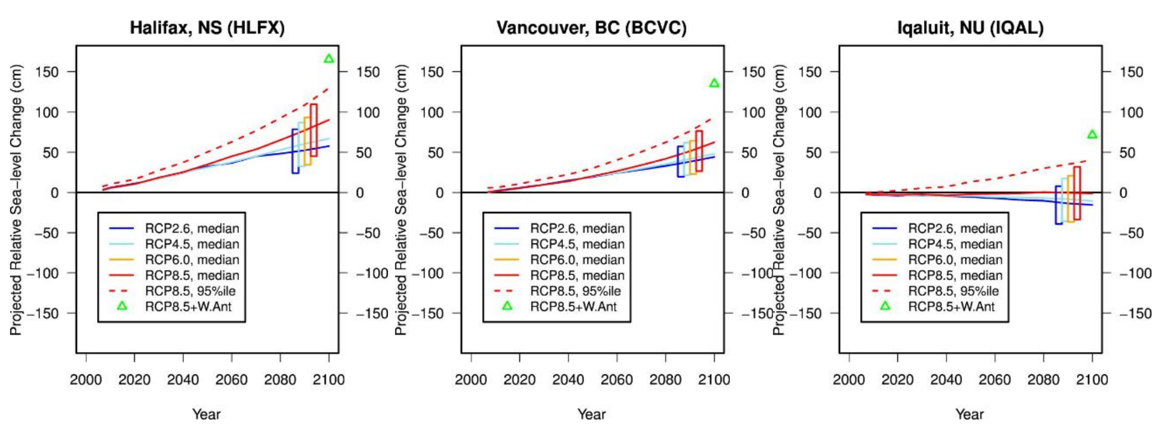

Figure 14. Projected relative sea-level change for Halifax, Vancouver and Iqaluit, relative to 1986–2005 (James et al., 2015), for four Representative Concentration Pathway (RCP) scenarios, and for an augmented scenario (green triangle) that provides and additional 65 cm of global sea-level rise at 2100 added to the median projection of the high-emissions RCP8.5 scenario.

In areas where relative sea level is projected to rise, there is high confidence that the frequency and magnitude of extreme high water levels will increase over time (IPCC, 2013; Lemmen et al., 2016; Greenan et al., 2018).

Projections of future (mean) sea-level change for Canada generally do not include potential changes in tidal amplitude (e.g., resulting from the lunar nodal cycle, or tide-bathymetry interactions), which can contribute substantially more to the frequency and magnitude of extreme sea levels on decadal time scales than global sea-level rise (Peng et al., 2019), and result in decadal fluctuations in coastal flood hazards (Talke et al. 2018). In the Bay of Fundy, projected changes to the tidal amplitude are expected to contribute to increased extreme water levels (Greenberg et al., 2012).

6.8.2 Sea and Lake Ice

Climate warming is projected to cause widespread reductions in the duration and extent of sea ice cover in Canadian coastal waters in the 21st century. Most Canadian Arctic marine regions could be sea-ice free for at least one month in the summer by 2050, based on multi-model simulations (Bush & Lemmen, 2019). Virtually ice-free winter conditions are projected by mid-century on the east coast under a high emissions scenario, although there is some uncertainty in these projections (Bush & Lemmen, 2019). The duration of seasonal ice cover on the Great Lakes is projected to decrease by 25 to 50 days by the middle of the 21st century, due to later freeze-up and earlier break-up. These projections of declining sea and lake ice cover have implications for the exposure of coastal buildings and infrastructure to storm surges, waves and other sources of flood hazard, with increases in the duration of the open-water season being a significant concern. Further details of projected sea and lake ice cover due to climate change effects are provided in Derksen et al. (2018).

6.8.3 Storm Surges and Extreme Waves

The frequency and magnitude of storm surges and extreme wave events are expected to increase in regions of Canada that currently have seasonal ice cover, as seasonal ice duration decreases. Projections for the 21st century point to a slight northward shift of storm tracks off Atlantic Canada, and increases in winter wave heights off the Pacific coast. There is low confidence in these projections, due to uncertainty associated with projections of storminess, as a result of limited observational data, inconsistencies amongst research findings, and differences in projections from global and regional climate models (Greenan et al., 2018).

6.8.4 Global and Regional Climate Model Data

Climate projections are based on global earth system models, which typically do not provide sufficient spatial and temporal resolution to support coastal flood risk assessments for regions, communities or building/infrastructure sites, where hazards are driven by variability at high frequencies and small spatial scales. Various strategies for downscaling global climate model projections are described by Flato et al. (2019). Both statistical and dynamical downscaling experiments have been carried out for North America, and data is freely available through the North American Regional Climate Change Assessment Program (NARCCAP: http://www.narccap.ucar.edu/) and the Coordinated Regional Downscaling Experiment (CORDEX: https://na-cordex.org/). These experiments provide historical simulations and projections for the 21st century (including for daily sea-level pressure and surface wind fields) from different regional climate models, driven by different global climate models. Ensembles of these datasets can be used to provide insight to potential changes in daily winds and sea-level pressures in regions of Canada, recognizing that no single model or combination of global/regional models is universally representative, and that coastal flood hazards may be influenced by higher-frequency (i.e., sub-daily) fluctuations.

6.9 Building and Infrastructure Data

When assessing vulnerability and risk for buildings and infrastructure (existing or proposed) exposed to coastal flood hazards, it is important to identify features that may affect damage levels, recoverability, or risks to human health. For example, the damage levels incurred by a building for a given hazard exposure will be influenced by the building type (or building classification), number of storeys, building footprint, main-floor elevation, and presence (or lack thereof) of a basement. Depending on the design/planning stage at which the coastal flood risk assessment is performed, whether the assessment is required to support new design or retrofitting, and/or whether the assessment is needed to determine potential impacts on flood risk to surrounding buildings and infrastructure; this information may be derived from inventories of available data for similar asset types, or from actual design documentation (e.g., drawings and specifications). In case of the former, it is important to consider how potential design changes that differ from historical norms could potentially influence vulnerability and risk, to inform decisions on building- and infrastructure-level measures to reduce risk.

6.9.1 Available Building and Infrastructure Data

For existing buildings, data can be obtained from municipal archives and may include addresses, building footprints, building heights/massing, and zoning/land use. This data can be combined with data from provincial land registry/title offices and property assessment authorities (e.g., BC Assessment, Ontario's Municipal Property Assessment Corporation), which may include information such as property type, number of occupants, number of households, building use, year of construction, total square footage, first-floor area, second-floor area, number of storeys, unfinished basement area, finished basement area, floor level, and assessed value. This information can be used to classify buildings for vulnerability and risk assessments (e.g., NRCan, 2017;[13] IBI Group and Golder Associates, 2015).

For buildings, the elevation of the main floor can significantly influence damage estimates. For existing buildings (e.g., assessments to support retrofits or understand risk), the elevation of the main floor may be surveyed using conventional techniques or estimated by adding the estimated height of the main floor (e.g., counting the number of steps to the front door) to the ground elevation from a DEM. For new (i.e., proposed) buildings, design documentation will indicate the main floor elevation.

Methods for quantifying flood damage to infrastructure assets, such as roads, bridges, culverts, storm and sanitary sewers, water lines, hydro lines and transformers, gas lines, and telephone/cable/internet lines are less well developed. Inventories of infrastructure and records of damage/maintenance can provide insight to damage levels sustained in response to coastal flood hazard events. Given the sensitivity of this information, particularly for critical infrastructure, this type of data can be challenging to obtain.

6.9.2 Building and Infrastructure Data Acquisition

For coastal flood risk assessments conducted at a community scale, site visits are recommended to confirm building inventory data, fill missing data, and create a photo database. Access to properties is typically not required as building classifications, number of storeys, number of steps to the front door (to estimate first-floor elevation), presence of basement, and other factors can be reviewed from the public right of way. For studies undertaken for a specific building or infrastructure, information should be obtained from the design drawings (e.g., bridge soffit elevations).

[13] In 2017, a draft, unpublished report on "Canadian Guidelines and Database of Flood Vulnerability Functions" was prepared for Natural Resources Canada as part of the Federal Floodplain Mapping Guidelines Series. The document is currently undergoing revision, prior to release/publication.

Data requirements vary between different vulnerability and risk assessment methodologies (see Section 9). Existing data sources should be reviewed to assess whether sufficient data exists for the selected assessment methodology.

6.9.3 Quality Control of Building and Infrastructure Data

Building and infrastructure data should be reviewed to confirm that the information is current and accurate. For example, the inventory, equipment, raw materials, structures, and clean-up costs will be different for different commercial building uses (e.g., restaurant, retail, office, etc.). Data should also be reviewed for missing, incomplete, duplicate, and suspect data.

6.10 Flood Damage Functions

Flood damage functions developed for buildings and infrastructure may be used to estimate the amount of damage to an asset by floodwaters. The most common type of damage functions, which are sometimes referred to as vulnerability or fragility curves, are known as “depth-damage curves” and provide an estimate of the damage incurred by a structure (and its contents, if applicable) for a given flood depth. In coastal regions, buildings and infrastructure may also be damaged by wave impacts, high-velocity flows (wave uprush/backrush), erosion, and debris (such as logs, ice, etc.). For example, wave-driven debris was implicated as a potential contributing or exacerbating factor in damage to a pier in White Rock, BC, during a windstorm in December 2018 (City of White Rock, 2019).

Comprehensive building and infrastructure damage functions are not widely available for storm waves and hydrodynamic loads in coastal regions. However, FEMA (2001) provides basic depth-damage curves for Coastal V Zones (e.g., breaking waves >3 feet, wave overtopping, etc.) based on the combined effects of high-velocity storm surge flooding, waves, and debris impacts. Post-storm damage inspections in the U.S. indicate that standard construction offers little to no resistance to breaking wave loads, with complete destruction of wood-frame walls and unreinforced masonry walls below the wave crest elevation (see e.g., FEMA, 2006, 2009, 2011). Reinforced concrete walls (e.g., foundation walls) are capable of withstanding moderate wave loads provided the structure is not undermined from wave scour and overtopping.

In some cases, the severity of damage may be influenced by the amount of warning time, duration of the event, weather conditions (temperature, precipitation, etc.), and other factors. For example, temporary protection and mitigation measures could be installed, or building contents moved, with adequate warning time.

6.10.1 Available Flood Damage Data

In 2017, NRCan published a draft report on *Canadian Guidelines and Database of Flood Vulnerability Functions* as part of the Canadian Floodplain Mapping Guidelines Series. At the time of writing these CFRA guidelines, the draft report is being revised. While the report was developed for riverine flooding, the terminology, vulnerability functions, and procedures are largely applicable to coastal regions. In particular, the depth-damage curves developed for riverine flooding can likely be used for coastal flood (storm surge) risk assessments where the depth of flooding is small and wave heights are limited. NRCan (2017) notes that current practice is to dispose of and replace all items that have come into contact with floodwaters (e.g., drywall, flooring, appliances, furniture, etc.) due to the risk of mold and contamination. Considering this practice, salvageability rates for riverine and coastal flooding are expected to be similar, and depend mainly on flood depth, as opposed to other flood characteristics (e.g., flood duration, warning time, mud content, fresh vs. saltwater, presence of waves, etc.). However, as advanced materials, construction techniques and finishes and “Build Back Better” principles become more widely applied in Canada as part of more comprehensive approaches to reducing flood risk, there will be a need to develop new damage functions that capture specifics of coastal flooding (e.g., damage due to wave action).

For exposed coastal locations, the probability of building collapse should be evaluated based on the anticipated wave loads and building characteristics. Alternatively, NRCan (2017) provides simplified tables to estimate the combination of water depth and water velocity that would cause the collapse of wood, masonry and concrete, and steel buildings (adapted from the HAZUS Multi-hazard model, FEMA, 2006). For wood-frame buildings, the tables indicate complete collapse at inundation depths greater than 3 m or at shallower depths where the water velocity is greater than 10 m/s. Very few buildings in Canada have been exposed to water depths and velocities of this magnitude during historical extreme coastal storm-generated floods. If the water depth and velocity are below the building collapse threshold, direct building damages can generally be based on depth-damage curves alone.

The depth-damage curves in NRCan (2017) were developed from post-flood inspections of buildings following the 2013 Calgary flood. The guide provides methods to adjust the costs to different regions in Canada and different years by using the Consumer Price Index, Survey of Household Spending, and Construction Price Index. Detailed tables are provided in the guide describing the cost to remove and replace building components for different building classifications. In general, the following depth thresholds apply for residential basement and main-floor flooding (depths are above the basement or main-floor elevation):

- 0 to 0.1 m: Replace all flooring, drywall up to the ceiling, vapor barrier, insulation, doors, cabinets, etc., and clean-up and structural drying.
- 0.3 m: Replace furnace (basement only).
- 0.6 m: Replace all electrical to service panel.
- 0.9 m to 1.5 m: Replace all windows (main floor/basement).

Alternatively, FEMA's HAZUS flood model uses depth-damage curves developed by the U.S. Federal Insurance Administration and USACE regional offices that report percent building damage for a given flood depth. The curves may not be appropriate for Canada due to differences in building construction (e.g., many U.S. buildings in coastal hazard zones are slab on grade or elevated on piles), relative exposure to coastal flood hazards (hurricanes), and age of the data (trends in building size, repair/salvageability, contents type and value). For example, depth-damage curves developed for buildings on the Gulf of Mexico are subject to hurricane winds, waves, and storm surges that far exceed what would be experienced on Canada's marine and Great Lakes coasts. The depth-damage curves developed for riverine flooding in Calgary, adjusted to different regions in Canada and for year using the indexing methods in NRCan (2017), are therefore likely to be more representative of coastal storm flood-generated damage to buildings in Canada but should still be used with caution. At the time of writing these guidelines, regional efforts are underway to develop depth-damage curves that reflect the local conditions (e.g., the Lower Mainland in BC).

Additionally, NRCan (2017) provides depth-damage curves, classified by building type and use, for non-residential buildings. For example, the finishes and contents of an office building will be different from a retail building with the same structural classification. NRCan includes a category for hospitals and another for institutional/other, which includes schools, libraries, etc. FEMA recognizes that the depth-damage curves for essential facilities (e.g., hospitals, fire halls, police stations, schools, etc.) are highly variable and HAZUS requires that depth-damage curves be defined by the user for essential facilities.

Dias & Edirisooriya (2019) present a method of obtaining mean damage curves for structures due to tsunami hazards, based on fragility functions. Tsunami fragility curves were developed for applications in Japan based on surveys following the 2011 Tohoku earthquake and tsunami (Suppasri et al., 2012). Japanese wood constructions differ significantly from typical Canadian houses (e.g., joint detailing, foundation design), and thus, the Japanese fragility curves do not accurately reflect Canadian building/infrastructure design (Rossetto et al., 2019).

6.10.2 Flood Damage Data Acquisition

Site visits can be conducted to compare the local building inventory with the building classifications that will be used for the vulnerability and risk assessment. If the building types are not well represented, synthetic depth-damage curves may be developed for buildings exposed to coastal flood hazards. NRCan (2017) provides guidance on data collection and development of synthetic content damage curves for residential buildings. Similar guidance for non-residential buildings is provided.

Alternatively, the depth-damage curves provided in NRCan (2017) may be modified to account for minor differences in building type, such as presence of crawlspaces, unfinished basements, interior and exterior contents, elevating utilities (e.g., hot-water heater, furnace, etc.), landscaping, and clean-up. For example, the depth-damage curves for a building with a crawlspace (no basement), and furnace and hot-water heater on the first floor can be modified to reflect a lower vulnerability to damage from basement/crawlspace flooding. Many residences in northern communities are on elevated foundations allowing airflow beneath to maintain permafrost, which may afford some protection against shallow flooding, but may increase the potential for damage during more extreme flood events. Nominal values applied for landscaping and exterior clean-up may also be refined by considering the contents and size of the yard and consequences of a flood for the local site conditions.

As more data becomes available on the performance of different building- and infrastructure-scale flood resistance/resilience/repairability measures (Section 11), performance issues unique to coastal flood events (e.g., wave effects on damage), and regional differences in building and infrastructure performance; depth-damage (or vulnerability/fragility) curve databases should be updated to facilitate more accurate assessments of vulnerability to coastal flood hazards.

6.10.3 Quality Control of Flood Damage Data

The depth-damage curves selected for the vulnerability and risk assessment should be reviewed to ensure that there are no obvious errors in the data, the building inventory matches the building classification scheme, and the building contents reflect current trends. For example, it may be necessary to create a hybrid building category if many buildings are between categories. As design practice, codes and standards evolve to include new or innovative flood-resistant design features, damage relationships based on the historical performance of different building categories may no longer be representative, and new approaches may be required to develop damage functions.

6.11 Socio-Cultural, Environmental and Indirect Consequence Data

Flood damages to a building can also have many consequences beyond physical damages. These can include a wide range of potential economic, social, cultural and environmental consequences, which should be assessed for a more holistic picture of flood risk. Six different indicator categories can be used to describe the wider consequences beyond physical damages:

1) Affected People

2) Mortality
3) Economy (Indirect Consequences)
4) Critical Infrastructure and Disruption of Basic Services
5) Environment
6) Culture

The categories presented above consider international best practice from the Sendai Framework and the UN Working Group on Indicators. However, it may be relevant to adjust or group indicators differently dependent on project scope. In the sections below, example datasets for each of the six indicators are given, recognizing however that data availability and local context will vary from site to site.

6.11.1 Available Socio-Cultural, Environmental and Indirect Consequence Data

6.11.1.1 Affected People

The number of directly affected people will be informed by, for instance, the number of residents in a planned/existing building. If considering more indirect consequences, the number of people in the neighbourhood who depend on services provided within the building or infrastructure (e.g., population served by an electrical substation, etc.) should be included. The number of building residents can be obtained from design plans for new buildings/neighbourhoods and from building operators for existing buildings. For the population of the neighbouring coastal reach, census data can be used, as well as more detailed data from municipal sources, if available. Census dissemination areas are typically large in rural areas where it can thus be difficult to pinpoint the number of potentially affected people. Natural Resources Canada (NRCan) is currently developing a "Patterns of Human Settlement in Canada" dataset that uses remote sensing data to distribute census information to areas of human settlement across Canada, which can be used to estimate population densities (Journeay et al., 2020).

The extent to which people reliant on a building or piece of infrastructure will be affected by flooding depends also largely on their own vulnerability. In this context, vulnerability describes the "characteristics… of a community… that make it susceptible to the damaging effects of a hazard" (UNISDR, 2009). Typically, the following population groups are considered to be particularly vulnerable to flood hazards ("social vulnerability") (AIDR, 2009):

- The elderly, or those with disabilities, who might not be able to understand or respond as quickly or without assistance.
- People with low income, as they might not have the resources and capacity to prepare or respond.
- Families with young children, as children are more susceptible to be injured by deep floodwaters, and evacuation might be challenging for parents with many children.
- Newcomers or tourists, who might not be aware of flood hazards or evacuation routes.
- People with different cultures or languages, who might have difficulties understanding emergency announcements, and where special attention should also be paid to ensure that emergency actions do not offend cultural sensitivities.
- People who have limited mobility (e.g., due to illness or lack of transportation).

Census data and the NRCan dataset can provide more information on social vulnerability characteristics.

6.11.1.2 Mortality

While risk of mortality for coastal storm-driven floods is typically relatively low (Public Safety Canada, 2019), tsunamis have a high risk of mortality, which could be estimated using mortality functions (e.g., Smith and

Rahman 2016) (see Section 9). Mortality might need to be addressed if the subject building or infrastructure is located within the tsunami hazard zone where velocities and water depths are projected to be high. Mortality is typically estimated based on the estimated number of affected people in the area, hazard characteristics (such as tsunami inundation depth and velocity), as well as access to evacuation routes or vertical evacuation structures (see Section 9). Thus, data requirements include estimated number of people in area (this should, for instance, also include day-visitors in tourist areas), as well as information on evacuation planning in the area.

6.11.1.3 Economy

Apart from the direct economic consequences of flooding associated with physical damage and building contents damage (as discussed in Section 9), indirect economic consequences may also occur. These may include, for example, interruption of businesses located within the building/infrastructure or planned neighbourhood. Information on building assets and surrounding businesses can be obtained from provincial Property Assessments,[14] municipal and provincial spatial data sources, OpenStreetMap[15] or stakeholder input. Indirect economic estimates can be estimated from direct economic damages, and therefore from the same datasets. More detailed economic calculations may be warranted in the case of potential critical infrastructure disruption (see below). More detailed information on economic impacts, and the data to support the calculation thereof, will be provided in a forthcoming publication on flood damage assessment being developed as part of the Federal Floodplain Mapping Guidelines Series (NRCan, 2017).

6.11.1.4 Critical Infrastructure and Disruption of Basic Services

Determining the criticality of a building or infrastructure is key information for assessing the required flood-resilient design (Section 5). If the building provides critical services to the community or region, cascading effects on society might be far-reaching, and thus require a more flood-resilient design. Criticality is informed by the (intended) use of the building or infrastructure (for descriptions of criticality levels associated with different building types, see Section 5.3.3).

Disruption of basic services, such as electricity, gas, water supplies, and road access can also lead to far-reaching consequences for a community—and for the operability of the building or infrastructure under assessment. Thus, when planning the flood-resilient design of a building, it is key to also assess its access to basic services, and the timeliness of recovery. For example, is there only a single road leading to the building, where flooding may restrict access and thus interrupt food and other supplies? Or is the infrastructure serviced by a single power line with no redundancies where flooding could lead to power outages, necessitating consideration of back-up generators (especially for critical infrastructure)? Data on basic service structures can be obtained from municipal and provincial data sources and service providers, as well as independent societies, such as the Integrated Cadastral Information Society[16] in BC.

Alternatively, cascading impacts information is sometimes available in the form of incident planning scenarios (Government of Canada, 2009) from asset owners. If appropriate, scenario exercises with stakeholders can be completed to aid in the development of a more robust understanding of potential disruption to inform design features and approaches.

6.11.1.5 Environment

Environmental consequences arising from flood-related building damages can be far-reaching, if hazardous materials are released, or if damaged building materials contaminate surrounding ecosystems. Two types

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[14] For example, BC Assessment: https://www.bcassessment.ca/.
[15] https://www.openstreetmap.org/#map=10/51.3928/-121.9579
[16] Integrated Cadastral Information Society (ICI): https://www.icisociety.ca/

of data are needed to assess environmental consequences: sources (such as contamination sources, including wastewater treatment plants, fuel/propane storage and other hazardous materials) and receptors (sensitive ecosystems). Further, the pathway (i.e., how contamination sources can reach receptors) should be considered. The planned building/infrastructure use and any stored materials/contents will provide insight as to whether the building or infrastructure may itself pose an environmental (or human health) hazard. Fuel storage containers adjacent to a building can also act as contamination sources, as can some commercial activities, such as gas stations, auto repair shops, etc. Provincial property assessments and municipal data sources can provide information on type of commercial activities. Lastly, the type of surrounding environment plays an important role in the consideration of potential environmental consequences. For instance, if a protected and sensitive ecosystem is located near a planned building, extra precautions should be taken to minimize hazardous spills in case of a flood event. Data on nearby ecosystems and parks can also typically be obtained from the municipality and from local stakeholders.

6.11.1.6 Culture

Infrastructure that is damaged or destroyed by coastal hazards has the potential to impact surrounding areas, which may have cultural value. The effects of flooding on the culture of a community is challenging to quantify. In the absence of good cultural data, proxies, such as the number of cultural sites, are used. Cultural sites may include community centres, schools, religious centres, art galleries, theatres, built heritage and others. Data on these sites can be obtained from local municipalities, OpenStreetMap, provincial Property Assessments, and other sources. Importantly, historical and archaeological sites should also be included, such as Indigenous pre-settler sites. Some data can be obtained through the archaeology branches of provincial governments, and this data is typically sensitive (i.e., it cannot be shared or presented on mapping products). Despite these challenges, it is important that cultural assets are represented and measured as well as possible. Ignoring these potential losses in a risk assessment risks the assessment not having merit. For example, with respect to building or infrastructure design, the cultural importance of a building to the local community should be considered, as well as potential negative consequences to surrounding cultural sites, should the building fail or experience damage due to flooding.

6.11.2 Socio-Cultural, Environmental and Indirect Consequence Data Acquisition

Data is typically obtained from municipal/provincial spatial online data repositories and can be further informed by field visits. Importantly, stakeholder workshops can provide additional information on local values and context, existing datasets, as well as the more intangible and indirect consequences.

6.11.3 Quality Control of Socio-Cultural, Environmental and Indirect Consequence Data

Considering the uncertainties that are associated with many of the socio-cultural, environmental and indirect consequence indicators and risk assessment, quality control for supporting data is essential. Field visits can serve well here, and importantly, ground-truthing of information with stakeholders (for instance in workshops) can deeply improve the risk assessment process. Stakeholders should be embedded in the process at an early stage (Section 4).

7 Selecting Appropriate Levels of Analysis

Risk assessments can provide information on the potential consequences of coastal floods or tsunamis for existing or new (proposed) buildings or infrastructure assets, as well as on the further societal, economic and environmental consequences that could result from flooding. Thus, risk assessments can provide important input to design (new or retrofit) of buildings or infrastructure within broader systems and communities. If the consequences of building or infrastructure failure due to coastal flooding will be severe, either for the asset owners or other stakeholders in the surrounding community/system, steps should be taken to mitigate or avoid them. The consequences of a flood hazard are systematically determined in a risk assessment, and can then be ranked as minimal, moderate, high or substantial to help guide design criteria, as described in Section 5.

However, the scope, scale, level of detail, and level of effort associated with risk assessments can vary, ranging from high-level to detailed, from national to local, from multi-year projects to scoping exercises lasting a few months, or from focusing on individual asset risk to considering cascading effects onto the wider society. Truly effective flood risk management practice considers whole-system states, processes and interactions, as well as broad societal goals (Sayers et al., 2013). Regardless of the level of detail, a flood risk assessment is an analysis of a complex system, where the study area (building, infrastructure asset, neighbourhood, town, region) describes the system and where drivers, such as changing hazards, influence system components. As in any complex system, a multitude of interactions between system components exists, which, if described in full detail, would render the task of a risk analysis an almost endless process, and often, the data needed for such a detailed analysis are also not available. It is therefore necessary to identify an appropriate level of analysis for each coastal flood risk assessment that can adequately address risk factors, tolerances and pre-defined objectives (e.g., as identified by design criteria).

In the following sections, factors affecting decisions surrounding the appropriate level of detail used in an analysis are discussed. Different tiers of analysis are described, and guidance on selecting an appropriate level of analysis is provided.

7.1 Relevant Factors

The level of risk assessment that is needed (or practically achievable) is determined by a range of underlying factors, which are often apparent at the outset of a risk assessment:

1. **Study Objectives (and Targeted Design Phase)**

First and foremost, the necessary level of analysis should be informed by the design criteria, which define needs and objectives. What is the intended use of the analysis? Will it be used to inform high-level planning, siting, or detailed building or infrastructure design? Specifically, which design phase (initial scoping, feasibility study, conceptual design or detailed design planning) is being targeted? For an initial scoping exercise, a cursory analysis might suffice, while a feasibility study or detailed design would require greater analysis.

2. **Spatial Extent of Study Area**

The spatial extent of the study area will also determine the level of detail for the analysis. For a large coastal reach, it might be more challenging (and resource-intensive) to conduct a detailed analysis, than when focusing on an individual building or neighbourhood. For large study areas, it might also be difficult to obtain datasets that are comparable throughout the region, allowing for a consistent assessment. Although the emphasis or objectives may be to assess coastal flood risks for an individual building or infrastructure asset, the need to consider system-wide processes may dictate requirements for the spatial extent of the study area. This may be related to the need to consider the vulnerabilities and interactions between the building/asset and broader community/infrastructure systems, or the needs for properly characterizing natural (e.g., physical) system processes. The following hypothetical examples illustrate the importance of a systems-based approach to determining the spatial extent of a study:

- Flood risks to a coastal highway are not just associated with the potential for direct damage and the associated costs of repair—the risks associated with loss of serviceability (e.g., preventing emergency response to nearby communities) should also be considered and mitigated appropriately through planning and design.
- Coastal flood risks for a planned building in Saint John, New Brunswick, must consider local tides, as well as storm surges and waves generated in and outside the Bay of Fundy.

3. Criticality of Buildings or Infrastructure

For risk assessments supporting the design of buildings and infrastructure, the criticality of the asset is an important factor affecting the level of required analysis. Different building categories were defined in Section 5.3, where buildings or infrastructure that provide essential services are associated with lower risk thresholds than residential buildings or temporary structures. For design of a critical asset (e.g., a wastewater treatment plant), a more detailed risk analysis might be required than for a warehouse, or even a single-family home. If a critical asset is damaged or experiences loss of serviceability in a flood, it could potentially have cascading effects on the neighbourhood and broader socio-economic or natural systems, especially if will take a long time (years) to recover.

4. Data Availability

The availability of existing data may determine the level of risk analysis that is possible, as it varies widely between jurisdictions. For instance, some municipalities have up-to-date flood mapping that is freely available online, while other jurisdictions may not have flood maps and require new hydraulic modelling studies. Similarly, the availability of exposure and vulnerability data can vary widely from location to location, where for some jurisdictions, detailed building surveys are available and for others, this data has not yet been collected. Census data, while providing essential information on population characteristics and being straightforward to use in dense population centres, is often challenging to use in rural areas, where dissemination areas are large and only a small portion of the dissemination area may be located within the flood hazard area. Census information is also limited on reserve lands.

In most cases, additional data will need to be collected (e.g., building surveys, digitization/categorization of building footprints from imagery), modelled, or assumed based on the working design, or inventories for other locations.

However, each of these additional steps will require further financial and technical resources. The quality and specificity of available data can significantly affect uncertainty levels for the analysis (for instance, when using inventory-based depth-damage curves from regions where building types are much different from building types of the study area).

5. **Resource Capacity**

One of the main limitations of the extent of risk assessments are the financial and time constraints, as well as the technical capacity and expertise that are available to conduct a risk assessment. This is particularly challenging for remote areas, where financial and resource capacities are often much more limited than in well-equipped cities.

7.2 Tiers and Dimensions of Analysis

Analysis can range from qualitative to quantitative analysis, can consider one hazard scenario or multiple, and can address present-day risk only or dynamic factors affecting risk. It can vary in the level of detail at every step of the risk assessment. In the following sections, these different tiers of analysis are described.

7.2.1 Quantitative versus Qualitative

Risk assessment can be quantitative or qualitative or fall somewhere in between. For example, the national all hazards risk assessment (AHRA) is a qualitative tool that can help to identify, analyze and prioritize a full range of potential threats (Public Safety Canada, 2012). This type of tool can be relatively simple to develop for prioritization exercises. However, to make decisions to reduce risk locally, in particular to support design of buildings and infrastructure assets, requires a more robust methodology—ideally a high-fidelity, quantitative risk assessment. A quantitative risk assessment is one that uses measurable and objective hazard, vulnerability and likelihood information to calculate risk and loss. The quantification of risk, although at times cumbersome, provides invaluable information for risk reduction through the provision of data for planning, decision making and design.

While quantitative measures are generally considered more robust, it is not always possible to source the appropriate hazard, exposure and vulnerability data to support this type of assessment. This may be because the data or methods simply do not exist or have not been collected, or because quantitative methods are not appropriate to measure intangible impacts of risk. In this case, rather than discounting the risk because it is too hard to calculate, qualitative measures—especially using expert elicitation and stakeholder input—can be appropriate. Expert elicitation is commonly applied to natural hazard and climate risk assessments because of the complexity of the problem. Alternately, a mixed approach, where quantifiable data are used in combination with expert opinion, can be taken, as with Canada's National Risk Profile.

7.2.2 Single-Scenario versus Multiple-Scenario Approach

In a risk assessment, single-hazard scenarios or multiple-hazard scenarios can be considered. If a single likelihood, for example, a 0.5% AEP event, is used to calculate damages and losses, this is called a single-scenario approach. This is the most common type of risk assessment completed in Canada, as it is relatively straightforward and requires only one hazard scenario to be calculated and mapped. Single scenarios are commonly used for emergency response planning, where a large probable maximum scenario informs exercises on the assumption that a plan for a catastrophic event will also be valid for smaller events. Single scenarios have also traditionally been used to support hazard mitigation decisions because this simple standards-based approach is relatively straightforward to calculate.

A multiple-scenario (or probabilistic) assessment, on the other hand, is one that considers a range of hazard scenarios and potential damage outcomes. The area under a curve (with likelihood and consequence as the axes) is integrated to give a full picture of risk (in contrast to the single point that can be obtained from a single-scenario approach). Although commonly used in many other developed nations, the multiple-scenario approach is rarely used in Canada at present, but it is considered best practice as it provides an understanding of the potential impacts of frequent small floods, as well as infrequent large floods. Multiple-scenario assessments can be resource-intensive, however, advances in technology and methods are reducing the required level of effort to conduct them.

Single-scenario approaches are the most commonly used in Canada—primarily because of the relatively low level of effort required. However, as discussed in Section 5.3, single-scenario or standards-based approaches lack the flexibility needed to address the dynamic nature of coastal flood risk in a changing climate, can create barriers to adaptation, and can perpetuate false perceptions of risk—all leading to poor decision-making and design practices. Multiple-scenario approaches are increasingly recognized as vital for reducing flood and other natural hazard risks in Canada, and are generally considered best practice. This is especially true as climate change affects risk profiles, and some smaller and medium floods become frequent, or nuisance flooding transitions to chronic flooding. Flood management and design decisions are affected by the analysis approach taken, and it is therefore important to choose an appropriate approach given the available resources, data and time. Particularly for critical infrastructure assets with service lifetimes exceeding 50 years and involving significant capital investment, the benefits and advantages of more detailed, multi-scenario analysis can substantially outweigh the cost and resource demands.

7.2.3 Consideration of Risk as a Dynamic Concept

Flood risk is not static. The variables that form risk (i.e., hazard likelihood and severity, exposure and vulnerability) are all prone to change over time (GFDRR, 2016). These changes are a result of both global issues, such as climate change, which can impact local hazard profiles, and local issues, such as land use decisions and land use change, which may affect exposure and vulnerability. For example, local sea level is projected to continue to rise for much of Canada's populated coastlines, and climate change will potentially also affect the likelihood of storm occurrence, resulting in increased flood risk (see also Section 6.8). Land use change (such as increasing the number of impervious surfaces through urbanization) might also increase flood hazard. Risk can also change by increasing the exposure, for example, by allowing increased development in hazard areas, or by population growth in coastal towns. However, even with increasing hazard likelihood, it is possible to maintain or decrease risk. Primarily this can be achieved by reducing the consequences of the hazard, either by changing the exposure or vulnerability of assets, and making the system more resilient overall to the natural hazard.

Thus, in any coastal flood risk assessment, the dynamic aspects of risk should be considered. The extent to which dynamic risk is considered depends somewhat on the level of analysis. However, even in a simplified or high-level risk assessment, it is essential that simple climate change stress scenarios (e.g., a best-guess probable climate scenario) should be included. Otherwise, significant changes in risk might be missed. This is particularly important for buildings or infrastructure with long design life, while for temporary structures with a short design life, it might not be essential. At the very least, it is important to consider different future trends (climate change, population growth, land use change, etc.), and assess these trends in relation to the design life of a planned building or infrastructure project.

7.2.4 Asset Risk or Systemic Risk

A risk assessment to support the design of buildings and infrastructure can merely focus on risks to the specific asset, or explore the wider systemic risk of building/infrastructure failure. Asset risk focuses on individual buildings and infrastructure and addresses the acute damage and failure of a single infrastructure asset (e.g., a power substation or a commercial building being flooded), in contrast to the broader systemic risk cascading down to different sectors (e.g., a portion of a town being without power for a period of time and the consequences thereof). The former is a relatively straightforward concept where asset (or object) risk is defined as an individual infrastructure asset being negatively impacted by a hazard. Systemic risk is a much more complex affair and can, at least theoretically, be expanded infinitely. For example, it could include cascading effects of a single point of failure within an electrical system to the broader electrical system. This could then be considered in the context of the interdependencies with other critical infrastructure (e.g., water treatment plants, telecommunications), and then further in the context of broader societal and economic impacts. Systemic risk and resilience should always be the ultimate goal. However, an understanding of asset risk is required to feed into the broader systemic risk context, and often asset risk constitutes the first step in a risk assessment and design to reduce risk.

7.2.5 Levels of Analysis within Steps of the Risk Assessment Process

For each step of the risk assessment process, there can be a range of analysis levels (from high-level to detailed), with a range of associated complexity and sophistication. For example, flood hazard assessments can include single or multiple scenarios, address the present-day only or include climate change scenarios, and the quality of flood mapping can also vary widely (hydraulic modelling or approximate inundation, as well as age of flood maps). Similarly, consequence assessment can vary, including only high-level exposure data or using detailed vulnerability assessments. Thus, risk assessments can range from simple scoping exercises to approximate and exposure-focused analyses, to fully detailed vulnerability-consequence-risk analyses for multiple hazard scenarios that address both asset risk and systemic risk. In an exposure-focused analysis, only the presence of the building or infrastructure asset in the flood hazard area is considered, but no building vulnerability data are included, nor are monetary consequences. A detailed risk assessment, on the other hand, would include the calculation of monetary consequences (e.g., via depth-damage curves), and the consideration of multiple indicator categories and future change scenarios.

7.3 Selecting a Level of Analysis

The level of analysis adopted for a coastal flood risk assessment intended to support the design of buildings or infrastructure should be aligned with the overall design objectives and design criteria, including identified risk tolerances (see Section 5). For example, the designer/builder, or purchaser of a single-family home may need to know the likelihood and cost of damage and loss for the single building, to inform decisions related to design for resilience, insurance or the need for retrofitting. At the other end of the spectrum, governments may need information to help them prioritize investment to develop, maintain and adapt entire portfolios of infrastructure assets, interconnected systems and communities. Each of these stakeholders will require different information, and require different methodologies for flood risk assessment.

An overview of different levels of risk assessments and their potential uses is provided in Table 5. Importantly, a risk assessment is typically a phased process. First, a high-level scoping analysis is conducted that allows prioritization of hazards and exposure. For locations with (initial) high risk, more data are then collected, which consequently allow for a more refined risk assessment. The phased nature of risk assessments is shown in Table 5, as the level of detail progresses from Step 1 (initial scoping), to Step 2 (high-level risk assessment) and Step 3 (detailed risk assessment that is focused on asset risk), and finally, Step 4 (detailed risk assessment that explores the cascading impacts on the wider society, i.e., the systemic risk). The level of detail in the analysis differs with the design criteria and objectives, and the design phase of the building/infrastructure that the risk analysis is informing. Criticality of the building/infrastructure also plays an important role, as does the spatial scale of the study area. The chosen analysis approach (hazard, exposure, vulnerability, consequence and risk assessments) and extent of stakeholder engagement will then vary according to these factors, as indicated in Table 5.

Considering that a risk assessment can become very complex and time and resource intensive, a phased approach is recommended. High-level screening of hazard and exposure can allow a more focused detailed risk assessment. The criticality of a building, where consequences of failure due to flooding (or tsunamis) could be especially damaging to people and the natural environment, also plays a key role in determining the level of necessary analysis.

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Table 5. Overview of different levels of analysis. Based on Lyle and Hund (2017) and Australian Institute for Disaster Resilience (2015).

Purpose	Criticality* and Design Phase	Spatial Scale of Study	Analysis Approach	Stakeholder and Public Engagement	Data Requirements
1. Initial Scoping					
- To screen risks quickly - To prioritize hazards/exposure for detailed assessment - To determine analysis method for next step - Focus is on asset risk - National-scale infrastructure planning	**Criticality:** All building types (Categories 1–4) **Design Phase:** Initial scoping	**Spatial Extent:** National, provincial/ territorial, regional **Spatial Resolution:** Aspatial to low	High-level screening, qualitative to semi-quantitative	Keep informed about process	**Hazard**: High-level flood identification, existing flood maps and/or tsunami maps, high-level climate change trends **Exposure**: Regional-scale data, consider high-level land use change and population growth trends **Vulnerability/Consequences**: Often not considered at this stage; high-level empirical loss methods, or qualitative matrices **Risk:** Product of Likelihood Score and Exposure/Consequence Score
2. High-Level Risk Assessment					
- To further prioritize hazards/exposure analysis and highlight key areas of concern - Focus is on asset risk - Provincial/territorial, regional (local) infrastructure planning and prioritization	**Criticality:** Most building types (Categories 1–2) **Design Phase:** Feasibility study	**Spatial Extent:** Provincial/ territorial, regional (local), coastal reach **Spatial Resolution:** Low to high	Focus on exposure analysis (what is in the flood hazard area?) and high-level vulnerability assessment; qualitative to (semi-) quantitative approach; single to multiple scenarios; simplified climate change scenarios; consider land use change and population growth trends.	Inform or consult about process	**Hazard**: High-level flood mapping, existing flood maps and/or tsunami maps, SLR (inundation approach, no additional hydraulic modelling), high-level climate change trends **Exposure**: Neighbourhood-level, regional data, multiple indicator categories with simplified proxies, high-level land use change and population growth trends **Vulnerability:** Generic building/infrastructure vulnerability information **Consequences**: Generic or synthetic depth-damage curves; high-level empirical loss methods, or qualitative matrices, direct/indirect impacts **Risk:** Product of Likelihood Score and Exposure/Consequence Score
3. Detailed Risk Assessment (Asset Risk)					
- Local government infrastructure planning - Risk mitigation decision making and design - Focus is on asset risk	**Criticality** Most building types (Category 2), and especially critical buildings (Categories 3–4) **Design Phase:** Conceptual design to detailed design	**Spatial Extent:** Local (small coastal reach to individual building/ asset) **Spatial Resolution:** High	Detailed full risk assessment, quantitative, risk for multiple indicator categories and including climate change and land use change	Consult and involve participants to inform on intangible consequences in particular	**Hazard**: Local-level detailed flood mapping (hydraulic modelling) and/or detailed tsunami mapping (hydrodynamic modelling), multiple annual exceedance probabilities, multiple climate change scenarios and time horizons **Exposure**: Parcel-level, local data, exposure mapping including expert knowledge, multiple indicator categories with multiple proxies; consider land use change and population growth trends **Vulnerability:** Individual building/infrastructure-based vulnerability information **Consequences**: Relevant, up-to-date depth-damage curves, consideration of direct/indirect impacts and tangible/intangible aspects **Risk:** Multiple-scenario/probabilistic risk assessment approach and annual average loss calculation; product of Likelihood Score and Consequence Score
4. Detailed Risk Assessment (Systemic Risk)					
- Focus is on systemic risk - Local to national government planning - Risk mitigation decision making and design - Emergency planning	**Criticality:** Critical buildings/ infrastructure (Categories 3–4) **Design Phase:** Detailed design (especially for critical infrastructure)	**Spatial Extent:** Local (can include regional to national consequences) Individual building (small coastal reach) **Spatial Resolution:** High	Assessment of systemic (society-wide) risk, qualitative and quantitative, risk matrices for multiple indicator categories and considering climate change	Consult and involve participants to inform on intangible consequences to wider society	**Hazard**: Local-level detailed flood mapping (hydraulic modelling) and/or detailed tsunami mapping (hydrodynamic modelling), multiple climate change scenarios and time horizons **Exposure**: Parcel-level, building footprints, exposure mapping including expert knowledge, multiple indicator categories with multiple proxies **Vulnerability:** Individual building/infrastructure-based vulnerability information **Consequences**: Relevant, up-to-date depth-damage curves, consideration of direct/indirect impacts and tangible/intangible aspects, considering cascading impacts for wider society **Risk:** Product of Likelihood Score and Consequence Score for the wider society

*Note: For criticality categories for building and infrastructure, please refer to Table 3 in Section 5.3.3.

8 Hazard Assessment

This section provides an overview of coastal flood hazards and describes a framework for assessing coastal flood hazards for existing or proposed building and infrastructure asset sites.

Coastal flood hazard assessment involves characterizing and understanding the probabilities of various flood-generating events that may occur, and their intensity (which may vary in time and space). Although the designer of a building or infrastructure asset may initially be concerned only with hazard metrics at the proposed site (e.g., peak depths, velocities, or wave heights for given AEPs), a broader spatial assessment of hazards is typically required to assess potential impacts on surrounding areas, and/or risk interdependencies. Consequently, the hazard assessment process typically involves producing hazard maps as outputs. As such, the methods and techniques for delineating and mapping flood hazards described by NRCan (2019) may provide useful guidance.

8.1 Framework and General Considerations

An overall framework for coastal flood risk assessment is provided in Figure 1 (Section 1.2) of this report, and includes a "Hazard Assessment" step. A suggested four-step process for this hazard assessment component is shown in Figure 15.

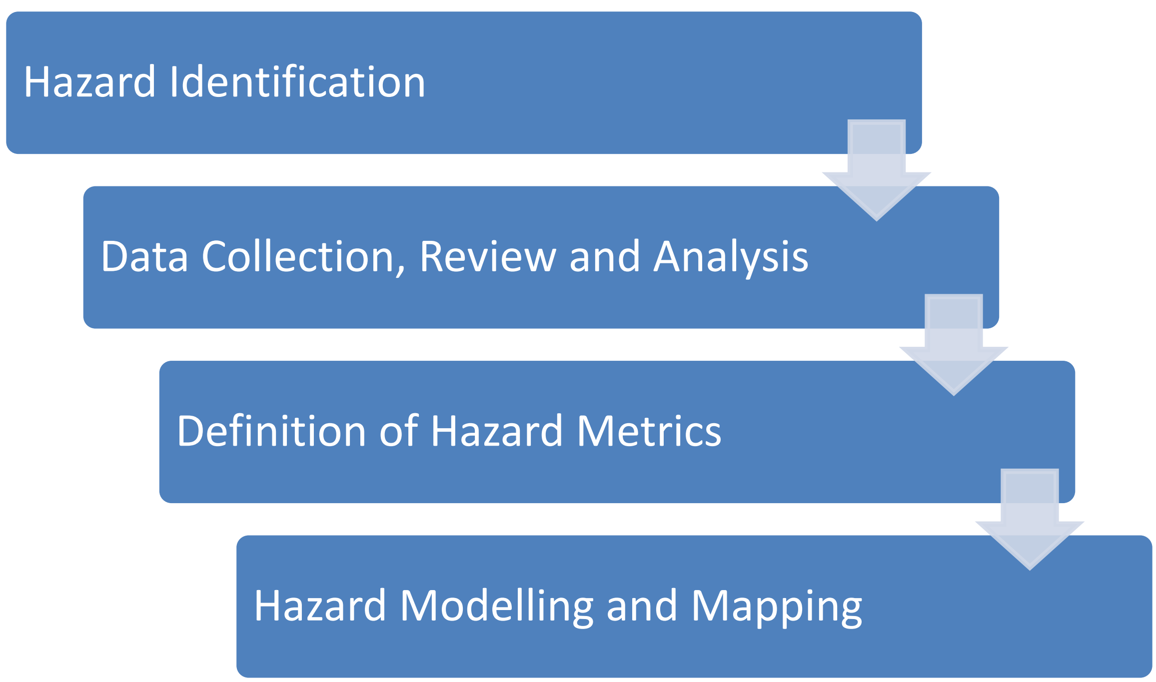


Figure 15. Coastal flood hazard assessment framework for building and infrastructure design.

As discussed in Section 7 (Selecting Appropriate Levels of Analysis), coastal flood hazard assessments may vary in the level of detail and complexity, from broad qualitative or semi-quantitative scoping studies through to detailed component-level or systematic analyses. The scope of coastal flood hazard assessments may also vary according to the spatial and temporal scales of interest, and defining characteristics of the natural system or infrastructure systems.

At regional scales, coastal flood hazards are typically evaluated without detailed consideration of interactions with structures (e.g., seawalls, bulkheads, revetments) or individual infrastructure components. This type of regional analysis is essential to capture coastal flood hazard-generating processes that may act over large spatial scales, and to ensure a system-based approach that captures all important physical processes (see discussion of system-based approaches in Section 4). Regional hazard assessments may also provide the basis for regional land use planning and strategic shoreline management. Such analysis will generally assess the horizontal extent of inundation, and the horizontal and vertical reach of wave action. The analysis is used to assess the extent and severity of exposure to the hazard and the safe bounds for a given risk level or levels (flood mapping). A more detailed hazard analysis is generally undertaken when considering risks to specific property and/or structures (engineering design phase). In these cases, processes acting over smaller spatial scales, such as wave-structure interaction, become important and more-detailed analysis is required.

Moving toward a risk-based approach for coastal flood hazards (as recommended in Section 5.3) adds a further dimension to hazard analysis. Rather than looking at a single flood AEP, as has traditionally been the approach to hazard assessment for land use planning and regulation in Canada, the analysis is expanded to consider a range of possible hazard events. This increases the number of possible flood-generating scenarios (e.g., combinations of possible tide, storm surge and wave conditions) that must be considered. Although various factors can influence decisions on which flood-generating scenarios to consider for a CFRA (Section 7.2.2), a good range of scenarios with probabilities ranging from very likely to very rare should be included. Too few scenarios can lead to a poor understanding of risk (Ward et al., 2011).

8.2 Hazard Identification

The first step in the coastal flood hazard assessment process is to identify the nature of coastal flood hazards at regional or local scales of relevance. This requires understanding the natural system characteristics and driving processes (i.e., hazard sources) and mechanisms that can lead to coastal flood hazards (pathways). The Source-Pathway-Receptor-Consequence model provides a conceptual framework for understanding flood hazard risk (Reeve et al., 2012; Narayan et al., 2012), identifying components at risk as well as the linkages between various infrastructure components, particularly flood control measures. For regional hazard assessments, the hazard is generally assessed independently from the receptor, and this may be a useful method for preliminary identification of hazards. It is important to consider how the building or infrastructure asset interacts with the hazard, both in terms of the impacts of the hazard on the asset (Section 9) and the impacts of the asset on the hazard. For example, wave-structure interaction and the shape and texture of coastal infrastructure (e.g., seawalls, piers, individual buildings) can greatly influence the reach and intensity of wave-related contributions to coastal flood hazards.

8.2.1 Sources

To assess coastal flood hazards, a clear understanding of the processes that contribute to those hazards (i.e., sources) is needed. Key sources of coastal flood hazards include:

- Water levels
- Waves
- Tsunamis

These sources may act alone, or in combination, to generate coastal floods. A key component of a coastal hazard assessment is to define the expected intensity and probability of occurrence of each of these hazards, as well as examining their interactions (Section 8.3). Joint probability analysis is a key aspect of understanding the combined likelihood of occurrence of combinations of water levels, winds and waves.

Contributions to coastal water levels include mean water levels, effects of relative sea-level rise, tides, atmospheric effects (barometric pressure, dynamic sea surface topography, storm surge), and wave effects (wave set-up and runup). Wave set-up, runup, impacts and overtopping of coastal defences (Figure 16 to Figure 18) are heavily influenced by shore geometry, which can be dynamic in response to tidal, wave and water level conditions.

Figure 16. Storm waves overtopping causeway at Cow Bay, Halifax, Nova Scotia (credit: M. Davies).

Figure 17. Wave impact, runup and overtopping at Stoney Creek, Lake Ontario (credit: M. Davies).

Figure 18. Waves hit the seawall on West Vancouver's Ambleside beach area at high tide, flooding the local John Lawson Park, on December 17, 2012 (credit: Mark Van Manen/PNG).

When beginning to identify potential coastal flood hazard-generating sources, it is useful to consider the role of regional storm meteorology in driving or contributing to extreme high water levels (e.g., winds and atmospheric pressure contributions to storm surges), extreme waves (generated by winds), erosion (often driven by extreme waves and storm-driven currents), and even tsunamis (i.e., meteotsunamis).

A description of the storm climatology for Canada's marine coasts is provided by Atkinson et al. (2016) and is summarized as follows.

Canada's Pacific coast does not experience tropical cyclones (typhoons or hurricanes). Storms typically consist of extra-tropical cyclones that originate over the open ocean and move under the influence of the jet stream to the Pacific coast of Canada, bringing significant moisture to the region. As stated by Atkinson et al. (2016), secondary storm systems are sometimes generated where warm and cold fronts meet, and "…can bring strong winds and heavy precipitation to Vancouver Island and the southern BC coast".

On the Atlantic coast of Canada, prevailing upper-level winds from the west and southwest drive continental storm systems into the region during spring and winter. Storms forming on the United States eastern seaboard move to the northeast and "…enter eastern Canada 36–48 hours after initial formation" (Atkinson et al., 2016). The strongest of these systems are typically referred to as "nor'easters". As stated by Atkinson et al. (2016), "Typically, hurricanes do not directly strike eastern Canada, with Hurricane Juan in September 2003 being a notable exception." Hurricanes tend to encounter the mainland United States to the south, where they weaken from tropical to extra-tropical cyclones. However, they remain very large, intense storms and can continue along a northeasterly trajectory toward eastern Canada. Due to their great spatial extent, these tropical and extra-tropical storms can have significant impacts over large regions "…and be almost as damaging as full hurricanes" (Atkinson et al., 2016).

The two most prominent storm tracks in the Canadian Arctic are (Atkinson et al., 2016): (i) from the east, into Baffin Bay via the Labrador Sea and Davis Strait; and (ii) from the west into the Beaufort Sea and Amundsen Gulf, affecting the western archipelago and the mainland coast of the Yukon, Northwest Territories and western Nunavut. Sea ice conditions significantly influence storm generation and propagation. As discussed by Atkinson et al. (2016), "…the large expanses of open water now found in the Arctic Ocean and marginal seas can provide the thermal gradients necessary to drive powerful storms of great areal extent." The shallow, gently sloping bathymetry and topography in the eastern Beaufort Sea and MacKenzie River delta also influence storm surge propagation.

Apart from the Pacific coast, ice cover is a major factor in the nearshore coastal conditions of most Canadian waters. The onset of winter ice generally reduces available open-water fetches for wind-wave generation and shore-fast ice dissipates wave energy and tends to protect the shoreline from wave action. Extensive sea or lake ice cover can also attenuate storm surges (Provan et al., in press; Kim et al., in press). Winter ice brings with it, however, its own set of natural hazards—including those associated with ice rafting and ice ridge interaction with the shore and nearshore structures.

8.2.2 Pathways

For coastal flood hazard risk to exist, there must be a pathway that links the hazard to a vulnerable receptor (e.g., infrastructure, properties, people, cultural assets and the environment).

There are numerous potential source-receptor pathways for coastal flooding. Four key pathways include:

- **Direct Inundation:** The sea level exceeds the elevation of the land (Figure 19). This generally occurs on low coastal plains and in estuarine areas, and may occur where a natural or constructed barrier is lacking.
- **Erosion:** In some coastal environments, the response of the shoreline or shoreline structures to ongoing and storm-related erosion processes can lead directly to flooding. This includes barrier breaching, whereby wave-driven flows, wave impacts and hydrostatic loading can cause the failure of a coastal barrier, allowing inland inundation. In parts of northern Canada (such as on the Beaufort Sea coast), permafrost thaw and sea-level rise is accelerating erosion (CSA W205), creating new pathways for coastal flooding.
- **Barrier Overtopping:** Mean water levels remain below the coastal barrier (which may be either natural or human-made) and overtopping occurs due to wave runup heights exceeding the crest of the barrier, allowing water to flow over the top of the barrier, flooding the land behind it.
- **Barrier Bypassing:** Floodwaters commonly circumvent coastal defences and dune barriers by exploiting inlets or washover channels, or by coming around the ends of the dune/defence systems.

Figure 19. Direct inundation at North Rustico, Prince Edward Island (credit: D. Jardine).

8.3 Defining Hazard Metrics

Hazard metrics and variables should be identified to guide the outputs of the hazard assessment. These metrics and variables will depend on design criteria (including needs identified by stakeholders, partners and the public—Sections 4 and 5), the level of analysis (Section 7), the availability of data (Section 6), and the nature of potential hazard sources and pathways (Section 8.2). Hazard metrics and variables should include timeframes (e.g., for projected sea-level rise), probabilities (AEPs), and intensity indicators. Coastal flood hazard intensity metrics may include water depths, velocities, wave conditions (heights, periods, directions, runup elevations), duration of flooding, debris quantities and flow velocities. For building and infrastructure design applications, hydrostatic loads can be computed from water depths alone. However, additional information on flow velocities, waves or debris may be needed to adequately describe dynamic loads or the potential for erosion/scour, which are typically a consideration in coastal settings.

8.4 Hazard Modelling and Analysis

In order to assess coastal flood hazards at a given site, the following questions are typically posed:

- **What are the meteorological and oceanographical ("met-ocean") conditions at the site and surrounding areas?**

Answering this question typically involves an assessment of weather conditions (winds, barometric pressure, temperature) and oceanographic/limnological conditions (water levels, currents, waves, ice cover and ice movement). Data sources include local weather stations, regional climate datasets and regional hindcasts (Section 6). The first step is typically to define “far-field” conditions from available data sources, which may then provide the basis for characterizing “near-field” conditions through modelling and analysis (i.e., “down-scaling”).

- **What are the physical characteristics of the site as they affect coastal hazards?**

  This involves assessment of bathymetry and topography, surficial sediments, bedrock geology and vegetation cover. Mapping and data from a wide range of sources need to be compiled to provide a description of past and present conditions at the site.

- **What are the nearshore conditions?**

  Tides, water levels, flow patterns and wave conditions near the coast are affected by interactions between offshore and nearshore physical processes, the local topography/bathymetry and local drivers (e.g., river flows). While empirical tools often give a preliminary estimate of nearshore conditions, analysis nowadays typically relies on computational modelling to evaluate these physical processes. Physical modelling can also be used for evaluation of nearshore hydrodynamics. Field observations can provide valuable insight into processes and can be essential in calibrating and validating models. Assessing nearshore conditions may extend beyond simply evaluating hazard sources (waves and water levels) to a more detailed evaluation of potential pathways that can lead to flooding, such as coastal erosion and wave overtopping.

- **What are the pathways that lead to coastal flooding?**

  Once nearshore hazards are quantified and source-receptor pathways identified (e.g., direct inundation, breaching, overtopping), various source-pathway scenarios (event-based and/or probabilistic) can be explored to determine local (overland) flood hazards.

8.4.1 Water levels

Water levels are the typical starting point for any evaluation of coastal flood hazards. Mean sea level, land subsidence, tides, atmospheric pressure, winds, tides and wave-driven processes, such as wave set-up and surf beat, all contribute to extreme water levels.

The individual components that contribute to the spatial and temporal variations in sea-level are quite complex. Pugh (1987) provides a comprehensive overview of tides, surges and mean sea-level as they relate to coastal water levels. Coastal floods can result from elevated water levels that include contributions by:

- Mean sea level (present-day).
- Change in relative sea level due to climate change and vertical crustal movement.
- Tides.
- Storm surges, typically understood to include wind set-up/set-down and atmospheric pressure set-up/set-down.
- Wave effects:
  - Wave set-up—the mean increase in water level at the shore required to balance onshore gradients in wave momentum flux, typically associated with wave breaking.

- Swash and infragravity wave action (surf beat).
- Wave runup (and overtopping).

In addition, it may be necessary to consider the effects of seasonal, interannual, or decadal fluctuations in water levels, seiches, river flow, and local runoff on water levels.

8.4.1.1 Vertical Datums

Establishing consistent vertical datums for both water levels and topography (and bathymetry, if used to support the hazard assessment) is a crucial prerequisite for accurately assessing coastal flood hazards. This task is often complicated by differences in datums used for land- and ocean-based applications, and evolving standards for establishing datums and vertical control. The following provides a brief description of datums used in Canada.

Until 2013, the term “geodetic datum” in Canada generally referred to the Canadian Geodetic Vertical Datum of 1928 (CGVD28), which was an approximation of mean sea level circa 1928, based on water level records at several gauge sites. In 2013, Natural Resources Canada released a new national geodetic datum, CGVD2013, which is a more sophisticated, detailed and up-to-date estimation of mean sea level. It is an equipotential gravitational surface that represents by convention the coastal mean sea level for North America.[17] To date, many municipalities have not yet transitioned from CGVD28 to CGVD2013, such that transformations and conversions of legacy datasets may need to be considered.

The vertical separation between the CGVD2013 and CGVD28 datums vary spatially across Canada, for example, the CGVD2013 datum is 15 cm below CGVD28 at Vancouver and 64 cm above it at Halifax. Furthermore, while CGVD2013 represents “by convention” mean sea level, actual mean water levels deviate quite a bit from CGVD2013. The mean water level at Vancouver is 19 cm above CGVD2013, while the mean water level at Halifax is 39 cm below it. This difference is due to variations in dynamic sea surface topography (effects of atmospheric pressure, water density and current patterns, and other factors that cause the mean sea surface to vary).

Floodplain topography and elevations of buildings and infrastructure are generally mapped relative to geodetic datum, whereas bathymetric data is typically reported relative to the local datum of hydrographic charts (chart datum, which is usually defined based on a low tide reference derived from water level records at a local tide gauge), while oceanographic studies more often use mean sea level as a reference datum. In the Great Lakes, the International Great Lakes Datum, IGLD85 is most commonly used, while the U.S. uses the NAVD88 vertical datum[18] based on mean sea level at Rimouski, Québec. The use of chart datum for bathymetric data can create challenges when conducting large-scale regional assessments of coastal flood hazards, which can encompass areas where bathymetric data is referenced to different local chart datums.

Care must be taken in ensuring that appropriate and consistent datums are being used in considering flood hazards and that the correct datum conversions are being applied. This is compounded by the fact that anecdotally both CGVD28 and CGVD2013 are referred to as “geodetic datum” or even “mean sea level”.

[17] www.nrcan.gc.ca/earth-sciences/geomatics/geodetic-reference-systems

[18] In 2022, the U.S. National Geodetic Survey (NGS) will replace the North American Vertical Datum of 1988 (NAVD88) with a geoid-based height reference system called the North American-Pacific Geopotential Datum of 2022 (NAPGD2022). This future U.S. datum has the same definition as CGVD2013 and at the time of release will enable a unified continental height system.
https://www.nrcan.gc.ca/height-reference-system-modernization/9054

In this document, the term "mean sea level" (MSL) refers to the local mean sea level as per hydrographic convention (IHO, 2011), not the geodetic mean sea level.

Attempts have recently been made to simplify datum conversions for hydrographic applications in Canada through the development of Hydrographic Vertical Separation Surfaces (HyVSePs) (Robin et al., 2016). These are surfaces that capture the spatial variability of tidal datums and levels using the geoid model, semi-empirical models, dynamic ocean models, satellite altimetry, relative sea-level rise estimates, and tide gauge observations. HyVSePs theoretically facilitates direct conversion between hydrographic elevations (chart datum, tidal elevations, mean sea level) to geodetic elevations (CGVD2013). However, care should be taken when applying the surfaces, considering the many assumptions and the uncertainty associated with models on which the surfaces are based, and local discrepancies with datum offsets at tide gauge sites and in areas where tides are affected by river flows, and/or shallow nearshore bathymetry. Natural Resources Canada's GPS-H software allows conversion between CGVD28, CGVD2013 and GPS-derived ellipsoid elevations (NRCan, 2019).

8.4.1.2 Relative Sea-Level Change

Coastal flooding is expected to become more frequent and severe in many areas of Canada due to local sea-level rise (Lemmen et al., 2016; Greenan et al., 2018). Relative sea-level change is due to a combination of global sea-level rise, land subsidence, or uplift, and adds to the challenge of predicting future coastal flood hazards. James et al. (2014) provide a detailed analysis of the effects of rising global sea levels, and changing land elevations (predominantly due to glacial isostatic adjustment) on local sea level change in Canada. Where relative sea level is projected to rise (most of the Atlantic and Pacific coasts and the Beaufort coast in the Arctic), the frequency and magnitude of extreme high water level events will increase (Greenan et al., 2018). The effect of sea-level rise on the frequency of flood events has been demonstrated for annual extremes of combined tide and surge for Halifax (Forbes et al., 2009; Atkinson et al., 2016) and Tuktoyaktuk (Lamoureux et al., 2015). Projections of relative sea-level rise over suitable time horizons (e.g., the design life of buildings or infrastructure) should therefore be considered in the hazard and risk assessment, to support design for resilience and/or adaptation.

The selection of future sea-level rise scenarios should take into consideration:

- **Planning/design horizons** or building/infrastructure design lifetimes, and the sensitivity/vulnerability of the assets-at-risk. For many residential and commercial buildings with limited system interdependencies, a planning/design horizon of 50 years or less may be considered appropriate, commensurate with the overall fiscal considerations (e.g., length of ownership, cost-benefit analysis of investment). From a land use planning perspective, or for more critical/sensitive infrastructure, longer time horizons should be considered. For land use planning, relative sea-level forecasts to 2100 are considered in many jurisdictions (e.g., British Columbia and New Brunswick).
- **Global emissions scenarios**, such as those described by the Intergovernmental Panel on Climate Change (IPCC) representative concentration pathways (RCPs). Of the four RCPs, RCP8.5 is the scenario with the highest emissions, assuming a future with little curbing of emissions, with a CO_2 concentration continuing to rapidly rise, reaching 940 ppm by 2100. There is no likelihood associated with the scenarios and, as pointed out by Greenan et al. (2018), scenarios resulting in even higher rates of global sea-level rise (e.g., that would result from rapid shrinking of the West Antarctic Ice Sheet and additional sea-level rise) cannot be ruled out.
- **Uncertainty in the projections.** Over shorter timeframes (i.e., to the middle of the 21st century), projected relative sea-level rise rates are similar for the various emissions scenarios and uncertainty is constrained, whereas toward the end of the 21st century, the projections for different

scenarios diverge and uncertainty ranges increase significantly. Some publications raise the possibility of larger amounts of global sea-level rise by 2100, primarily associated with higher rates of release of Antarctic ice to the oceans (Greenan et al., 2018). Projections by Han et al. (2015, 2016) are as much as 1 m higher by 2100 than guidance presented in James et al. (2014) that is based on the IPCC. The higher projections follow the upper bound sea-level scenarios presented by NOAA (Sweet et al., 2017), which are based, in part, on a sea-level projection method that was accorded low confidence by the IPCC (Church et al., 2013).

- **Potential for adaptation over time.** As datasets grow and climate models improve, predictions will evolve and uncertainty will decrease. Opportunities to adapt to observed sea-level change, and evolving climate and relative sea-level change projections should, where possible, be incorporated into the assessment and design processes.

Case Study: Charlottetown Harbour, Prince Edward Island

The annual exceedance probabilities for different water levels in Charlottetown Harbour under present-day and projected future sea levels (median estimate for one representative concentration pathway or global emissions scenario—RCP 8.5) are shown in Figure 20. Projected mean sea levels in 2045 are expected to exceed today's level by approximately 20 cm; by 2090, levels are projected to be 62 cm higher than today. Presently, a water level of 4.25 m above chart datum—high enough to flood much of the waterfront—has a 1% chance of occurring or being exceeded in any given year; by 2045, the annual exceedance probability of such an event will have risen to 2.5% and, by 2090, an event of this magnitude will have an AEP of 20%. These estimates do not include considerations for potential future changes in climate variability or the frequency and intensity of storms (e.g., Barnard et al., 2015), modification of storm surges and tidal ranges due to changes in water depths (locally and globally) (e.g., Schindelegger et al., 2018), or the nodal modulation of tides over decadal timescales that dominates mean annual tidal ranges on the East Coast (Houston & Dean, 2011).

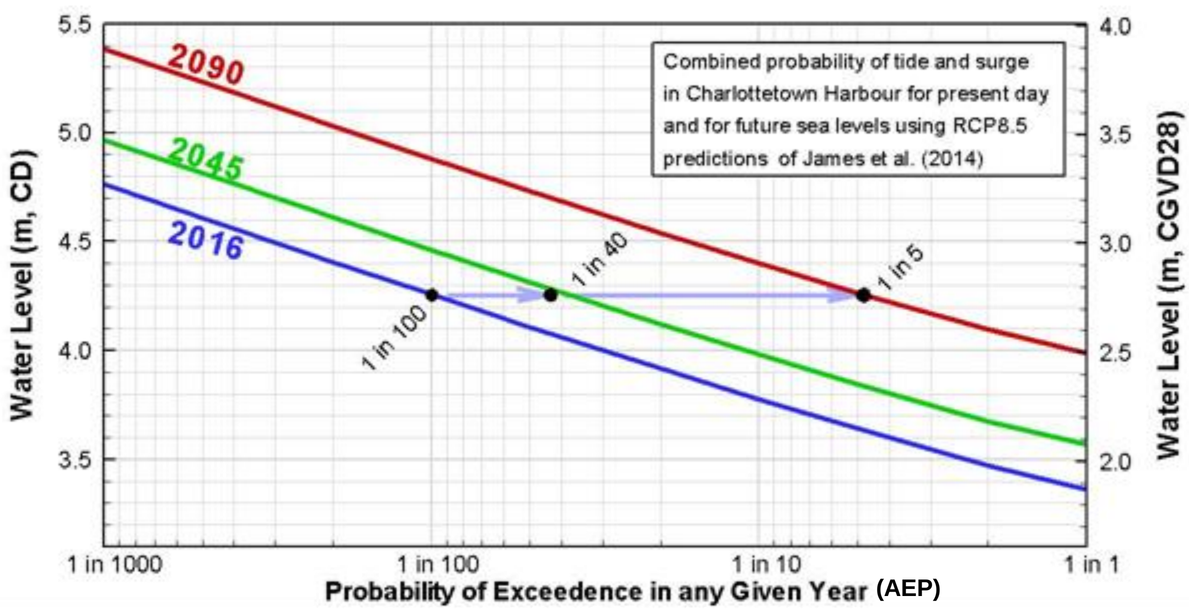


Figure 20. Probability of encountering high water levels (tide + storm surge) in selected years.

On the Great Lakes, overlake precipitation, evaporation and land surface run-off are major drivers of lake levels on interannual to longer time scales (Gronewold et al., 2013). Climate-induced changes in precipitation and ice cover will influence evaporation rates and therefore lake levels. Although future projections are uncertain (Lofgren and Gronewold, 2014), there is evidence that more extreme water levels (high and low) will occur on the Great Lakes in the future (International Joint Commission, 2014). Human activity on the Great Lakes, such as regulation of the outflows from Lake Superior and Lake Ontario, has influenced water level fluctuations. Possible adaptive management and regulation of the lake water levels could further affect the statistical distribution of water levels and waves that contribute to flooding into the future.

8.4.1.3 Tides

The available tidal measurements, tidal models and resulting databases of harmonic tidal constituents described in Section 6.1 provide information on astronomic tide levels for most Canadian waters, although coverage remains sparse in some regions (e.g., the Arctic). As discussed in Section 6.1.1.2, harmonic analysis of a water level record can be used to estimate the tidal contribution to the total water level and obtain tidal constituents (Foreman, 1977; Pugh, 1987; Pawlowicz, 2002), which can be used to reconstruct or predict time series and probability distributions of tides. These can be combined with storm surge and other contributions to extreme high water levels to establish joint probability distributions. Storm surge–tide interactions and wave-tide interactions can complicate this type of analysis. For sites where water level data is not available, hydrodynamic modelling may be used to evaluate tidal contributions to extreme water levels, assuming the model can be calibrated and validated against data for a nearby location.

8.4.1.4 Storm Surge

As noted in Section 6.1, information pertaining to storm surges can be derived from water level records at tidal gauges and from numerical models. Analysis of surge statistics from observed water level (tide gauge) measurements has been traditionally performed by computing the “residual”—the instantaneous elevation difference between the observed water level and the expected astronomic tide as predicted by harmonic analysis. While the non-tidal residual primarily consists of the surge, it may also contain harmonic prediction errors, timing errors and non-linear interactions (Haigh et al., 2016). For example, harmonic analyses of tide gauge data from stations in British Columbia typically result in residual time series exhibiting pronounced semi-diurnal periodicity (Murphy et al., 2016; Zhai et al., 2019), typical of macro-tidal sites where meteorological effects and other physical processes interact with the tides (e.g., Horsburgh & Wilson, 2007). Recently researchers (Williams et al., 2016; Wahl & Chambers, 2015) have been advocating for the use of the “skew surge” statistic, which is the difference between the maximum observed sea level and the predicted (astronomical) tidal level, regardless of their timing during the tidal cycle. The skew surge is largely independent of tides for large events, thereby allowing a simplified approach to the problem of joint probabilities of tides and surge.

Simplified methods for evaluating storm surge at a particular site typically involve the use of analytical models or empirical formulae to predict contributions by wind and atmospheric pressure effects to water levels. This approach generally requires simplifying assumptions to be made with respect to the nearshore bathymetry, shoreline geometry (e.g., straight and parallel bottom contours), or the local response of water levels to wind and atmospheric pressure fluctuations. Consequently, this type of methodology is only appropriate in restricted situations where the simplifying assumptions are valid and/or for preliminary assessments. Examples of these methods are provided in Chapter 4 of the Rock Manual (CIRIA et al., 2007), Pugh (1987) and Volume G – Part 4 of the Ontario Ministry of Natural Resources guidance (2001).

There have been significant advances in the capabilities of numerical models to predict storm surge, including the development of coupled wave-surge models (Bode & Hardy, 1997; Resio & Westerink, 2008) and global reanalyses (Muis et al., 2016). Multi-scale modelling approaches can now be used to downscale storm surge predictions from oceanic to coastal reach scales (Barnard et al., 2014). Numerical storm surge models of differing complexity are in wide use. Most storm surge models are either two-dimensional (i.e., based on shallow water equations) or three-dimensional, and allow for prescription of temporally and spatially varying wind fields, pressure fields and tidal boundary conditions (for coastal models) to generate storm surge predictions. General considerations for storm surge modelling studies are described in Barnard et al. (2014), FEMA (2016), Muis et al. (2016), and Resio & Westerink (2008). Reviews of various numerical models and approaches to storm surge modelling are provided by de Vries et al. (1995) and Murphy & Khaliq (2017).

8.4.1.5 Seiches

Seiches are long wave amplifications that typically occur when some forcing (e.g., meteorological events, or long waves propagating from the open ocean into a coastal harbour or bay) results in oscillations at the natural (resonant) periods of a lake, bay or harbour, known as eigen periods (Rabinovich, 2009). Seiches can represent significant contributions to extreme water levels in large lakes (e.g., Great Lakes, Lake Winnipeg) and coastal bays, inlets or harbours (e.g., Halifax) (Forbes et al., 2009). There are a variety of mechanisms by which seiches can be generated, including:

- Direct generation of long waves by atmospheric pressure fluctuations or wind acting upon the sea or lake surface.
- Transfer of very low-frequency energy (e.g., storm surges) into slightly higher frequencies by topographic and meteorological effects.
- Transfer of swell wave energy to large-scale and lower-frequency motions due to nonlinear frequency dispersion (e.g., infragravity waves and surf beat).
- Tsunamis (including meteotsunamis).

The potential for seiching can be established by a variety of methods, including direct observations, analysis of nearby water level gauge or velocity measurements (Abraham, 1997; Forbes et al., 2009), or by estimating the natural frequencies (fundamental and harmonic modes) of the lake/bay/harbour and comparing them to frequencies associated with natural forcing phenomena (such as long period waves) to estimate the excitation response. The latter analysis can be undertaken by using analytical solutions for the natural frequencies of representative basins of simple geometric form, detailed numerical hydrodynamic modelling (Kofoed-Hansen et al., 2005), or physical modelling for small bays/harbours (Kofoed-Hansen et al., 2001).

8.4.1.6 Combined Water Levels

For coastal flood hazards, the combined contributions of tides and storm surge to extreme high water levels are key parameters of interest. This section provides an overview of the types of analysis that could be undertaken for varying levels of study detail.

Scoping and High-Level Assessments

For scoping studies and other analyses at a relatively low level of detail, extreme high water levels would typically be based on simplified methods or regional values provided in published provincial guidance documents (e.g., Daigle, 2017; OMNRF; 2001), some of which use the conservative assumption that peak storm surge occurs simultaneously with peak astronomical tide. For the East Coast, preliminary estimates of combined tide-surge water levels have been developed for many communities (Daigle, 2017) by combining CHS tidal station values of Higher High Water Large Tides (HHWLT) with storm surge statistics based on a 40-year hindcast for the northwest Atlantic (Bernier & Thompson, 2006). For the West Coast, BC guidelines provide storm surge statistics for eight long-term tide gauges in BC waters (Ausenco-Sandwell, 2011). Similar to the East Coast approach, the simplest approach to estimating total water levels described in the BC guidelines uses the sum of HHWLT and a storm surge value corresponding to the AEP of the “designated storm” (“combined method”). A non-exhaustive summary of other regional guidance on evaluating coastal water levels in Canada is provided by Murphy & Khaliq (2017).

Detailed Analyses

More detailed analyses of storm surge and water level statistics would typically include evaluation of the joint probabilities of storm surges and tides. This could be obtained directly by statistical analysis of combined tide-surge water levels from the nearest available tide gauges. When there are no sufficiently nearby long-term gauges, or where tidal conditions at the site of interest differ significantly from those at the nearest gauging station, an estimate of combined total water levels must be developed. This can be done by storm signal reconstruction, using storm surge records extracted from the nearest long-term tidal gauge combined with local estimates of tidal levels based on either regional tidal modelling or published tidal harmonic constituents. Alternatively, this can be done in a probabilistic manner by determining the univariate (marginal) probability distributions for tide and for surge to create a bivariate joint probability distribution of total water levels. The correlation between high tide and storm surge can be described by a regional tidal factor (Pugh, 1987) that relates the expected extreme combined water level to an astronomical tide statistic.

Case Study: Prince Edward Island (Coldwater, in press)

Recent studies of coastal flood hazards in Prince Edward Island (Coldwater, in press) relate the expected peak water level to the Highest Astronomical Tide (HAT) by β_{100}, a regional correlation factor for the joint probabilities of tides and surge. In the absence of site-specific analysis, β_{100} =1 provides a conservative estimate of the 1% AEP high water level, by assuming that the 1% AEP storm surge occurs in combination with HAT. Around Prince Edward Island, for example, values of β_{100} range between 0.44 and 0.72. These relatively low coefficients are related to non-linear tide-surge interactions. Bernier & Thompson (2007) demonstrated using large-scale circulation modelling that storm surges in Northumberland Strait are almost twice as likely to occur at low tide than at high tide (Figure 21).

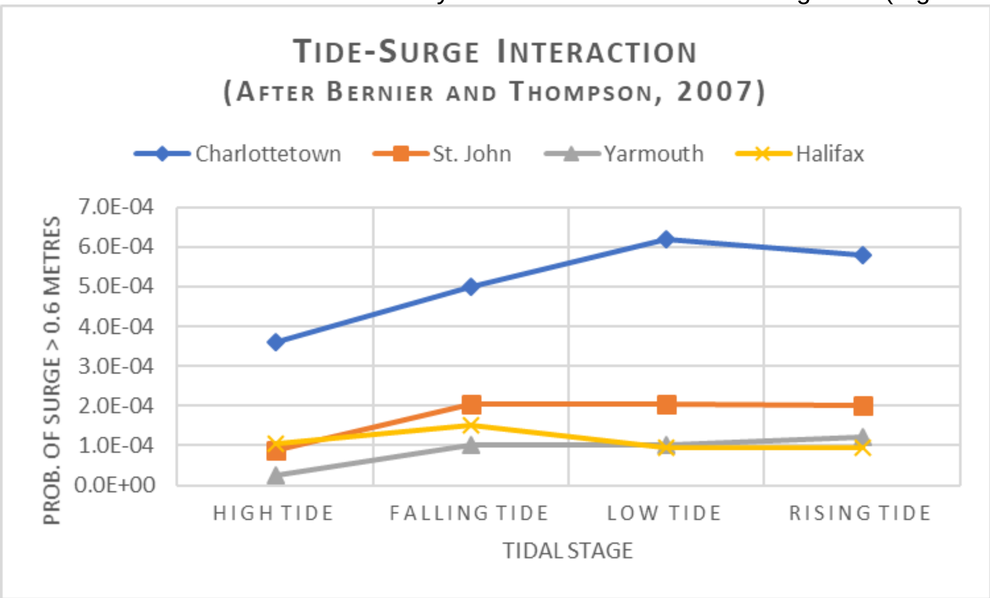


Figure 21. Tide-surge interaction at Charlottetown (after Bernier & Thompson, 2007).

Pugh (1987) describes three approaches for analyzing extreme water levels due to the combined effects of tide and storm surge.

1) Where reasonably long tide gauge measurements are available, extreme value analysis of the annual maximum water levels is shown to provide estimates of extreme events, noting that as a general rule, extrapolation should be limited to no more than four times the period of annual maxima available for analysis (e.g., a minimum record length of 25 years is needed to estimate the 1% AEP event). For practical purposes, any trends or other forms of non-stationarity in data are typically removed in advance of extreme value analyses (Hawkes et al., 2008). If desired, it is possible to perform a non-stationary extreme value analysis (Coles, 2013; Mudersbach & Jensen, 2010) but this adds complexity to the analysis and is often impractical. Further guidance on extreme value analysis of water levels for coastal and large lake areas, including length of records, data preparation, statistical analysis and sensitivity analysis is provided by Murphy & Khaliq (2017). A rigorous assessment of key concepts underlying, and practical implications of, different approaches to extreme value analysis is given by Mazas (2019).

2) Regional analysis can be used to extend measured surge statistics from a local reference tide gauge to nearby sites. Under the assumption that regional surge statistics show less spatial variation that tide statistics, a regional factor, $\propto_{100}$, can be defined as:

$$\propto_{100}= \frac{\eta_{100}}{HAT + S_{100}}$$

Where η_{100} is the 1% AEP storm water level, HAT is the highest astronomical tide, and S_{100} is the 1% AEP surge (tidal residual).

3) A third approach described in Pugh (1987) and Pugh & Vassie (1980) is the Joint Probability Method (JPM), which involves the development of marginal probability distributions for surge and tidal levels and then creates a joint-probability matrix through convolution. This approach can provide a comprehensive picture of the combined probabilities of surge and tides assuming that any tide-surge interactions are negligible. The challenge with these approaches is that accurate delineation of the upper tail of the probability distributions (particularly for surge) requires fitting to a Generalized Extreme Value (GEV), Pareto or similar extreme value function, which may not necessarily represent the bulk of the distribution.

More detailed analysis of storm water levels may require regional numerical storm surge, tide and/or wave modelling. This may involve long-term hindcasts, or investigation of real or hypothetical scenarios to capture a broad range of deterministic or probabilistic storms or combined events.

Canadian Extreme Water Level Adaptation Tool (CAN-EWLAT)

Zhai et al. (2014, 2015) provide recommendations for vertical allowances or changes in the elevation of coastal buildings or infrastructure assets required to maintain the same likelihood of future flooding as that a site has experienced in the recent past (i.e., maintaining the status quo). The allowances are determined from the statistics of historical tides and storm surges (based on tide gauge data), and regional projections of sea-level rise and associated uncertainty as presented in James et al. (2014). These allowances and the relative sea-level rise projections are available as part of the federal government's Canadian Extreme Water Level Adaptation Tool (CAN-EWLAT) (http://www.bio.gc.ca/science/data-donnees/can-ewlat). The vertical allowances provided by CAN-EWLAT are based on historical records and do not incorporate potential future changes in climate variability or the frequency and intensity of storms, modification of storm surges and tidal ranges due to changes in water depths, or nodal modulation of tides over decadal timescales (see references above).

The vertical allowance presented in CAN-EWLAT is based on the work of Hunter (2012). The allowance is computed by analyzing available long-term water level records (or using storm surge modelling results in some cases) to determine the scale and location parameters of the Gumbel extreme value distribution. The ratio of the variance of the estimated uncertainty in the relative sea-level rise estimate to the scale parameter gives the sensitivity term to add to the estimate of relative sea-level rise. CAN-EWLAT provides a useful starting point for determining extreme water levels at various locations in Canada.

8.4.2 Waves

Wave runup and overtopping can be major contributors to coastal flooding and can lead to the breaching of coastal barriers. The forces generated by wave action on structures, as well as impacts from wave-borne debris, can add strong dynamic loading components to coastal flooding conditions. Evaluation of wave effects requires an understanding of offshore (open-water) wave conditions, wave propagation/transformation processes in nearshore areas, and interactions with shore-based features and structures. Buildings and infrastructure located close to the shore (i.e., in the first line of defence) are typically exposed to higher wave hazards than those located further inland.

8.4.2.1 Selection of Analysis Approach

Evaluation of wave climatology and wave transformation analysis can be challenging and time-consuming undertakings. There are several layers of analysis that can be undertaken. For low-risk situations, or as part of a scoping study, empirical techniques can be sufficient, and where more detailed analysis is required, these empirical techniques can help guide the selection of analysis conditions and methodologies.

Summary offshore wave statistics from regional wave hindcasts and nearby wave buoy data can both provide a quick assessment of offshore wave conditions. Wave time series, whether originating from numerical model hindcasts (e.g., MSC50), or from wave buoy measurements (Section 6.4), both offer similar statistical summaries on an hourly basis of wind and wave direction and intensity. These datasets can form a starting point for an evaluation of offshore wave conditions. Care needs to be taken to evaluate the effects of wave spectral characteristics, including frequency and directional spectra, since proper characterization of spectral characteristics can be key to identifying the roles of swell and directional spreading in nearshore wave transformation.

Useful summary statistics of offshore wave conditions may include:

- Return values of significant wave height (H_s) and associated sea state parameters (e.g., peak wave period, T_p), sorted by directional sector.
- Joint H_s-T_p scatter diagrams.
- Wave persistence tables (duration of wave height-period combinations by direction).

- Wave roses (directional/compass plots of the frequency of occurrence of wave height classes).

Depending on the level of detail required, nearshore wave transformation analysis may be based on the case-by-case modelling of select offshore wave conditions in order to develop equivalent nearshore wave conditions. A matrix of offshore wave conditions representing the full climate of wave heights, periods and directions can be run through the wave transformation analysis to obtain an equivalent nearshore matrix, thus maintaining the full probability distribution of wave conditions. All, or select portions, of the offshore wave time series can be entered as input conditions into the wave transformation analysis in order to obtain a nearshore, transformed wave time series (hindcast). For large domains, these matrix and hindcasting techniques can become time-consuming and data intensive, especially if multiple climate change scenarios are also required as part of the wave transformation modelling. The scale and level of effort placed on wave transformation modelling relies on the judgment of the professional conducting the analysis. In some situations, the nearshore waves are fully depth-limited. In which case, nearshore wave heights are almost completely controlled by water depth, allowing the potential for relaxation of some of the wave transformation modelling requirements. Wave set-up, surf beat and other non-linear processes can still necessitate detailed analysis.

Tools for characterizing nearshore wave conditions range from parametric equations to 1D and 2D numerical wave transformation models. These can be used to simulate single events, a range of events to cover a band of probabilities, or as a hindcast tool to generate a time series of nearshore conditions. The output parameters from this process may include nearshore wave heights, periods, directions, spectral shapes, and changes to mean water levels (set-up and set-down). Additionally, wave-current interaction modelling can determine the effects of currents (tidal, fluvial or wind-driven) on wave conditions, as well as the effects of wave conditions on nearshore currents. Physical modelling can also be used to evaluate wave transformations and wave-current interactions, generally over small scales (up to a few kilometres).

8.4.2.2 Nearshore Wave Transformation Modelling

Once the offshore wave conditions have been established (either from an open-water hindcast or from offshore wave data), these need to be transformed to nearshore conditions. This is typically accomplished using so-called third-generation spectral wave models, such as SWAN (The SWAN Team, 2009), CMS-Wave (Lin et al., 2008; Sanchez et al., 2014), MIKE21 SW (DHI, 2017), or TOMAWAC (Benoit et al., 1996). These are phase-averaged models that simulate the growth, decay and transformation of wind-waves and swell in offshore and coastal areas through the solution of the wave-action balance equation. Such models typically capture processes including wave generation by wind, wave refraction, shoaling, whitecapping, breaking, wave-wave interactions, wave-current interactions, and energy dissipation. Typically, these models do not explicitly simulate wave diffraction. Most third-generation spectral wave models approximate diffraction effects through a phase-decoupled refraction-diffraction approach. All of these models can optionally be coupled to nearshore circulation models to include the effects of tides and currents (Manson et al., 2016b).

Wave transformation analysis can often involve a nested procedure. The outer domain may use a relatively large-scale model (e.g., a third-generation spectral wave model, such as SWAN, MIKE21 SW, CMS-Wave or TOMAWAC) to transform waves from deep water into an intermediate depth, accounting for local wind-wave growth, wave-wave interaction, shoaling, refraction and breaking. The results of this analysis can then be passed to finer-scale (typically phase-resolving) models with higher density bathymetric grids and the possibility of including more detailed physics (see examples in Section 8.4.2.4).

Coupling of wave and circulation models can be essential to capture local wind-wave growth in the presence of currents, as well as to capture wave-current interactions.

Analysis of nearshore conditions can be based on statistical analysis of offshore conditions and stationary (steady-state) transformation of specific sea states to the nearshore, resulting in a piece-wise reconstruction of nearshore wave statistics. A second approach is to extend the hindcast timeframe to nearshore conditions through hour-by-hour simulation of coupled wind-wave growth, wave transformation and circulation interactions. The latter can involve unsteady (non-stationary) or quasi-stationary wave transformations, where sequential stationary simulations are used to capture changes in wave conditions with time. The use of stationary simulations to approximate time-varying wave conditions requires that the time for waves to propagate from offshore to nearshore be less than the time for significant changes in offshore wave conditions to occur.

8.4.2.3 Wave Set-up

Wave set-up is the the mean increase in water level at the shore required to balance onshore gradients in wave momentum flux, typically associated with wave breaking. Wave set-up is typically 3–10% of the offshore wave height (Dean, 2005), and can represent an important contribution to nearshore water levels, allowing floodwaters and wave action to reach further inland. In the Gulf of St. Lawrence and Great Lakes, offshore significant wave heights of 5 m would result in wave set-up of 0.15 m to 0.5 m. More exposed shorelines, such as western Vancouver Island or southern Nova Scotia, are exposed to offshore wave heights exceeding 10 m, which could generate wave set-up of 0.3 to 1 m. Infragravity waves and surf beat can strongly influence wave set-up and low-frequency oscillations on water levels in the swash zone. Guidance on evaluating wave set-up in coastal areas is provided in a number of international publications, including the Coastal Engineering Manual (U.S. Army Corps of Engineers, 2002), the Rock Manual (CIRIA et al., 2007) and FEMA (2015).

8.4.2.4 Wave Runup and Overtopping

As explained in FEMA (2005), wave runup is a complex phenomenon that depends on the local water level (including surf beat or infragravity wave effects), incident wave conditions (height, period, steepness, direction), and the characteristics of the shore (slope, reflectivity, height, permeability, roughness). When wave runup exceeds the crest elevation of a beach berm or coastal barrier, water flows over the crest (green water overtopping), which can lead to inundation and coastal flooding. 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). Evaluating wave runup and overtopping can be the most technically challenging components of a coastal flood hazard assessment.

The vertical elevation reached by wave runup can be a critical factor in defining damage potential near the shore. Wave runup varies with significant wave height, H_s, wave period, T_p, and the slope over which the waves break (this can be the beach slope or the structure slope depending on the situation—or it can be a combination of the two slopes). Wave runup is strongly influenced by the slope—a broad sandy beach will dissipate wave energy resulting in wave runup that is typically 4–7% of the incident wave height. For structures in relatively deep water, or those exposed to non-breaking waves, wave runup heights increase with slope steepness, and can be in the range 1.5 to 3 times the incident wave height.

For beaches, where wave energy is gradually dissipated through wave breaking, the vertical extent of wave runup, R_u, is generally proportional to incident wave height, H_s, and the surf similarity parameter, ξ_b.

$$\frac{R_u}{H_s} = f(\xi_b)$$

$$\xi_b = \frac{m}{\sqrt{H_s/L_o}}$$

Here m is the cotangent slope, H_s is the significant wave height and L_o is the deepwater wavelength, $L_o = gT^2/(2\pi)$.

The surf similarity parameter provides a heuristic model for the surf zone, wave breaking, and for wave-structure interaction (Battjes & Janssen, 1978). For typical sand/gravel beaches with slopes less than 0.01, (values of ξ_b less than 0.5) the surf zone is wide, and the wave breaking process is dissipative with spilling breakers, and nearshore water levels are dominated by wave set-up and the actions of infragravity waves and surf beat. As ξ_b increases (steeper beaches and/or lower wave steepnesses) the surf zone becomes narrower and less dissipative, and wave breaking becomes more intense, ranging from plunging to collapsing or surging. Under these conditions, the shore becomes more reflective and water levels become dominated by runup processes. These changes in beach behavior control runup: low ξ_b beaches are set-up-dominated while steeper shores, with collapsing/surging breakers, are runup-dominated.

Empirical formulae, numerical modelling and physical modelling can all be used to provide estimates of wave runup and overtopping at coastal sites (Murphy & Khaliq, 2017). A review of wave runup estimation techniques is presented in Melby (2012) and Melby et al. (2012) along with a critical review of the efficacy of available predictors. Empirical methods use a simplified representation of the physics of the wave runup and overtopping process presented in (usually dimensionless) equations to relate the main response parameters (2% wave runup elevation, mean overtopping discharge, etc.) to key wave and structure or shore parameters (EurOtop II, 2017; FEMA, 2018b). Empirical coefficients and constants used in the formulae have typically been derived from physical model testing or field measurements. 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, 2018; FEMA, 2005; ; FEMA, 2018b; U.S. Army Corps of Engineers, 2002). They should be thought of as providing order-of-magnitude approximations only (EurOtop, 2007; Ontario Ministry of Natural Resources, 2001), and should be used with caution by experienced practitioners with knowledge of the origins, limitations and applicability of the formulae, considering local environmental conditions (Didier et al., 2020). Due consideration should be given to the appropriate level of analysis to support the objectives of the risk assessment (Section 7), to decide whether more sophisticated techniques (e.g., numerical physical modelling) may be required.

EurOtop II (2018)

The revised EurOtop guidance for overtopping of coastal structures provides an important insight into the role of wave heights and the overtopping flows generated by individual waves. The original EurOtop report (2007) reflected the common practice of the time to characterize wave overtopping by the mean discharge rate, *q* (L/s/m). In many cases the intensity of the peak overflow rate is more critical than the long-term average. In recognition of this, EurOtop II (2018) introduced the concept that the mean overtopping rate should be coupled to the wave height causing that discharge. Maximum overtopping volume, V_{max}, captures the intensity of overtopping flows with respect to their potential to generate high forces, erosion and structural damage. Revised allowable overtopping rates are presented in EurOtop II (2018) that use both the mean overtopping rate, *q*, and the incident wave height, H_s, to capture the intensity of overtopping flows.

Allowable or tolerable overtopping rates (in terms of both *q* and maximum volume, V_{max}), are provided for grassed slopes and rubble mound structures, property and operations behind coastal defences, and for people and vehicles.

Summaries of different types of numerical models used to assess wave runup and overtopping are provided in FEMA (2005), EurOtop II (2018) and Murphy & Khaliq (2017). Capturing the complexity of wave runup and overtopping processes requires phase-resolving models that are computationally demanding, which typically limits the temporal and spatial scales over which they can be applied. Most numerical models used for evaluating wave runup and overtopping use information from nearshore wave transformation models at their open-water boundaries. Three categories of phase-resolving numerical models used to simulate wave runup and overtopping are defined as follows (further details are provided in Murphy & Khaliq, 2017):

- Non-Linear Shallow Water (NLSW) equations models, including Boussinesq models, such as BOUSS-2D (Nwogu and Demirbilek, 2001), MIKE21 BW and FUNWAVE (Kirby et al., 1998).
- Non-hydrostatic models, which solve the NLSW equations with the addition of a vertical momentum equation and a non-hydrostatic pressure term in the horizontal momentum equations, such as SWASH (Zijelma et al., 2011).
- Computational fluid dynamics (CFD) solvers, such as OpenFOAM and DualSPHysics (Crespo et al., 2015). Due to the high computational demand, CFD solvers have typically been limited to research applications but are becoming more widely used with advancements in computing technologies.

8.4.3 Tsunamis

Tsunamis are destructive and deadly natural hazard events (Nistor et al., 2017). In shallow water, tsunamis may reach heights of 30 m or more (Clague al., 2003) and generate extreme loads on buildings and infrastructure, including hydrodynamic loads and debris loads. Tsunami hazards may include those associated with inundation, high-velocity flows (and associated erosion potential), forces exerted by flooding and receding waves, wave resonance/amplification in harbours and inlets, impact loads from waterborne debris (including ships) and dispersion of contaminants, such as fuel oil and gasoline (Clague et al., 2003).

The preliminary tsunami hazard assessment for Canada by Leonard et al. (2012, 2014) provides a useful initial basis for assessing regional tsunami hazards, summarizing earthquake- and landslide-generated tsunami sources that have the potential to threaten Canadian coasts. Leonard et al. (2014) notes that, in addition to the threat posed by far-field tsunamis, large tsunamis from M≈9 Cascadia megathrust earthquakes have impacted the BC coast on average once every 500 years, but can occur more frequently. Atlantic Canada and the St. Lawrence estuary are also prone to landslide-generated tsunamis, particularly near the Charlevoix seismic zone and along the edge of the Grand Banks. While less is known about Arctic tsunami hazards in general, landslide-generated tsunami are increasingly recognized as a significant hazard for coastal communities on the fjord coasts of eastern Nunavut (Forbes et al., 2018; Gosse et al., 2020).

Leonard et al. (2012) provide probabilistic tsunami hazard maps for runup heights of ≥1.5 m and ≥3 m at a 2% AEP level. The maps illustrate (Figure 22) that much of the Pacific west coast is vulnerable to a 3 m or higher tsunami-generated runup at an encounter probability of 10–40% within a 50-year window. This reduces to 2–10% in the inner waters of the Strait of Georgia. On Canada’s East Coast, the Bay of Fundy, Nova Scotia’s Atlantic shoreline and southeast Newfoundland see encounter probabilities of 2–10%, while the probability for the rest of Canada’s coastline is less than 2%. The hazard report also maps out those areas vulnerable to local waves from subaerial or submarine landslides or glacial calving (Figure 23).

While the risk is highest on the Pacific coast, tsunamis can and have occurred throughout Canada's coastal waters. In 1929, a tsunami struck the Burin Peninsula in Newfoundland, which was caused by submarine slope failure triggered by a 7.2 magnitude earthquake. Estimated 10-m high waves caused 28 deaths (Fine et al., 2005). The Burin tsunami has been analyzed as part of a tsunami runup mapping exercise conducted on behalf of Emergency Preparedness Canada (Ruffman, 1997). In 1964, Port Alberni, BC, was struck by a tsunami triggered by a 9.2 magnitude earthquake in Alaska, killing more than 100 people as it moved down the U.S. west coast. About 260 homes in Port Alberni were destroyed, with economic damage estimated at $10 million (Clague et al., 2003).

In addition to earthquake-driven tsunamis, tsunamis can be triggered by rockslides (e.g., 1964 event in Alaska), explosions (Halifax Harbour event in 1917) and meteorological events (meteotsunamis) (Thomson et al., 2009). The term "meteotsunami" has also been adapted for use in the Great Lakes to describe seiche-driven flood waves (Bechle, et al., 2016).

A report on tsunamigenic landslides in Québec (Locat et al., 2015) describes the 1908 Notre-Dame-de-la-Salette slide in the Lievre River north of Ottawa, which resulted in 34 deaths, the La Grande River slide in 1987, which generated a 14-m high runup, and a large rockslide at Cap Trinité in the Saguenay Fjord of 1870.

Melting glaciers can generate enormous tsunamis, through glacier calving and/or related rockslides. The Taan Fiord tsunami in Alaska in 2015 generated a tsunami with vertical runup of 193 m that devastated the local landscape. One analysis of tsunamis that generated runup of 50 m or greater in the past century showed that 10 out of those 14 events resulted from subaerial landslides into fjords or lakes in glaciated mountains, while only 1 (the Indonesian tsunami of 2004) was triggered by an earthquake (Higman et al., 2018). More recently, in 2017, a landslide in Karrat Fjord in Greenland triggered a 100-m high tsunami that washed away 11 homes, killing 3 people (Schiermeier, 2017). The largest recorded landslide-driven tsunami is the Lituya Bay slide of 1958, which generated a tsunami runup of 524 m (Miller, 1960). These events in Greenland and Alaska are illustrative of the type of tsunami risk that may exist in fjord-like environments in Canada's north.

Tide-gauge records and field evidence (Leonard et al., 2014) of historical tsunami events, as well as numerical modelling of prehistoric tsunamis (e.g., Cherniawsky et al., 2007; Fine et al., 2008) have demonstrated significant site specificity and variability of the response to tsunamis in coastal waters. Variability is most pronounced within the inlet systems and fjords that are predominant physical features of many Canadian coastal environments (such as in British Columbia). Complex geomorphologies and macro-tidal conditions (such as those in parts of coastal British Columba and Atlantic Canada) have a significant influence on the relative exposure and vulnerability of individual sites to tsunami hazard from different sources.

In October 2015, the Canadian Standards Association published the first edition of an Express Document (CSA EXP276.1-2015) intended to provide advisory guidance and minimum requirements for the design of marine structures associated with liquified natural gas (LNG) facilities. As summarized in Murphy et al. (2016), CSA EXP276.1-2015 recommends that tsunami hazards at the locations of LNG marine facilities should be assessed in two phases. During the early stage of a project development, a general assessment of the magnitude of tsunami hazard should be carried out to support site selection and layout development. This would typically involve a review of literature, tsunami catalogs, local topography and offshore bathymetry. During the design stage, a more detailed tsunami assessment is required to identify mitigation requirements. CSA EXP276.1-2015 indicates that this should include estimating return periods for credible tsunami sources, numerical simulation, consideration of the joint probability of occurrence with other water-level events (e.g., tides, storm surge, seiches and sea-level rise), and allowance for the possibility of co-seismically induced subsidence or uplift. Where practical, the guidance recommends designing for the maximum credible tsunami event or 2,475-year return period. The tiered approach to tsunami hazard assessment described in CSA EXP276.1-2015 above is consistent with the discussion and ideas presented in Section 7.

More detailed methods of tsunami hazard assessment can include Probabilistic Tsunami Hazard Assessments (PTHA). These probabilistic methods recognize that historical records alone do not provide an adequate indicator of the potential hazard (Chock, 2016), and have an advantage over deterministic methods by allowing the likelihood and uncertainty of different conditions to be assessed (Geist, 2005; Geist & Parsons, 2006), consistent with risk-based approaches. However, the difficulties in characterizing aleatory variability of tsunami hazard levels, particularly uncertainty relating to the natural variability of the earthquake/tsunami-generation process, remain a significant challenge and the cause of some debate regarding the future of PTHA within the scientific community (Yeh et al., 2005; Geist, 2005). Despite this debate, the Tsunami Loads and Effects Subcommittee of the American Society of Civil Engineers/Structural Engineering Institute (ASCE/SEI) 7 Standards Committee has developed a new chapter on "Tsunami Loads and Effects" in the 2016 edition of the ASCE standard "Minimum Design Loads for Buildings and Other Structures" (ASCE 7-16), which references tsunami hazard maps that were developed using a PTHA-based approach. The basic steps in the PTHA process used for ASCE 7-16 (Chock, 2016), which focused on earthquake-generated tsunamis, are synopsized as follows:

1. Source characterization: assessment of characteristics of multiple sources, including moment magnitude and slip, source locations and recurrence based on seismology.
2. Generation: tsunami waveform generation modelled based on source characteristics.
3. Propagation: numerical simulations of tsunami propagation from the source regions to offshore (100-m depth) waters using shallow-water wave models. Wave amplitudes and periods associated with the 2,475-year mean recurrence interval (maximum considered tsunami or "MCT") assessed at the 100-m depth contour.
4. Inundation: inundation limits and wave runup elevations for the MCT determined by non-linear wave propagation models.
5. Mapping: development of probabilistic (2,475-year mean recurrence interval) maps of offshore wave amplitude, inundation limits and wave runup for each region.

The MCT with a mean recurrence interval of 2,475 years is based on the hazard level (at the 100-m depth contour offshore) with a 2% probability of being exceeded over a 50-year period, and is consistent with the maximum considered earthquake of the ASCE 7 seismic design provisions (Chock, 2016). ASCE 7-16 includes guidance on two methods for evaluating local tsunami-generated flow depths and velocities based on data provided by the probabilistic tsunami hazard maps (offshore amplitude, period or runup/inundation limit). These include a simplistic (but conservative), one-dimensional transect-based approach (referred to as energy grade line analysis) and a two-dimensional numerical simulation-based method (Chock, 2016). The resulting inundation depths and velocities provide key inputs to assessments of loads on structures (hydrostatic, hydrodynamic and debris) and design of foundations. Debris loading represents a significant component of the design considerations for tsunami-resistant structures (Chock, 2016; Nistor et al., 2017)

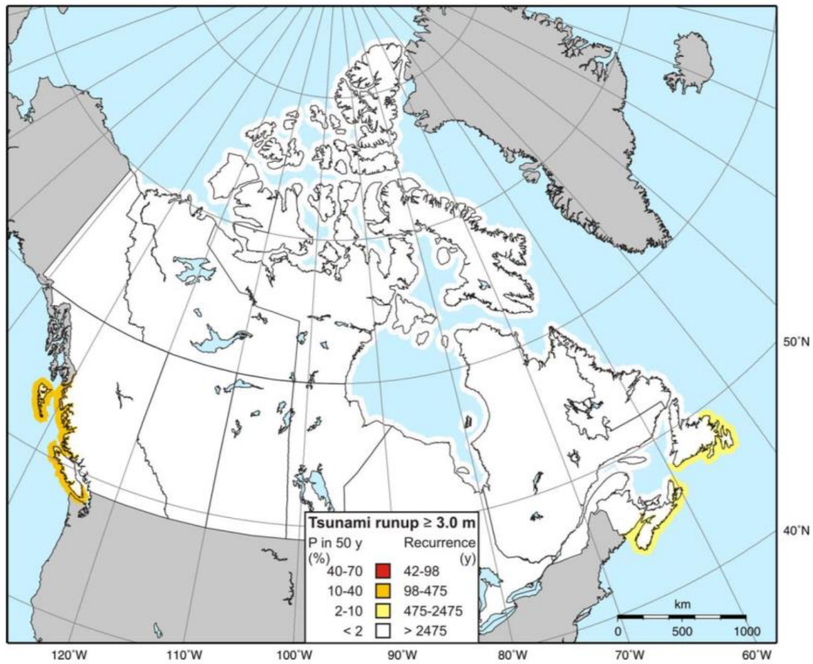


Figure 22. Probabilistic tsunami hazard map for Canada (runup exceeding 3 m in 50 years) for exceedance on a runup >=3 m (Fig. 18 of Leonard et al., 2012).

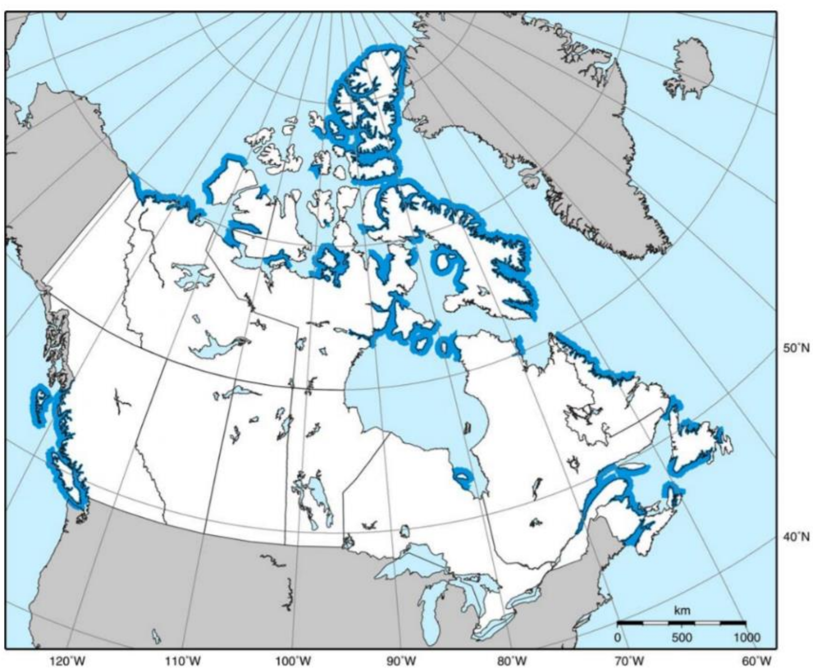


Figure 23. Canadian coastlines (blue) susceptible to local waves triggered by subaerial or submarine landslides or glacial calving (Fig. 19 of Leonard et al., 2012).

8.4.4 Ice

As discussed in Section 6.3, sea and lake ice effects can affect coastal flood hazards through their influence on nearshore coastal hydrodynamics, particularly by changing open-water fetch distances and by attenuating waves and storm surges (Manson et al., 2016a; Provan et al., in press; Kim et al., in press), as well as the more direct effects of ice pile-up and ride-up (Barker & Timco, 2017; Kovacs & Sodhi, 1980; Forbes & Taylor, 1994; Forbes et al., 2004, 2018). The potential for ice to affect flood hazards at a coastal site should be considered by reviewing available historical data (Section 6.3) and projected future changes in ice conditions (Section 6.8.2). For example, the decline in sea ice cover and lengthening of open-water seasons observed in Canada's coastal regions in the last half-century is projected to continue in the 21st century, and will likely result in increased exposure to waves and storm surges (Greenan et al., 2018). Hydrodynamic models incorporating the physics of air-ice-water interactions may be used to explore scenarios, sensitivities, and potential impacts of changing ice cover on storm surges and tides (Provan et al., in press; Kim et al., in press). It is also possible that thinner ice cover in the future may be more mobile and intensify flood hazards. Hindcast data for years with relatively low and high ice cover may be used to create proxy scenarios to investigate the effects of changing ice cover on coastal flood hazards. However, it is worth considering whether historical storm surge events coinciding with periods of extensive ice cover may have been mitigated (i.e., attenuated) by ice. The potential for similar events to occur during periods of reduced ice cover or open water under future climate change scenarios may be a consideration.

8.4.5 Fluvial Flows (Estuarine Areas)

For coastal storms associated with significant precipitation (e.g., atmospheric river events on the Pacific coast), coastal and riverine sources of flood hazard can combine to increase flood and other hazards near river mouths (FEMA, 2005). For example, elevated coastal water levels (e.g., due to storm surge or sea-level rise) can increase backwater effects in estuaries, leading to flooding. In estuarine areas, the combined effects of riverine and coastal flooding should therefore be considered. The type of analysis may range in complexity from separate (univariate) analyses of riverine and coastal flood hazards, to fully integrated modelling and consideration of the joint probability of extreme coastal water levels and river flows. The choice of analysis will depend on the relative importance of coastal and riverine sources of flood hazards, available data and the tier/level of analysis appropriate for the study. Suggested approaches for assessing combined riverine and coastal flood hazards are provided by FEMA (2005).

8.4.6 Joint Probabilities/Multivariate Analysis

Nearshore wave transformation, wave runup and coastal hazards tend to be complex, multivariate problems. Establishing a representative storm scenario (e.g., 1% AEP) is challenging because there are many combinations of tides, storm surge, offshore waves, and seasonal, interannual and intradecadal factors that can combine to create severe overland flow and hazards.

There are four fundamentally different approaches used in the statistical analysis of coastal flooding:

1. Univariate parametric analysis
2. Joint probability and multivariate statistical methods
3. Hindcasting
4. Stochastic-deterministic methods

Univariate parametric analysis uses parametric fits to historical surge (or wave) data to develop probability distributions for extreme events (e.g., Muir & El-Shaarawi, 1986). This approach is usually based on measured datasets from tide (or wave) gauges, possibly combined with numerical simulations forced by reconstructions of historical wind fields. This approach uses peak water levels from annual records or hindcasts combined with parametric fitting techniques, typically based on rank–order plotting position (Makkonen, 2005), to estimate the annual exceedance probability (AEP),

$$AEP(z) = 1 - F(z)$$

where *z* is the surge height at a given location and F(z) is the cumulative distribution function (CDF). The AEP should be viewed in terms of frequency of exceedance, rather than a fixed interval between exceedances, since the interval between exceedances is a random quantity. Two approaches are typically used in selecting extreme events: the block maxima approach (e.g., annual maximum water level), or the peaks-over-threshold approach (e.g., Bernardara et al., 2014). Both methods use best-fit parameters to interpolate and extrapolate parameterized probability distributions to estimate values at the desired AEPs. Since many estimates lie beyond the historical record length, these methods rely heavily on assumptions of sample independence and the existence of a homogeneous population over the observed dataset. A review of various methods of univariate analysis for evaluating extreme water levels in coastal and large lake areas is provided in Murphy & Khaliq (2017). Methods of conducting univariate extreme value analysis for waves are described in Goda (2010) and Mazas & Hamm (2011).

Joint probability methods use a parameterization of two or more flood hazard variables to create a multivariate distribution that represents a set of storms, or responses, that could occur in an area. A discussion of the joint probability method for tides and storm surges by Pugh (1987) is described in Section 8.4.1.5. The JOIN-SEA approach developed in the UK (HR Wallingford, 1998) was followed by a guide to best practice for addressing joint probability methods in flood management (Hawkes, 2008). A direct joint probability analysis of water levels and waves applied for dike overtopping was conducted by Liu et al. (2010) for Richmond, British Columbia. For bivariate problems, copula modelling is often used to generate bivariate statistical descriptions of incident conditions (Masina et al., 2015; Couasnon et al., 2018; Mazas & Hamm, 2016, 2017). The number of variables considered in a joint probability analysis should be consistent with natural system processes. Storm intensity, storm track, tidal level, relative sea level, ice cover, wave height, spectral shape, and wave direction can all play important roles in determining the extent and intensity of coastal flood hazards.

While joint probability analysis is frequently employed to look at the combined effects of two or three parameters (e.g., storm surge and tides, or waves and water levels), a comprehensive assessment of all of the parameters contributing to coastal flood hazards is typically impractical and/or too uncertain to be worthwhile.

An alternative approach is a physical process-based analysis wherein nearshore wave transformations are modelled and/or analyzed for a wide range of offshore conditions, in order to develop a statistical description of onshore conditions, such as flood depths or wave runup elevations. This analysis can be done through statistical binning of offshore conditions in order to build a transformed statistical description of nearshore conditions (e.g., Cornett & Zhang, 2008), or through hindcasting, where a time series of offshore events is run to create a continuous time series of transformed parameters, such as flood depth or runup height.

Stochastic-deterministic track methods use a combination of physically based models and stochastic storm track behavior to create a large set of synthetic storms. Resio et al. (2017) describes the approaches taken for parametric hindcasting, joint probability analysis and stochastic-deterministic track methods for U.S. coastal flooding studies. Recent coastal flood mapping for Boston (Douglas et al., 2016) demonstrates the use of stochastic-deterministic methods for coupled wave and storm surge modelling using SWAN and ADCIRC.

For infrequent events, such as hurricanes, a better picture of flood hazard may be obtained through consideration of a wide range of possible storm tracks, extending beyond the period of available observations or hindcast data. This is typically done using Monte Carlo simulations of storm tracks that are then modelled using a coastal circulation model to simulate the surge associated with a given storm scenario. Modelling of multiple storm tracks while also considering wave and tidal interactions is computationally intensive and not commonly undertaken for Canadian waters, although the practice is well established in regions where hurricanes are more frequent and severe.

8.5 Climate Change Effects and Non-Stationarity

Most probabilistic assessments of coastal flood hazards are based on an assumption of stationarity, that is, that there are no significant trends or jumps/shifts in the data over time (Murphy & Khaliq, 2017). This assumption may be challenged both for the period of available historical data, and, going forward, for the design life of buildings and infrastructure. Non-stationary extreme value analyses can be performed on non-stationary hazard datasets (e.g., Section 8.4.1) but are relatively complex undertakings, and there are few known examples in practice.

8.5.1 Climate Change Scenarios

The representative concentration pathway (RCP) scenarios were developed for the climate modelling community to integrate work being performed by research organizations around the world. The four scenarios are shown graphically in Figure 24 and can be summarized as follows (van Vuuren et al., 2011):

- **RCP2.6** is a reduction scenario in which global emissions concentrations peak around mid-century, then fall to low levels by 2100. Its development was based on approximately 20 published scenarios.
- **RCP4.5** is a stabilization scenario in which global emissions concentrations is stabilized shortly after 2100, without overshooting the long-range targets. It takes an intermediate approach to both emissions and mitigation efforts.
- **RCP6** is a stabilization scenario in which global emissions concentrations are stabilized shortly after 2100, without overshooting the long-range targets. It is very similar to RCP4.5 but assumes different mitigation efforts. Its development was based on approximately 10 published scenarios.
- **RCP8.5** scenario is based on increasing global emissions over time and is a high emissions scenario. Its development was based on approximately 40 published scenarios.

Recent emissions track closely to RCP8.5 (Zhai et al. 2014) and projections (e.g., for sea-level rise) based on upper range of the RCP8.5 projections (Section 6.8) may be more relevant for application to coastal areas (Forbes et al., 2009; James et al., 2014). Some Canadian jurisdictions have adopted RCP8.5, referred to as a "business as usual" scenario, for planning/design of critical infrastructure (Metro Vancouver, 2018) on the basis that it is prudent to plan for an RCP8.5 future until there are significant changes in global climate. More severe sea-level rise scenarios are noted in the literature (e.g., James et al., 2014; Han et al., 2016; and Sweet et al., 2017), and are commonly presented as "upper bounds" to projections. The differences in projections for various emissions scenarios tend to be less significant at relatively short time horizons (before mid-century) but diverge by mid-century.

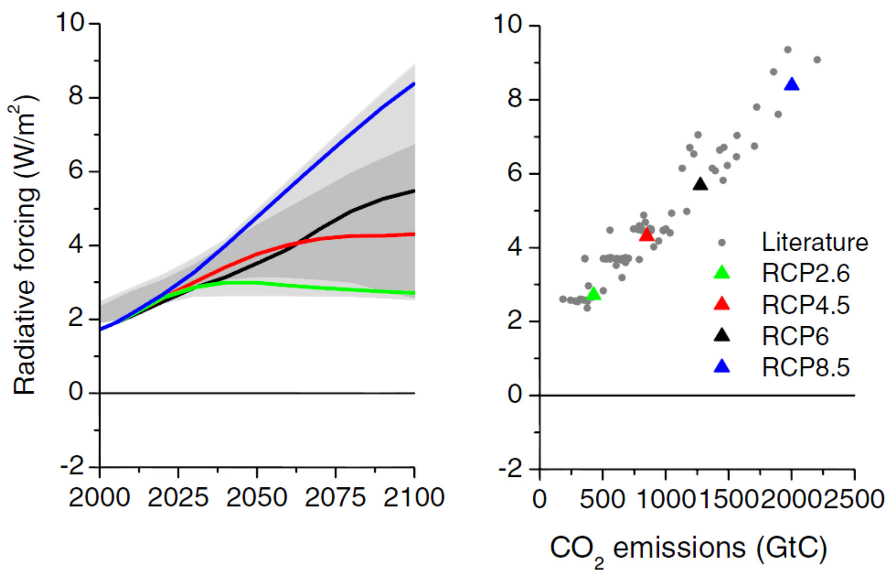


Figure 24. Characteristics of the four RCP scenarios (van Vuuren et al., 2011).

8.5.2 Dealing with Uncertainty in Future Projections

Incorporating future relative sea levels into a flood risk analysis is a non-trivial problem. There is considerable uncertainty in the rate at which sea levels will respond to climate change. Risk analysis related to extreme events typically relies on the assumption of stationarity, which implies that the statistical properties of extremes in the future will be similar to those of recent observations. Recent papers have noted that climate change challenges this assumption (Milly et al., 2008).

The future effects of climate change on coastal flood risks to buildings and infrastructure are clouded by high levels of uncertainty in, for example, rates of relative sea-level rise, changes in storm patterns and intensity, changes in sea and lake ice cover and open-water season durations, morphological changes to coastlines, and future societal behaviours/actions. There are various approaches that can be taken to address uncertainty. The preferred approach will depend on the design philosophy, risk tolerances and capacity to adapt the design to future changes or improved projections.

8.5.2.1 Adaptation Pathways

The "adaptation pathways" approach provides an analytical framework for exploring and sequencing actions in an uncertain future based on alternative external developments over time (Haasnoot et al., 2012, 2013). This approach was applied in the Netherlands to address uncertainty in sea-level rise projections and associated flood risks, and has since been adapted and tested for other applications and locations, including Australia and Canada (Coulter, 2019). The approach described by Coulter (2019) involves five basic stages:

- Define goals and objectives
- Analyze current situation
- Assess possible futures
- Develop pathways
- Implement, monitor and learn

If adopted as part of the design philosophy, the adaptation pathways approach can be integrated in a coastal flood hazard and risk assessment (see also Section 5.3.7).

8.5.2.2 Observational Method

Lessons can perhaps be drawn from the field of geotechnical engineering, where design is often challenged by uncertainties in natural ground conditions. The observational method was originally developed for geotechnical engineering to address uncertainties in soil conditions (Peck, 1969). As reported in Spross & Johansson (2017), a similar approach known as ‘‘active design” was successfully applied in Sweden in the 1980s. Today, the observational method is—with some modifications from Peck’s original version—an accepted design approach in Eurocode 7 (CEN, 2004), which is the European standard for the design of geotechnical structures.

The observational method is effectively a framework for adaptive design. The preliminary design is based on what is known at the time, a monitoring plan is used to track the performance of the structure, and contingency plans are implemented should defined limits of acceptable behaviour be exceeded. For this to work, the preliminary design must have a sufficiently high probability of avoiding costly and complex contingency actions. The design must also be capable of accommodating the range of foreseen adaptation measures. One of the challenges in implementing the observational method is ensuring that the reliability of the resulting structure is both acceptable and suitably quantified.

Recently, the American Society of Civil Engineers (ASCE) has developed a “manual of practice” for Climate-Resilient Infrastructure: Adaptive Design and Risk Management (MOP 140) (ASCE, 2018b), which explores adapting observational method techniques to the problem of coastal climate change. The ASCE’s proposed adaptation of the observational method to the design of climate-resilient infrastructure is as follows:

1. Project design is based on the most-probable weather or climate condition(s) rather than the most unfavorable. The most-credible unfavorable deviations from the most-probable conditions are identified.
2. A course of action or design modification is devised (in advance) for every foreseeable unfavorable weather or climate deviation from the most-probable condition(s).
3. The performance of the project is observed over time (using preselected quantities) and the response of the project to observed changes is assessed.
4. Design and construction modifications (previously identified) can be implemented in response to observed changes.

Defining the “most probable” weather or climate conditions and the “most-credible” unfavorable deviations provides the opportunity to incorporate those climate scenarios that are widely accepted as realistic scenarios along with allowing consideration of the maximum credible values that are considered physically possible. Maximum credible values of relative sea-level rise could, for example, include consideration of the additional 0.65 m in sea-level rise suggested in James et al. (2014) to account for faster reduction in the mass of the West Antarctic Ice Sheet (providing 1.39 m of sea-level rise at 2100). The United States National Oceanic and Atmospheric Administration (NOAA) provides “high” and “extreme” global mean sea-level increases of 2.0 m and 2.5 m by 2100 (Sweet et al., 2017) and notes that these scenarios are intended to “test plans and policies against extreme cases with a low probability of occurrence but severe consequences if realized”. The NOAA scenarios are based, in part, on a sea-level projection method on which the Intergovernmental Panel on Climate Change placed low confidence (Church et al., 2013).

The high-emissions RCP8.5 scenario has been termed the “business as usual” scenario, but global carbon emissions are slowing their increase and an intermediate-emission scenario (RCP4.5 or RCP6) may now be a “most probable” emissions scenario (Hausfather and Peters, 2020) (Figure 25). One implication of this development, should it continue and the global carbon emissions policies continue to slow the increase of carbon emissions, is that estimates of “extreme” global sea-level rise based on intermediate-emissions scenarios may be of interest, while extreme estimates based on larger amounts of global carbon emissions may overestimate projected sea-level change.

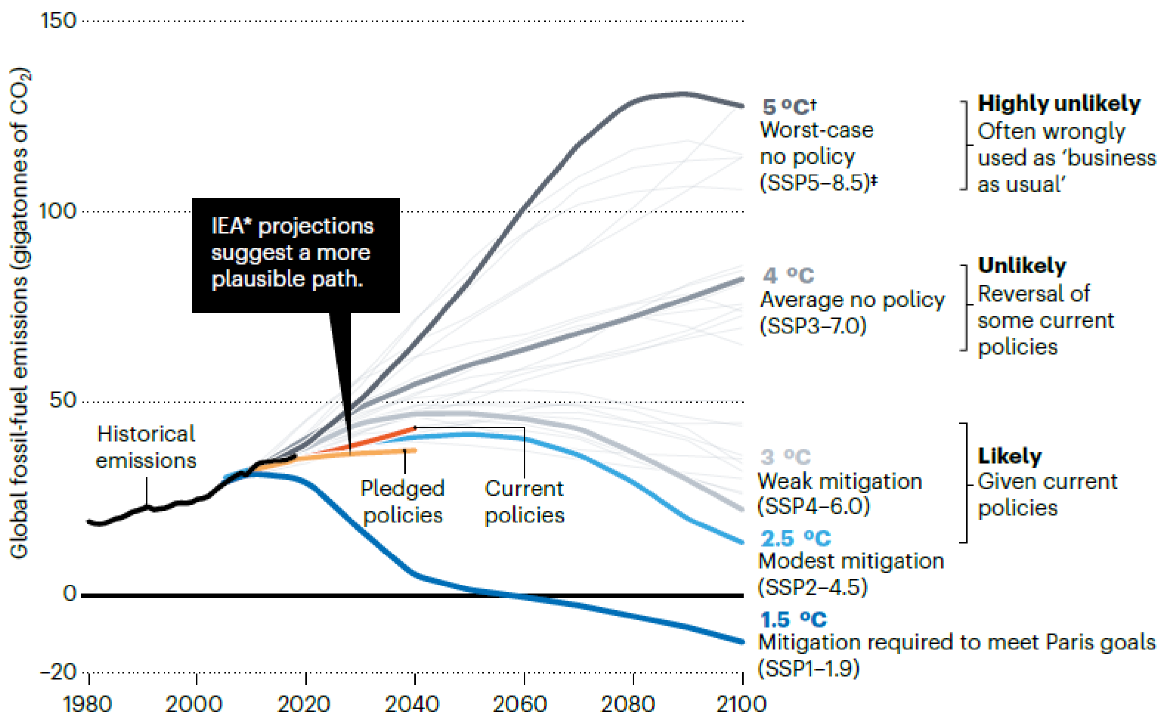


Figure 25. Carbon emissions trajectories and global temperature change through the 21st century for a range of emissions scenarios (Hausfather & Peters, 2020). Shown are the pledged carbon emissions policies (yellow line) and the current projected trajectory based on current policies (red line) through to 2040, indicating that an intermediate-emissions scenario may be suitable as the "most-probable" scenario.

Identifying courses of action for deviations from the most probable conditions requires consideration of a wide range of possible scenarios. For example, sea-level rise could approach upper-bound estimates, storminess could greatly reduce the associated AEP of a given design storm event, morphological changes (erosion and/or sedimentation) could change site exposure and nearshore wave transformation. Ideally, a practical design modification or other course of action would be developed for each such scenario, although in practice, resource and knowledge constraints may limit a comprehensive treatment.

8.6 Hazard Mapping

Flood hazard mapping is typically required to illustrate the level of hazard at the site, as well as interdependencies and linkages to surrounding areas and hazards.

Coastal flood hazard mapping for land use planning and regulation purposes in Canada has traditionally been "elevation-based" or "profile-based", in which the elevations associated with extreme water levels and wave effects are combined to provide a representative flood elevation and translated to representative cross-shore topography profiles. This analysis provides minimum elevations or lateral setback distances to avoid flood hazards for designated events or probabilistic scenarios, for example, Ontario (Ontario Ministry of Natural Resources, 2001), British Columbia (BC Ministry of Environment, 2012), U.S. Flood and Emergency Management Administration (FEMA, 2018).

> The nature of the flood hazard can change significantly moving inland, away from the water's edge. At some distance back from the reach of wave attack, the flood hazard may be reduced to that associated with either the static sea/lake level or the flow of overtopping water, or steep slopes may exacerbate flood flows and contribute to the hazard. It is not always appropriate that a representative elevation combining water levels and wave effects at the shore be mapped directly onto the overland region.

Static flood level mapping, or "bathtub mapping", incorporates additional information about local topography. Extreme water level and wave effects are again combined to provide a representative flood elevation, which is mapped onto digital elevation models (DEMs). All land lying below the flood level is typically treated as inundated. This approach does not take into account the dynamics of flood water propagation or pathways to flooding, and typically only provides information about inundation/water depths (i.e., not velocities, wave action, flood durations or other hazard metrics).

Hydro-enforced mapping is a refinement of the static flood level mapping where the DEM is modified to include hydraulic connections that are not captured in the original DEM. Culverts and bridges, for example, are edited to enforce the hydraulic connection across the barrier. Flood maps are then prepared using algorithms that propagate flood levels from offshore to the inland extent of flooding (Webster et al., 2004).

Hydrodynamic modelling can be used to develop detailed flood hazard maps through simulation of the physical processes of flood propagation and overland flow. Hydrodynamic models used are typically two- or three-dimensional unsteady flow models, such as CMS, ADCIRC, Delft3d, MIKE 21/3, POM or TELEMAC, which may optionally be coupled to wave transformation models, such as CMS-Wave, SWAN, MIKE21 SW or TOMAWAC. Depending on the pathways leading to coastal flooding (e.g., direct inundation or overtopping), boundary conditions for the overland flow models are typically provided by nearshore wave and/or hydrodynamic models or calculations of wave overtopping discharges.

For sandy shores, it is sometimes necessary to consider the effects of storm-induced erosion of beaches and dunes. FEMA has adopted a simplified dune erosion approach for inclusion in profile-based coastal flood hazard assessments. More detailed morphological modelling of beach erosion is still a field of active research. XBeach (Roelvink et al., 2018) has recently been successfully applied to reproduce the combined erosion and flooding processes generated by Hurricane Sandy (de Vet et al., 2015). In Canadian waters, XBeach has recently been applied to the simulation of erosion and flooding processes at Maria, near the Gaspé in Québec (Didier et al., 2019).

Flood hazard maps can display a variety of information, such as areas inundated during a particular AEP event (Figure 26), flood depths for different land use or infrastructure classifications (Figure 27), velocities, wave conditions (heights, periods), or the landward limit of flood, wave and erosion hazards (Figure 28).

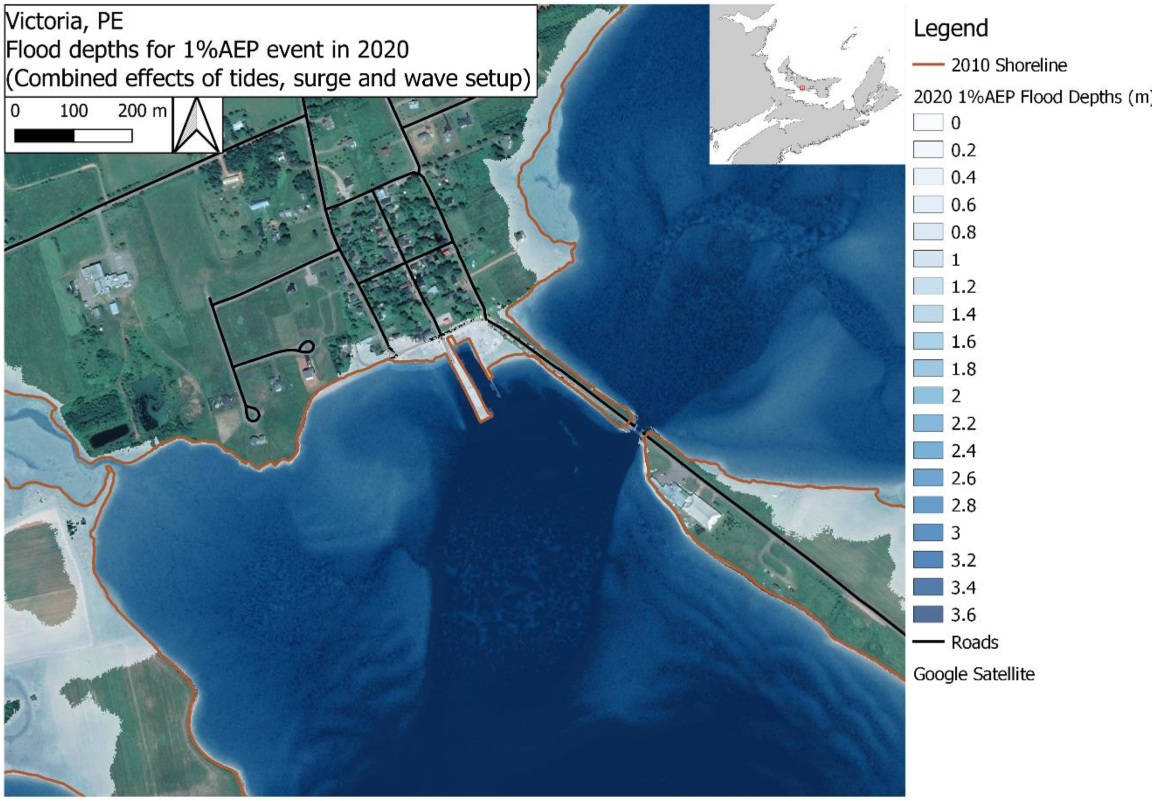


Figure 26. Example of inundation map for Victoria, Prince Edward Island (credit: M. Davies, 2019).

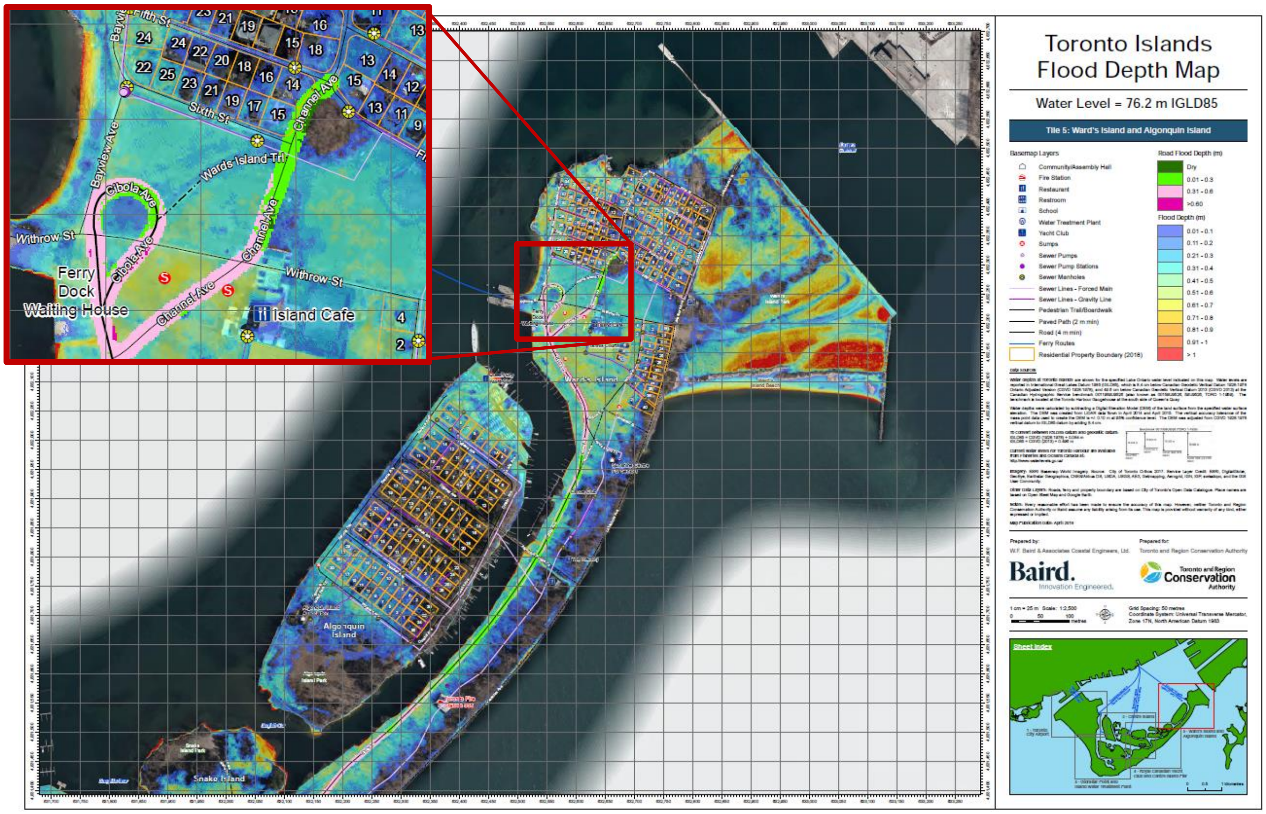


Figure 27. Example of a flood depth map for Toronto Islands (credit: Baird, 2019).

Figure 28. Example map showing flood hazard limits (solid blue line), erosion hazard limits (solid yellow line), and 1% AEP flood level (dashed blue line) (credit: Baird, 2019).

9 Vulnerability and Consequence Assessment

As explained in Section 2.1, the **consequences** of a coastal flood are a function of hazard characteristics (e.g., extent and severity), the **exposure** of a system (e.g., a building, infrastructure, a community) to the hazard, and the **vulnerability** of the system (i.e., its ability to resist, recover and mitigate damage that can result from those hazards). Vulnerability reflects the **susceptibility** or **fragility** of a building or infrastructure to a hazard. For the same level of exposure, a reinforced concrete building may be more robust than a wooden building and, therefore, potentially less vulnerable to damage from coastal flooding, wave impacts and tsunamis.

A consequence assessment intended to support or inform the design of buildings or infrastructure involves combining information derived from the hazard assessment (Section 8), which determines exposure to coastal flood hazards, with information on susceptibility (e.g., depth-damage curves) to determine the consequences of flooding.

9.1 Role of Vulnerability and Consequence Assessment in Design Practice

Where there is exposure to coastal flood hazards (under present-day or future scenarios), the design process for buildings and infrastructure represents an opportunity to incorporate measures that can help to prevent or mitigate damages arising from coastal flooding, and by doing so, reduce risk. Most design methodologies incorporate some element of vulnerability or consequence assessment, either implicitly or explicitly. For example, the Canadian Highway Bridge Design Code (CSA Group, 2019) includes a “consequence factor” for the design of foundations and geotechnical systems, which adjusts the target reliability depending on the consequences of failure, and a “resistance factor”, which takes into account the variability of materials, quality of workmanship, mode of failure and uncertainty (all of which impact the vulnerability of the system). Building and infrastructure vulnerability data, such as depth-damage curves, provide a means to assess the consequences of flooding for a given system configuration (i.e., building or infrastructure design). This allows information on building and infrastructure resistance, resilience and repairability (i.e., vulnerability) to be integrated in a coastal flood risk assessment (Sections 6.10 and 10.3) to inform design decisions.

The output from a consequence assessment feeds into the risk assessment (Section 10). Depending on the outcomes of the risk assessment, needs for additional measures to reduce vulnerability may be identified. These may include building and infrastructure design measures (which typically do not affect exposure but enhance the ability to resist, recover and mitigate damage) and/or other flood risk reduction measures (e.g., land use planning, community flood protection schemes, or the use of natural infrastructure to reduce exposure). The benefits and costs of different measures can be incorporated in iterations of the consequence and risk assessments, to support robust and economical design.

9.2 General Approach

The overall approach to vulnerability assessment can range from qualitative to quantitative, depending on a variety of factors (refer to Table 5 in Section 7.3). In some cases, it may be appropriate to use exposure as a proxy indicator for vulnerability, in case susceptibility to different hazard levels is difficult to reliably determine. While quantitative measures are generally considered more robust, it is not always possible to source the appropriate data to support this type of assessment.

Qualitative vulnerability assessments can involve discussions with local residents to gain a better understanding of which buildings and infrastructure systems have been exposed to flood events in the past, and how they have responded to, or withstood, those events. This experiential approach can inform the design of new buildings or guide retrofitting choices, but may miss important vulnerabilities in the context of changing risk profiles (Section 2.3) and thus, it is preferable to include quantitative approaches as well, where possible.

Quantitative vulnerability assessments for buildings and infrastructure systems typically involve using damage functions (other terms used include vulnerability curves, susceptibility curves, fragility curves, or depth-damage curves—see Section 6.10). These functions quantify expected damages for a given hazard exposure metric (e.g., water depth). Building and infrastructure damage functions can be used to estimate the percent damage and/or financial damages to the structure and contents, or probability of a specified level of damage (e.g., minor damage, building collapse, etc.) for the water depth (or wave height, velocity, momentum flux, etc.) at the building or infrastructure location. Financial damages should be combined with other consequence indicators (Section 9.5.5) to provide a more holistic picture of the consequences of flooding.

9.3 Assessing Exposure

Exposure describes what is located within a flood hazard zone, and should be assessed for multiple flood hazard scenarios. The exposure of proposed or existing buildings and infrastructure to coastal flood hazards can be determined from existing coastal flood hazard mapping or site-specific hazard assessments (see Section 8). Hazard mapping should, at a minimum, delineate the region inundated by specific AEP flood events and may include information on inundation depths, water velocities, and/or wave conditions (e.g., wave height, period, forces, wave runup elevations, wave overtopping discharges). For tsunami studies, inundation areas (based on maximum runup elevations), depths and/or momentum flux (or tsunami-induced velocities) may be used as hazard metrics (Section 8). The assessed hazards can then be classified and compared to the location (existing or proposed) of buildings, infrastructure and other receptors to determine exposure. Exposure is then typically assessed by overlaying flood hazard extents (and potentially other hazard characteristics) with the location of existing or proposed building/infrastructure footprints and other socio-cultural and environmental datasets. For initial and high-level risk assessments (see Section 7.3), or if no detailed data on building/infrastructure vulnerability is available, the exposure assessment alone can provide valuable insight to coastal flood risk. It provides estimates of total impacts (e.g., total number of affected buildings or infrastructure—or total number of affected people—in a flood hazard zone).

9.4 Assessing Vulnerability (or Fragility)

The fragility of proposed or existing buildings and infrastructure to coastal flood hazards can be characterized by existing damage functions derived from post-flood surveys (see Section 6.10), site-specific studies or surveys, or from experimentally or analytically determined fragility functions. Building and infrastructure damage functions can be used to estimate the percent damage and/or financial damages to the structure and contents, or probability of a specified level of damage (e.g., minor damage, building collapse, etc.) for the water depth (or wave height, velocity, momentum flux, etc.) at the building or infrastructure location.

9.5 Assessing Consequences

Consequences (or impacts) of flooding can be described as tangible (monetary values can be assigned) or intangible (more difficult to assign monetary values), and direct (occurring as a direct result of exposure to flood hazards) or indirect (occurring as a secondary result of a flood event). Examples of tangible, direct consequences include the cost of repair and restoration of damaged objects (contents damages) and physical systems (physical damages). Examples of tangible, indirect consequences are costs incurred as a result of business disruption, lost productivity, and post-flood clean-up. Intangible consequences can be direct (e.g., loss of archaeological sites due to flooding, or contamination of ecosystems through direct contact with contaminated floodwaters) and indirect (e.g., trauma resulting from flooding).

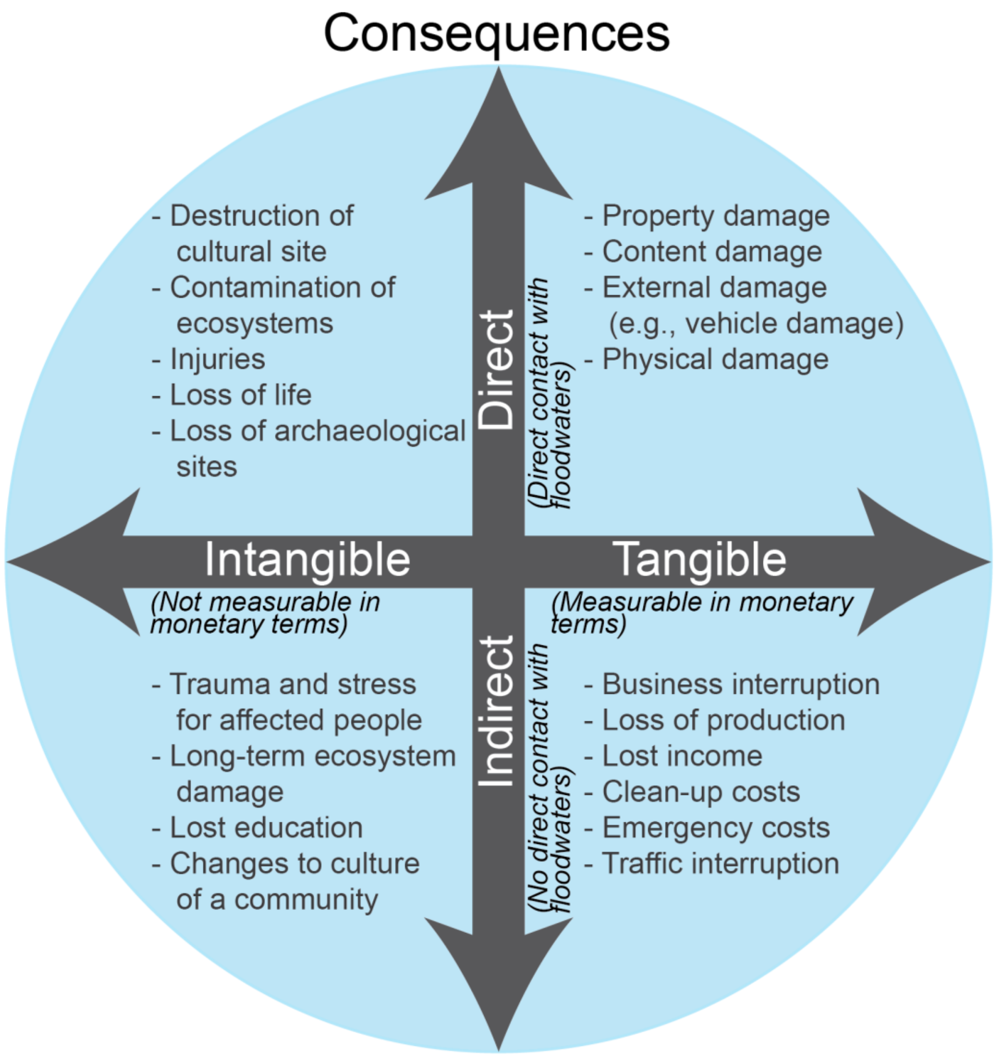


Figure 29. Types of consequences to flooding (adapted from UNDRR with additional input from Messner et al., 2006, and NRCan, 2017).

9.5.1 Coastal Storm Floods

For coastal areas exposed to storm surge and/or tidal flooding where flood depths are small (implying low wave heights) and/or wave exposure is limited (e.g., short fetches), the depth-damage curves provided in NRCan (2017) for riverine flooding may be used, if no other more locally relevant fragility curves exist. The NRCan (2017) depth-damage curves assume low salvageability, with complete replacement of flooring and walls (drywall, insulation, etc.) for any depth of flooding. Additional damage that may result from small waves, contamination from salt water, minimal warning time, etc. may be insignificant when compared to the longer flood durations and higher mud content typical of riverine flooding. For coastal areas exposed to large wave heights, the possibility of major building damage and collapse should be considered. Post-hurricane building inspections on the U.S. Gulf Coast reported complete destruction of wood-frame walls and unreinforced masonry walls below the wave crest elevation (see e.g., FEMA, 2006, 2009, 2011). In some coastal regions, waterborne debris can be a major factor affecting damages during coastal flood events, particularly affecting buildings and infrastructure located close to the shore. However, there is presently limited data available to assess potential damages associated with waterborne debris. Literature on debris impacts on coastal infrastructure is primarily confined to tsunamis (Nistor et al., 2017) and inland (riverine) environments, where scales and driving processes are significantly different from storm conditions in coastal waters.

For coastal storm surge flooding (limited wave heights), direct damages can be estimated from the following information particular to each building (see NRCan, 2017):

- **Flood Level:** Water surface elevation of the specified AEP event.
- **Building Classification:** Quality of building and number of storeys. Assessed value or photographs may be used to classify the building.
- **Building Use:** Residential, commercial, institutional use.
- **Presence of Basement or Below-Grade Parkades:** Large damages can occur for finished basements.
- **First-Floor Elevation:** Depth of flooding (basement and first floor) is calculated relative to the first-floor elevation.
- **First-Floor Area:** Total building damages are calculated from the damages unit rate ($/m^2) and first-floor area.

9.5.2 Tsunamis

Until fragility curves are developed for Canadian applications, the tsunami fragility curves developed from the 2011 Tohoku earthquake and tsunami for Japan (Suppasri et al., 2012) are recommended, while noting that they may not accurately reflect Canadian building/infrastructure design (Section 6.10.1). Furthermore, the fragility curves are empirical curves that were derived from post-disaster assessment surveys, and are thus specific to the 2011 Japanese tsunami, and associated damages may vary strongly when applied in Canada (Rossetto et al., 2019). In cases where it is possible a tsunami is generated by a proximal earthquake, the seismically induced consequences (such as building/infrastructure damages) of the earthquake preceding the tsunami should be considered.

For tsunami inundation, the probability of a specified level of damage to a building can be estimated from Suppasri et al. (2012):

- **Building Material Type:** Reinforced concrete, steel, wood, or masonry.
- **Number of Storeys:** For reinforced concrete and wood buildings only.
- **Water Depth:** The curves were developed for water depths from 0.5 to 20 m.

Direct damages due to a tsunami can be estimated from the assessed value of the building and damage level (see e.g., Wiebe and Cox, 2014).

9.5.3 Direct Building Damages

The level of **physical damage** sustained by buildings during a flood event is generally related to the building characteristics (e.g., materials, building quality, number of storeys, etc.), while the level of **contents damage** is typically related to the building use and elevation of utilities and other components. For example, a building with elevated utilities is less susceptible to damage than a building with utilities on a lower level (e.g., basement). When the exposure of a building to coastal flood hazards has been ascertained, potential damages can be assessed for a range of scenarios.

As discussed in Section 6.10, depth-damage curves for buildings exposed to flooding are provided in NRCan (2017). Although this report is presently being revised, the depth-damage curves represent one basis for assessing damages to building physical components and contents under various coastal flood hazard scenarios and for different building types. These fragility functions can be used to estimate the amount (or probability) of damage for a specified flood parameter (e.g., water depth). The curves can be easily modified to assess the impact of elevating some utilities (e.g., furnace, hot-water heater, electrical panel) or using more flood-resistant materials (e.g., concrete flooring). Over time, it is anticipated that additional datasets will become available to better characterize the impacts of different hazard types (e.g., waves), building types, or building-level resilience measures on damage levels, or to better reflect different local conditions.

9.5.4 Direct Infrastructure Damages

For infrastructure such as roads and other transportation infrastructure, direct damage unit rates may be based on previous repair and replacement costs. NRCan (2017) notes that roads and bridges are the largest component of public infrastructure damages and municipalities generally have reliable information on these costs.

Infrastructure damage functions are not widely available and should be estimated based on site-specific conditions (flood duration, water depth, water velocity, waves, scour) where possible. Public infrastructure located within coastal flood hazard zones may include: roads and transportation infrastructure (bridges, street lights, etc.); parks and recreational facilities (paths, benches, parking lots, washrooms, etc.); water, sanitary and storm sewer systems; electric power distribution systems; and communication networks. Possible direct infrastructure damage may include washed out bridges, culverts, and roads; swamped sanitary sewer systems; damaged pump stations; contaminated potable water systems; damaged electrical systems; damaged street light and traffic light controls; etc.

The cost to repair and replace roads and bridges following flood events is a significant component of public infrastructure damages (NRCan, 2017). Infrastructure damages include initial repair costs and reduced service life (which is difficult to quantify). Unit replacement costs derived from actual project costs (e.g., cost per kilometre of road) may be used to estimate damages for existing infrastructure or new infrastructure exposed to similar hazards, provided there is sufficient information available pertaining to the hazard (e.g., depths, velocities, etc.). As quantitative risk assessments become more widely practiced, it is anticipated that additional damage datasets will become available for different types of infrastructure and flood resistance/resilience measures, and will support improved decision making by designers.

9.5.5 Socio-Cultural, Environmental and Indirect Economic Consequences

For buildings and infrastructure exposed to flooding, there can be many consequences beyond physical damages. These can include a wide range of potential economic, social, cultural and environmental consequences, which should be assessed for a more holistic picture of flood risk. A holistic approach to risk assessments is recommended by international best practice (UNISDR, 2015; United Nations, 2016) and in Canada through the "whole-of-society" concept within the Emergency Management Strategy for Canada (Public Safety Canada, 2019b). Holistic consequences inform the overall risk associated with flood damages to a building or infrastructure, where higher potential consequences require higher levels of flood-resilient design.

To quantify and summarize these diverse consequences consistently, indicators are typically used. These can be based on the UN document on "Indicators for Disaster Risk Reduction" (United Nations, 2016; UNISDR, 2016), which encompasses the targets for disaster risk reduction as formulated in the Sendai Framework (UNISDR, 2015), the Australian risk assessment guidelines (AIDR, 2015) and the revised Canadian risk profile (Stantec Consulting Ltd. and Ebbwater Consulting, 2017). Based on these resources, the following 6 different indicator categories are recommended for assessment:

1) Affected People
2) Mortality
3) Economy
4) Critical Infrastructure and Disruption of Basic Services
5) Environment
6) Culture

Considering that consequences to flooding can be varied, ranging from direct to indirect consequences, and from the more tangible to the intangible (Messner et al., 2006) (Figure 29), it can be challenging to quantify and measure them. Therefore, proxies are typically used to describe measurable consequences for each of the indicators where direct data is not available. Proxies can be quantitatively assessed for different flood scenarios (e.g., number of people in a flood hazard area, or economic value of buildings in flood hazard area). While these proxies typically cannot fully capture all flood consequences to a community and to ecosystems, they still provide a good starting point for review and discussion, especially given that most indirect and intangible impacts are difficult to quantify and to monetize.

Indirect damages (e.g., lost productivity, displacement, clean-up, etc.) depend on many factors, such as the severity of the flood and the availability of resources to repair and rebuild. Residential indirect damages are typically estimated as a percentage of direct damages, while commercial and institutional indirect damages may be estimated based on the building use. Business disruption functions provided in NRCan (2017) can be used to estimate lost productivity and the length of disruption from the building use (e.g., office, retail, etc.) and depth of flooding. NRCan (2017) advises that residential displacement durations be estimated based on local conditions considering issues such as availability of contractors, inspectors, and equipment.

Data availability is a major limitation even when defining proxies (Section 6.11). For example, the data needed for a spatially detailed assessment is often not available at sufficient resolution (e.g., census population is typically reported in dissemination areas, which are relatively small for city centres, but often range over many square kilometres in rural areas). Assumptions are usually required, which introduces uncertainty. Confidence levels can be assigned to quantify uncertainty and include it in the risk assessment (AIDR, 2015).

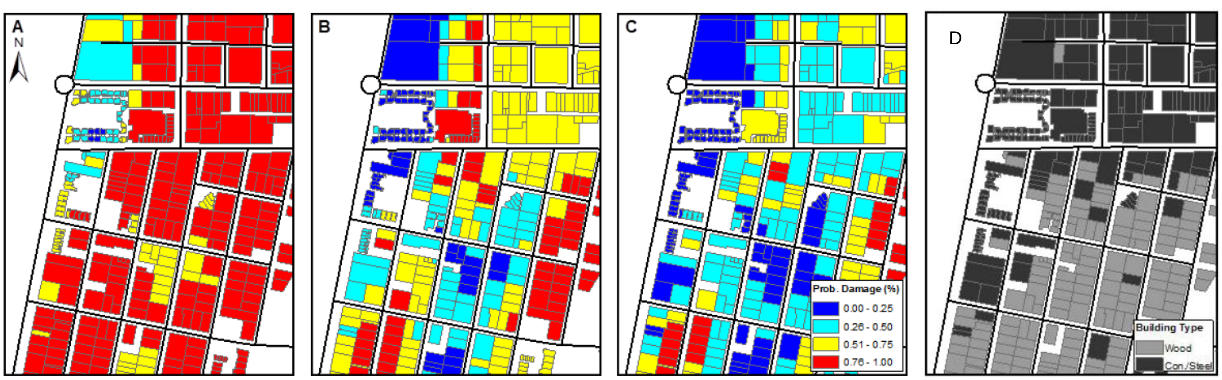
Proxies for intangible consequences should be informed by local values and context. For instance, in one community, people may care deeply about the sensitive environment that surrounds them, indicating that a flood risk assessment should consider potential environmental consequences of flood-related building damages (e.g., release of hazardous material) with more detail. Considering local values will also support acceptance of a building or infrastructure project in the local community. Engagement of stakeholders (including partners, the general public and other interested or affected parties), as discussed in Section 4, is of key importance for understanding these local values, targeting a flood risk assessment to local needs, and informing selection of proxies for the quantitative risk assessment. It can also add a more qualitative component to the quantitative risk assessment that can help to get at the more intangible and indirect consequences.

Intangible impacts on human health are highly dependent on age, existing medical conditions, income, family and community support, preparedness, and other factors (NRCan, 2017). Simply tallying the estimated number of affected people at different AEP scenarios along with other demographic information can be informative.

9.6 Presenting Information on Vulnerability and Consequences

Mapping is an effective way to communicate the probability or level of damage buildings or infrastructure systems may sustain for a given hazard (e.g., storm surge flooding, tsunamis) and AEP. While hazard maps delineate the geographic extents of the hazard for a given AEP, vulnerability maps incorporate additional information about the ability of different building and infrastructure types to withstand, resist or recover from flood hazards.

An example of a building vulnerability map is shown in Figure 30 for the town of Seaside, Oregon. The maps show that the likelihood of sustaining moderate damage is similar for nearly all buildings (panel A), but that the likelihood of major or complete damage (panels B and C) varies by building material type and exposure to the tsunami hazard.



Panels A, B and C show the probability of moderate, major and complete damage, respectively, for a specified AEP tsunami event based on the building material type (panel D shows wood buildings in light grey and concrete or steel buildings in dark grey) and tsunami hazard metrics (water depths and momentum flux) derived from numerical modelling.

Figure 30. Example of building vulnerability maps (adapted from Wiebe & Cox, 2014).

Vulnerability information may also be presented in tables or diagrams that allow for comparison of the relative performance of different building types or infrastructure system components with exposure to a hazard.

10 Risk Assessment

As outlined in Section 2, **risk** is a function of the **likelihood** of an event occurring and the **consequences** if that event occurs. Once hazard and consequence assessments have been completed, the risk assessment is completed by multiplying the probability of coastal flood hazard events with the consequences (e.g., damages) of each event. The risk assessment may be at a relatively high level (e.g., counting number of assets affected) or may be more detailed, where direct, indirect, tangible and intangible damages are estimated for a range of AEP scenarios. A key consideration is how to effectively communicate the resulting risk information to stakeholders and inform decision making. The following sections describe several example risk indicators and methods of communicating risk.

10.1 Average Annual Damages

For quantitative risk assessments, average annual damages are a useful risk indicator, and may be used to support comparative assessments and prioritization of mitigation alternatives, or to evaluate the return on investment for different flood risk management strategies (such as building resilience measures). Average annual damages (AAD), or expected annual damages, express the monetized damage costs that may be expected in a given year, on average over many years. Given the stochastic nature of flooding, actual damage costs in any given year may be much higher or lower than the AAD. If the damages associated with multiple AEP events can be monetized (Figure 31, left panel) as outputs of the hazard and vulnerability assessments, the resulting relationships can be used to extrapolate and interpolate damages for other events (Olsen et al., 2015). Typically, damages increase with increasing return period (decreasing AEP), as shown in Figure 31 (left panel). The integral of this damage-probability curve over all AEPs gives an estimate of AAD (e.g., Messner et al., 2006; Meyer et al., 2009). Thus, the AAD metric provides a full picture of risk over many hazard likelihoods – from small, but frequent events to rare catastrophic events, and their cumulative impacts over time. However, the severe events that lead to substantial damages have a lower probability of occurrence, and therefore a lower weight in terms of their contribution to AAD. This is illustrated by the risk density curve, which is obtained by multiplying the probability of each event by the associated damages (Figure 31, right panel). This curve is useful for identifying events that contribute most to the overall risk.

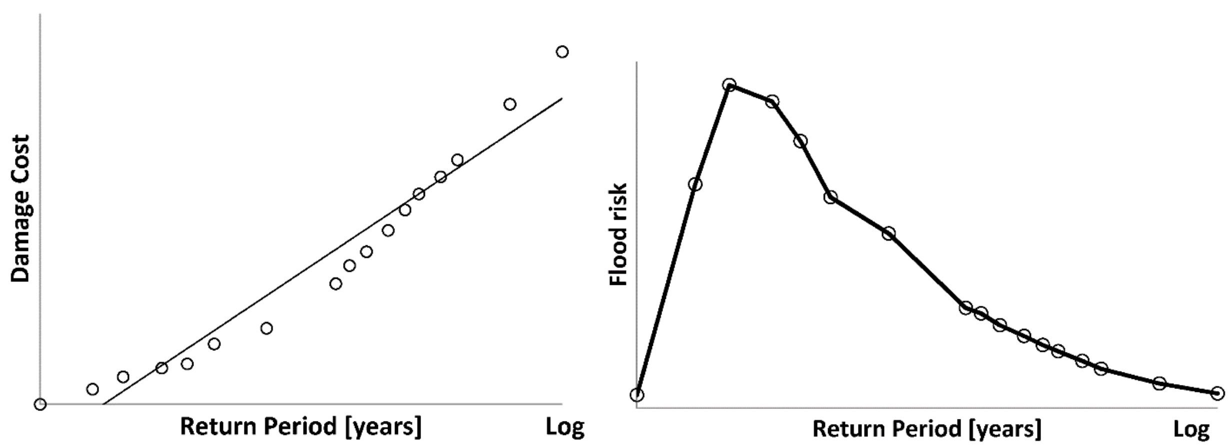


Figure 31. Relationship between AEP and damages (left) and flood risk density curve (right) (source: Olsen et al., 2015).

10.2 Risk Maps, Tables and Figures

Flood risk information may be presented in maps, tables and figures. Flood damage estimates and quantitative risk information can be presented for individual buildings and infrastructure assets, or aggregated (e.g., to protect the privacy of residents and businesses in the case of community risk assessments). Examples of different methods of presenting risk information are provided in case studies for Tofino, BC, and Toronto Islands, ON, below. Increasingly, technologies such as virtual reality are being used to improve presentation and dissemination of flood risk information (Solinska-Novak et al., 2018).

Case Study: Tofino, British Columbia

Spatial risk maps were developed using a multi-scenario risk assessment approach for a coastal flood risk assessment completed for the District of Tofino, British Columbia (Ebbwater, 2019). Flood risk was assessed for a set of indicators, including people, economy, critical infrastructure, environment and culture. For each indicator, consequences to coastal storm floods were assessed for five AEPs (6.7%, 2%, 1%, 0.5% and 0.2%) and three relative sea-level rise scenarios. Using the consequence results, exceedance probability curves were developed, and total risk was calculated by integrating the area under the flood risk density curve. Total risk therefore portrayed the approximate long-term average of flood consequences on an annualized basis (e.g., average annual damages). Spatial risk maps (average annual damages) were produced for each indicator on a 50 m x 50 m grid. The grid was applied to provide a consistent picture of risk, but also to manage public perception by minimizing the likelihood of an individual property being identified as high risk. The resulting maps highlight areas of high risk of coastal storm flooding, incorporating both likelihood of occurrence and associated consequences, and therefore accounting for both the cumulative effects of small, but frequent floods, and of rare catastrophic floods. The risk map for economy (total building value) for the 1 m relative sea-level rise scenario is shown in Figure 32.

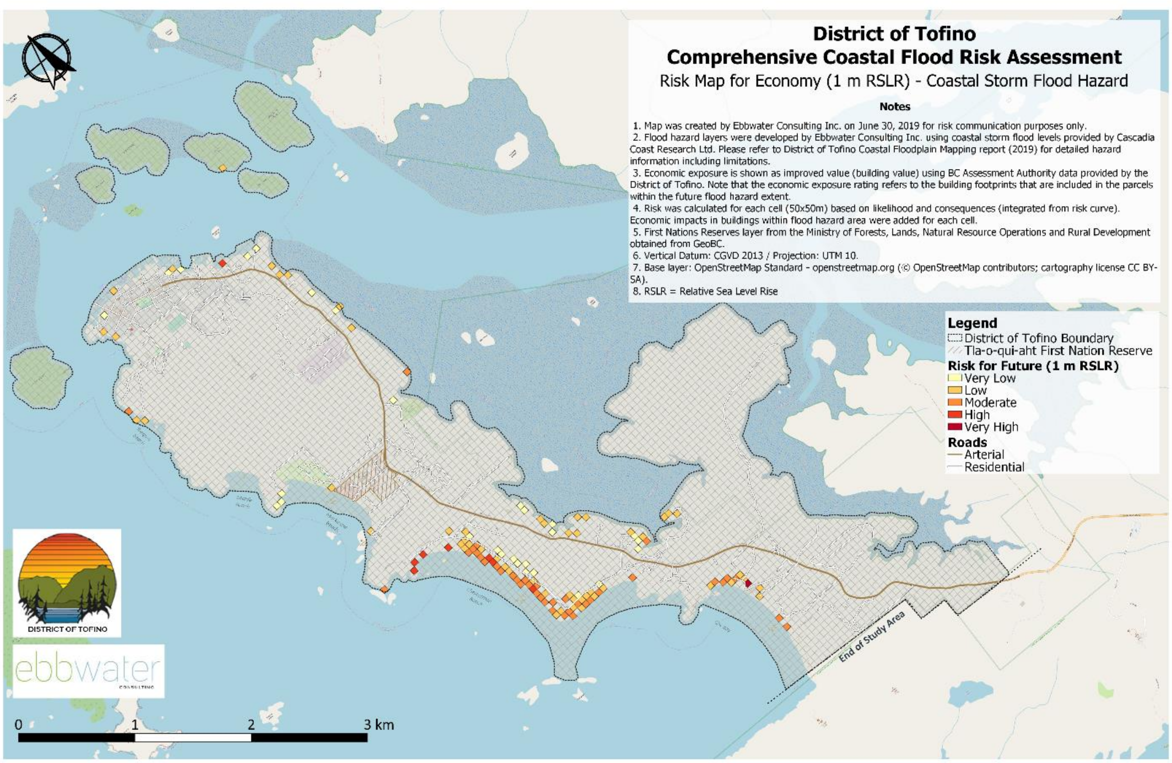


Figure 32. Risk map for the economy indicator for the District of Tofino, considering 1 m of relative sea level rise.

Case Study: Toronto Islands, Ontario

A coastal flood risk assessment was completed for the Toronto Islands (Lake Ontario) to understand the risks to buildings and infrastructure on the islands, and to support the development of conceptual flood mitigation alternatives (Baird, 2019). The number of residential buildings affected by different AEP flood events is shown in Table 6, which indicates that the crawlspaces of 51 homes are subject to frequent flooding (>10% AEP) and that the majority of these are located on Ward's Island. This information helps to convey the spatial distribution of risk, which can be used to support decisions on where temporary and long-term mitigation should be directed and to inform emergency response (i.e., water level thresholds for evacuation).

Table 6. Estimated number of houses on Toronto Islands flooded at specified AEP water levels.

AEP	50%	20%	10%	4%	2%	1%	0.5%	0.2%
Ward's Island	6	6	45	111 (1)	133 (5)	134 (16)	139 (38)	139 (77)
Algonquin Island	0	0	6	25	46	54	62	74 (11)
Total	6	6	51	136 (1)	179 (5)	188 (16)	201 (38)	213 (88)
% of All Homes	2%	2%	20%	53%	69%	73%	78%	83%

*Estimated number of residential buildings with first-floor flooding shown in parentheses

Direct and indirect damages to the buildings on Toronto Islands were estimated by Baird (2019) following the procedures in NRCan (2017). The estimates include physical and contents damages, and indirect damages including business disruption and clean-up (Figure 33). The figure indicates that damages are concentrated on Ward's Island (residential) but are increasingly significant on Algonquin Island (residential) and the other islands (commercial) at lower AEPs. The business disruption damages become substantial at the lower frequency AEPs. The average annual damages for the residential and commercial buildings was estimated to be $492,000 per year.

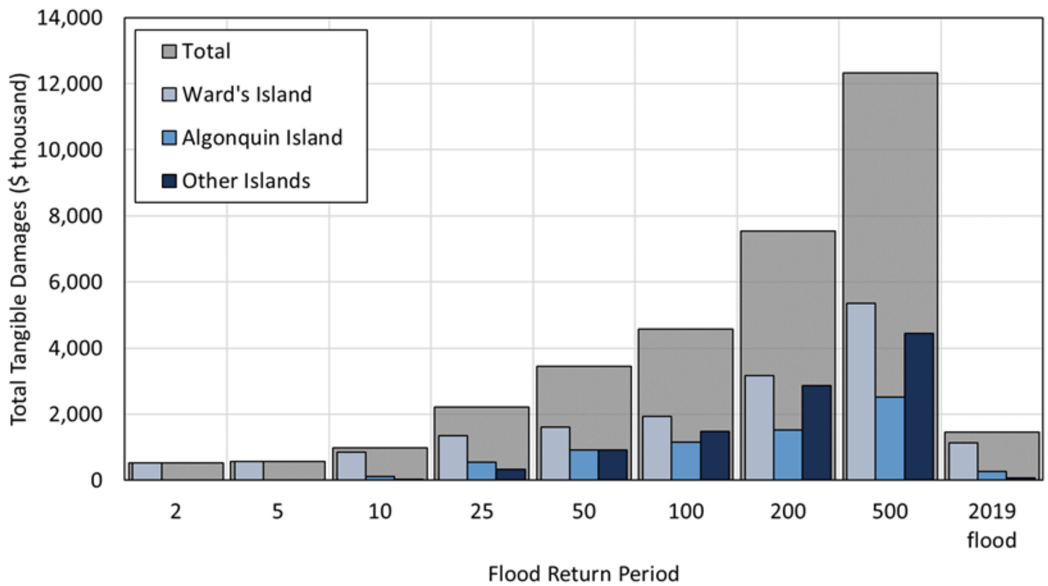


Figure 33. Estimate of total financial damages at different AEPs for Toronto Islands.

10.3 Risk Matrices

The outputs from qualitative or semi-quantitative flood risk assessments can be communicated using a risk matrix, which is a table listing information about the identified risks (Figure 34). The risk matrix may use a relative scale to score the consequences (e.g., low to high) and probability of an event (e.g., unlikely to likely). The risk rating (or score) is the product of consequence score and likelihood score. The risk ratings can be linked to risk tolerance criteria (Section 5). Risk matrices are relatively easy to understand and therefore useful tools for involving multiple stakeholders in risk assessments, but they have some disadvantages in terms of resolution (i.e., potentially assigning the same risk score to quantitatively very different risks), subjectivity and ambiguity; hence, they primarily apply to qualitative or semi-quantitative risk assessments.

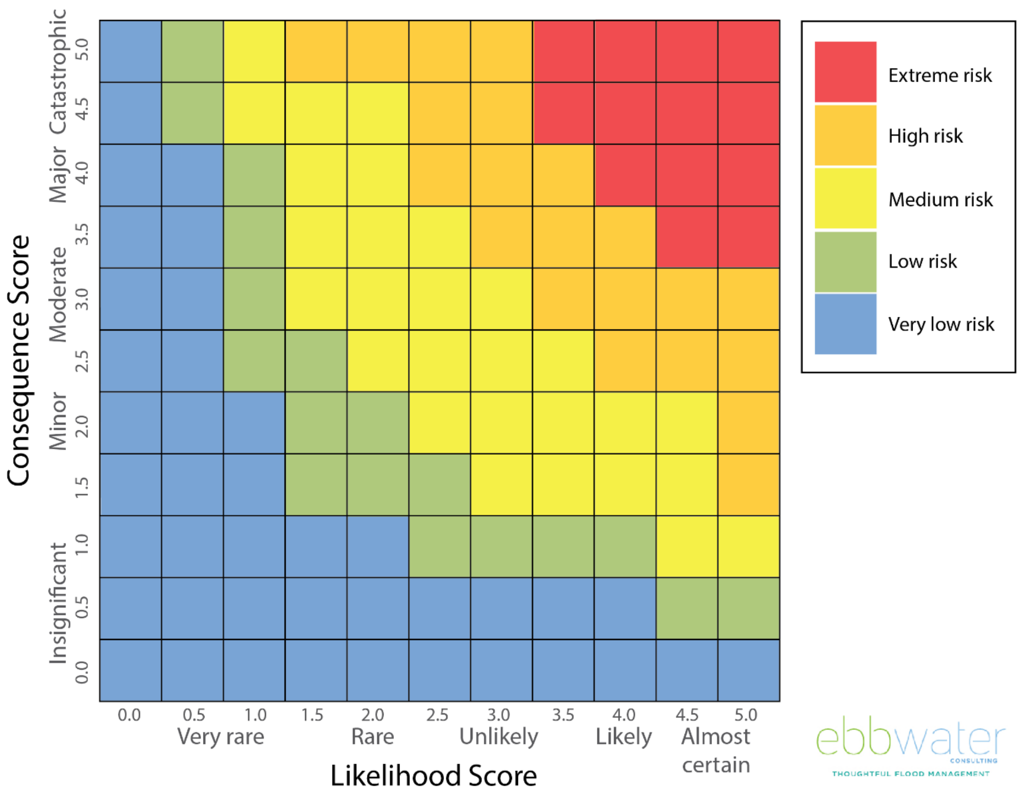


Figure 34. Example flood risk matrix (Ebbwater Consulting Inc., 2019, CC BY-NC-ND).

11 Risk Management, Mitigation and Adaptation

Once flood risks to coastal buildings and infrastructure are well understood and/or quantified, appropriate steps can be taken, or strategies can be implemented, to manage those risks. As explained in Section 1.4.4, the purpose of these guidelines is not to identify specific measures for coastal flood risk management, mitigation or adaptation. However, this section provides some contextual information on strategic approaches to coastal flood risk management, to illustrate how the information derived from a coastal flood risk assessment can be used to support decision making for managing, mitigating and adapting to flood risks to coastal buildings and infrastructure.

Current thinking surrounding strategies for flood risk management is that *avoidance* is generally the preferred option for new buildings and infrastructure (Bowker et al., 2007; Proverbs & Lamond, 2017). This type of strategy can be implemented through planning and regulatory tools that restrict development in areas exposed to moderate or high flood hazards (e.g., by situating buildings and infrastructure above flood levels or prescribing setback distances). Community-scale flood protection schemes (e.g., incorporating dikes, seawalls, natural or nature-based defences) are also commonly used to mitigate risk. These have traditionally been the primary strategies adopted by provincial and municipal governments to manage flood risk in Canada. However, avoidance may not be a viable strategy in circumstances where there is no reasonable choice but to construct new buildings or infrastructure in the flood hazard area (e.g., bridges), where the benefits of constructing in areas prone to flooding outweigh the risks, and/or where there are existing buildings and infrastructure exposed to flood hazards. Even in the latter case, planned/managed realignment or retreat is increasingly being considered as a potential avoidance measure.

No management strategy completely eliminates the flood risk at a given site—there is always some residual risk (Bowker et al., 2007). A storm event with a lower probability of occurrence than that chosen as the basis for a dike design (or for prescribing building setback distances) may result in damaging or nuisance floods. Furthermore, changing climatic conditions or structural deterioration may be expected to lead to changes in flood risk over time at a given site (e.g., relative sea-level rise may lead to increased flood risks at some coastal sites), and occasional, nuisance flooding may transition to chronic or more severe flooding. As such, adaptive management should be considered an important part of any effective flood risk management strategy, both at the building/infrastructure scale and at broader, system-wide scales.

A variety, or combination, of strategies may need to be considered to reduce the residual risk of coastal flooding to acceptable levels. As described in Section 5.3.6, these may be categorized as (Bowker et al., 2007):

1. Avoidance – building away from or above areas of known flood hazard exposure, or preventing floodwaters from reaching the site of a building or infrastructure asset.
2. Resistance – the use of local measures to resist the effects of flooding at a site and preserve structural integrity, including the use of local flood barriers, pumping systems, water-resistant design, structural strengthening, scour protection, etc.
3. Resilience – the use of materials, construction techniques and finishes to reduce the risk of damage and to speed up recovery, repair, and return to service.
4. Repairability – the use of materials, construction techniques and finishes to speed up and reduce the costs of repair following a damaging flood event.

As discussed in Section 5.3.6, items 2 through 4 above apply to building- and infrastructure-level interventions, and are therefore readily steered by building codes, infrastructure design standards and construction guidance. Codes and standards may prescribe specific measures to be applied depending on the residual risk at a given site. The primary effect of such measures would be to reduce the vulnerability of buildings and infrastructure. For example, the dashed grey line in Figure 35 illustrates (qualitatively) the potential effect of eliminating basements and incorporating enhanced design, materials, finishes and construction techniques on the depth-damage curve for a one-storey residential building. These and other resistance, resilience and repairability measures have the potential to alter depth-damage curves (or other vulnerability functions), delaying the onset of damage and reducing the impacts of frequently occurring (or less severe) flood events. In turn, this lowers the damage-probability curve in higher AEP regions (Section 10.1), and reduces overall risk metrics, such as AAD. This example illustrates at a conceptual level how the effects of building- and infrastructure-level design interventions can affect overall flood risk, and how risk assessments can inform the design process. However, research is needed to develop a quantitative understanding of the effects of building or infrastructure enhancements on susceptibility to flood hazards, so that design and risk assessment practices can be effectively integrated.

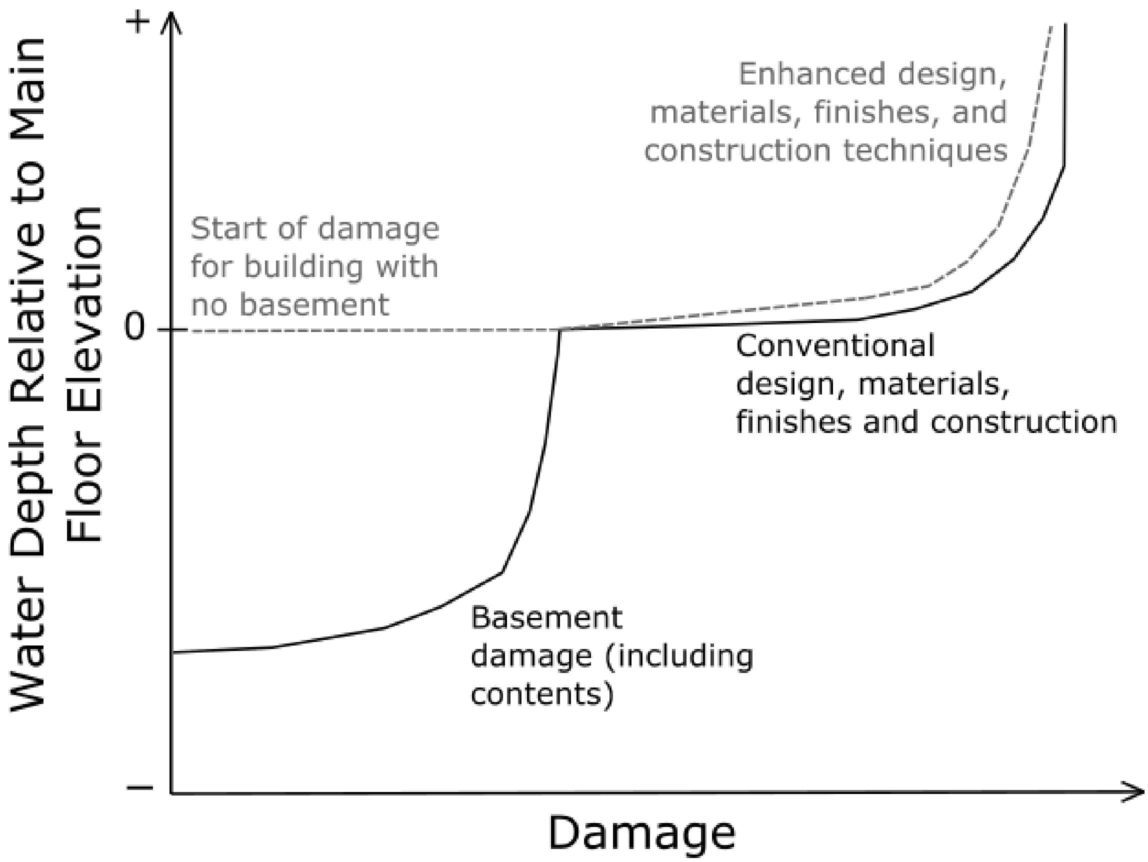


Figure 35. Potential effect of building design measures on vulnerability of a residential one-storey building (depth-damage curve adapted from NRCan, 2017).

Where resistance, resilience and repairability measures are considered, the compatibility of solutions with the nature of anticipated flooding hazards, and potential adverse impacts on flood risks to surrounding areas should be assessed. For example, resilience or repairability strategies may not be effective in areas exposed to frequent or severe flood hazards. This is the premise of the hierarchy of flood risk management strategies shown in Figure 36, which indicates avoidance as the preferred option. However, the strategies are not mutually exclusive and can be applied in combination as part of a portfolio of tools to manage coastal flood risks. Indeed, it is recognized that multi-layered strategies, and multiple “lines of defence”, are often required or preferred to reduce flood risks to acceptable levels (e.g., Green, 2010; Lopez, 2009).

When developing and evaluating options for managing flood risks at the site of a new or existing building or infrastructure asset, the effects of the measures on vulnerability and risk should be assessed, to see if risk tolerance criteria are satisfied for the intended design or service life of the structure/asset. This may require some iteration to arrive at solutions that reduce risks to within acceptable levels, as indicated in Figure 8.

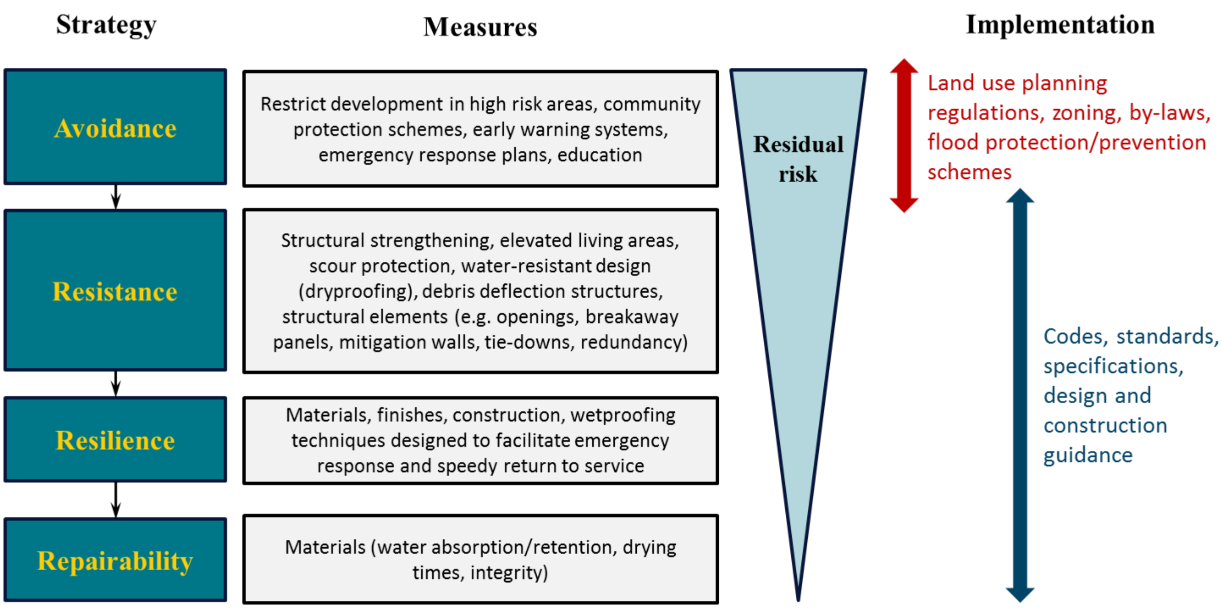


Figure 36. Hierarchy of flood risk management strategies and implementation (adapted from Bowker et al., 2007).

12 Concluding Remarks

These guidelines provide a possible framework and technical reference for conducting coastal flood risk assessments, specifically for application to design (and retrofitting) of buildings and infrastructure in Canada for enhanced flood resistance and resilience. Assessing risk is just a first, if crucial, step toward managing coastal flood risk; applying this understanding of risk to improve building and infrastructure design is another, and is beyond the scope of the guideline. Work is needed to embed flood risk management concepts and principles in building and infrastructure design codes, standards and practice. However, improved building and infrastructure design practice is not a panacea for flood risk. More broadly, there is a need to continue strengthening strategic flood risk management knowledge and practice across Canada to better serve societal needs, which must be driven by input from multiple stakeholders and technical disciplines. Designers and proponents of building and infrastructure projects must participate, and play prominent roles, in such a process if it is to be successful.

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