Adaptive Flood Management
From Fragility to Flexibility

Final Report

July 31, 2023

ebbwater

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Table Of Contents

1 The Flood Challenge **3**
1.1 HAZARD SHIFTS DUE TO CLIMATE CHANGE 5
1.2 HAZARD AND EXPOSURE SHIFTS DUE TO LAND COVER AND LAND USE CHANGE 6
2 Flood Management as a Responsibility **7**
2.1 LAYER MODEL 8
2.2 SAFE DEVELOPMENT PARADOX 8
3 Compounding Uncertainties **9**
3.1 CLIMATE AND HAZARD UNCERTAINTY 10
3.2 UNCERTAINTY IN EXPOSURE TO FLOODS 11
3.3 UNPROJECTED SHOCKS AND DISRUPTIONS 11
4 Status Quo Flood Management: Fragile and Entrenched **12**
4.1 SYSTEM RELIABILITY AND FRAGILITY 13
4.2 ENTRENCHED PATHWAYS 13
5 A Solution: Moving from entrenched fragility to adaptive flexibility **14**
5.1 ACCEPTANCE OF FUTURE UNCERTAINTY 15
5.2 ACKNOWLEDGE FUTURE SHOCKS 15
5.3 EXPAND THE TOOLBOX 15
5.3.1 The Value of Land Use-Based Approaches to Risk Reduction 15
5.3.2 The Value of Nature-Based Solutions 15
5.4 REVERSIBLE AND FLEXIBLE OPTIONS 15
5.4.1 Planning for Pathway Flexibility 16
5.5 NO-REGRETS OPTIONS 16
5.6 MAKE MISTAKES AND BE BRAVE 16
6 Conclusion **17**
References 19

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1

The Flood Challenge

1. The Flood Challenge

Floods are the most commonly occurring natural hazard in Canada and account for the largest portion of disaster recovery costs on an annual basis (McClearn, 2022; Public Safety Canada, 2022a). In 2021 alone, $4.5 Bn in flood claims were made through the federal Disaster Financial Assistance Arrangements (Public Safety Canada, 2022b), which forms only a portion of the total financial costs. And of course, financial costs describe only part of the short and long-term impacts associated with flood events. Human lives are lost and disrupted; social networks are disconnected; and natural systems are damaged, among many other impacts.

Progress on limiting future flood damages in Canada is possible. It will require concerted efforts to better understand the challenge, as well as the flood mitigation solutions that best fit the future challenges. This primer provides background on a starting point for a shift in flood management towards adaptive approaches.

Waterbodies that overflow their banks are not a problem; in fact flooding provides many positive benefits to a natural ecosystem. It is when flood waters interact with things we care about on the floodplain, causing damage and negative consequences that we have cause for concern. Risk is the term used to describe these interactions.

Risk is the potential loss of life, injury, or destroyed or damaged assets which could occur to a system, society, or a community, determined probabilistically as a function of hazard, exposure, and vulnerability (UNDRR 2017; UN 2016).

Mitigating flood risk is key to decreasing impacts to affected communities and reducing pressures on the public purse. By proactively investing in flood mitigation activities, a community secures practical investments for its future growth and prosperity, reducing the potential for substantial disaster recovery costs, productivity losses, economic losses, destruction of non-monetary cultural assets, environmental damage, injuries, and deaths.

Mitigating flood risk is complicated by the fact that risk is a moving target. The components of risk (hazard, exposure, and vulnerability) are all prone to change over time.

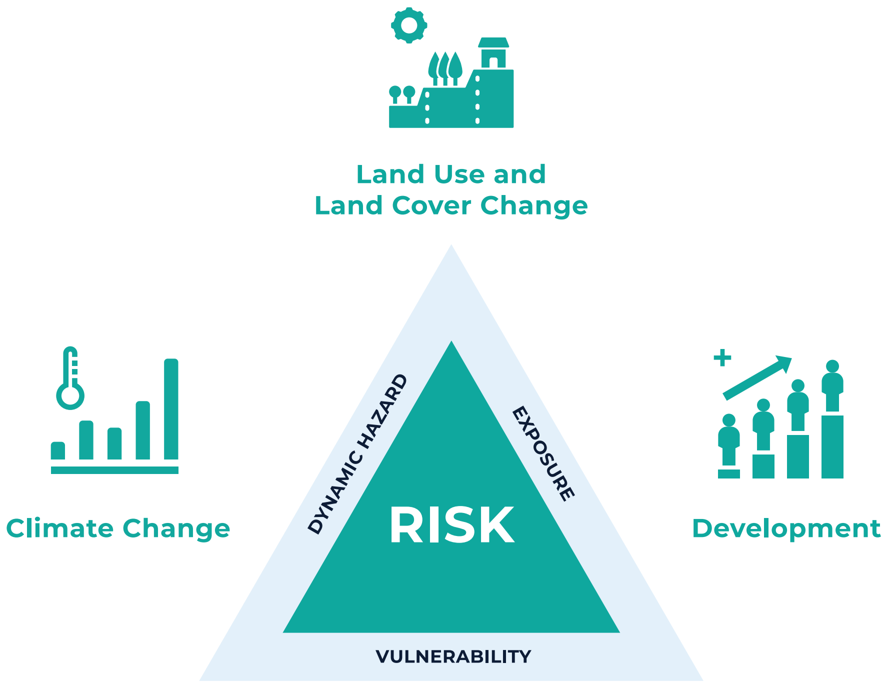

Figure 1-1: Simple model of risk.

In one model of risk, the amount of risk is defined by the total area of a triangle, whose sides are hazard (in this case flood), exposure (that is the things we care about that are exposed to flood waters) and the vulnerability of these things to damage by flood waters.

1.1 Hazard Shifts due to Climate Change

The world is warming. Global mean temperatures have been rising steadily for decades, with an estimated average increase of 0.85°C since 1880 (Bush & Lemmen, 2019). The rate of change is intensifying over time, with the eight hottest years on record having all occurred since 2015 (World Meteorological Organization, 2023). This is a result of human interventions affecting the climate system in the form of Green House Gas emissions.

These global temperature increases have real-world implications for the characteristics of flood hazard across Canada. Sea level rise is increasing the overall hazard along Canada's many coastlines (See Figure 1-2) (James et al., 2021). Precipitation and temperature shifts are also affecting the riverine and pluvial (floods from intense rainfall) flood hazard across the country (See Figure 1-2). Gaur et al., (2018) have shown changes to flood magnitudes and timings across Canada with future climate change. They generalize that at a regional scale flood magnitudes will trend toward an increase across the north of the country as well as in southern Ontario, whereas the prairies and northwestern Ontario will see a reduction in flood frequency. They also highlight that regions of Canada that generally experience snowmelt-driven floods (i.e., nival regimes) are likely to see flood peaks earlier in the season.

These varied shifts in flood hazard over time and across the country make Canada's flood risk profile dynamic.

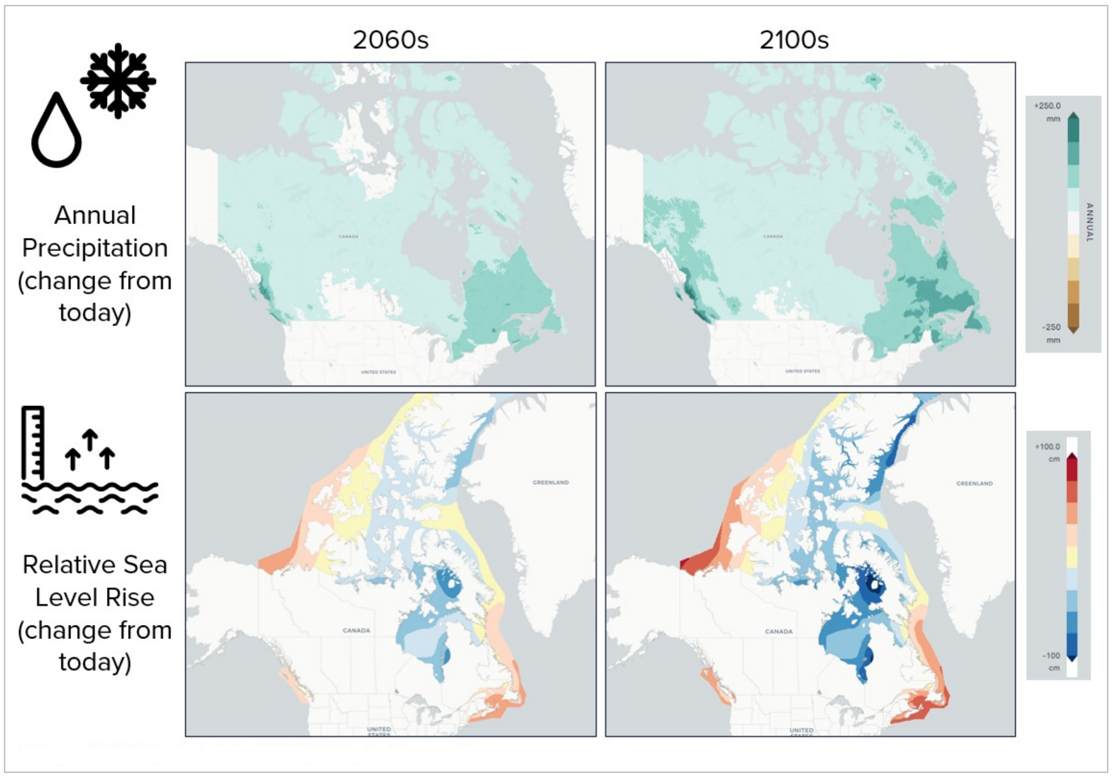

Figure 1-2: Climate and flood hazard change.
(All data: www.climatedata.ca, moderate emissions (SSP2-4.5), CMIP 6, gridded data representation)

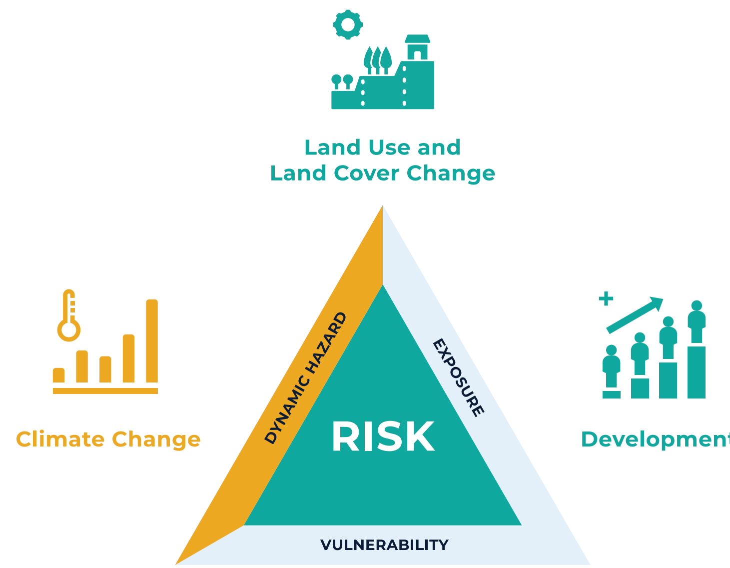

Figure 1-3: Simple model of risk showing changing hazard with climate change.

1.2 Hazard and Exposure Shifts due to Land Cover and Land Use Change

Like climate hazards, Canada's land cover and land use is shifting with time. Between 2010 and 2015, large shifts from natural ecosystems and agricultural land to urban and suburban uses were seen, and even larger shifts were seen from natural ecosystems to agricultural uses (See Figure 1-4).

This land cover and land use change drives changes to hydrology, especially on shorter time scales (Y. Li et al., 2022; Ross & Randhir, 2022). These changes to hydrology naturally impact shifts in the flood hazard over time.

Importantly, shifts in land use compound changes to risk; as we replace natural ecosystems with agriculture, urban, and suburban uses, we are steadily increasing exposure as well as changing the hazard. Areas that previously had no vulnerable valued assets are suddenly home to people, communities, and critical infrastructure.

Canadians face a real flood risk in the present day, and this risk is constantly morphing and shifting across time and space.

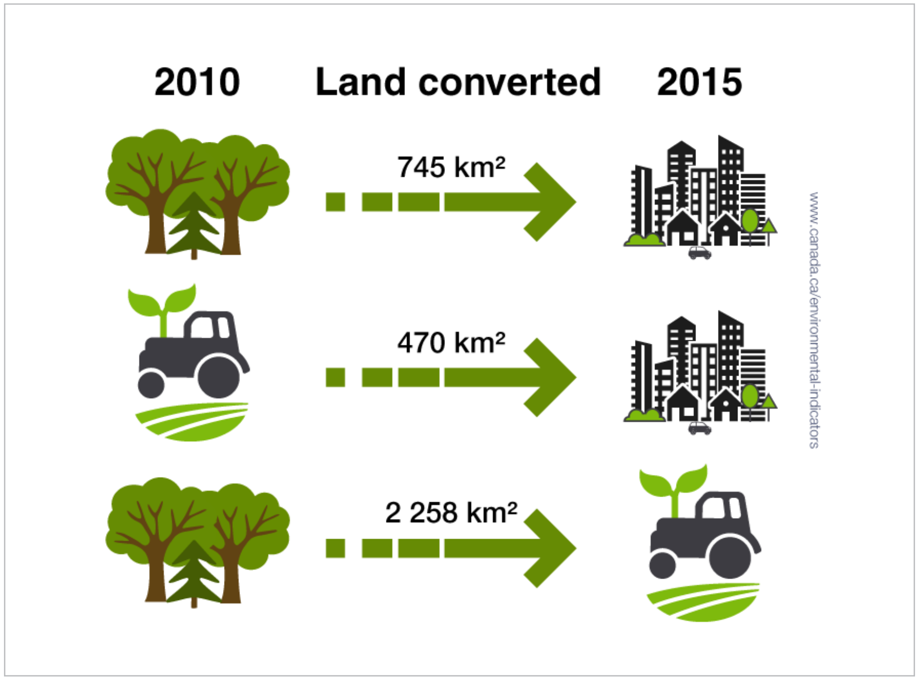

Figure 1-4: Land cover change in Canada
(Environment and Climate Change Canada (2021) Canadian Environmental Sustainability Indicators: Land-use change. Figure 1)

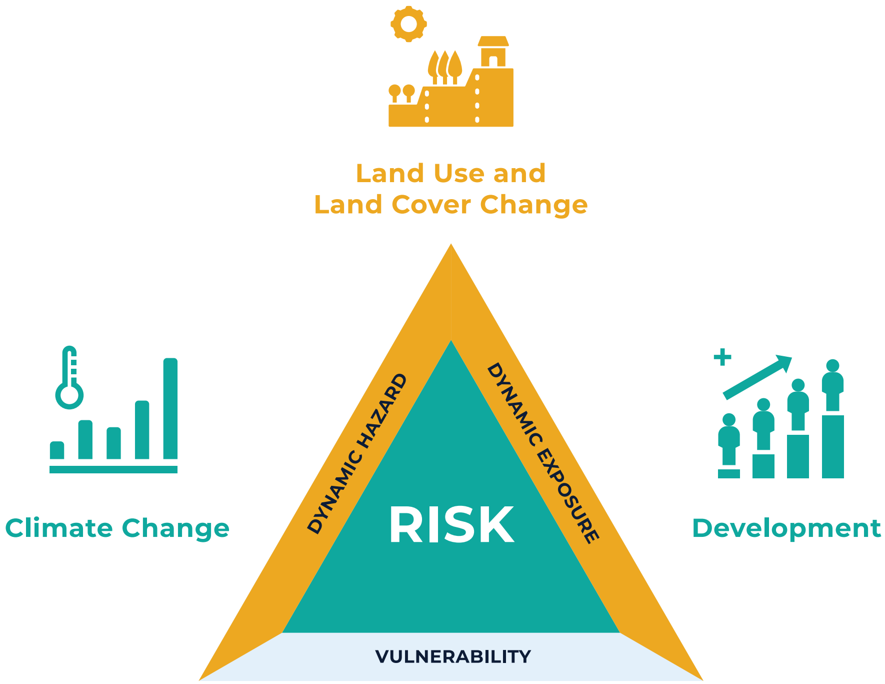

Figure 1-5: Simple model of risk showing changing hazard and exposure with land use and land cover change.

2

Flood Management as a Responsibility

2. Flood Management as a Responsibility

In our drive to reduce risk from flooding, humans adjust and manage the landscape and the activities that take place in flood hazard areas. These adjustments to the landscape have important long-term implications.

Flood management is the "process of data and information gathering, risk analysis and evaluation, appraisal of options, and making, implementing and reviewing decisions to reduce, control, accept or redistribute flood risks" (Sayers et al., 2014).

2.1 Layer Model

Changes to the landscape happen at varied timescales. Natural systems ebb and flow over centuries and millennia; rivers meander and avulse, and deltas are formed on these timescales. Human interventions affect the landscape for shorter but substantial periods. Network infrastructure such as linear roads and railways as well as core gathering places (e.g., libraries, schools) and critical infrastructure hubs (e.g., hospitals, water treatment plants) once on the landscape will dictate land use on the scale of decades and centuries. Small scale occupation, like the construction and use of buildings on the land occurs on an even shorter time frame of decades. These varied land processes and uses can be thought of as stacking on top of each other in a "layer model" (X. Li et al., 2012) (See Figure 2-1).

Importantly, some flood management actions, especially structural flood controls, fall in the middle network "layer". Effectively, this means that flood management decisions can affect generations to come. Decisions made in the 1950s, in the era of big-engineering in Canada, are still affecting flood risk as well as land use and occupation today (Lyle, 2001). Similarly, decisions made today will be imprinted in the landscape into the next century. Simply, flood management decisions are a long-term responsibility.

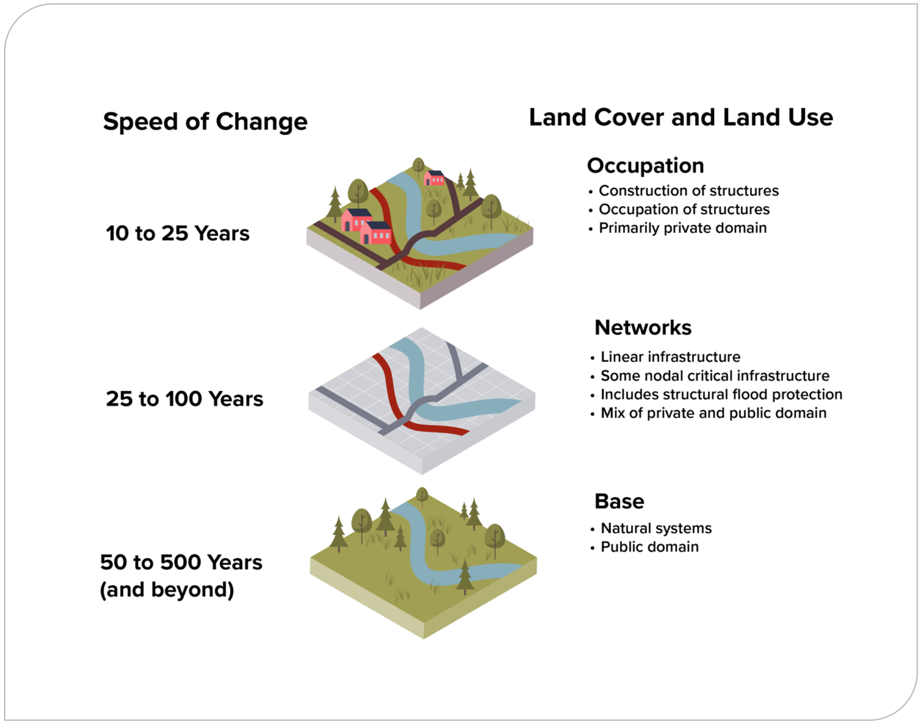

Figure 2-1: Land use layer model with the lens of flood mitigation.

2.2 Safe Development Paradox

In addition to building the foundations of a network layer through flood protection infrastructure, flood management decisions can also lead to unintended increases in risk through what is known as the "safe development paradox" (sometimes also called "the levee effect", "the serial engineering cycle" or the "safety dilemma"). These all describe that "increased [perception in] safety can induce increased development [in high hazard areas], ultimately leading to higher losses in the event of failures of the structural safeguards in place" (Breen et al., 2022). For example, the construction of a dike will naturally create a perception that the flood hazard is removed, which creates incentive to develop land behind the dike. This is an increase in exposure and potentially risk that will be realized if the flood protection infrastructure fails.

This concept builds on and enhances the idea that flood management is a deep responsibility, and that decisions related to flood should be made thoughtfully.

3

Compounding Uncertainties

3. Compounding Uncertainties

As today's flood planners sit down with their colleagues to make decisions related to flood risk reduction, they are setting in motion actions that will have repercussions decades from now.

Therefore, they need to be cognizant of what that future might look like to ensure that the investments of today are still worthwhile down the road. And, as described above there is an additional challenge that the flood risk that needs to be mitigated is constantly shifting in time, in an inherently uncertain way.

The future is uncertain, and not only because of climate change. The world will continue to be tested by local and global shocks and stressors from other hazards – pandemics, earthquakes, and wars, to name just a few. These in turn create uncertainty in our political and financial futures as a nation, as well as globally.

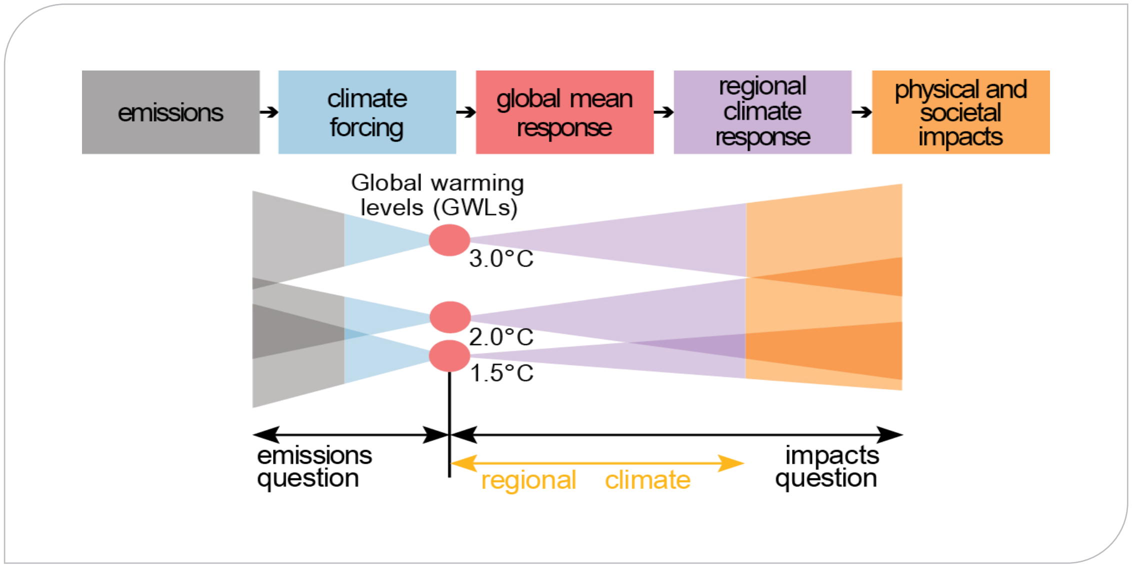

Figure 3-1: Schematic representation of relationship between emissions scenarios, global warming levels, regional responses, and impacts. (Cross-Chapter Box 11.1, Figure 1 in IPCC, 2021)

3.1 Climate and Hazard Uncertainty

The major challenge with designing disaster mitigation for a future climate is the uncertainty associated with climate projections. This stems from uncertainty associated with emissions scenarios (how will anthropogenic emissions change over time given worldwide climate policy and action or inaction), uncertainty in global climate models, and then uncertainty with how global climate models are downscaled to local areas (see Figure 3-1 (Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 2021)). There is also much uncertainty associated with translating the primary drivers and projected elements of climate, such as temperature and precipitation, into metrics relevant for flood hazard (e.g., streamflow).

In summary, although we understand trends in flood characteristics over time, there is a huge possible range of flood conditions.

3.2 Uncertainty in Exposure to Floods

Compounding the uncertainty associated with our future flood hazard are the uncertainties associated with our future exposure and vulnerability to floods. How will Canada's population grow and evolve? Where will new Canadians live and work? How much increased exposure to flood hazards can we expect over time?

Considering population growth as a proxy for flood exposure change over time, Statistics Canada (2022) provides a range of possible futures. From an almost doubling of our current population by 2068 at the upper extreme, to a low growth scenario where only five million additional Canadians are expected over the same period (Figure 3-2). If we consider the timescale of networks (25 to 100 years) that flood managers should be planning for, this means a huge range of future exposure (and risk).

3.3 Unprojected Shocks and Disruptions

In addition to our collective understanding of future trends through projections, there are uncertainties in our future that we just cannot know; these are the unknown "what-ifs":

- What if we are facing runaway climate change that our current best science has not yet foreseen?
- What if we face large macroeconomic downturns? And these limit the financial resources for Disaster Risk Reduction or emergency response? What if we can no longer pay for the maintenance of critical flood protection infrastructure?
- What if the public loses faith in government institutions? And this limits our collective ability to plan and implement regional scale flood management?
- What if Canada faces concurrent disasters? Will a future pandemic limit our collective ability to plan for and respond to flood events?

Simply, there are many future unknowns and potential tipping points that may challenge our current approach to flood management.

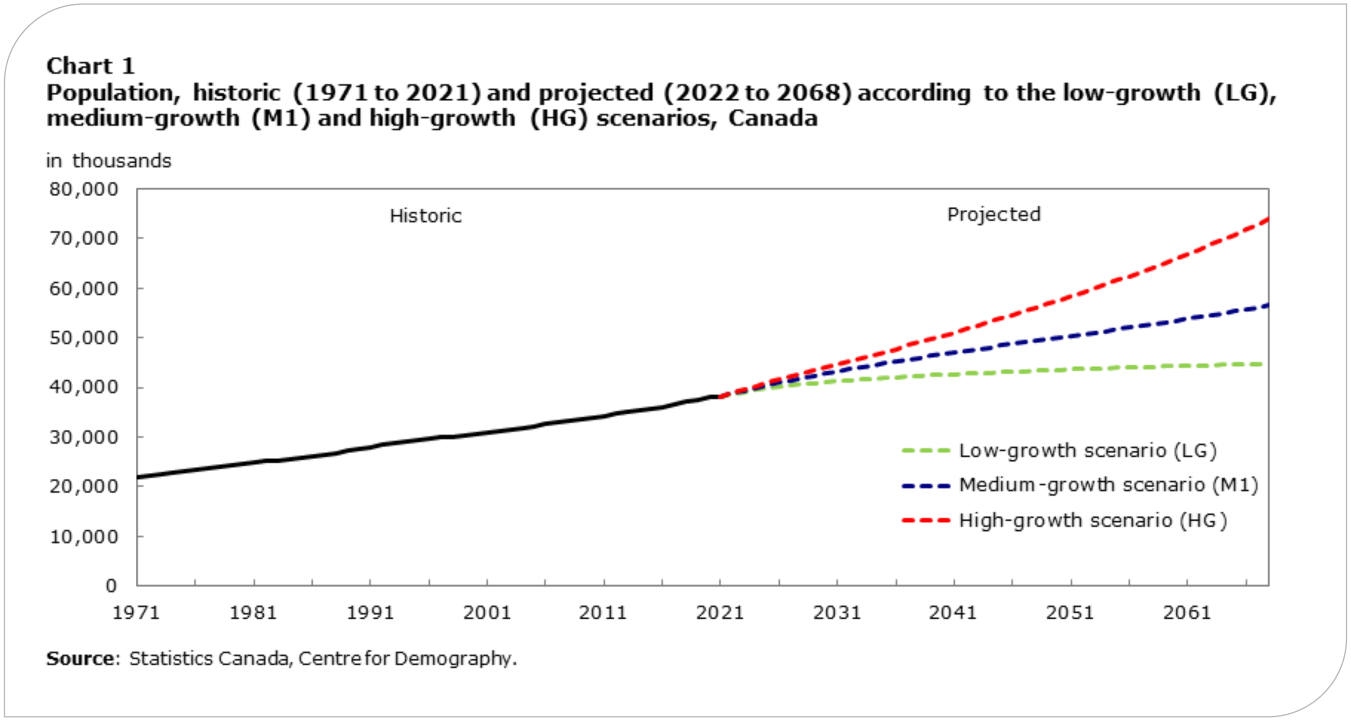

Figure 3-2: Population scenarios for Canada. (Statistics Canada 2021.)

4

Status Quo Flood Management: Fragile and Entrenched

4. Status Quo Flood Management: Fragile and Entrenched

Flood managers in the last century had an advantage over today's professionals - they were working with more certainty. They were also working within a different policy and social context. As a result, there is a lot of structural flood protection in place across the country, and these were predominantly designed to specific hazard-based standards (i.e., a 100 year annual recurrence interval flood event).

4.1 System Reliability and Fragility

"Structural flood protection" describes systems of dams, dikes, floodboxes, pumps, and other structures that are intended to mitigate flood waters interacting with exposed assets in flood hazard areas. The larger systems are effective only when all components are working; "they are essentially series systems with little to no redundancy" (Jongejan & Maaskant, 2015).

Structural systems are particularly vulnerable to failure if the design conditions are exceeded, noting that only one part of the system needs to fail to have a complete catastrophic system failure. With an uncertain future, it is increasingly likely that design conditions will be exceeded. It is also worth noting that the long-term reliability of the system is very dependent on continued operations and maintenance (Vonk et al., 2020), along with the funding and will to conduct it (Hegger et al., 2014).

It is further worth noting that in addition to challenges associated with design conditions being exceeded, there are implications to design conditions never being met with rigid structural systems. For example, a dike that is designed and built for an extreme design scenario that is never realized, means that resources were expended unnecessarily, at a cost usually to the public purse (See Figure 4-1).

In summary, the rigid nature of status quo structural systems will be tested under elastic and uncertain climate futures.

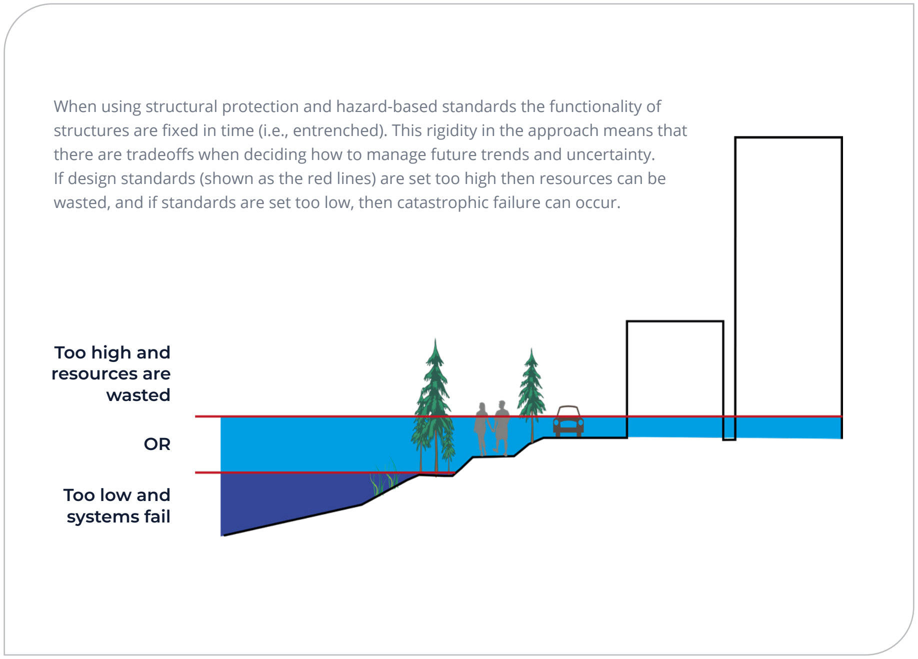

Figure 4-1: Illustration of rigidity of structural flood protection and hazard-based standards.

4.2 Entrenched Pathways

Humans are generally entrenched in how things are done; this is no different for how floods are managed. For the most part, despite the signals that the current system is not working, we continue to be bound by our existing regimes.

In the context of flood management, we have strong entrenched pathways as it relates to preferred mitigation strategies. Structural (resistance-based) strategies are the norm in Canada, and our governance structures (i.e., policy, funding, decision-making, etc.) have developed around them (Morrison et al., 2018). Adopting a new pathway will require, in many instances, that we first break out of our existing pathway. This movement away from path dependency will not be easy (Gralepois et al., 2016), it is important that this change occurs.

5

A Solution: Moving From Entrenched Fragility To Adaptive Flexibility

5. A Solution: Moving from entrenched fragility to adaptive flexibility

Our current flood management systems are fragile and entrenched. Adaptive flood management simply means making decisions that are not so rigid, but flexible and adaptive to better manage future deep uncertainty (van Buuren et al., 2018; Sayers et al., 2014).

Six ideas to move towards more adaptive systems are presented here. The first two relate to an acceptance that the future is deeply uncertain, the next three relate to the choice of mitigation strategies used for flood, and finally the last relates to a shift in tolerance for innovation and failure.

1 Acceptance of Future Uncertainty +
2 Acknowledge Future Shocks

As a first step in the development of adaptive flood management plans, it is important to acknowledge that we do not know what the future holds. Work should be undertaken to understand the most probable futures, as well as the bands of uncertainty associated with this, but at the end of the day, we need to recognize that this deep uncertainty is best managed by implementing mitigation measures that work across multiple futures.

Proposed mitigation measures should be tested across multiple projected futures as a key part of any planning and decision-making process. And it is recommended that mitigation measures are also stress-tested against a number of "what-if" scenarios.

3 Expand the Toolbox

There are three levers to increase or reduce risk. Hazard, exposure, and vulnerability reduction can all play a role in overall risk reduction. This more complex, but important, take on flood mitigation, means that there are many more tools available to support risk reduction.

In the last hundred or so years, many western governments have focused on trying to stop water from interacting with assets through the construction of large engineering works. This effectively limits risk reduction options to one of three possible levers (i.e., hazard). Leaving additional options, some of which are described here, unused.

5.3.1 The Value of Land Use-Based Approaches to Risk Reduction

Land use is a key driver of flood risk. Risk only exists when vulnerable elements are exposed to flood hazard. Land use planning (at local, regional, and larger scales) is the primary instrument that creates or conversely reduces exposure and therefore flood risk.

Land use-based approaches to reduce flood risk are consistently effective. Removing or reducing the vulnerability of exposed elements on floodplains immediately results in reduced risks and will result in reduced damages over time. Land use-based approaches also have the benefit of being generally robust across multiple flood scenarios and futures.

Further, land use-based planning for flood risk reduction generally brings with it co-benefits; whereas flood infrastructure often serves a single purpose. For example, land uses that are flood-resilient (such as open spaces or recreational spaces) bring additional value to communities.

Applying land use planning as the primary tool to support flood management will reduce risk, support the development of thriving and resilient communities, and better manage future uncertainty.

5.3.2 The Value of Nature-Based Solutions

Nature-based Solutions (NbS) describe the group of "actions to protect, sustainably manage, and restore natural and modified ecosystems" (IUCN & UNEP, 2021). These types of flood mitigation actions are particularly valuable in the context of future uncertainty. They have the capacity to gently absorb and take the "edge off" the full range of flood events. They are robust systems that will fail safely or not fail at all when design thresholds are exceeded, whereas structural systems can fail catastrophically under the same conditions.

4 Reversible and Flexible Options

Since we don't know what the future holds, it is wise to proceed in ways that continue to keep a range of options available to us, rather than painting ourselves into a corner. For example, while engineered "hard" infrastructure can be appropriate in some instances, it can lock us into a path that can create greater risk over time (e.g., as more development occurs behind a dike) and where resources cannot be redirected if we need to change course.

It is important to design for adaptability and to avoid fragility in disaster mitigation projects. Adaptable designs are those that can be easily adjusted or retrofitted over time as climate hazards change (e.g., a dike that is designed and sited so that it can be raised in future).

5.4.1 Planning for Pathway Flexibility

An adaptation pathway describes a planning trajectory, where individual or groups of actions are taken over time (Werners et al., 2021). Pathways can be entrenched or flexible. An entrenched pathway decision, once locked-in, is nearly impossible to modify in the future. For example, many structural responses to disaster risk create a situation where it becomes necessary to continue with the pathway. If a dike is built to stop coastal flooding and development occurs landside of the dike then it will be nearly impossible to do anything other than continue to build up the dike to match sea level rise. A flexible pathway at a decision point allows movement between pathways relatively easily. Using the same example as above, if an avoid strategy is used and development is not allowed in a high hazard area, it would be relatively easy in the future to jump to a structural protect strategy should this become preferred over time.

Given the uncertainty of future climate, as well as general future state (e.g., of land use, development, economy, population), flexible pathways are generally preferred as they allow for accommodation of multiple different futures.

5 No-Regrets Options

The flood mitigation toolbox is large, especially when all three levers of risk are used. Some, if not many, of these tools can be considered "no regrets". These are options that will provide risk reduction or increased resiliency benefits regardless of future decisions and future flood conditions. For example, public education and better emergency readiness are generally considered no-regrets.

Another form of no-regrets mitigation in the context of flood are options that have co-benefits. For example, the restoration of a riparian park will improve ecological function and create recreational opportunities. Even if the flood attenuation benefits of such a park are never realized, the park is a community asset.

6 Make Mistakes and Be Brave

Incremental adaptation strategies for climate change will not be enough in some cases, and large-scale, systemic pathway shifts will be required (Fedele et al., 2019). This will require a measure of bravery, and an acceptance that we should be allowed to test and fail new ideas and solutions (see text box on Leading Practice). Realistically, this will take time, as flood managers will have to become more comfortable with uncertainty and potential failure, and governance systems will have to adjust to allow for more innovation (and potential failure). But, the benefits of the transformational shifts, when successful, will be enormous.

Innovating through Leading Practice

Best practice is a commonly used term in policy to describe a methodology or activity that is widely considered preferred because it is the most effective or efficient. A **Leading Practice** is one that is currently novel and shows early indications of success. A leading practice, if preferred over time, will become a best practice, but may also be shown to be less effective or efficient and ultimately be dismissed. The inclusion of leading practices allows for greater flexibility in potential approaches to match and keep-up with the uncertainty associated with climate change and future disaster risk. Simply, leading practices also allow for potential failure but with the trade-off that this new practice might be the most successful method to manage a new paradigm.

Conclusion

6

6. Conclusion

Canada's floodplains are the commercial, social, and ecological arteries of the country. The assets, and communities they support, that sit on these floodplains are subject to damage and disruption when floods occur. We use floodplains for these purposes partly for historic reasons (e.g., for access to fresh water, transportation, flat and fertile land), but have continued to grow and entrench our communities into these areas because they are desirable places to live, work and play.

If we continue to use floodplains for these purposes, we need to acknowledge and plan for flooding. Some of the approaches that we have traditionally relied on, such as dikes and emergency protection and response, have limitations, especially in the face of climate change. We are now at a criticaljuncture where we need to apply adaptive, flexible flood management solutions, if we are to avoid catastrophic failures and spiralling costs in future.

Building The Foundation For Adaptive Flood Management Within Flood Hazard Identification and Mapping Program

The elements of an adaptive approach to flood management will require some shifts to the status quo approaches to flood mapping:

1. **Map a range of events:** Importantly, an adaptive management approach requires that mitigation activities are tested across a large range of flood events (from small and frequent to large and rare) and futures. This will require that flood maps are developed for an equally wide range of events.

2. **Acknowledge and communicate uncertainty in maps:** The uncertainty associated with map development should be communicated on the maps themselves, especially for lay audiences. This means lay language and all-encompassing titles (e.g., future rare event vs. present day frequent event). It may also mean not presenting flood hazard zones as binary polygons (i.e., one side of the line is in the flood hazard zone, and the other is not), but instead using shading and other mapping tools to better represent uncertainty.

3. **Use modelling and mapping resources wisely:** We have limited resources to develop hydrologic and hydraulic models and associated maps. Given the deep uncertainty associated with these models and inputs to them for future events, it requires that we thoughtfully select where to expend our efforts. Refining and tweaking models to the best available information may not be the best use of resources given the inherent uncertainty. Instead, simple incremental ramping approaches (i.e. create maps for a range of flows at consistent increments) may be a more appropriate use of resources.

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Final Report

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