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Retrospective Benefit-Cost Analysis of BC Disasters: Technical Report

By the Institute for Catastrophic Loss Reduction
For Emergency Management and Climate Readiness

March 2024

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ICLR's mission is to reduce the loss of life and property caused by severe weather and earthquakes through the identification and support of sustained actions that improve society's capacity to adapt to, anticipate, mitigate, withstand and recover from natural disasters. ICLR is achieving its mission through the development and implementation of its programs *Open for business*, to increase the disaster resilience of small businesses, *Designed for safer living*, to increase the disaster resilience of homes, and *RSVP cities*, to increase the disaster resilience of communities.

ICLR has been designated as an IRDR International Centre of Excellence. IRDR International Centres of Excellence (ICoEs), established through the IRDR Scientific Committee (SC) and the relevant National Committee (NC), provide regional and research foci for the IRDR program. ICoE research programs embody an integrated approach to disaster risk reduction that directly contribute to the ICSU/IRDR Science Plan for Integrated Research on Disaster Risk and its objectives, as well as the IRDR Strategic Plan (2013-2017).

Executive summary

Figure ES-1. Well-understood mitigation measures can avoid predictable losses in (A) floods, (B) wildfires, and (C) earthquakes.

This study asks how much loss and suffering can be avoided by prudent mitigation using accepted procedures most strongly recommended by authorities such as the Institute for Catastrophic Loss Reduction, National Research Council of Canada, and U.S. Federal Emergency Management Agency. These measures have been shown to have a high benefit-cost ratio and effectively reduce damage in severe storms, wildfires, and earthquakes. It estimates what it would have cost to comply with these measures before three large, historic storms and fires in British Columbia and before four large, hypothetical – but inevitable – future earthquakes, as shown in Table ES-1. It reaches three major findings:

1. We can reduce flood and storm losses through pluvial and fluvial flood mitigation measures and by improving connections between building elements to resist strong winds. Undertaking these measures to improve 12,400 buildings prior to the 2021 November Rainstorm would have cost $1 billion but avoided $2.3 billion in losses, for a retrospective benefit-cost ratio of 2:1.
2. We can reduce wildfire losses through vegetation management, use of noncombustible building materials, and undertaking community protection measures. For 100 Lytton buildings to comply with the National Guide for Wildland-Urban Interface Fires would have cost $2 million to avoid $300 million in losses, for a retrospective benefit-cost ratio of 170:1. For 6,400 buildings affected by the 2017 Wildfires to similarly comply would have cost $110 million but avoided $340 million in losses, for a retrospective benefit-cost ratio of only 3:1.
3. We can reduce losses in inevitable future earthquakes by strengthening weak foundations in older woodframe buildings, strengthening the soft-story parking level of older woodframe apartment buildings, and adding engineered tie-downs to manufactured homes. Mitigation prior to four hypothetical earthquakes would require retrofitting 50,000 to 80,000 buildings at a total cost of $1 billion to $4 billion, avoiding up to twice the retrofit cost in losses. Retrospective benefit-cost ratios are approximately 2:1.

Table ES-1. Estimated retrospective costs and benefits of mitigation

Event	Number of buildings needing mitigation	Cost 2023 $M (range)	Benefit 2023 $M (range)	Benefit-cost ratio (range)
2021 November Rainstorm	12,400 (8,400 for basement flood, 3,900 for fluvial flood, 100 for wind)	1,000 (700-1,500)	2,300 (1,500-3,500)	2 (1-5)
2021 Wildfires	100	1.7 (1.3-2.6)	330 (220-440)	170 (85-340)
2017 Wildfires	6,400	110 (80-160)	340 (230-460)	3 (1-6)
M9.0 Cascadia subduction zone earthquake	78,000 (55,000 cripple-wall houses, 9,000 soft-storey apartment buildings, and 14,000 manufactured homes)	4,400 (3,000-6,000)	8,300 (5,500-11,000)	2 (1-4)
M7.3 Leech River Fault earthquake	52,000 (37,000 cripple-wall houses, 7,000 soft-storey apartment buildings, 8,000 manufactured homes)	3,100 (2,100-4,200)	4,300 (2,900-5,800)	1.4 (1-3)
M7.0 Georgia Strait earthquake	59,000 (43,000 cripple-wall houses, 7,000 soft-storey apartment buildings, 9,000 manufactured homes)	3,400 (2,300-4,600)	6,600 (4,400-8,800)	2 (1-4)
M7.1 Sidney earthquake	61,000 (50,000 cripple-wall houses, 11,000 manufactured homes)	1,200 (800-1,600)	1,800 (1,200-2,400)	2 (1-3)

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Abbreviations and notation

The following list omits the many mathematical parameters used in this study, which are defined close to where we first use them.

B	Billions
BC	British Columbia
C	Degrees Celsius
C1	Reinforced concrete moment frame
C3	Reinforced concrete moment frame with infill masonry walls
CAD	Canadian dollars
CAL FIRE	California Department of Forestry and Fire Protection
CanSRM1	Canadian Seismic Risk Model
CO_2	Carbon dioxide
CPI	Consumer price index
DFAA	Disaster Financial Assistance Arrangement
EF	Enhanced Fujita scale
g	Acceleration due to gravity
HC	High code
LC	Low code
m	Metre
m^2	Square metre
M	Millions or magnitude, according to context
MC	Moderate code
MH	Manufactured home
MMI	Modified Mercalli Intensity
N/A	Not applicable
PC	Pre-code
PC1	Tilt-up precast concrete construction
PGA	Peak ground acceleration
PTSD	Post-traumatic stress disorder
RES1	Single-family dwelling
RES6	Nursing home
RM1	Reinforced masonry with flexible diaphragms
sf	Square feet
SSP	Shared socioeconomic pathway
URM	Unreinforced masonry construction
US	United States
USD	United States dollars
VSL	Value of a statistical life
W1	Light-frame construction of one or two storeys
W2	Light-frame construction of three or more storeys
W4	Like W1 but with light cripple-wall frames between the foundation and first floor

1. Introduction

1.1 Objectives

The project has three main objectives:

1. Help the province understand the costs of past disasters in British Columbia and how accepted mitigation measures could have helped reduce those costs. By disasters, we particularly mean (a) severe summer and winter windstorms and their attendant precipitation and flooding; (b) fire in the wildland–urban interface; and (c) earthquakes and their attendant ground shaking, liquefaction, landslide, and post-earthquake conflagrations. “Mitigation measures” refer to preventive disaster and climate risk reduction actions, that is, well-defined methods to strengthen or otherwise modify buildings and other infrastructure to reduce damage and loss. It also means processes that reduce harm to people despite damage to infrastructure, such as warning systems. “Accepted mitigation measures” mean measures either that have been shown to be cost-effective or that reputable authorities recommend as best practices.

2. Help the province understand how the climate crisis will drive future costs. The study estimates trends in disaster frequency, severity, or both, considering BC climate projections for two shared socioeconomic pathways: moderate (SSP1-2.6), which corresponds to 1.3-2.4 C warming relative to pre-industrial levels by 2081-2100, and high (SSP3-7.0), which corresponds to 2.8-4.6 C warming relative to pre-industrial levels by 2081-2100 (Masson-Delmotte et al. 2021).

3. Support disaster risk reduction, adaptation, funding, and policy. The study cites prior disaster risk reduction and adaptation efforts undertaken by other governments, including their documents, contact people or agencies, sources of funding, and references to important policy issues those prior efforts confronted.

More subtly, the project provides resilience advocates with evidence to inform British Columbians about how changes to the built environment can reduce their risk from natural disasters, thus improving their lives. The evidence speaks to monetary and emotional values.

1.2 Scope

The project is limited to British Columbia, three kinds of disasters (storms, fires, and earthquakes), and readily available historical loss data, at least for frequently occurring disasters. For example, the leading source of loss data from CatIQ reflects 2008 to 2023, although we have searched for earlier sources. Since large, damaging earthquakes are rare and have not occurred recently, we characterize costs and benefits using four hypothetical BC earthquakes with magnitudes of 7.0 and greater modelled in the Canada Seismic Risk Model (CanSRM1) developed by the Geological Survey of Canada.

This project estimates the mitigation costs and avoided losses. Here, “avoided losses” means the difference between the losses that BC experienced and those that it would have experienced if the mitigation measures had been implemented. These avoided losses are different from probabilistic benefits, which are the expected present value of avoided future losses before one knows where disasters will occur and with what severity. Rather we ask how much less the loss would have been if the damaged buildings had been retrofitted before the event occurred.

The project aims to estimate the losses avoided to private property (buildings and contents), direct time-element losses (additional living expenses and direct business interruption costs), indirect business interruption costs, carbon costs (using the May 2023 Canadian federal carbon price per tonne), and an acceptable cost to avoid future statistical deaths and injuries (this is not the value of human life, but rather the money that people will spend to make small changes for their own safety.)

1.3 Organization of the report

This chapter introduced the objectives and scope of the work. Each of the next three chapters offers a self-contained retrospective benefit–cost analysis for one kind of disaster: severe storms (chapter 2), fires (chapter 3), and earthquakes (chapter 4). Each chapter reviews the most relevant literature, offers a methodology specific to that kind of disaster, and shares results of applying the methodology. Chapter 5 presents conclusions, and chapter 6 includes references cited.

2. Severe storms

2.1 Literature

2.1.1 Climate and weather

The present study attempts to estimate retrospective costs and benefits of severe storms, fires, and earthquakes – that is, what the losses would have been had certain mitigation measures been undertaken before the disaster occurred. For that reason, the future climate does not matter very much to this analysis, though it may be useful to consider the implications of climate change.

Masson-Delmotte et al. (2021) describe five shared socioeconomic pathways for the Intergovernmental Panel on Climate Change. Each pathway represents a scenario of projected socioeconomic global changes up to 2100 and a greenhouse gas emissions scenario with associated climate policies. Two pathways reasonably bracket BC's future weather: SSP1-2.6 reflects warming of 1.3-2.4 C, and SSP3-7.0 reflects warming of 2.8-4.6 C, both relative to pre-industrial levels, by 2081–2100.

Environment and Climate Change Canada's climate resource, Climatedata.ca, provides estimates of future precipitation, temperature, and other variables relevant to severe storms in BC. The climate crisis is not projected to strongly affect the number of precipitation days in BC. Figure 1 shows the projected change in precipitation days by the period 2071-2100 under shared socioeconomic pathway SSP2-4.5. Figure 2 shows the projected change in maximum one-day precipitation, and Figure 3 shows the projected change in maximum five-day precipitation. Changes are slight.

To understand the scale of the changes shown in these maps, it may be helpful to consider time series for particular locations. Figure 4 shows estimated precipitation days in southwestern BC, near Vancouver, under shared socioeconomic pathway SSP2-4.5, while Figure 5 and Figure 6 show maximum one-day and maximum five-day precipitation in Vancouver. All are projected to increase by a maximum of 10–20% over the rest of the century and are not substantially higher now than in recent decades. Similar trends seem to hold in southeastern BC (Figure 7, Figure 8, and Figure 9 for similar projections for Golden, BC) and central BC (Figure 10, Figure 11, and Figure 12 for Fraser Lake, BC).

The resource does not offer estimates of future high winds, hail, snow, or flooding. Its historical data about peak gust velocity show no strong temporal trend in Vancouver over the past 25 years (Figure 13). If some past disasters were to recur today, there seems to be no strong indication that climate change would increase precipitation or wind speed.

Regarding flooding, Wing et al. (2018) estimate that in the US, 13 million people live in special flood hazard areas, while another 27.8 million live in other places with comparable flood hazard (at least 1% chance of flooding per year). Thus, perhaps three times as many people are subject to 1% annual chance of flooding as US flood maps suggest. Wing et al. (2018) do not offer similar statistics for Canada, but it seems reasonable to assume that the ratio of pluvial to fluvial flood risk in Canada is comparable to that of the US. The two countries have similar topography, which tends to govern hydraulics and hydrology (i.e., the overland flow and natural drainage of watersheds). They also share similar design of stormwater and sewer systems, which affect urban flooding.

Figure 1. Very little projected change in wet days by 2071–2100 (Climatedata.ca).

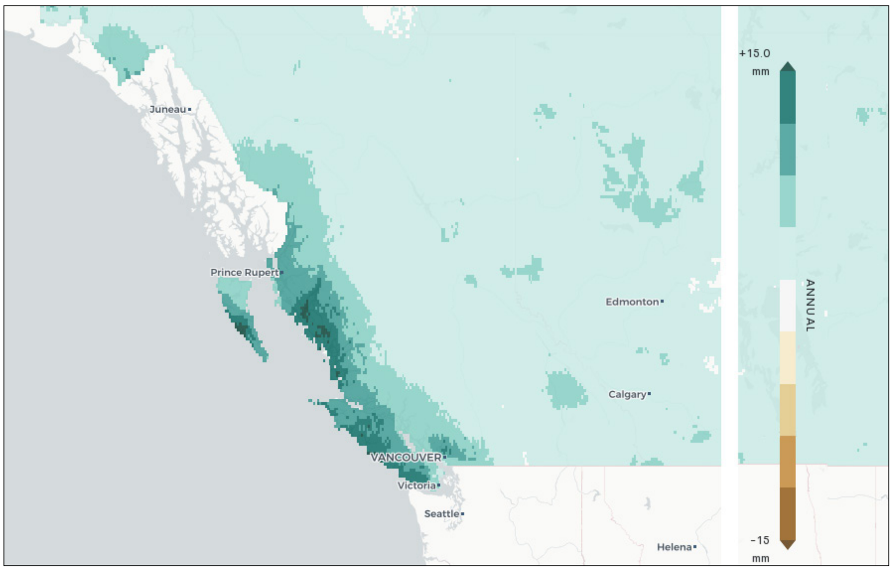


Figure 2. Modest projected change in maximum one-day precipitation by 2071–2100 (Climatedata.ca).

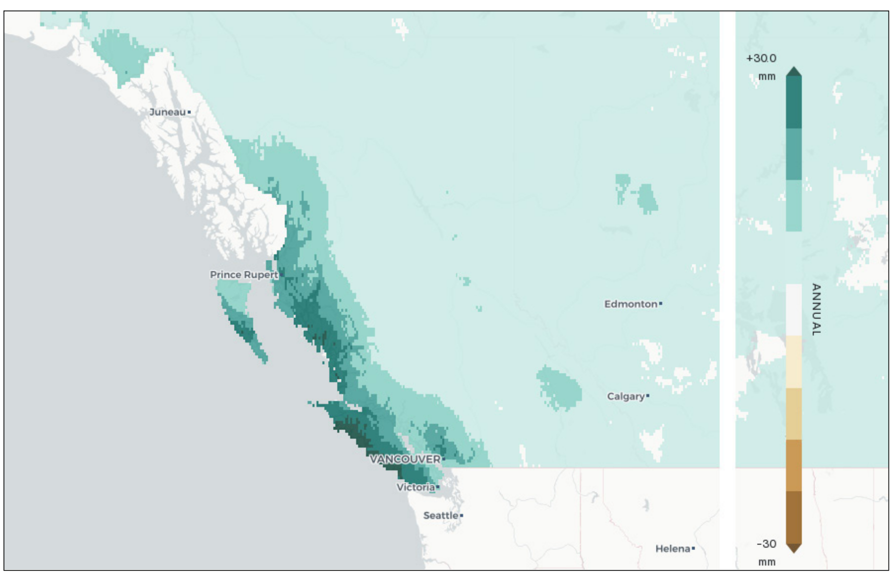


Figure 3. Modest projected change in maximum five-day precipitation by 2071–2100 (Climatedata.ca).

Figure 4. Climate change will not substantially affect precipitation days in Vancouver (Climatedata.ca).

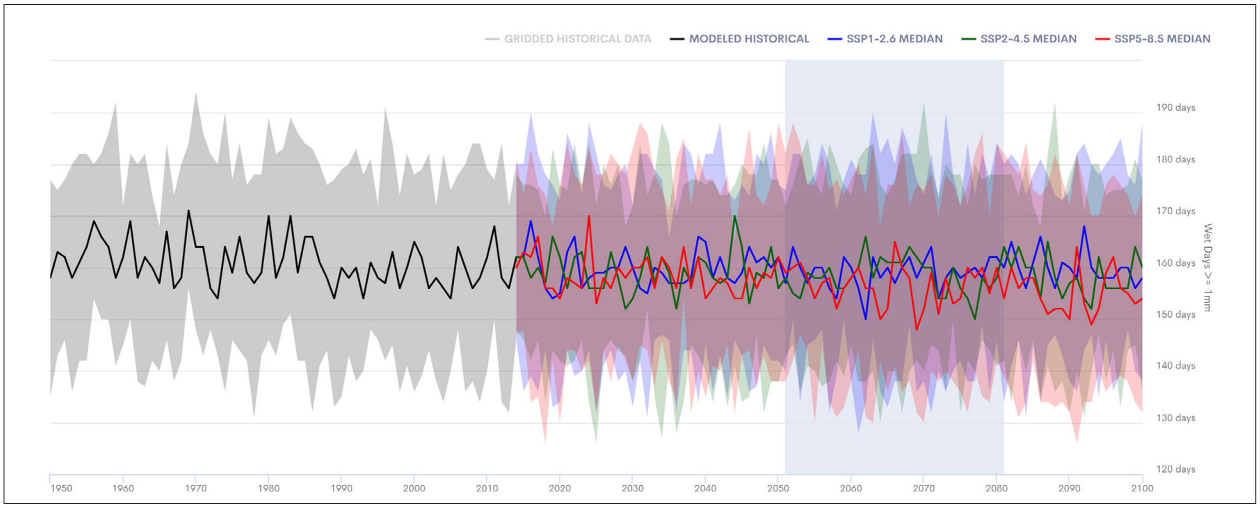


Figure 5. Maximum one-day precipitation will increase 10–20% by the end of the century in Vancouver (Climatedata.ca).

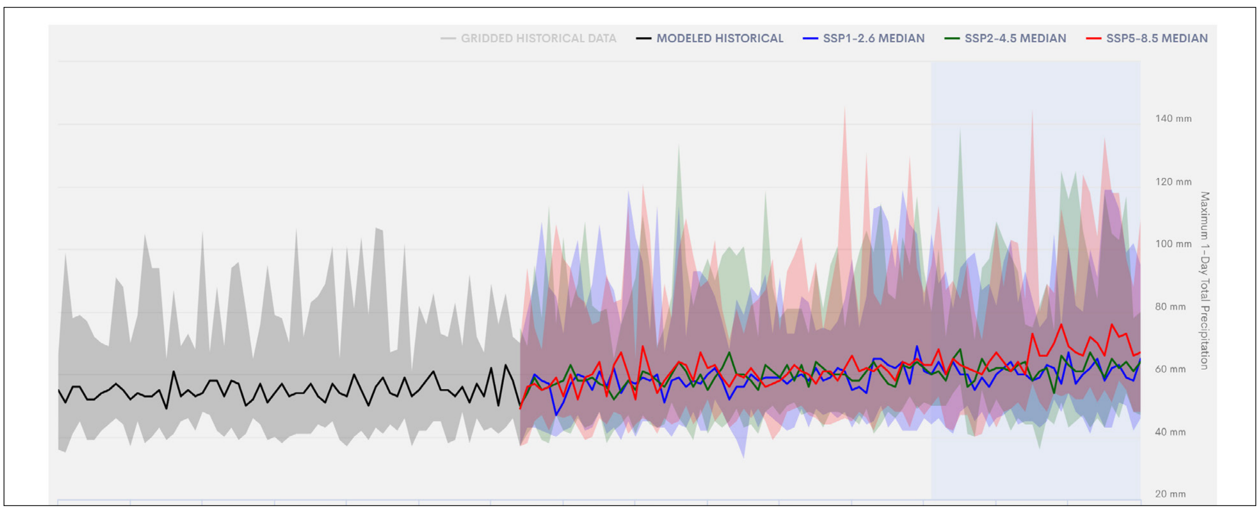


Figure 6. Maximum five-day precipitation will increase 10–20% by the end of the century in Vancouver (Climatedata.ca).

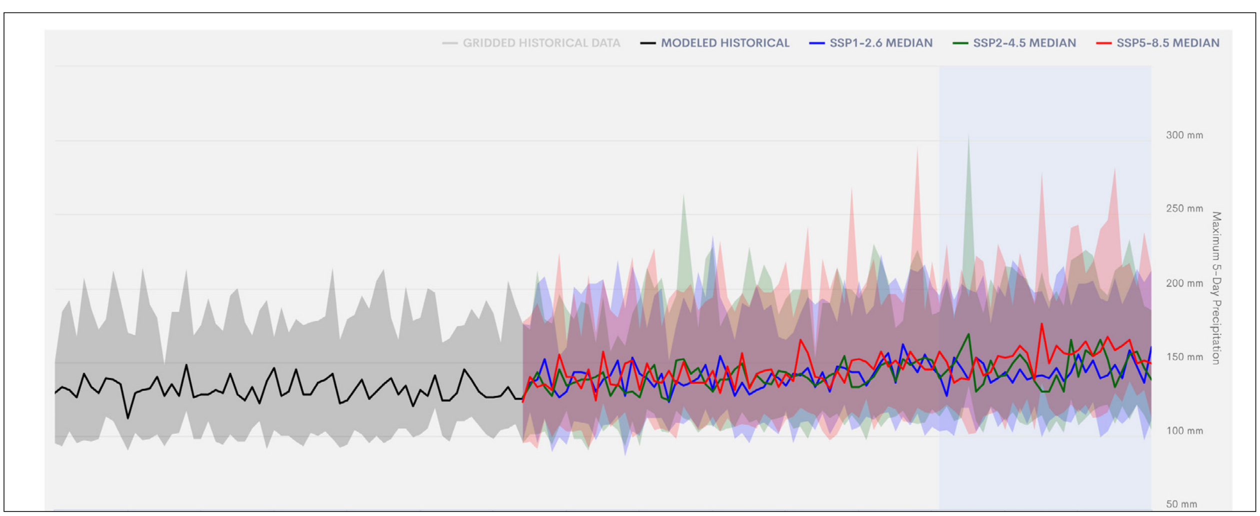


Figure 7. Climate change will not substantially affect precipitation days in southeastern BC (Climatedata.ca for Golden, BC).

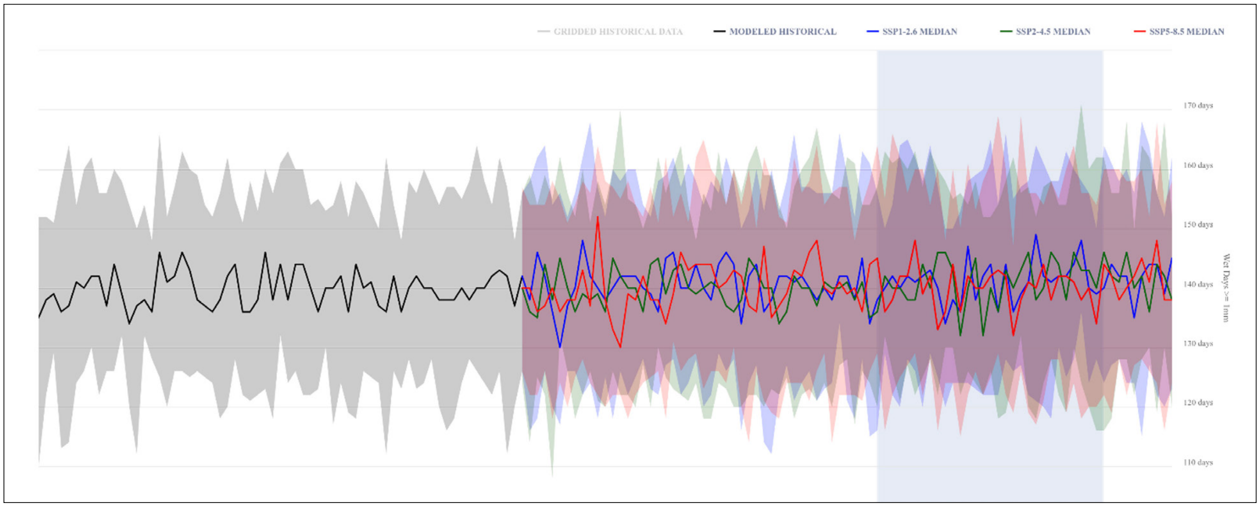


Figure 8. Maximum one-day precipitation will increase 10–20% by the end of the century in southeastern BC (Climatedata.ca for Golden, BC).

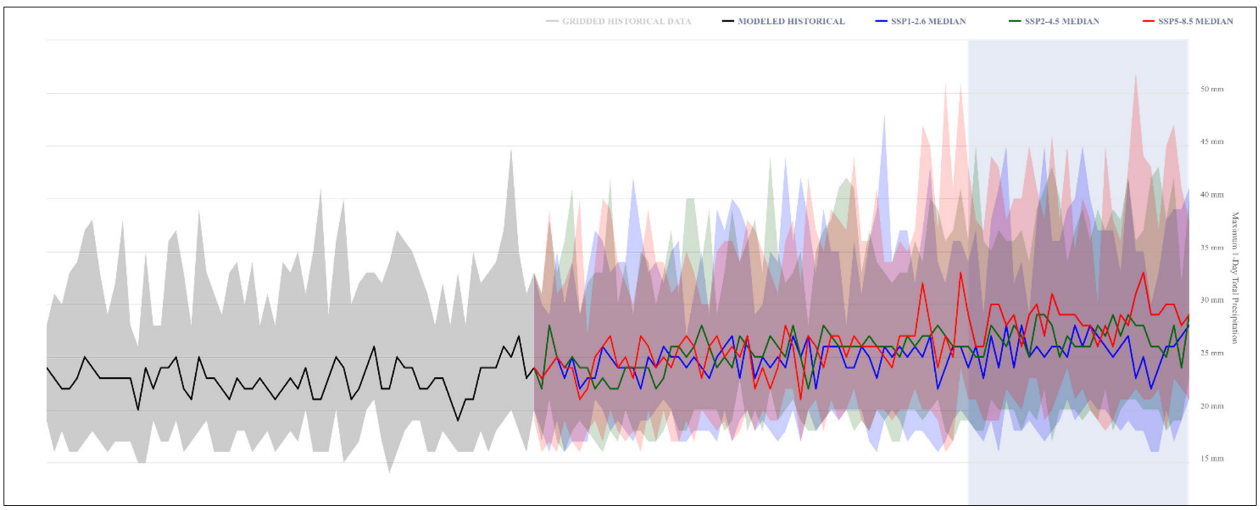


Figure 9. Maximum five-day precipitation will increase 10–20% by the end of the century in southeastern BC (Climatedata.ca for Golden, BC).

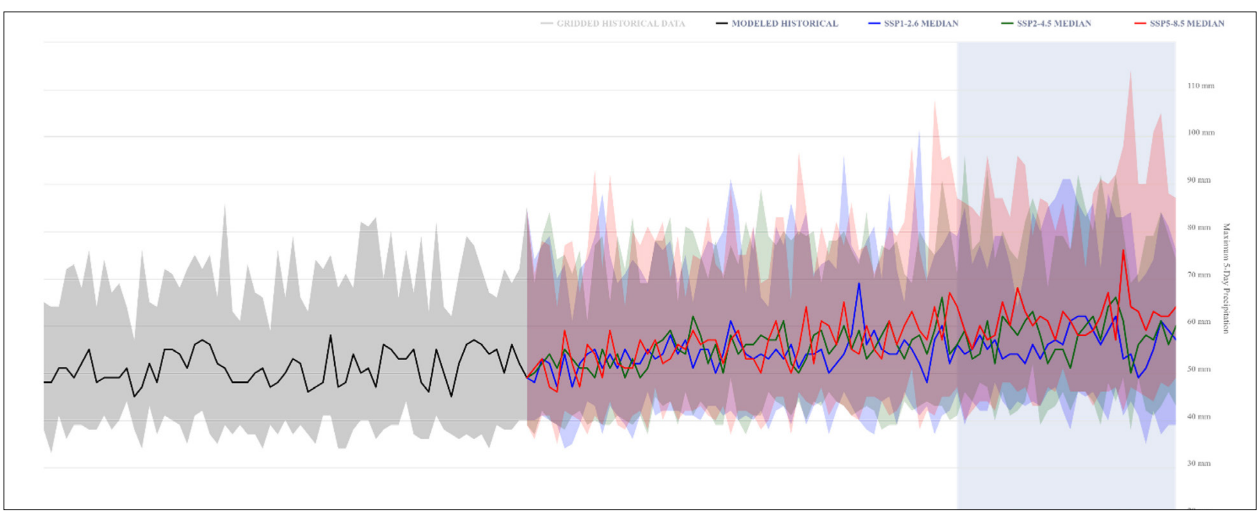


Figure 10. Modest change is projected in precipitation days in central BC (Climatedata.ca for Fraser Lake, BC).

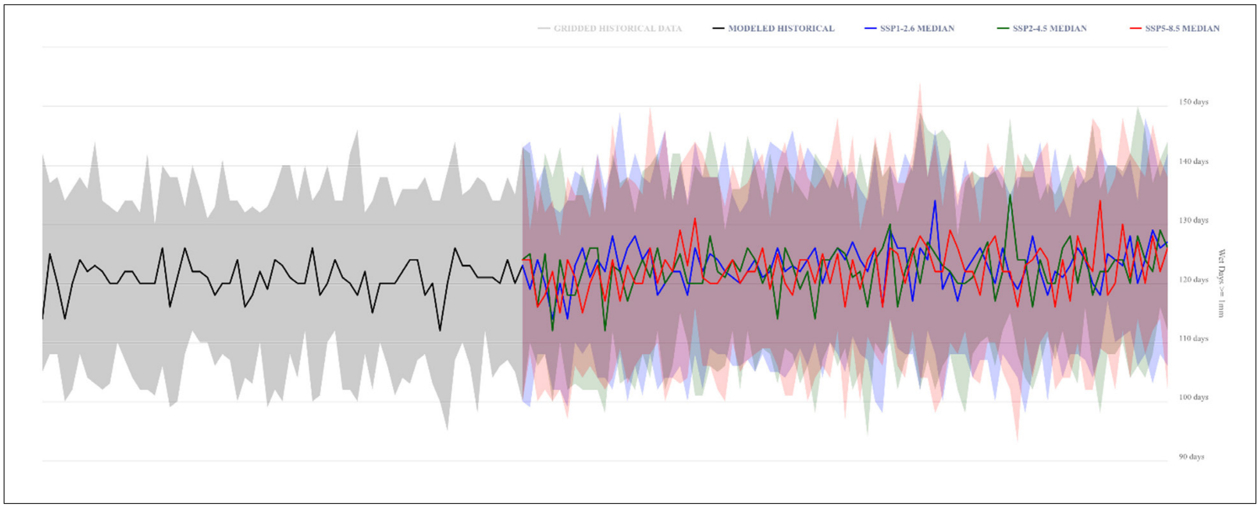


Figure 11. Maximum one-day precipitation will increase 10–20% by the end of the century in central BC (Climatedata.ca for Fraser Lake, BC).

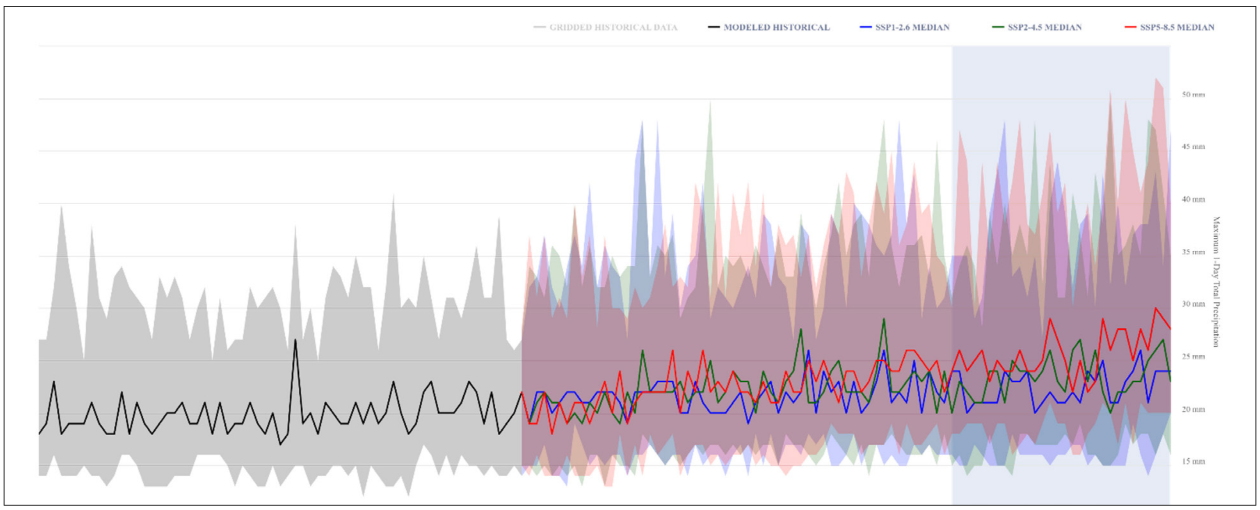


Figure 12. Maximum five-day precipitation will increase 10–20% by the end of the century in central BC (Climatedata.ca for Fraser Lake, BC).

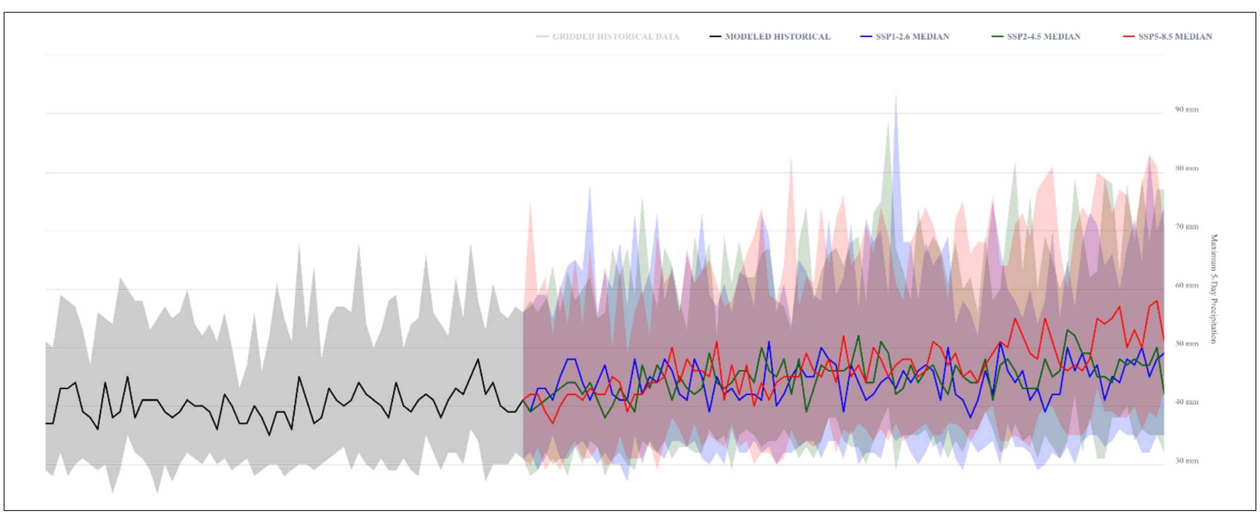
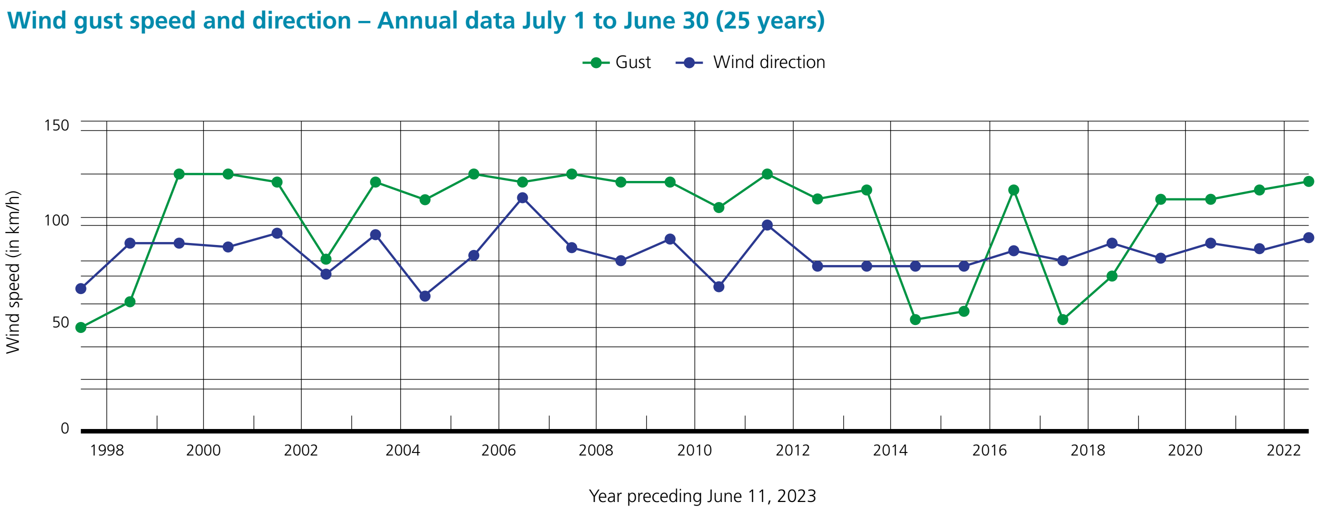


Figure 13. Peak gust velocity in Vancouver does not seem to have increased over the past 25 years (vancouver.weatherstats.ca).



2.1.2 Past storm disaster data

CatIQ (2023) offers a commercial database of insurance losses in 143 natural catastrophes since 2008. Data for each catastrophe include:

- a text identifier;
- a short description of the catastrophe;
- the type of disaster (earthquake, windstorm, hail, fire, flood, sewer backup/water, or volcanic eruption);
- affected provinces;
- affected municipalities;
- claims count;
- dollar total of claims incurred; and
- allocated loss adjustment expenses by province, line of business, and coverage (auto, commercial lines property damage, commercial lines non-property damage, personal lines property damage, personal lines non-property damage, and personal lines sewer backup/water).

Dollar figures do not account for inflation but reflect event-year dollars. CatIQ (2023) also provides a commercial insurance exposure database, meaning a time series (from 2016 through 2022, inclusive) of the number of policies and insured values by province, forward sortation area (designating postal delivery area), line of business, and disaster type.

Analyzing the CatIQ (2023) data reveals useful statistics, such as the average claim severity by catastrophe, line of business, and coverage. For example, the average personal lines insurance claim from sewer backup/water in the 2021 November Rainstorm was $36,000 (2023 CAD).

The Canadian Disaster Database (Public Safety Canada 2023a) contains disaster information on 1,000 natural, technological, and conflict events since 1900 that have directly affected Canadians. It includes events in which 10 or more people were killed, 100 or more people were affected (i.e., injured, infected, evacuated, or made homeless), there was an appeal for national or international assistance, there was historical significance, or enough damage was done that the affected community could not recover on its own. The database describes the event date and location; number of deaths, injuries, and evacuations; and the estimated total monetary costs. The Canadian Disaster Database does not include the number of people or households affected in ways other than deaths, injuries, and evacuations.

In large-scale natural disasters, the Government of Canada provides financial assistance to provincial and territorial governments through the Disaster Financial Assistance Arrangements (DFAA) program, administered by Public Safety Canada (2023b). The assistance scales in proportion to provincial expenses per capita. For calendar year 2023, the program pays 50% of provincial expenses between $3.61 and $10.85 per capita ($19 million to $59 million for a population of 5.4 million people), 75% of expenses between $10.85 and $18.09 per capita ($59 to $98 million for 5.4 million people), and 90% of expenses beyond that. Public Safety Canada (2012), the Office of the Parliamentary Budget Officer (2015), and the BC Ministry of Emergency Management and Climate Readiness (2023) report disaster recovery payments made under the DFAA program. Table 1 reports public expenditures in two storms as reported by the BC Ministry of Emergency Management and Climate Readiness (2023). The table shows costs incurred by the province up to the second quarter of the 2024 fiscal year. Response and recovery efforts for the 2021 November Rainstorm (an active DFAA event as of this writing) will continue for many years and costs will continue to rise. DFAA provides financial assistance when the per-capita threshold is met. Regarding the 2015 Southwest BC windstorm, the DFAA threshold was not met. Figures for that event reflect BC Disaster Financial Assistance (DFA) expenditures only.

Table 1. Public payouts in two past BC storms

CatIQ event name	DFAA event	Response cost (millions)	Recovery cost (millions)
2021 Southwest B.C. Flooding	2021 November Rainstorm	$365	$473
2015 southwestern BC windstorm	N/A	$0	$1

The Multi-Hazard Mitigation Council (2019) estimates the costs and benefits of mitigation for many US disaster categories, including severe storms, fires, and earthquakes. The authors use analytical models that estimate a variety of benefit categories, namely reduced losses associated with:

- Property repair costs (buildings, contents, and other fixed assets, such as utilities and transportation infrastructure)
- Casualties (numbers of deaths, nonfatal injuries, post-traumatic stress injuries, and the US government's acceptable regulatory costs to avoid future statistical casualties)
- Additional living expenses and direct business interruption costs, which accrue because one cannot use one's property (sometimes called direct time-element losses); for example, additional living expenses accrue from renting temporary lodging if one's home is unusable or direct business interruption losses accrue through loss of sales or additional costs associated with moving one's workplace
- Indirect business interruption costs, which are borne by the rest of society because of damage that occurred elsewhere; for example, business may be interrupted because one cannot buy from or sell to other businesses that suffered damage.

In addition, one can calculate the benefits associated with reducing embodied carbon. "Embodied carbon" means the quantity of carbon dioxide (CO_2) emissions associated with manufacturing, transporting, assembling, demolishing, or replacing buildings or infrastructure. Embodied carbon is measured in tonnes of CO_2 and in social value of carbon emissions, for example, using the Canadian federal carbon price per tonne, currently $65 and increasing $15 annually to $170 in April 2030 (Environment and Climate Change Canada 2022).

The ratios between benefits can be useful if dollar losses for some loss categories in BC disasters, but not others, can be estimated. That is, if a resource allows estimates of one kind of mitigation benefit in BC, such as reduced building repair cost, but not another, such as reduced indirect economic losses, the relative values of the two benefit categories from US sources could potentially be used to extrapolate BC indirect economic losses from BC building repair costs.

Readers may prefer to think about losses in constant dollars, even if we do not attempt to estimate the effects of population growth. Statistics Canada (2023a) provides a time series of consumer price index nationwide by province or territory, by smaller census areas, and by products and product groups annually since 1914. The products and product groups that might be most relevant to catastrophe losses are (1) all items, (2) shelter, and (3) household furnishings.

2.1.3 Other values related to disasters

As suggested by the Multi-Hazard Mitigation Council (2019), governments care about the benefits and costs of mitigation measures, often expressed in terms of the benefit–cost ratio. The same study shows that individuals often unequally share the costs and benefits of mitigation with co-beneficiaries, so the portion of the costs and benefits that falls to the decision-makers matters.

But people care about more than just monetary values. Individuals often make decisions based less on costs, benefits, and calculated probabilities and more on emotional values. People will spend money to enhance their life safety, such as buying a bicycle helmet and paying extra for optional automotive safety features. Each measure has a cost, and one can estimate the incremental improvement to life safety, for example in reduction in risk of premature death. The ratio of the benefit to the cost provides an estimate of the value people place on their own safety, normalized to a per-person basis. The Urban Institute (1991) considers many such safety measures to estimate that value, and the US government has used and updated these values to assess acceptable regulatory costs that enhance life safety.

Chestnut and de Civita (2009) introduce the concept of the value of a statistical life (VSL) in the Canadian context. They estimate that the value of a statistical life for Canadians is $6.5 million. The Government of Canada's Cost-Benefit Analysis Guide for Regulatory Proposals (Treasury Board of Canada Secretariat 2023) also uses the value of $6.5 million as an acceptable cost to avoid the death of an unknown person at an unknown time in the future, sometimes called value of reduced mortality risk or value of micromort reduction. The Treasury Board of Canada Secretariat (2023) recommends converting this value to the year of interest using the Statistics Canada consumer price index. With this conversion, $6.5 million in 2007 equals $8.9 million in 2023.

The Treasury Board of Canada Secretariat (2023) does not offer comparable costs for nonfatal injuries. In the US, the Federal Highway Administration (1994) assigns values for avoiding nonfatal injuries based on fractions of VSL and measures the nonfatal injuries using the abbreviated injury severity scale, a 1-to-6 scale where 1 is any of a wide variety of minor injuries and 6 is death, as proposed by the Association for the Advancement of Automotive Medicine (2001). The value of nonfatal injuries varies between 0.002 × VSL (for severity 1) to 0.76 × VSL (for severity 5). Considering the distribution of injuries experienced by victims of the 1994 Northridge earthquake, Porter et al. (2006b) estimated a weighted average value of about 0.0032 × VSL, or about $30,000 in 2023 CAD.

The present study can express the benefits of mitigation in terms that people care about by addressing the following emotional values:

- Catastrophic nature and dread (Slovic et al. 1981). People care more about disasters that have larger single-event outcomes than many small events that result in the same long-term average outcome. For example, they care more about avoiding large disasters that they dread, such as a commercial aviation disaster, than about threats with small individual outcomes, such as consuming alcoholic beverages.
- Availability bias – how easily people can imagine the catastrophe (Tversky and Kahneman 1974). The more detailed and representative the picture, the more people care about it. For example, the State of California undertook expensive seismic retrofit programs after big earthquakes, even though the problems that many of the retrofits addressed were well understood beforehand (White and Yanev 2020).
- How clearly people can see the reward. Closely related to the availability bias, people value an action more highly when they can see the reward more clearly or have it vividly described to them. Berridge and Kringelbach (2015) explain that dopamine motivates people to act if they see a reward coming, which could be depicted conceptually. For example, when talking about how a mitigation measure might increase a home's resale value, one can show a sold sign and the increased value in dollars or percentage.
- A sense of efficacy – whether people perceive that their individual and collective actions can improve the outcome (Bandura 1997). For example, Environment and Climate Change Canada (2018) provides lists of things Canadians can do in their workplace, school, and neighbourhood to mitigate climate change and improve the environment, including carpooling, planting trees, and conserving energy. Each list is preceded by the phrase "to make a difference." To show the efficacy of seismic retrofit, the California Earthquake Authority (2020) uses a photo (Figure 14) showing two adjacent houses shaken in the 2014 South Napa earthquake, one damaged and one undamaged – the latter having been seismically retrofitted beforehand.
- Last steps needed to accomplish a goal. Closely related to a sense of self-efficacy, Zeigarnik (1927) found that unfinished tasks leave people with a feeling of unease. People more highly value an activity when it represents a final step or completion. For example, hiring a contractor to floodproof a newly purchased house could be described as the last step to acquiring a safe home.
- The magnitude of the occurrence probability, regardless of the period considered. That is, people care more about a disaster if it is estimated to have a 10% chance of occurring within 10 years than if one speaks about it as having a 1% occurrence probability in a year, even though they are mathematically equivalent (Bonstrom et al. 2012).
- Freedom. Carpenter (2013) found that people value their autonomy. Mentioning that the decision-maker is free to not comply – even simply saying, "But you are free to decline," "Don't feel obligated," "See for yourself," etc. – tends to increase compliance. For example, Guéguen et al. (2002) found that when experimenters asked passersby for money, 10% complied; however, 47.5% complied when the experimenters concluded their request with, "But you are free to accept or to refuse."
- Loss aversion. In general, people want to avoid loss more than they want to achieve a gain (Kahneman and Tversky 1979). Therefore, speaking about mitigation in terms of avoiding losses, rather than achieving savings, highlights what people value. For example, it may be more effective to say that protecting one's home from basement flood can help to *avoid losing* $45,000 in repair costs, rather than saying that it saves $45,000.

Figure 14. The California Earthquake Authority (2020) uses this photo to illustrate the efficacy of seismic retrofit.

This house was not retrofitted and slid off its foundation in an earthquake

This house had a completed seismic retrofit and withstood earthquake shaking

Photo credit: Janiele Maffei

The following additional values reflect the seven principles of persuasion, based on social psychological research summarized by Cialdini (2021):

- Authority: People tend to value the advice of trusted experts.
- Consistency: People value acting consistently with their previous commitments and actions. Someone trying to persuade another to take some mitigation action could remind that person about some prior action they have taken, such as buying a safer car or wearing a bike helmet, before asking that they undertake the desired action.
- Liking: People tend to value advice from people they like; hence, celebrity spokespeople or well-liked local leaders can be valuable for channelling a specific message.
- Reciprocity: People tend to want to reciprocate when they have been given a favour or gift first, even when the gift is of low value.
- Scarcity: People tend to value that which is scarce, which in the present case could include mitigation features that are scarce among available options or that have limited time availability. For example, the chance to protect oneself from the next disaster decreases the longer one waits to act.
- Social proof: People tend to value what many other people seem to value. In the present case, this could mean showing evidence that many other people have undertaken a mitigation action.
- Unity: People value what others in their identity group value. In this situation, mitigation actions could be connected to the values of an individual’s racial, ethnic, religious, or other social group, using that group’s expressions and distinctiveness.

Readers may object to expressing benefits in terms of these emotional values, but these are things that people care about. Using these terms to explain why one should do mitigation merely speaks to people’s values and can complement a more mathematical analysis.

2.1.4 Costs and benefits of leading severe storm mitigation measures

Box 2-1 lists eight leading flood mitigation measures. The box draws on several sources: the Institute for Catastrophic Loss Reduction’s (2011) guidance on protecting homes from basement flooding, the Multi-Hazard Mitigation Council’s (2023) estimates of the benefits of these measures, and the Multi-Hazard Mitigation Council’s (2019) *Natural Hazard Mitigation Saves* report.

Box 2-1: Costs and benefits of building flood-risk mitigation measures

Measures for all buildings, especially those subject to overland flow (urban flooding, pluvial flooding):

1. ***Side grading and downspout extensions:*** Side grading means ensuring that the soil within 3 metres (10 feet) of the edge of the building slopes away from the walls and drops at least 15 cm (6 inches). This costs about $4,000 (2023 CAD) to fix. Downspout extensions mean light metal or plastic tubes attached to the bottom of eavestrough downspouts that discharge water 1.8 metres away from the building and neighbouring buildings. This can cost $400 (2023 CAD) to fix.
2. ***Backwater valve:*** For buildings on streets with a combined sewer and stormwater system, a valve prevents water from flowing back from the sewer into the building. This can cost $4,000 (2023 CAD) to fix.
3. ***Sump pump battery backup:*** For buildings with a basement or slab-on-grade foundation, a battery backup sump pump removes water from the sump pit and pumps it away from the building. Adding battery backup costs $1,300 (2023 CAD).

Multi-Hazard Mitigation Council (2023) estimates that adopting the first three measures avoids up to $40,000 (2023 CAD) in loss per pluvial flood occurrence. For a location with a 2% annual chance of urban flooding, the measures produce a long-term average benefit–cost ratio (BCR) of 5:1. The BCR scales linearly with annual chance of flooding, with the BCR approximately equal to 250 times the flood frequency.

Measures for existing buildings in a special flood hazard area (fluvial flooding):

4. ***Wet floodproofing.*** In this retrofit, the owner or a specialty contractor removes damageable contents from the basement and changes basement wall openings to reduce hydrostatic pressure on the exterior walls that can allow flood water to break basement walls. Doing so does not change the chance of water entering the house, but it does reduce the loss when flooding occurs. Multi-Hazard Mitigation Council (2019) estimates this retrofit costs $250 per square metre (2023 CAD, based on $15.49 2018 USD per square foot) and produces a long-term average benefit–cost ratio of 2:1 for a realistic mix of lowest-floor elevations relative to base flood elevation.
5. ***Equipment elevation.*** In this retrofit, a specialty contractor raises damageable equipment such as heat pumps, furnaces, and air conditioning units higher above the basement or ground level to reduce the chance that flood water will reach, contaminate, and damage the equipment. This retrofit costs approximately $15,000 (2023 CAD) for an average-sized house of 2,000 square feet (based on $5.03 2018 USD per square foot according to Multi-Hazard Mitigation Council 2019.) Multi-Hazard Mitigation Council (2019) estimates that the measure produces a long-term average benefit–cost ratio of 2:1 for a realistic mix of lowest-floor elevations relative to base flood elevation.
6. ***Dry floodproofing.*** In this retrofit, a specialty contractor adds protection to the outside of a building, including a waterproofing membrane and removable barriers at openings that prevent flood water from entering the building. Dry floodproofing is more commonly applied to non-residential buildings than to houses. This retrofit costs $20,000 (2023 CAD) for an average-sized wood building.
7. ***Building elevation retrofit.*** In this approach, a specialty construction contractor temporarily disconnects the building from its foundation, adds several feet of height to the walls between the foundation and the ground floor, and reconnects the building. Doing so raises the building relative to flood waters and reduces the likelihood that water will reach the ground floor. This retrofit costs $80,000 (2023 CAD) for an average-sized wood house. Multi-Hazard Mitigation Council (2019) estimates that the measure produces a long-term average benefit–cost ratio of 2:1 for a realistic mix of lowest-floor elevations relative to base flood elevation.
8. ***Buyout.*** In this approach, one removes the building, and typically all the buildings in a neighbourhood that frequently floods, and changes the land use to something that can tolerate flooding, such as a park or wetland. Buyouts are mostly used in places with repetitive losses, so the loss avoided in one disaster is not really the goal; rather, the long-term, cumulative avoided losses are more important. This approach costs a reasonable market value for the building. According to Multi-Hazard Mitigation Council (2019), buyouts produce a long-term average benefit–cost ratio of 6:1 for a mix of locations with first floor levels between 1 and 8 feet below base flood elevation (the elevation with 1% annual chance of riverine flooding).

(continued on next page)

Box 2-1: Costs and benefits of building flood-risk mitigation measures *(continued)*

Multi-Hazard Mitigation Council (2019) estimates the approximate mix of existing residential buildings subject to each kind of retrofit for fluvial flooding as 60% acquisitions, 20% elevation retrofits, 10% basement wet floodproofing, 5% air conditioning/heat pump and ductwork elevation, and 5% furnace and water heater elevations. For this mix, the long-term average benefit–cost ratio was approximately 5:1, and the average cost was $241,000 per house (2023 CAD, based on $154,000 2018 USD); the cost was dominated by acquisitions and elevation retrofits, which mostly or entirely prevent the loss.

Measures for new buildings:

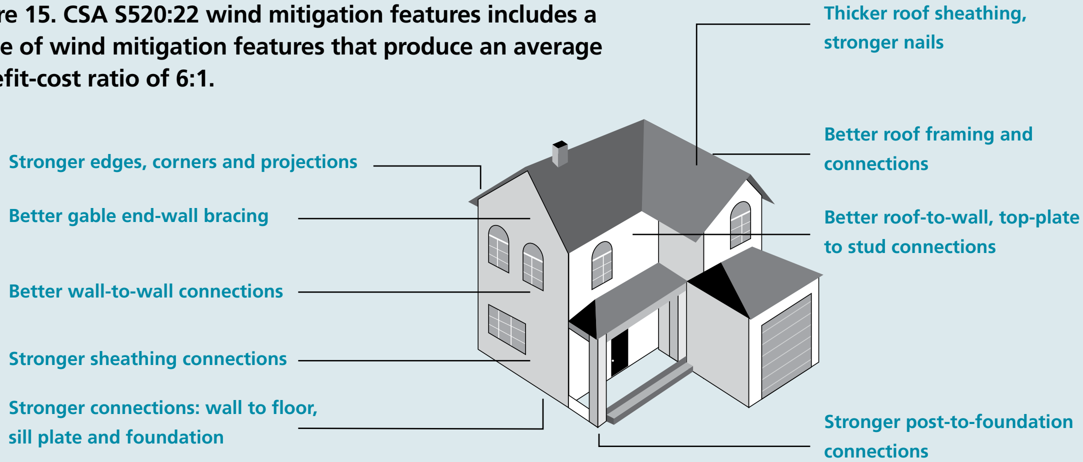
9. ***Building elevation***. Build the building so that the first floor and all equipment are located 1.8 metres (5 feet) above base flood elevation. Multi-Hazard Mitigation Council (2019) estimates that this measure adds $5,000 (2017 USD, $8,600 2023 CAD) to the construction cost for a 200-square metre (2,000-square foot) wood building and produces a benefit-cost ratio of 5:1.

Box 2-2: Wind risk mitigation measures. All costs are approximate

1. The Insurance Institute for Business and Home Safety (2023) offers a voluntary construction standard called FORTIFIED Home Roof to prevent roof damage that commonly occurs during high winds, hurricanes, hailstorms, severe thunderstorms, and even tornadoes up to EF-2. This standard includes stronger edges (wider drip edge and a fully adhered starter strip), a sealed roof deck (covering the seams between sheathing panels), stronger nails to attach the roof sheathing to the framing below, wind- and rain-resistant attic vents, and, in hail-prone areas, class-4 impact-resistant shingles. Awondo et al. (2023) estimate that retrofitting a 220-square metre home to comply with FORTIFIED Home Roof costs approximately $15,000 (2023 CAD). Multi-Hazard Mitigation Council (2019) estimates its long-term average benefit–cost ratio to be 6:1 in places with design wind speeds like those of southwestern BC, but that study does not report the avoided loss per event. We can assume that this retrofit effectively avoids most of the damage (e.g., 95%) that would otherwise occur to the average house in a severe (non-hurricane) storm from wind and wind-driven rain. Based on four recent severe BC windstorms, the average per-claim property damage varied between $13,000 to $39,000 (2023 CAD), with a per-claim weighted average among 6,000 total claims of $14,000, including building, contents, and time-element losses.

2. The Canadian Standards Association (2022) published a new standard, CSA S520:22, containing best-practice guidance for the design and construction of low-rise, woodframe buildings to withstand high winds corresponding to EF-2 tornado-level wind speeds. The standard mostly includes the features shown in Figure 15. The vertical load-path elements cost about $3,600 (2023 CAD) for a 200-square metre new house and produce an average benefit–cost ratio of 6:1 (Porter 2023).

Figure 15. CSA S520:22 wind mitigation features includes a range of wind mitigation features that produce an average benefit-cost ratio of 6:1.



2.1.5 Demographic and insurance penetration data; First Nations, Metis, and Inuit impacts

As previously noted, a leading data source for past climate disaster losses only reflects insured values exposed to loss and the losses they experienced. Statistics Canada (2023c) offers a statistical database that includes information like the number of residential properties in British Columbia of all property types, use categories, and ownership types. CatIQ records the number of current personal-lines fire insurance policies in BC.

To scale insured losses up to the societal level, we may need to know the fraction of the total population and building stock those values represent. Kovacs and Li (in press) estimate that in 2018, 39% of households with fire insurance also purchased flood insurance. By 2021, that figure had increased to 55%. By value insured, the fractions were 45% in 2018 and 53% in 2021. The fractions vary geographically, with urban forward sortation areas tending to have take-up rates around 70% and rural rates at 40 to 60%.

CatIQ data exclude uninsured losses, including uninsured First Nations, Metis, and Inuit people. Oftentimes, especially in flooding, Indigenous peoples are disproportionately impacted. We attempt to address this issue by scaling up losses using insurance penetration rates.

2.2 Methodology

2.2.1 Select catastrophes with the largest loss or the most victims

Considering some of the emotional values discussed in the previous section, we propose to depict how mitigation would have improved outcomes in recent severe storms that were rich in photographic and video evidence and, ideally, where we can clearly show how people from different identity groups avoided loss.

We propose to select one or two climate catastrophes for each kind of disaster: one that produced the largest societal dollar loss and one that affected the largest number of households, both regardless of the fraction of losses and number of households that were insured. The two catastrophes may be the same, or they may be different, especially if the event with the largest number of households affected communities with lower income.

To find those catastrophes, we will:

1. Use the CatIQ database to identify the one or two catastrophes since 2008 (the earliest CatIQ data) that produced the largest insured dollar loss for each kind of disaster. The event that produced the largest societal dollar loss may be among these candidates. We calculate the total value of claims paid in present dollars using the consumer price index.
2. Quantify real losses from these catastrophes that are not reflected in CatIQ claims: uninsured property repairs; uninsured direct business interruption costs; uninsured additional living expenses; indirect business interruption (i.e., economic loss beyond the property line of damaged buildings, utilities, and transportation infrastructure that resulted from their impairment); the value of deaths, nonfatal injuries, and psychological injuries that occurred; externalized costs of carbon embodied in property repairs; emergency response costs; and repair costs of utility and transportation infrastructure. We can express these costs separately and in sum, both in monetary value and the number of people or households affected. See Box 2-3 for these calculations. We include all these other losses because the costs of mitigation are clearer than the benefits, which result from reducing many of these other losses. As more losses are omitted, the benefits of mitigation are more undervalued. Furthermore, distinct categories of loss matter to distinct groups. If one speaks only of insured losses, some members of the public may incorrectly perceive that they will be paying for mitigation, but insurers will get the benefits. Also, the more detail included in the picture of loss, the more clearly people can imagine it and perceive the value of avoiding it.

3. Identify the one or two catastrophes in the CatIQ database that produced the largest number of insured claims. The event that affected the largest number of households may be among these candidates. “Affected” means the number of households that experienced property damage costing more than a few hundred dollars to repair.
4. Use the Canadian Disaster Database to identify the catastrophe between 1983 and 2007 (i.e., the year before the CatIQ database begins) that produced the largest insured dollar loss for each disaster type. (We only go back to 1983, not 1900, because of the availability bias discussed in section 2.1.3. People care more about disasters that they can easily visualize, either because they experienced the disaster or can see rich imagery from it.) The event that produced the largest societal dollar loss may be among these candidates. We factor its losses to present-value dollars and present population, and add the monetary values that it probably omits, as shown in equation (8).
5. Identify the catastrophe between 1983 and 2007 in the Canadian Disaster Database that affected the largest number of people. The event that affected the largest number of households may be among these candidates.
6. Select the largest event(s). If the event with the largest societal monetary loss is the same as the event that affected the largest number of households, this event is selected. Otherwise, both events are selected

Box 2-3: Estimating total societal loss from events in the CatIQ database

Let

CPI	=	Consumer price index
i	=	Index to *n* loss-producing events that takes on a value of {0, 1, 2, … *n*-1}; an index of events can be created using the CatIQ (2023) loss database
$L1_i$	=	Insured property damage and non–property damage loss in event *i*, from CatIQ (2023)
$L2_i$	=	DFAA expenditures from Public Safety Canada
y_t	=	Total societal loss from event *i*, using equation (1)
F_{1i}	=	Inflation factor, to convert loss in year *t* of event *i* to current-year currency using equation (2), from Statistics Canada (2023a)
F_{2i}	=	Population factor; that is, population in the current year as a factor of the population in year *t*, for purposes of estimating the loss that would occur with current-year population, from Statistics Canada (2023b)
F_{3i}	=	Insurance penetration factor in year *t*; that is, the fraction of the population covered by insurance to estimate the loss to the entire population using equation (5). Note that the number of policies may exceed the number of buildings, but not everybody has insurance, so we cap F_3 at 99%.
F_4	=	Indirect business interruption factor; that is, the ratio of indirect business interruption loss to property loss plus direct time-element losses, borrowed from ratios observed or estimated elsewhere (e.g., Multi-Hazard Mitigation Council 2019)
F_5	=	Fatality factor; the average ratio of the monetary value of deaths in excess of average life insurance coverage to property and time-element losses, using the acceptable cost to avoid statistical deaths (i.e., the acceptable cost to avoid the death of an unknown person at an unknown place and time), borrowed from ratios observed or estimated elsewhere (e.g., Multi-Hazard Mitigation Council 2019, chapter 2)
F_6	=	Nonfatal injury factor; like F_5 but nonfatal injuries, borrowed from ratios observed or estimated elsewhere (e.g., Multi-Hazard Mitigation Council 2019)
F_7	=	Post-traumatic stress injury factor; like F_5 but for psychological injuries, including the cost of treatment, borrowed from ratios observed or estimated elsewhere (e.g., Multi-Hazard Mitigation Council 2019, chapter 2)

Box 2-3: Estimating total societal loss from events in the CatIQ database *(continued)*

F_8 = Carbon factor; like F_5 but for embodied carbon in property repairs, from equation (6)

F_9 = Property loss as a fraction of the sum of property and direct time-element losses, borrowed from ratios observed elsewhere (e.g., Multi-Hazard Mitigation Council 2019, figure 2-1)

f_{10} = Emergency response, damage to utility and transportation infrastructure, and other public losses, using Figure 16, which reflects the DFAA cost-sharing discussed in section 2.1.2 (Public Safety Canada 2023b)

f_{11} = Acceptable costs to avoid statistical deaths and injuries, taken as the larger of two values: one extrapolated from CatIQ monetary losses using ratios observed elsewhere, or one based on reported deaths and injuries in the Canadian Disaster Database

$M_{BC,i}$ = Number of BC buildings in year *i*, using equation (4)

$M_{Can,2023}$ = Number of buildings in Canada in 2023 » 16 million dwellings + 482,000 non-residential buildings (Natural Resources Canada 2023)

$P_{BC,i}$ = BC population in year i, from Statistics Canada (2023b)

$P_{Can,2023}$ = Population of Canada in 2023, » 36,991,891, from Statistics Canada (2023b)

n = Number of events of disaster type *p* in year *t*, from CatIQ (2023)

N_{1i} = Number of fatalities in event *i*

N_{2i} = Number of nonfatal injuries in event *i*

N_{4i} = Number of BC risks (policies) that cover the disaster from event *i*, from CatIQ (2023)

U_1 = Canadian federal carbon price per tonne, currently $65, increasing $15 annually to $170 in April 2030 (Environment and Climate Change Canada 2022)

U_2 = Average replacement cost per square metre of dwelling (e.g., $1,750 from Gordian 2022)

U_3 = Tonnes of embodied carbon per square metre of average dwelling, about 0.2 tonnes (Magwood et al. 2023)

V_1 = Acceptable cost to avoid a statistical death (i.e., the death of an unknown person at an unknown place and time in the future) = $8.9 million

V_2 = Acceptable cost to avoid a statistical nonfatal injury

$$y_i = L_{1i} \cdot F_{1i} \cdot F_{2i} \cdot \left(\frac{1}{F_{3i}}\right) \cdot \left(1 + F_4 + F_6 + F_7 + F_8\right) + f_{10}\left(L_{2i} \cdot F_{1i} \cdot F_{2i}\right) \cdot \left(1 + F_8\right) + f_{11} \quad (1)$$

$$F_{1,i} = \frac{CPI_{2023}}{CPI_i} \quad (2)$$

$$F_{2,i} = \frac{P_{BC,2023}}{P_{BC,i}} \quad (3)$$

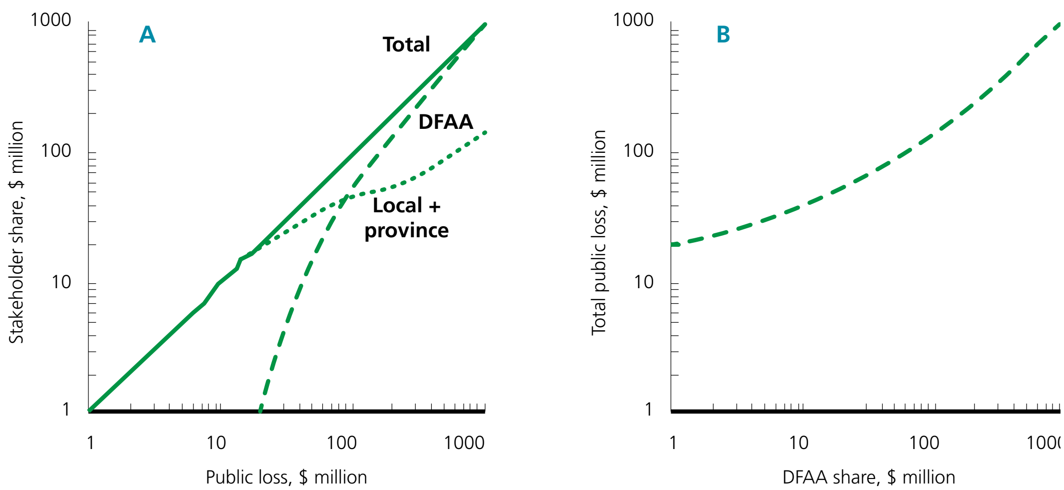
$$\begin{aligned} M_{BC,i} &= P_{BC,i} \cdot \frac{M_{Can,2023}}{P_{Can,2023}} \\ &= P_{BC,i} \cdot \frac{16{,}482{,}000}{36{,}991{,}891} \\ &= P_{BC,i} \cdot 0.456 \end{aligned} \quad (4)$$

$$\begin{aligned} F_{3i} &= \frac{N_{4,i}}{M_{1,i}} \\ &\leq 0.99 \end{aligned} \quad (5)$$

$$F_8 = \frac{U_1 \cdot U_3}{U_2} \cdot F_9 \quad (6)$$

$$f_{11} = \max\left(L_{1i} \cdot F_{1i} \cdot F_{2i} \cdot \frac{1}{F_{3i}} \cdot F_5, N_{1i} \cdot V_1 + N_{2i} \cdot V_2\right) \quad (7)$$

Figure 16. (A) Allocation of total public loss to DFAA. (B) Inverting relationship to get total public loss from DFAA expenditures.



Box 2-4: Estimating total societal loss from events in the Canadian Disaster Database

Let

i = Index to n loss-producing events in BC in the Canadian Disaster Database; takes on a value of {0, 1, 2, … n-1}

L_i = Monetary loss in BC in event i, from Public Safety Canada (2023a)

y_t = Total societal loss in BC in event i, using equation (8)

F_{1i} = Inflation factor to convert loss in year t of event i to current-year currency, from Statistics Canada (2023a)

F_{2i} = Population factor; BC population in the current year as a factor of the population in year t, for estimating the loss that would occur with current-year population, from Statistics Canada (2023b)

F_4 = Indirect business interruption factor; the ratio of indirect business interruption loss to property loss plus direct time-element losses, borrowed from ratios observed or estimated elsewhere (e.g., Multi-Hazard Mitigation Council 2019, figure 2-1 for flood [0.19], figure 2-12 for earthquake [0.21], figure 2-17 for fire [0.03], figure 2-22 for wind [0.10], and the average of flood and wind for undifferentiated storms [0.15])

F_8 = Carbon factor; like F_5 but for embodied carbon in property repairs, from equation (6)

F_9 = Property loss as a fraction of the sum of property and direct time-element losses, borrowed from ratios observed elsewhere (e.g., Multi-Hazard Mitigation Council 2019, figure 2-1)

F_{12} = Psychological injury factor; the ratio of the number of people suffering post-traumatic stress injuries as a multiple of the number of people displaced

n = Number of BC events of disaster type p in the Canadian Disaster Database

N_{1i} = Number of fatalities in event i

N_{2i} = Number of nonfatal injuries in event i

N_{3i} = Number of people displaced by event i

U_1 = Canadian federal carbon price per tonne, currently \$65, increasing \$15 annually to \$170 in April 2030 (Environment and Climate Change Canada 2022)

U_2 = Average replacement cost per square metre of dwelling (e.g., \$1,750 from Gordian 2022)

U_3 = Tonnes of embodied carbon per square metre of average dwelling, about 0.2 tonnes (Magwood et al. 2023)

V_1 = Acceptable cost to avoid a statistical death (i.e., the death of an unknown person at an unknown place and time in the future)

V_2 = Acceptable cost to avoid a statistical nonfatal injury

V_3 = Additional living expenses associated with being displaced

V_4 = Acceptable cost to avoid a post-traumatic stress injury

$$y_i = L_i \cdot F_{1i} \cdot F_{2i} \cdot \left(1 + F_4 + F_8 + F_9\right) + N_{1i} \cdot V_1 + N_{2i} \cdot V_2 + N_{3i} \cdot V_3 + N_{3i} \cdot F_{12} \cdot V_4 \tag{8}$$

2.2.2 Estimate how many buildings would have benefited from mitigation

Estimate the number of damaged buildings N5i (in units of 200-square metre equivalent buildings) with equation (9)

$$N_{5i} = N_{4i} \cdot F_{2i} \cdot \frac{1}{F_{3i}} \tag{9}$$

Then we estimate the number of properties that could have benefited from fluvial mitigation N_{6i}, N_{7i}, and N_{8i}, where

N_{6i} = Number of buildings damaged by pluvial flooding in disaster *i*

N_{7i} = Number of buildings damaged by fluvial flooding in disaster *i*

N_{8i} = Number of buildings damaged by wind in disaster *i*

F_{12i} = Approximate fraction of properties damaged by flood rather than wind; one of the sources discussed earlier reports that information, so it may be necessary to guess

F_{13} = Approximate fraction of flood-damaged properties damaged by pluvial flooding; we estimate $F_{13} \approx 0.68$, using the ratio mentioned by Wing et al. (2018) (68% outside the special flood hazard area) and assuming that the majority of people living outside special flood hazard areas are subject to pluvial rather than fluvial flooding.

$$\begin{aligned} N_{6i} &= N_{5i} \cdot F_{12i} \cdot F_{13} \\ N_{7i} &= N_{5i} \cdot F_{12i} \cdot \left(1 - F_{13}\right) \\ N_{8i} &= N_{5i} \cdot \left(1 - F_{12i}\right) \end{aligned} \tag{10}$$

2.2.3 Apply unit costs and benefits to the asset count

Section 2.1.4 offered average costs per house or per square foot for a variety of mitigation measures. Let us define several variables to reflect mitigation costs and losses avoided per building and estimate their values as shown in Table 2.

Table 2. Estimated unit costs and unit benefits for flood and wind mitigation measures

Parameter	Value	Comment, source
Cost per building for pluvial flood mitigation, U_6	$5,700	Pluvial flood retrofit for existing average house, from Multi-Hazard Mitigation Council (2023).
Cost per building for fluvial flood mitigation, U_7	$240,000	Weighted average cost of acquisitions, elevation retrofits, and other retrofits, from Multi-Hazard Mitigation Council (2019).
Cost per building to retrofit to FORTIFIED Roof, U_8	$15,000	Awondo et al. (2023).
Avoided property damage per building from pluvial flood mitigation, U_9	$45,000	Multi-Hazard Mitigation Council (2023). Includes building and content repairs plus direct time-element loss valued at 20% of building repairs. Assumes mitigation avoids 90% of basement flood damage. Omits indirect time-element losses and carbon costs.
Avoided property + direct time-element loss per building from fluvial flood mitigation, U_{10}	$460,000	Assumes fluvial flooding produces a total loss of $1,600/m² building replacement cost, contents valued at 50% of building replacement cost, and direct time-element loss valued at 20% of building replacement cost. Assumes buyouts and elevations avoid 90% of the loss. Omits indirect time-element loss and carbon cost.
Avoided property loss per building from wind mitigation, U_{11}	$15,000	Based on average personal lines property damage claims in four BC windstorms. Assumes building repairs represent 67% of the property damage and adds direct time-element loss valued at 20% of building repairs. Assumes mitigation avoids 90% of wind loss. Omits indirect time-element loss and carbon cost.

The total retrofit costs for pluvial (C_1), fluvial (C_2), and wind (C_3) mitigation can be estimated as follows:

$$\begin{aligned} C_1 &= N_6 \cdot U_6 \\ C_2 &= N_7 \cdot U_7 \\ C_3 &= N_8 \cdot U_8 \end{aligned} \tag{11}$$

The total avoided losses for pluvial (B_1), fluvial (B_2), and wind (B_3) mitigation can be estimated as follows:

$$\begin{aligned} B_1 &= N_6 \cdot U_9 \cdot (1 + F_4 + F_8) \\ B_2 &= N_7 \cdot U_{10} \cdot (1 + F_4 + F_8) \\ B_3 &= N_8 \cdot U_{11} \cdot (1 + F_4 + F_8) \end{aligned} \tag{12}$$

2.2.4 Characterize the values omitted from benefit–cost analysis

The benefit–cost analysis proposed here fails to quantify a few important loss categories. People feel pain of dislocation when they are displaced from their homes and community and when they lose mementos and pets. Some people become excessively fearful that the disaster will repeat and move away. Others become homeless. Suicide rates rise among disaster victims. Omitting these losses tends to result in a conservatively low benefit-cost ratio

2.3 Results

2.3.1 Catastrophes with the largest losses or most victims

Table 3 presents summary statistics about the CatIQ (2023) data. The table only reflects property insurance losses in BC between January 2008 and June 2023, including personal lines, commercial lines, and auto insurance. Dollar figures are inflated to millions of 2023 CAD using the all-items consumer price index (Statistics Canada 2023a). Claim counts and claims incurred are not increased to account for population growth. Columns labelled flood, windstorm, etc., reflect a subset of the catastrophes that included that kind of disaster, possibly among several others, so the columns do not sum. Note that CatIQ does not include a category for summer storms. The column labelled "summer storm" refers to any flood, water, or windstorm catastrophe that occurred between April and September. Winter storms include those that occurred from October to March.

The column labelled "Flood" refers to riverine flooding, when streams and other water bodies overflow their banks and cause damage. The column labelled "Water, sewer backflow" refers to pluvial flooding. Pluvial flooding occurs when the rainfall exceeds the capacity of urban storm water drainage systems or the ground to absorb it. This excess water flows overland, ponding in hollows, basements, low-lying areas, and behind obstructions.

The data reflects 12 catastrophic BC storms from 2008 to 2023. Judging solely by insurance losses, the largest storm of the 12 and the most catastrophic winter storm was the 2021 November Rainstorm of November 13, 2021, through December 2, 2021. That storm included losses from flood, water, and wind totalling $673 million in insured losses from 8,790 claims. It produced losses an order of magnitude larger than the summer storm with the largest insured loss – the windstorm on August 29, 2015, that produced $40 million in insured losses from 3,710 claims. Thus, the November 13, 2021, flood was the largest severe storm, both in terms of monetary losses and claims incurred.

Table 3. Severe BC storms since 2008

Parameter	Flood	Water, sewer backflow	Windstorm	Winter storm	Summer storm	All
Catastrophes	6	9	9	9	3	12
Event with largest claim count						
Property claims	8,790	8,790	8,790	8,790	3,710	8,790
Claims incurred ($ M)*	$673	$673	$673	$673	$40	$673
Event	13 Nov 2021 SW BC flood	13 Nov 2021 SW BC flood	13 Nov 2021 SW BC flood	13 Nov 2021 SW BC flood	29 Aug 2015 windstorm	13 Nov 2021 SW BC flood
Event with largest insured monetary loss						
Property claims	8,790	8,790	8,790	8,790	3,710	8,790
Claims incurred ($ M)*	$673	$673	$673	$673	$40	$673
Event	13 Nov 2021 SW BC flood	13 Nov 2021 SW BC flood	13 Nov 2021 SW BC flood	13 Nov 2021 SW BC flood	29 Aug 2015 windstorm	13 Nov 2021 SW BC flood

*All dollar figures are in 2023 CAD inflated using the consumer price index.

Table 4 shows the inflation factor F_{1i}, based on equation (2). Table 5 shows the population factor F_{2i}, using equation (3). Note that Statistics Canada (2023b) provides population data every five years, not every year, so between census years we assume annual growth given by equation (13) and year-*i* population given by equation (14), where *j* refers to a census year and i refers to any year. Table 6 provides the insurance penetration factor F_3, using equations (4) and (5). In the table, CPI refers to the consumer price index.

$$g = \left(\frac{pop_{j+5}}{pop_j} \right)^{\frac{1}{5}} \tag{13}$$

$$pop_i = pop_j \cdot g^{i-j} \tag{14}$$

Table 4. Estimating F_1 inflation factor

Year, i	*CPI*	*$F_{1i} = CPI_{2023}/CPI_i$*
2008	114.1	1.345
2009	114.4	1.342
2010	116.5	1.318
2011	119.9	1.280
2012	121.7	1.261
2013	122.8	1.250
2014	125.2	1.226
2015	126.6	1.212
2016	128.4	1.195
2017	130.4	1.177
2018	133.4	1.151
2019	136.0	1.129
2020	137.0	1.120
2021	141.6	1.084
2022	151.2	1.015
2023	153.5	1.000

Table 5. Estimating F_2 population factor

Year, i	*Census year, j*	*Pop. in census year, j*	*Growth per year, g*	*Pop. (year i)*	*F_{2i}*
2008	2006	4,113,487	1.014	4,225,804	1.22
2009				4,283,108	1.20
2010				4,341,189	1.19
2011	2011	4,400,057	1.011	4,400,057	1.17
2012				4,448,575	1.16
2013				4,497,628	1.14
2014				4,547,221	1.13
2015				4,597,362	1.12
2016	2016	4,648,055	1.015	4,648,055	1.11
2017				4,716,570	1.09
2018				4,786,095	1.08
2019				4,856,644	1.06
2020				4,928,234	1.04
2021	2021	5,000,879	1.015	5,000,879	1.03
2022				5,074,595	1.01
2023				5,149,397	1.00

Table 6. Estimating insurance penetration factor F_3

Parameter	Flood	Water, sewer backflow	Windstorm	Winter storm	Summer storm
Catastrophe year	2021	2021	2021	2021	2021
F_1[(a)]	1.084	1.084	1.084	1.084	1.084
F_2	1.03	1.03	1.03	1.03	1.03
Commercial + personal lines policies	1,391,629	1,656,882	2,506,163	2,506,163	2,506,163
Population	5,000,879	5,000,879	5,000,879	5,000,879	5,000,879
Buildings	2,228,177	2,228,177	2,228,177	2,228,177	2,228,177
F_3 insurance penetration	0.62	0.74	0.99	0.99	0.99

(a) Included in Table 3.

Table 7 provides the indirect business interruption factor F_4. Its calculation relies on quantities from Multi-Hazard Mitigation Council (2019). It is calculated as shown in equation (15), where F_{10} denotes indirect business interruption as a percentage of benefit, F_{12} denotes property loss as a percentage of benefit, and F_{13} denotes direct business interruption and additional living expenses as a percentage of benefit.

$$F_4 = \frac{F_{10}}{F_{12} + F_{13}} \tag{15}$$

The row in Table 7 labelled $F_5 + F_6 + F_7$ reflects a factor to estimate the acceptable regulatory cost to avoid statistical deaths, injuries, and cases of post-traumatic stress disorder. It is calculated as shown in equation (16), in which F_{11} denotes deaths, injuries, and cases of post-traumatic stress disorder as a percentage of benefit, again from Multi-Hazard Mitigation Council (2019).

$$F_5 + F_6 + F_7 = \frac{F_{11}}{F_{12} + F_{13}} \tag{16}$$

The row labelled F_9 presents a helper variable: property loss as a fraction of property loss plus direct time-element losses, from equation (17).

$$F_9 = \frac{F_{12}}{F_{12} + F_{13}} \tag{17}$$

The row labelled F_8 reflects the carbon factor, the current value of the carbon embodied in the repairs. It is calculated as shown in equation (18) using the following inputs:

U_1 = \$65/tonne, Canadian cost of carbon per tonne

U_2 = \$1,750/m² replacement cost per square metre of dwelling (e.g., from Gordian 2022)

U_3 = 0.2 tonne/m², average tonnes of carbon per square metre

$$\begin{aligned} F_8 &= \frac{U_1 \cdot U_3}{U_2} \cdot F_9 \\ &= \frac{\$65 / ton \cdot 0.2 ton / m^2}{\$1,750 / m^2} \cdot F_9 \\ &= 0.0074 \cdot F_9 \end{aligned} \quad (18)$$

Table 7. Estimating F_4 through F_9

Parameter	Flood	Wind	Earthquake
Multi-Hazard Mitigation Council (2019) figure	2-21	2-22	2-24
F_{10} Indirect business interruption as % of benefit	3%	7%	14%
F_{11} Deaths, injuries, and post-traumatic stress disorder as % of benefit	0%	0%	14%
F_{12} Property loss as % of benefit	87%	56%	43%
F_{13} Direct business interruption + additional living expenses, % of benefit	7%	14%	29%
F_4 Indirect business interruption factor	0.03	0.10	0.19
$F_5 + F_6 + F_7$ *Deaths + injuries + PTSD factor*	0.00	0.00	0.19
F_9 *Helper variable*	0.93	0.80	0.60
F_8 *Carbon factor*	0.0069	0.0059	0.0044

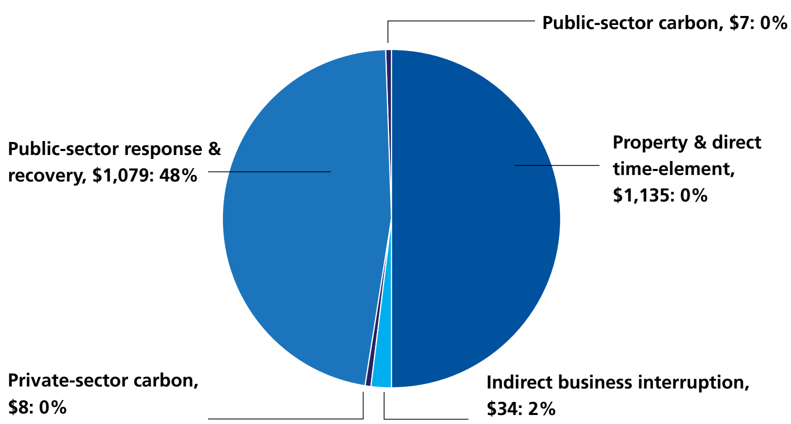
Table 8 presents the resulting estimate of the total economic value of losses experienced in the 2021 November Rainstorm. The total estimated loss of \$2.3 billion (2023 CAD) is mostly insured loss and DFAA expenditures. Figure 17 illustrates the relative contribution of losses from six sources considered here. The loss figure represents a best estimate based on imperfect knowledge and a simplified model and is probably accurate only within a factor of perhaps 1.5 (based on judgment), meaning the true losses might be between approximately \$1.5 billion and \$3.5 billion.

Table 8. Estimate of the total economic loss in the 2021 November Rainstorm

Parameter	Value	Comment
Year	2021	Event year
L_1	$620	Then-year insured loss, $ million
L_2	$838	DFAA expenditure, then-year $ million (BC Ministry of Emergency Management and Climate Readiness)
F_1	1.08	Inflation factor
F_2	1.03	Population growth factor
F_3	0.61	Insurance penetration rate
F_4	0.03	Indirect business interruption factor
$F_5 + F_6 + F_7$	0	Casualty factor
F_8	0.0069	Carbon factor
F_9	0.93	Property loss as a fraction of property loss plus direct time-element loss
$L_2 \times F_1 \times F_2$	$932	DFAA expenditure factored for inflation and population growth, 2023 $ million
Results, 2023 $ million		
Property + direct time-element losses	$1,135	Private-sector property loss, direct business interruption, and additional living expenses
Indirect business interruption	$34	Indirect business interruption losses
Casualties	$0	Acceptable cost to avoid statistical casualties
Private-sector CO_2	$8	Economic value of embodied carbon in private-sector repairs
Public-sector response + recovery	$1,079	Total public response and recovery costs
Public-sector CO_2	$7	Embodied carbon in public-sector response and recovery
Sum	$2,263	Total economic value of the event
	$1,500-3,500	Reasonable range for the true economic loss

Thus, the most severe storm in the CatIQ database is estimated to have cost between $1.5 billion and $3.5 billion (2023 CAD), when one adds uninsured private-sector losses, public-sector response and recovery costs, losses from indirect business interruption, and the current economic value of embodied carbon in the repairs

Figure 17. Estimated societal cost of the 2021 November Rainstorm in $ millions (2023 CAD).



2.3.2 Number of buildings that would have benefited

Equations (9) and (10) produce estimates of damaged buildings shown in Table 9. The table shows results rounded to two significant figures to reduce the appearance of excessive accuracy.

Table 9. Estimated number of damaged buildings

Parameter	Value	Comment
N_5	12,400	Damaged buildings
F_{11}	99%	Estimated fraction of properties damaged by flood rather than wind
F_{12}	67%	Estimated fraction of flood-damaged homes affected by pluvial flooding
N_6	8,400	Buildings damaged mostly by pluvial flooding
N_7	3,900	Buildings damaged mostly by fluvial flooding
N_8	100	Buildings damaged mostly by wind

2.3.3 Costs and avoidable losses

Equations (11) and (12) produce estimates of costs and avoided losses shown in Table 10. Results are rounded to two significant figures to reduce the appearance of excessive accuracy, and totals may not sum exactly because of rounding. Both cost and benefit figures depend on simplifications and approximations. A reasonable, judgment-based range for the actual total mitigation cost is perhaps $700 million to $1.5 billion. A reasonable, judgment-based range for the actual total mitigation benefit is perhaps $1.5 billion to $3.5 billion, or approximately double the cost.

Table 10. Estimated costs and avoided losses in the 2021 November Rainstorm

Parameter	Value, $ millions (2023 CAD)	Comment
C_1	50	Mitigation costs for pluvial flood retrofit
C_2	950	Mitigation costs for fluvial flood retrofit
C_3	2	Mitigation costs for wind retrofit
$C_1 + C_2 + C_3$	1,000	Estimated total mitigation cost
	700-1,500	Reasonable range for total mitigation cost
B_1	400	Avoided loss from pluvial flood mitigation
B_2	1,900	Avoided loss from fluvial flood mitigation
B_3	2	Avoided loss from wind mitigation
$B_1 + B_2 + B_3$	2,300	Estimated total avoidable loss
	1,500-3,500	Reasonable range for total avoidable loss

These results suggest that the prior expense of $1 billion would have avoided $2.3 billion of the losses in the 2021 November Rainstorm. Both figures come with important caveats.

Cost caveats

1. The cost estimate only counts damaged buildings. It omits the costs to mitigate buildings that did not suffer losses.
2. The cost estimate ignores community flood protection, such as taller or better maintained levees and other flood barriers, which could have cost less than the buyouts, elevations, and other retrofits considered here. It also ignores the substantial increase in highway design requirements.

Avoided loss caveats

1. Similar to the first cost caveat, the avoided loss estimate only counts buildings damaged in this storm.
2. The avoided loss estimate omits losses that the same mitigation efforts will avoid in future storms. Fluvial flood mitigation can avoid repetitive losses, with lower-lying buildings suffering more frequent losses.
3. The estimate of the avoided losses depends on important assumptions, especially about the fraction of homes subject to pluvial rather than fluvial flooding.

3. Fires

3.1 Literature

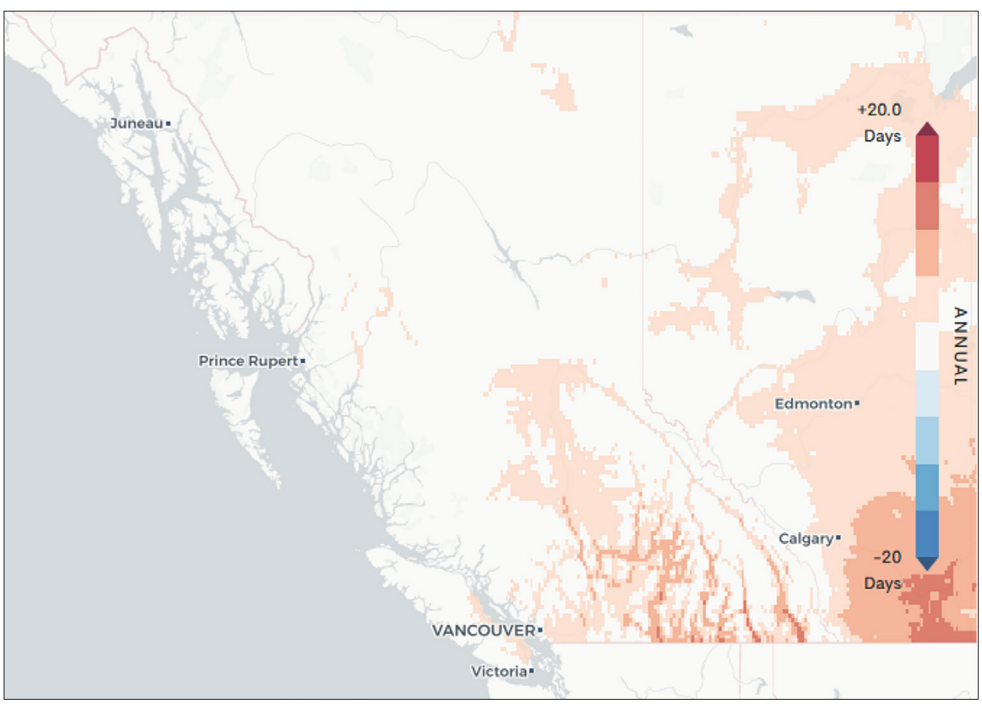
3.1.1 Climate and weather

Much of the literature cited in section 2.1 applies to fire mitigation, but we also examined a few additional resources on how climate and weather affect fire. According to Natural Resources Canada (2021), fire season begins when the ground is free of snow and noon temperatures are about 12 C for three consecutive days. Fire season ends when there has been snow on the ground for seven consecutive days or when noon temperatures fall below 5 C. It estimates that from 2014 to 2070, the BC fire season will be between one week and one month longer than its current length of five to seven months, depending on location.

This expected lengthening of the BC fire season agrees with estimates of the increasing number of hot days, which are important for fire ignition, behaviour, and spread. Writing for *Firefighting in Canada*, Brouwer (2017) explains the 30-30 crossover rule: When temperatures exceed 30 C and humidity drops below 30%, firefighters should know that "fires will start faster; they should expect severe burning conditions, erratic fire behaviour, and rapid rate of spread."

Climatedata.ca does not estimate 30-30 days, but it does offer days per year with maximum temperatures exceeding 30 C. Figure 18 illustrates the estimated increase in hot days (temperatures exceeding 30 C) in 2001–2030 relative to 1971–2000, under the modelling parameters of the Coupled Model Intercomparison Project, Phase 6. For example, from 1971 to 2000, Lytton, BC, experienced a median of about three weeks of days with temperatures exceeding 30 C. It now experiences four to five weeks of hot days every year

Figure 18. Much of southern BC is now experiencing an additional 1-2 weeks of temperatures above 30 C, relative to 1971-2000 (image: Climatedata.ca).



3.1.2 Past fire disaster data

As with severe storms, CatIQ (2023) provides data on fire-related losses since 2008 and insurance penetration, and the Canadian Disaster Database (Public Safety Canada 2023a) reports fire losses since 1900. Public Safety Canada (2023b) offers information about federal financial assistance to provincial and territorial governments through the DFAA program. We can use the same resources discussed in the storm methodology section for demographic data.

As of this writing,the Canadian Disaster Database does not yet include the 2021 Lytton Creek Wildfire, but CBC News (2021) reported two deaths and "several" injuries.

The August 16, 2003, Okanagan Mountain Park wildfire near Kelowna, BC, was the costliest fire in Canadian history until May 2011, when it fell to second place behind the Slave Lake fire in Alberta. The Canadian Disaster Database does not provide a clear loss estimate for the Okanagan Mountain Park wildfire. It mentions an estimated $31 million in losses, elsewhere $8.2 million in property damage, and elsewhere insured losses in British Columbia of $200 million (2003 CAD), but it does not reconcile these figures. The BC Wildfire Service (2018) reported loss or damage to 238 homes and 14 trestles. Various secondary sources report a loss of $200 million (2003 CAD), but they either cite an unavailable source or provide no citation. Crucially, they do not indicate what is included in this estimate, such as insured losses, broader societal property damage, or firefighting costs.

The BC Ministry of Emergency Management and Climate Readiness (2023) provides the data shown in Table 11 about public expenditures to recover from the 2017 and 2021 wildfires. Both events affected several communities. The payouts are shown in then-year dollars, before accounting for inflation. Amounts in Table 11 reflect actual and estimated costs as of this writing and may change.

Table 11. Public payouts under the DFAA program in two past wildlfires

CatIQ event name	DFAA event	Response cost (millions)	Recovery cost (millions)
2017 Williams Lake Wildfire	2017 Wildfires	$380	$22
2021 Lytton Creek Wildfire	2021 Wildfires	$438	$4

3.1.3 Costs and benefits of leading fire mitigation measures

The National Guide for Wildland–Urban Interface Fires (Bénichou et al. 2021) recommends changes to buildings, yards, and community infrastructure, including construction changes and vegetation management, to reduce the risk of fire in the wildland–urban interface. Construction features include noncombustible cladding and roofing, enclosed eaves, up to one-hour fire-rated insulation beneath the cladding and outside the wall studs, and various details intended to prevent small embers from penetrating the building envelope. Vegetation management features include a noncombustible apron (e.g., gravel rather than plants) within 1.5 metres of the building perimeter and trimmed vegetation at greater distances. One can trade the more costly construction features and rely instead on less expensive vegetation management. Changes to community infrastructure include trimming vegetation away from power lines, creating hard roadway surfaces for firefighting apparatus access, and ensuring firefighting water supply. FireSmart Canada (2022) and the *International Wildland-Urban Interface Code* in the US (International Code Council 2021) offer guidance that resembles the *National Guide for Wildland-Urban Interface Fires*.

The Multi-Hazard Mitigation Council (2019) estimates the costs and benefits of complying with the US-oriented *International Wildland-Urban Interface Code* (International Code Council 2015). The authors estimate a very wide retrofit cost range – $4,000 to $80,000 USD per house – and the authors use a conservatively high estimate of $72,000 USD.

Porter et al. (2021) estimate the costs and benefits of following the recommendations of the similar (though not identical) *National Guide for Wildland-Urban Interface Fires* by the National Research Council. That work estimated societal a benefit-cost ratio of 4:1 and location-specific benefit cost ratios as high as 34:1. The latter work quotes evidence from the California Department of Forestry and Fire Protection (CAL FIRE) about the reduction in ignition probability and damage for protected buildings in wildfires. It shows that in most places in the Canadian wildland-urban interface, it is cost-effective to build new buildings to comply with construction-oriented options. The National Guide offers five options for how to comply with its recommendations, allowing the homeowner to balance upfront costs with long-term maintenance. Table 12 shows estimated square-foot costs for new construction for five options of mitigation measures. The cost can vary significantly, but a reasonable average is $5 per square foot ($55 per square metre) for a structural approach to new construction (i.e., changing the building and requiring little or no vegetation management). For a new 2,200 square-foot (200 square metre) house, compliance would add approximately $11,000 to the construction cost.

Table 12. Square-foot compliance costs for new construction (Porter et al. 2021)

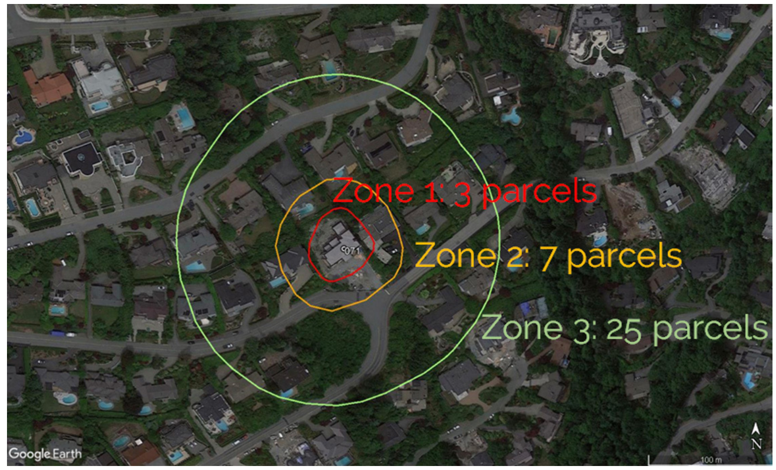
Exposure level	**Priority zones that follow National WUI Guide Section 3.4**				
	None	**1A**	**1A and 1**	**1A to 2**	**1A to 3**
Ember-only or low	$6	$6	$2	$2	$24
Moderate	$6	$6	$2	$2	$24
High	$6	$6	$7	$2	$24

Table 13 shows Porter et al.'s (2021) estimated unit costs to retrofit existing houses. An approach that relies mostly on vegetation management might cost $6 to $8 per square foot ($65 to $85 per square metre), or up to about $17,000 over the life of a 2,200-square foot (200-square metre) property in a high exposure zone with vegetation control from priority zones 1A to 2. Compliance requires keeping vegetation trim over decades and cooperating with several neighbours if one opts for vegetation management within 30 metres of a house (shown as zone 2 in Figure 19).

Table 13. Square-foot compliance costs for retrofitting existing houses (Porter et al. 2021)

Exposure level	**Priority zones that follow National WUI Guide Section 3.4**				
	None	**1A**	**1A and 1**	**1A to 2**	**1A to 3**
Ember-only or low	$16	$15	$6	$6	$35
Moderate	$16	$17	$8	$6	$35
High	$16	$17	$19	$8	$35

Figure 19. Controlling fire risk through vegetation management can be highly cost-effective but can require cooperating with several neighbours over the life of the property (Porter et al. 2021).



Porter et al. (2021) use CAL FIRE ignition and loss statistics to estimate the benefits of compliance. Accounting for the individual features of a compliant house, Porter et al. (2021, p. 70) estimate that compliance reduces the expected value of loss if the house is in a fire from 51% (non-compliant) to 28% (compliant) of the replacement cost of the house. Those figures reflect how compliance changes ignition probability and repair costs if ignition occurs. Thus, compliance reduces losses by a factor of (0.51 – 0.28)/0.51, or about 45%.

3.1.4 Demographic and insurance penetration data

As with storms, CatIQ data provides the number of fire insurance policies and insured fire losses since 2008. One can use Statistics Canada (2023c) to estimate the number of residential properties in British Columbia, whether insured or uninsured.

3.2 Methodology

We propose to use the same methods as in section 2.2.1 to identify the costliest fires in recent BC history. In particular, one can estimate total societal loss, *y*, using equations (1) through (7) to extrapolate from insurance claims and loss data to include uninsured property and several other forms of loss. For disasters before 2008, one can use equation (8) and the loss data in the Canadian Disaster Database.

Total retrofit costs, *C*, can be estimated as follows. Assuming that owners could have retrofitted all the buildings that were eventually damaged, let *N* denote the number of buildings, counted in units of equivalent 200-square metre houses. Retrofit costs using vegetation management including priority zones 1A to 2 (up to 30 m from the house) in high-exposure areas have a present value of $8 per square foot of house over the life of the property; for an average 2,200-square foot (200-square metre) house, therefore, unit cost U is $17,000 in equation (19).

$$C = N \cdot U \tag{19}$$

Total avoided losses, B, can be estimated as shown in equation (20), where y denotes the total societal loss and F_{13} is the factor by which compliance reduces that loss, taken here as 0.45, based on Porter et al. (2021)

$$B = F_{13} \cdot y \tag{20}$$

3.3 Results

3.3.1 Fires with the largest loss or most victims

Table 14 summarizes BC fire catastrophes since 2008, including the number of catastrophes in CatIQ that included fire losses and events with the largest claim count and the largest insured monetary loss. The Lytton Creek wildfire of June 30, 2021, represents BC's largest fire loss at $116 million (2023 CAD) from 509 insured claims; however, the July 15, 2017, Williams Lake wildfire resulted in more claims (5,578), with a total insured loss of $104 million (2023 CAD). Table 15 shows insurance penetration F3 in both events near 100%.

Table 16 shows the remaining factors F_4 through F_9. To calculate F_4, F_8, and F_9, let

G_1 = Indirect business interruption as a percent of benefit (e.g., from Multi-Hazard Mitigation Council 2019)

G_2 = Monetary value of avoided deaths, injuries, and cases of post-traumatic stress disorder, percent of benefit (e.g., from Multi-Hazard Mitigation Council 2019)

G_3 = Property loss as percent of benefit (e.g., from Multi-Hazard Mitigation Council 2019)

G_4 = Direct business interruption and additional living expenses as percent of benefit (e.g., from Multi-Hazard Mitigation Council 2019).

One can calculate F_4, the business interruption factor, as shown in equation (21). We lack the detail to calculate separate factors for deaths (F_5), nonfatal medical injuries (F_6), and post-traumatic stress injuries (F_7) separately, but we can calculate their sum – the casualty factor – as shown in equation (22). We can calculate the carbon factor (F_8) and property loss as a fraction of the sum of property and direct time-element losses (F_9), as shown in equations (23) and (24)

$$F_4 = \frac{G_1}{G_3 + G_4} \tag{21}$$

$$F_5 + F_6 + F_7 = \frac{G_2}{G_3 + G_4} \tag{22}$$

$$F_9 = \frac{G_3}{G_3 + G_4} \tag{23}$$

$$F_8 = 0.0074 \cdot F_9 \tag{24}$$

One can now extrapolate from insured loss to total societal loss in these two fires. Table 17 shows the resulting estimate of the total societal cost of the 2021 Lytton wildfire to be $735 million. The total reflects an uncertain best estimate. The DFAA expenditure figures are preliminary and could change. A reasonable range for the actual total societal loss might be $500 million to $1 billion. Figure 20 illustrates the relative contribution to the total Lytton wildfire losses from the loss categories estimated here.

Table 18 shows the resulting estimate of the total societal cost of the 2017 Williams Lake wildfire to be $753 million. This figure also reflects simplifications and uncertain quantities; the true figure might reasonably lie between $600 million and $1.2 billion. The range is higher than that of the Lytton fire because the large number of displaced people from Williams Lake makes the best estimate seem low. Figure 21 illustrates the relative contribution to the Williams Lake wildfire losses from the loss categories estimated here.

Table 14. BC fire catastrophes since 2008

Parameter	Value
Catastrophes	6
Event with largest claim count	
Property claims	5,578
Claims incurred ($ M)*	$104
Event	15 Jul 2017 Williams Lake
Largest insured monetary loss	
Property claims	509
Claims incurred ($ M)*	$116
Event	30 Jun 2021 Lytton

*In 2023 CAD, inflated using the consumer price index.

Table 15. Estimating insurance penetration factor F_3

Parameter	Williams Lake	Lytton
Catastrophe year	2017	2021
$F_{1(a)}$	1.177	1.084
F_2	1.09	1.03
Commercial + personal policies	2,055,748	2,507,203
Population	4,716,570	5,000,879
Buildings	2,101,501	2,228,177
F_3 insurance penetration	0.98	0.99

(a) Included in Table 14.

Table 16. Estimating F_4 through F_9

Parameter	Value
Multi-Hazard Mitigation Council (2019) figure	2-17
G_1 Indirect business interruption, % of benefit	2%
G_2 Deaths, injuries, and cases of post-traumatic stress disorder, % of benefit	5%
G_3 Property loss, % of benefit	70%
G_4 Direct business interruption + additional living expenses, % of benefit	3%
F_4 Indirect business interruption factor	0.03
$F_5 + F_6 + F_7$ Casualty factor	0.07
F_9 Property loss as a fraction of the sum of property and direct time-element losses	0.96
F_8 Carbon factor	0.0071

Table 17. Estimate of the total economic loss in 2021 Lytton wildfire

Parameter	Value	Comment
Year	2021	Event year
L_1	$106	Then-year insurance loss, $ million
L_2	$442	DFAA expenditure, then-year $ million
F_1	1.08	Inflation factor
F_2	1.03	Population growth factor
F_3	0.99	Insurance penetration rate
F_4	0.03	Indirect business interruption factor
$F_5 + F_6 + F_7$	0.07	Casualty factor
F_8	0.0071	Carbon factor
F_9	0.96	Property loss as a fraction of property loss plus direct time-element loss
$L_2 \times F_1 \times F_2$	$492	DFAA expenditure factored for inflation and population growth, 2023 $ million
N_1	2	Number of deaths (CBC News 2021)
N_2	10	Number injured, interpreting "several" as 10
Results, 2023 $ million		
Property, direct business interruption (DBI), additional living expenses (ALE)	$120	Private-sector property loss plus direct time-element losses
Indirect business interruption	$3	Indirect business interruption losses
Casualty losses, from $F_5 + F_6 + F_7$	$8	Factoring from property losses as past proportions
Casualty losses, from $N_1 + N_2$	$18	Based on number killed and injured, VSL, and 0.0032 x VSL for injuries
Casualty losses, F_{11}	$18	Larger of the prior two
Private-sector CO_2	$1	Economic value of embodied carbon in private-sector repairs
Public-sector response & recovery	$590	Total public response and recovery costs
Public-sector CO_2	$4	Embodied carbon in public-sector response and recovery
Total economic loss	$735	Estimated total societal cost of the event
	$500-1,000	Reasonable range for the true economic loss

Figure 20. Losses in 2021 Lytton wildfire, 2023 $ millions

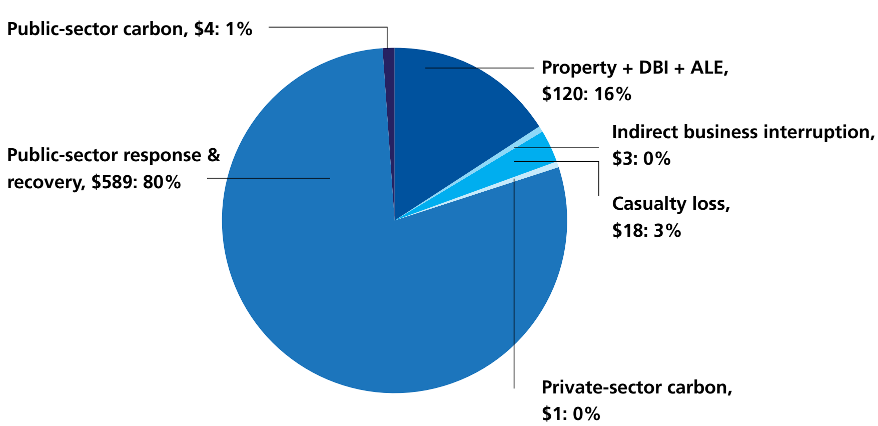
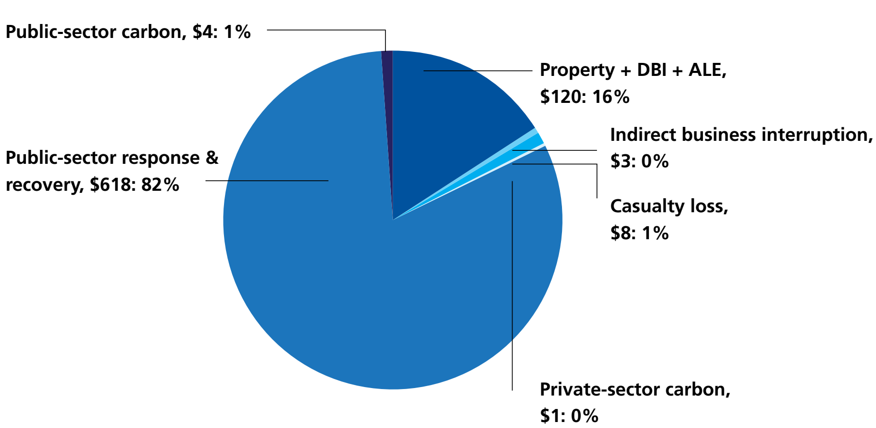


Table 18. Estimate of the total economic loss in 2017 Williams Lake wildfire

Parameter	Value	Comment
Year	2017	Event year
L_1	$89	Then-year insurance loss, $ million
L_2	$402	DFAA expenditure, then-year $ million
F_1	1.18	Inflation factor
F_2	1.09	Population growth factor
F_3	0.96	Insurance penetration rate
F_4	0.03	Indirect business interruption factor
$F_5 + F_6 + F_7$	0.07	Casualty factor
F_8	0.0071	Carbon factor
F_9	0.96	Property loss as a fraction of property loss plus direct time-element loss
$L_2 \times F_1 \times F_2$	$517	DFAA expenditure factored for inflation, population growth, 2023 $ million
N_1	0	Number of deaths
N_2	Unknown	Number injured
Results, 2023 $ million		
Property, direct business interruption (DBI), additional living expenses (ALE)	$119	Private-sector property loss plus direct time-element losses
Indirect business interruption	$3	Indirect business interruption losses
Casualty losses, from $F_5 + F_6 + F_7$	$8	Factoring from property losses as past proportions
Casualty losses, from $N_1 + N_2$	$0	Based on number killed and injured, VSL, and 0.0032 x VSL for injuries
Casualty losses, F_{11}	$8	Larger of the prior two
Private-sector CO_2	$1	Economic value of embodied carbon in private-sector repairs
Public-sector response & recovery	$618	Total public response and recovery costs
Public-sector CO_2	$4	Embodied carbon in public-sector response and recovery
Total economic loss	$753	Estimated total societal cost of the event
	$600–1,200	Reasonable range for the true economic loss

Figure 21. Losses in 2017 Williams Lake wildfire, 2023 $ millions



3.3.2 Number of buildings that would have benefited

The 2021 Lytton wildfire destroyed about 100 buildings in Lytton, based on Google Earth imagery. CatIQ insurance claims data (2023) suggest that the Williams Lake wildfire damaged approximately 6,400 buildings.

3.3.3 Costs and avoidable losses

Applying equations (11) and (12) produces the estimates of costs and avoided losses shown in Table 19 (Lytton) and Table 20 (Williams Lake). Results are rounded to two significant figures to reduce the appearance of excessive accuracy. Totals may not sum exactly because of rounding.

Table 19. Estimated costs and avoided losses in 2021 Lytton wildfire

Parameter	Value	Comment
y	$740	Total societal cost of the event, 2023 $ million
N	100	Number of buildings that would have benefited from retrofit
U	$17,000	Cost per house to retrofit to the National WUI Guide
C	$1.7	Estimated retrofit and lifetime maintenance cost, 2023 $ million
	$1.3-2.6	Reasonable range for retrofit and lifetime maintenance cost, 2023 $ million
F_{13}	0.45	Avoided loss as a fraction of total societal cost of the event
B	$330	Estimated total avoidable loss, 2023 $ million
	$220-440	Reasonable range for total avoidable loss, 2023 $ million

Table 20. Estimated costs and avoided losses in 2017 Williams Lake wildfire

Parameter	Value	Comment
y	$750	Total societal cost of the event, 2023 $ million
N	6,400	Number of buildings that would have benefited from retrofit
U	$17,000	Cost per house to retrofit to the National WUI Guide
C	$110	Estimated retrofit and lifetime maintenance cost, 2023 $ million
	$80-160	Reasonable range for retrofit and lifetime maintenance cost, 2023 $ million
F_{13}	0.45	Avoided loss as a fraction of total societal cost of the event
B	$340	Estimated total avoidable loss, 2023 $ million
	$230-460	Reasonable range for total avoidable loss, 2023 $ million

Thus, Table 19 suggests that the Village of Lytton could have avoided $220 million to $440 million in societal losses (out of $500 million to $1 billion total societal loss) through mitigation measures costing from $1.3 million to $2.6 million. This could have been done through vegetation management as suggested by Bénichou et al. (2021), FireSmart Canada (2022), International Code Council (2021), and others. The Williams Lake wildfire cost $600 million to $1.2 billion. As shown in Table 20, retrofit would have cost $80 million to $160 million over the life of the properties and would have saved $230 million to $460 million in this single fire.

These figures come with important caveats:

Cost caveats

1. As with the storm analysis, the cost estimate only counts buildings in Lytton and Williams Lake; it omits the costs to mitigate buildings outside of these communities that did not suffer losses.
2. The cost estimate ignores community fire protection, which the National Wildland–Urban Interface Fire Guide describes as measures including vegetation management around power lines, provision of hard road surfaces, and provision of community evacuation centres.

Avoided loss caveats

1. Similar to the first cost caveat, the avoided loss estimate only counts buildings damaged in this fire. It is retrospective, meaning that it is conditioned on this fire occurring.
2. The avoided loss estimate omits losses that the same mitigation efforts will avoid in future fires. For example, Lytton suffers frequent wildfires; in July 2022, the Nohomin Creek fire forced the evacuation of the First Nation reserve near Lytton and destroyed several buildings.

4. Earthquakes

4.1 Literature

4.1.1 Past and future BC earthquakes

A few key existing resources may be useful to the methodology presented in section 4.2. The US Geological Survey (2023) offers a catalog of global earthquakes of magnitude 2.5 or greater. Using this catalog, one can estimate that 329 earthquakes of magnitude 5 or greater have struck BC since 1900 (Figure 22). Three are known to have been deadly: A magnitude-7.5 earthquake on June 23, 1946, on Vancouver Island killed two people; a magnitude-7.8 earthquake on July 9, 1958, in Lituya Bay, Alaska, killed five; and a magnitude-7.8 earthquake struck Haida Gwaii on October 27, 2012, killing one. In addition to these historic earthquakes, a magnitude-9 earthquake occurred on January 26, 1700, in the Cascadia subduction zone, one in a sequence of large earthquakes that recur every 300 to 600 years

The Geological Survey of Canada estimates the likelihood, locations, and magnitudes of future earthquakes with a model called an earthquake rupture forecast. It estimates how strongly the ground shakes nearby with a model called a ground-motion-prediction equation that, in turn, relies on a model that estimates soil conditions in the strongly shaken area. Together, these three models comprise a seismic hazard model. Figure 23 shows one important product of the Canada Seismic Hazard Model 6th Generation: a map of the 5% damped short-period spectral acceleration response on site class C, with 2% probability of being exceeded in 50 years (Kolaj et al. 2020).

Figure 22. Approximately 329 earthquakes of magnitude 5 or greater have struck in or near BC since 1900 (US Geological Survey 2023).

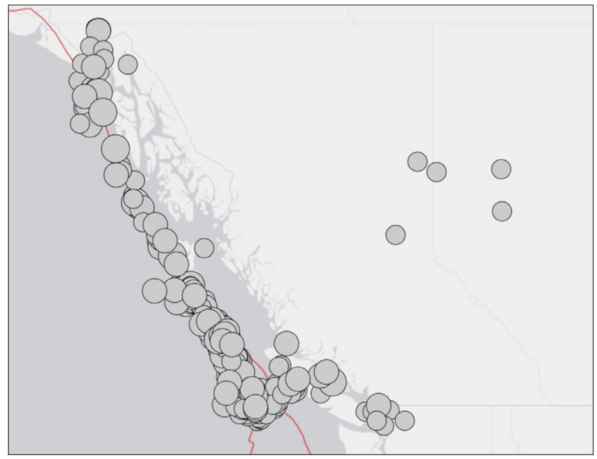
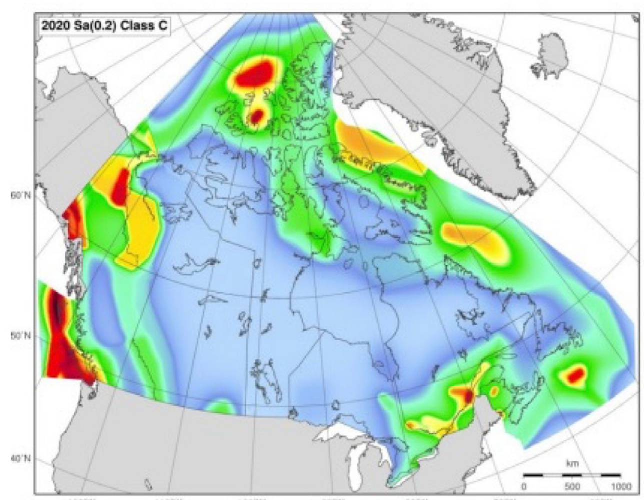


Figure 23. Hazard map from the Geological Survey of Canada 2020 National Seismic Hazard Model.



4.1.2 Overview of earthquake losses

Because earthquakes are less common in BC than severe storms and fires, it seems worthwhile to review the leading earthquake hazards. Earthquakes damage buildings and injure people through several mechanisms.

Building collapse causes most earthquake fatalities. Human behaviour and nonstructural damage cause most nonfatal injuries (Seligson and Shoaf 2003). In most earthquakes, ground shaking causes most building damage on average. Ground-failure processes such as liquefaction, landslides, lateral spreading, and fault rupture cause approximately one tenth of the damage (Applied Technology Council 1985). In rare circumstances, damage from tsunamis or fire following earthquake – both of which threaten BC – can exceed shaking damage. A large earthquake in the Cascadia subduction zone could cause tsunami runup of up to 15 metres (e.g., Clague et al. 2000) and severe damage. A large earthquake near a metropolitan area could cause severe damage from post-earthquake fires (e.g., Scawthorn 2020).

Other causes of loss include hazardous material release, radioactivity from damage to nuclear power plants, and inundation from dam and levee failure.

4.1.3 Canadian earthquake loss studies

Rich literature is available on Canada's earthquake hazard and risk; this section will focus on a few relevant works. First, as part of its mission to keep Canada safe from natural hazards and related risks, the Geological Survey of Canada has created the Canada Seismic Risk Model, CanSRM1 (Hobbs et al. 2023). The model comprises data and algorithms encoded in software to estimate building damage, building collapse probability, building repair costs, and deaths in future Canadian earthquakes. It considers only earthquake shaking damage to buildings and does not yet include ground failure, tsunami, fire following earthquake, or other hazards mentioned earlier. It calculates results at the neighbourhood and aggregate scale.

Of particular relevance, the model developers have estimated shaking, damage, and loss in nine realistic hypothetical future earthquakes – five in BC, one in Ottawa, two near Montreal, and one in Yukon – and present the results via the Risk Profiler web page, https://www.riskprofiler.ca/scenarios/index.html.

More importantly, RiskProfiler.ca provides detailed databases of shaking, damage, and loss by combination of detailed occupancy type (e.g., RES1), building type (e.g., W4), code era (e.g., PC), and small geographic area. For example, the database of results for an M9.0 Cascadia subduction zone earthquake are presented at https://opendrr.github.io/earthquake-scenarios/en/#SIM9p0_CascadiaInterfaceBestFault. The reader who lacks skill with geographic information systems can convert the geopackage files to comma-separated value files with common software, such as the GeoConverter software offered by OST Eastern Switzerland University of Applied Sciences Rapperswil (no date).

Table 21 summarizes the estimated losses in five BC earthquake scenarios. In the table, "damaged buildings" refers to the number of completely damaged buildings, that is, buildings that cost as much or more to repair than to replace. Natural Resources Canada lists many sources of uncertainty, but it does seem to attempt to quantify reasonable ranges as we have done in earlier sections when similar levels of uncertainty apply (i.e., a factor of perhaps 1.5 either way, based on judgment)

Table 21. RiskProfiler.ca BC earthquake scenarios

Scenario	Magnitude	Deaths	Damaged buildings	Collapsed buildings	Repair cost (million)
Georgia Strait	4.9	<10	30	0	$730
Georgia Strait	7.0	770	10,000	800	$30,000
Sidney	7.1	900	6,100	420	$20,000
Leech River Fault	7.3	990	6,900	520	$20,000
Cascadia subduction	9.0	3,400	18,000	1,500	$38,000

Scawthorn (2020) estimates the possible losses from fire following earthquake in the Leech River M7.3 and Cascadia subduction zone M9.0 scenarios. He also estimates losses in a larger Georgia Strait earthquake of M7.3 rather than M7.0. Table 22 shows Scawthorn's estimates of the median number of fires ignited by each earthquake. It also shows his estimates of the median number of large fires, meaning fires that grow to require response by multiple engine companies, and the median cost of property damage caused by the fires.

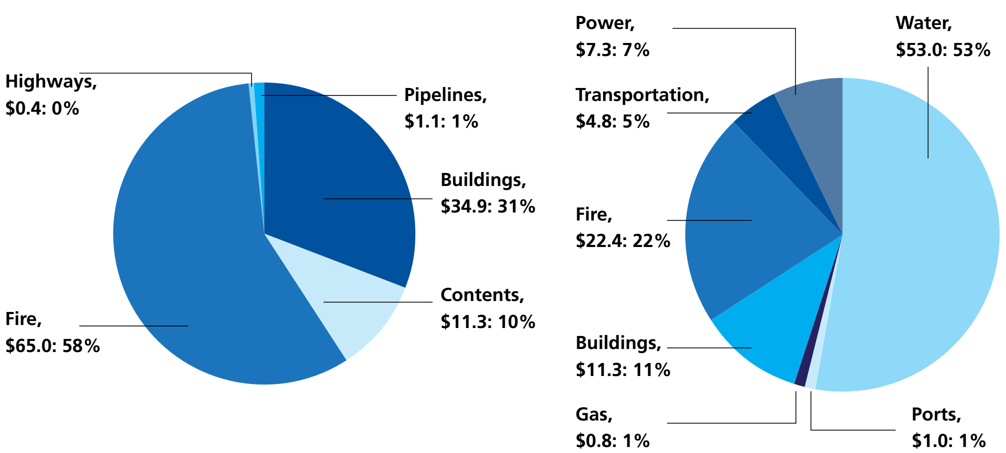
Table 22. RiskProfiler.ca BC earthquake scenarios

Scenario	Magnitude	Ignitions	Large fires	Repair cost (million)
Georgia Strait	7.3	216	47	$10,700
Leech River Fault	7.3	4	~0	$10
Cascadia subduction	9.0	16	1	$160

Western University Prof. Sheri Molnar is developing maps of liquefiable soil in the Vancouver metropolitan area, but the work is not yet complete. It must still be integrated into hazard and loss models before it can be used for a study like the present one.

Jones et al. (2008) estimates a broad range of human and economic costs of a large hypothetical, but highly realistic, California earthquake, which may be useful for estimating economic losses omitted from the Canada Seismic Risk Model and Scawthorn's study of fire following earthquake. Figure 24 shows estimated losses in the southern California ShakeOut scenario: a hypothetical M7.8 rupture of the southern San Andreas fault. Figure 24A shows property repair costs, while Figure 24B shows the losses associated with direct and indirect business interruption. The scenario also leads to 1,800 fatal injuries, 50,000 nonfatal injuries, 2 million cases of psychological distress, and 234,000 cases of post-traumatic stress disorder (Shoaf and Schreiber 2008).

Figure 24. (A) Property losses and (B) direct and indirect business interruption losses in the hypothetical southern California ShakeOut scenario, in billions of 2008 USD (after Jones et al. 2008).



4.1.4 Building inventory data

The Canada Seismic Risk Model includes the National Human Settlement Layer (NHSL), which contains data about the built environment (Journeay et al. 2022). The data "describe the physical and social characteristics of communities across Canada in the context of their vulnerability to natural hazards." The dataset delineates settled areas by dissemination block. It quantifies buildings by a combination of occupancy class (Table 23) and engineering-based construction types and design levels (Table 24). Table 23 also shows the average area for each occupancy class. "Construction type" means a combination of structural material such as reinforced concrete, a seismic force-resisting system such as shearwall, and height category such as one to three storeys. "Design level" is a category system that reflects the seismic design requirements at the time of construction. The Canada Seismic Risk Model estimates building populations for daytime hours (9 a.m. to 5 p.m.), commute hours (7 a.m. to 9 a.m.; 5 p.m. to 7 p.m.), and nighttime hours (7 p.m. to 7 a.m.). The model provides replacement values separately for buildings and contents.

Table 23. CanSRM1 occupancy classes and their average area (after Journeay et al. 2022)

General occupancy class	Specific occupancy class	Description	Average area (sf)
Single-family dwellings	RES1	Single-family dwelling	2,250
	RES2	Mobile home	1,250
Multi-family dwellings	RES3A	Multi-family dwelling, 2 housing units	4,390
	RES3B	Multi-family dwelling, 3-4 housing units	7,060
	RES3C	Multi-family dwelling, 5-9 housing units	8,745
	RES3D	Multi-family dwelling, 10-19 housing units	14,440
	RES3E	Multi-family dwelling, 20-49 housing units	28,460
	RES3F	Multi-family dwelling, 50+ housing units	95,424
Group housing	RES4	Temporary lodging (hotels, motels)	36,135
	RES5	Institutional dormitory (group housing)	22,010
	RES6	Nursing home	42,490
Commerce	COM1	Retail trade	8,500
	COM2	Wholesale trade	22,500
	COM3	Personal and repair services	3,650
	COM4	Professional and technical services	17,480
	COM5	Banks	4,500
	COM6	Hospital	76,190
	COM7	Medical offices and clinics	14,200
	COM8	Entertainment and recreation	11,700
	COM9	Theatres	18,500
	COM10	Parking	62,740

(continued on next page)

General occupancy class	Specific occupancy class	Description	Average area (sf)
Industry	IND1	Heavy industry	18,500
	IND2	Light industry	14,225
	IND3	Food, drugs, and chemicals	16,500
	IND4	Metal and mineral processing	9,370
	IND5	High technology	7,250
	IND6	Construction	11,700
	AGR1	Agriculture	8,750
Civic	REL1	Church and non-profit	8,125
	GOV1	Government general services	15,200
	GOV2	Government emergency response	8,650
	EDU1	Grade schools	46,490
	EDU2	Colleges and universities	82,800

Table 24. CanSRM1 building types (Journeay et al. 2022, p. 89)

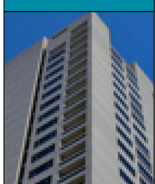
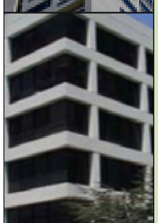
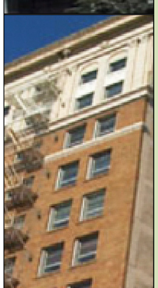
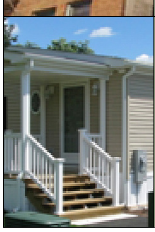
Hazus building taxonomy (FEMA P547)						
Model	**Construction material**	**Typology**	**Height**	**Wall type**	**Description**	**Design epoch**
	Concrete	**C1H**	> 8 floors	C1: Moment frame	Consists of concrete framing, either a complete system of beams and columns or columns supporting slabs without gravity beams. Lateral forces are resisted by cast-in-place moment frames that are stiffened by mechanical connections of the column and beams.	PC: < 1973, LC: 1974-1989, MC: 1990-2004, HC: 2005-present
		C1M	4-7 floors			
		C1L	< 3 floors			
		**C2H**	> 8 floors	C2: Shear wall	Consists of concrete with flat slab or precast plank floors and concrete bearing walls. Little, if any, of the gravity loads are supported by the beams and columns. Building Type C2f has a column and beam or column and slab system that essentially carries all gravity load. Lateral loads are resisted by concrete shear walls surrounding shafts, at the building perimeter, or isolated walls placed specifically for lateral resistance.	PC: < 1973, LC: 1974-1989, MC: 1990-2004, HC: 2005-present
		C2M	4-7 floors			
		C2L	< 3 floors			
		**C3H**	> 8 floors	C3: Masonry infill	Consists of older buildings with an essentially complete gravity frame assembly of concrete columns and floor systems. The floors can consist of a variety of concrete systems including flat plates, two-way slabs, and beam and slab. Exterior walls, and possibly some interior walls, are constructed of unreinforced masonry, tightly infilling the space between columns horizontally and between floor structural elements vertically, such that the infill interacts with the frame to form a lateral force-resisting element.	PC: < 1973, LC: 1974-1989
		C3M	4-7 floors			
		C3L	< 3 floors			
	Manufactured	**MH**	< 2 floors	MH: Light frame	Consists of buildings constructed using self-supporting steel chassis or frames that are designed to support transportation on wheels from one location to another. They are integral structures but can be designed in sections and assembled on-site. Floor and roof framing are most commonly wood-frame joists and rafters supported on wood stud walls.	PC: < 1973, LC: 1974-1989, MC: 1990-2004, HC: 2005-present

Table 24. CanSRM1 building types (Journeay et al. 2022, p. 89) *(continued)*

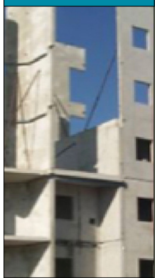
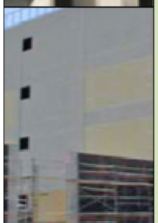
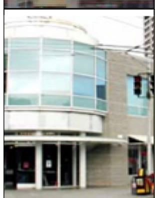
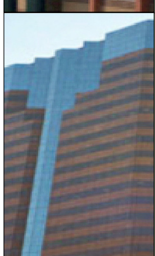
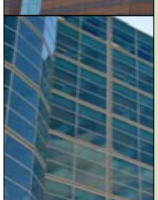
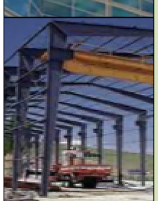
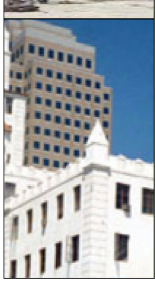
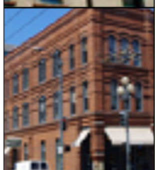
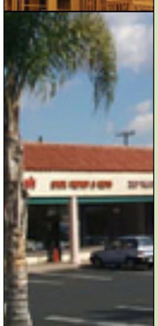
Hazus building taxonomy (FEMA P547)						
Model	**Construction material**	**Typology**	**Height**	**Wall type**	**Description**	**Design epoch**
	**Precast**	**PC1**	< 3 floors	PC1: Tilt-up	Consists of buildings constructed with concrete walls, cast on site and tilted up to form the exterior of the building. They are used for many occupancy types including warehouse, light industrial, wholesale and retail stores, and office. The majority of these buildings are one story; however, there are tilt-up buildings of up to three and four stories, and a limited number with more stories exist. Lateral forces in PC1 buildings are resisted by flexible wood or steel roof diaphragms and tilt-up concrete shear walls. Floor diaphragms are most commonly composite steel decking.	PC: < 1973, LC: 1974-1989, MC: 1990-2004, HC: 2005-present
		**PC2H**	> 8 floors	PC2: Shear wall	Consists of buildings that include wide ranging combinations of precast and cast-in-place concrete elements. Precast members may be limited to a floor system of hollow core or T-beam construction, or may include all elements of the gravity and lateral load systems. PC2 includes concrete wall or frame buildings in which any of the horizontal or vertical elements of the lateral load system are made of precast concrete.	PC: < 1973, LC: 1974-1989, MC: 1990-2004, HC: 2005-present
		PC2M	4-7 floors			
		PC1L	< 3 floors			
	**Reinforced masonry**	**RM1M**	4-7 floors	RM1: Wood/ metal diaphragm	Consists of buildings that are constructed with reinforced masonry perimeter walls with a wood or metal deck flexible diaphragm. RM1 construction can be separated into two categories. RM1u is a multi-story structure and typically has interior concrete masonry unit walls and shorter diaphragm spans, and RM1t structures are large, typically one-story buildings similar to concrete tilt-ups.	PC: < 1973, LC: 1974-1989, MC: 1990-2004, HC: 2005-present
		RM1L	< 3 floors			
		**RM2H**	> 8 floors	RM2: Precast diaphragm	Consists of buildings made of reinforced masonry walls and concrete slab floors that may be either cast-in-place or precast. This building type is often used for hotel and motels and is similar to the concrete bearing wall type C2.	PC: < 1973, LC: 1974-1989, MC: 1990-2004, HC: 2005-present
		RM2M	4-7 floors			
		RM2L	< 3 floors			
	**Steel**	**S1H**	> 8 floors	S1: Moment frame	Consists of buildings characterized by a complete frame assembly of steel beams and columns. Lateral forces are resisted by moment frames that develop stiffness through rigid connections of the beam and column created by angles, plates, and bolts, and/or welding. Floors are cast-in-place concrete slabs or metal decks infilled with concrete. Some S1 structures may have floors and roofs that act as flexible diaphragms such as wood or un-topped metal deck.	PC: < 1973, LC: 1974-1989, MC: 1990-2004, HC: 2005-present
		S1M	4-7 floors			
		S1L	< 3 floors			
		**S2H**	> 8 floors	S2: Braced frame	Consists of buildings with a frame assembly of steel beams and columns. Lateral forces are mainly resisted by diagonal steel members placed in selected bays. Floors are cast-in-place concrete slabs or metal decks infilled with concrete. Some S2 buildings may have floors and roofs that act as flexible diaphragms such as wood or un-topped metal deck.	PC: < 1973, LC: 1974-1989, MC: 1990-2004, HC: 2005-present
		S2M	4-7 floors			
		S2L	< 3 floors			
		**S3**	< 3 floors	S3: Light frame	Consists of buildings with a frame assembly of flexible steel studs, joists and rafters that are used to establish a complete structural system. They are designed to support axial loads other than self-weight and the weight of attached finishes, which can include masonry veneer, metal cladding, stucco, synthetic veneers and integrated exterior insulation and finish systems.	PC: < 1973, LC: 1974-1989, MC: 1990-2004, HC: 2005-present
		**S4H**	> 8 floors	S4: Concrete shear wall	Consists of buildings with an essentially complete frame assembly of steel beams and columns. The floors are concrete slabs or concrete fill over metal deck. These buildings feature a significant number of concrete walls effectively acting as shear walls, either as vertical transportation cores, isolated in selected bays, or as a perimeter wall system. The steel column and beam system may act only to carry gravit loads or may have rigid connections to act as a moment frame to form a dual system.	PC: < 1973, LC: 1974-1989, MC: 1990-2004, HC: 2005-present
		S4M	4-7 floors			
		S4L	< 3 floors			

Table 24. CanSRM1 building types (Journeay et al. 2022, p. 89) *(continued)*

Hazus building taxonomy (FEMA P547)						
Model	**Construction material**	**Typology**	**Height**	**Wall type**	**Description**	**Design epoch**
	**Steel**	**S5H**	> 8 floors	S5: Unreinforced masonry infill	Consists of buildings with an essentially complete gravity frame assembly of steel floor beams or trusses and steel columns typical of older construction practices. The floor consists of masonry flat arches, concrete slabs or metal deck and concrete fill. Exterior walls, and possibly some interior walls, are constructed of unreinforced masonry, tightly infilling the space between columns and between beams and the floor such that the infill interacts with the frame to form a lateral force-resisting element.	PC: < 1973, LC: 1974-1989
		S5M	4-7 floors			
		S1L	< 3 floors			
	**Unreinforced masonry**	**URMM**	4-7 floors	URM: Unsupported	Consists of unreinforced masonry bearing walls, usually at the constructed along the building perimeter. The floors are typically made of wood joists and wood sheathing supported on the walls and on interior post and beam construction.	PC: < 1973, LC: 1974-1989
		URML	< 3 floors			
	**Wood**	**W1**	< 2 floors	W1: Light frame	Consists of one- and two-family detached dwellings of one or more stories. Floor and roof framing are most commonly wood-frame joists and rafters supported on wood stud walls. The first floor may be slab-on-grade or framed. Lateral forces in W1 buildings are resisted by wood-frame diaphragms and shear walls.	PC: < 1973, LC: 1974-1989, MC: 1990-2004, HC: 2005-present
		**W2**	3-6 floors	W1A/W2: Light frame		
		**W3**	< 4 floors	W3: Heavy frame	Consists of commercial, institutional, and smaller industrial buildings constructed primarily of wood framing. The first floor is most commonly slab-on-grade, but may be framed. Floor and roof framing may include wood joists, wood or steel trusses, and glulam or steel beams, with wood posts or steel columns. Lateral forces in W2 buildings are primarily resisted by wood-frame diaphragms and shear walls, sometimes in combination with isolated concrete or masonry shear walls, steel braced frames, or steel moment frames. Diaphragm spans may be significantly larger than in W1, W1A and W2 buildings.	PC: < 1973, LC: 1974-1989, MC: 1990-2004, HC: 2005-present
		**W4**	< 2 floors	W4: Light frame/ Cripple wall	Consists of buildings that are similar in construction to W1 light frame structures, but distinguished by wood cripple wall frames built on irregular foundations and/or open subfloor crawl spaces. Lateral forces are resisted by wood-frame diaphragms and shear walls in structural elements above the main floor level. However, cripple wall and subfloor wall systems are often unsupported and not bolted to the foundation and subfloor creating a structural weakness to lateral forces.	PC: < 1973, LC: 1974-1989, MC: 1990-2004, HC: 2005-present

4.1.5 Leading retrofit measures, costs, and benefits

This section briefly recaps a few sources for leading seismic resiliency problems, retrofit opportunities, costs, and information about vulnerability and benefits. Table 25 lists eight BC building types or groups of building types that share common seismic deficiencies. The column labelled "Building category" contains Journeay et al.'s (2022) building type abbreviations, such as W1 HC and W4 HC, along with a plain language description of the building type. The table briefly describes the deficiency and cost-effective seismic retrofit measures for each category. It shows the approximate retrofit cost and offers a few references with more information about retrofit design, costs, and seismic vulnerability (the relationship between seismic excitation and loss). The list is not exhaustive but represents perhaps 80-90% of the amount of money that could be spent cost-effectively to build new buildings better and to retrofit existing buildings in BC. The table focuses on buildings, rather than utility and transportation infrastructure.

Table 25. Cost-effective seismic mitigation measures for BC's most common needs

ID	Building category	Deficiency	Mitigation measure	Cost/sf	Retrofit design, cost, and vulnerability references
1	All but W1, W4, and MH: New engineered buildings, meaning all but part-9 buildings	Suboptimal strength and stiffness	Lifecycle cost design: increase strength and stiffness requirements to assure life safety and minimize total societal ownership cost	$4	Retrofit, cost, vulnerability: Multi-Hazard Mitigation Council (2019).
2	W4 PC and LC: Existing pre- and low-code wood house with cripple walls	Weak cripple walls (between foundation and first floor)	Brace and bolts retrofit: brace cripple walls and bolt foundations	$7	Retrofit, cost: Federal Emergency Management Agency (2018), Maffei (2023). Vulnerability: Porter et al. (2006a) or treat post-retrofit as higher code.
3	W2 PC and W2 LC: Existing pre- and low-code soft-story woodframe apartments with tuck-under parking	Weak, open ground storey	Soft-story woodframe retrofit: add portal frames, cantilever columns, sheathing, or a combination	$17	For retrofit, cost, and vulnerability: Applied Technology Council (2009), Porter and Cobeen (2012), or treat post-retrofit as higher code.
4	C1 PC, C1 LC, C3 PC, and C3 LC: Existing nonductile reinforced concrete moment frame buildings	Brittle beams and columns	Add shearwalls, braced frames, or column jackets	$250	Porter et al. (2002), Krawinkler et al. (2005), Fung et al. (2020), or treat post-retrofit as higher code.
5	URM: Existing unreinforced masonry bearing wall buildings (collapse prevention goal)	Weak parapets, weak walls, weak roof-to-wall connections	Brace parapets, add wall anchors	$20	Retrofit and cost: McGowan (2023), Fung et al. (2020). Vulnerability: Rutherford and Chekene (1990).
6	MH PC, MH LC, and MH MC: Existing manufactured homes	Poor lateral strength between ground and building	Add engineered tie-downs	$1.30	Multi-Hazard Mitigation Council (2019), or treat post-retrofit as higher code.
7	PC1 or RM1, PC, LC, or MC: Older tilt-up concrete and reinforced masonry with flexible diaphragms	Weak roof-to-wall connections, weak diaphragm continuity	Strengthen roof-to-wall connections and diaphragm continuity	$79	Cost: Fung et al. (2020). For vulnerability, treat post-retrofit as higher code.
8	RES1 through RES6 (different from building types): residential contents	Unsecured furnishings fall	Secure tall furniture, gas water heaters, cabinet doors, and shelf contents	$0.20	Multi-Hazard Mitigation Council (2019).
9	All buildings	Occupants can take self-protective action	Speed adoption of earthquake early warning system	N/A	Earthquakes Canada (2021), Porter and Jones (2018).

Section 4.2 addresses the methodology used here to estimate benefits by benefit category. It will be useful to have past studies' estimates of the relative benefit from different benefit categories. Table 26 provides estimates of the relative contribution to the long-term average benefits from nine mitigation measures, according to the Multi-Hazard Mitigation Council (2019).

Table 26. Relative contribution from various benefit categories, from Multi-Hazard Mitigation Council (2019)

Mitigation measure	Building, contents	Direct business interruption, additional living expenses	Indirect business interruption	Deaths, injuries, PTSD	Urban search and rescue	Multi-Hazard Mitigation Council (2019) reference
Lifecycle cost design	35%	32%	14%	18%	1%	Figure 2-13
Adopt current code	43%	29%	14%	14%	0.30%	Figure 2-24
Soft-story retrofit	58%	26%	13%	3%	0%	Figure 2-52
Add engineered tie-downs	49%	21%	11%	19%	0%	Figure 2-56
Secure hot water heaters	42%	5%	3%	50%	0%	Figure 2-58
Add cabinet latches	93%	5%	2%	0%	0%	Figure 2-60
Strap bookcases	100%	0%	0%	0%	0%	Figure 2-62
Strap monitors	97%	2%	1%	0%	0%	Figure 2-64
Secure fragile objects	87%	9%	4%	0%	0%	Figure 2-66

Note that Table 26 combines deaths, injuries, and cases of post-traumatic stress disorder into a single benefit category. It does so because the Multi-Hazard Mitigation Council (2019) does not break out the relative contribution from reduced deaths, injuries, and instances of post-traumatic stress disorder. However, our file contains the underlying data. Table 27 includes previously unpublished values of the relative contribution of each of these three subcategories.

Table 27. Unpublished relative benefit contribution from deaths versus nonfatal injuries versus PTSD, from Multi-Hazard Mitigation Council (2019)

Mitigation measure	Deaths	Nonfatal injuries	PTSD
Lifecycle cost design	10%	89%	1%
Adopt current code	36%	63%	1%
Soft-story retrofit	56%	40%	3%
Add engineered tie-downs	23%	70%	7%
Secure hot water heaters	74%	22%	4%

Table 28. Unpublished relative benefit contribution from buildings versus contents repairs, from Multi-Hazard Mitigation Council (2019)

Mitigation measure	Buildings	Contents
Lifecycle cost design	121%	-21%
Adopt current code	34%	66%
Soft-story retrofit	98%	2%
Add engineered tie-downs	98%	2%
Secure hot water heaters	68%	32%

Table 26 also combines reduced losses to buildings and contents into one benefit category because the Multi-Hazard Mitigation Council (2019) does not break out their relative contributions. Again, our file contains the underlying data, shown in Table 28.

4.2 Methodology

4.2.1 Select hypothetical earthquakes to examine

For two reasons, it seems most practical either to estimate future losses in the five earthquakes that Hobbs et al. (2023) examine (Table 21) or, where practical, to consider seismic sources that Hobbs et al. (2023) and Scawthorn (2020) both consider (i.e., those shown in Table 22). The first reason is convenience: One can sum the losses under as-is conditions from the two studies and extrapolate the missing loss categories from prior studies, such as Jones et al. (2008). The second reason is synergy for potential future uses: The province will be able to collaborate with the Geological Survey of Canada on future projects of mutual interest without the challenge of creating a new common set of references. We will examine these earthquakes before and after the remediation measures shown in Table 25.

Hobbs et al. (2023) considers an M7.0 Georgia Strait earthquake, while Scawthorn (2020) considers an M7.3 earthquake. The two earthquakes differ substantially in energy release and ground motion; so while the geographic areas that are most strongly shaken are comparable, shaking would be much stronger in the larger earthquake.

4.2.2 Estimate the quantity of buildings that would benefit from mitigation

The geodatabases created by Journeay et al. (2022) for CanSRM1 tabulate building quantities in the same terms as the retrofit measures listed in Table 25. Equation (25) calculates the quantity in square feet of buildings that would benefit from retrofit i that experience scenario k, denoted by Q_{ik}. In the equation, A_{ij} denotes the average area of a building to which retrofit i would apply, where j refers to the occupancy class. See Table 23 for building areas. Let N_{ik} denote the number of buildings that would benefit from retrofit i in scenario k. The number is available in the databases distributed at RiskProfiler.ca.

$$Q_{ik} = \sum_{j} N_{ik} A_{ij} \qquad (25)$$

A challenge to applying equation (25) is to decide the level of shaking that a building needs to undergo to “experience” an earthquake. Where is the geographic boundary to calculate costs and avoidable losses? Let us consider three kinds of boundaries:

1. All of British Columbia.
2. Modified Mercalli Intensity (MMI) I or greater. We can estimate costs and avoided losses for all buildings that RiskProfiler.ca includes in its results tables, which includes motions as low as MMI I, which cannot be felt, and is associated with shaking less than 0.2% of the acceleration due to gravity.
3. Strong motion. We can count costs and avoided losses only for those buildings that experience strong motion in the given earthquake. Engineers tend to consider that a site has experienced “strong motion” if its peak horizontal ground acceleration exceeds 5% of the acceleration due to gravity (0.05 g), which is associated with MMI V or greater, following the examples of Page et al. (1972) and Bolt (1973). At this level of shaking, one begins to see nonstructural damage, such as plaster cracks and contents falling. At this and higher levels of shaking, earthquake early warnings can help prevent injuries, and measures to secure contents can reduce content loss.

For the purpose of this study, it seems reasonable to include the costs and benefits associated with remediating buildings that experience strong motion. The present effort aims to quantify the costs and avoided losses associated with remediating buildings conditioned on the occurrence of a particular disaster, which suggests that it should include buildings that go through that disaster, not those that stand far away from it.

Note that we perform the calculation using the detailed geopackage databases as input. With these databases, one can sum total building areas, building counts, and loss values for a relevant combination of occupancy type, building type, and code era, over all geographic areas that experience motion exceeding an arbitrary threshold in a given earthquake. For example, to calculate the benefit of the brace and bolts retrofit in the Cascadia subduction zone earthquake, one acquires the relevant database and sums the deaths, repair costs, areas, and building counts for all W4 buildings (woodframe with cripple walls) with unbraced cripple walls (i.e., with pre-code, PC, or low-code, LC, design level) in places that exceed 0.05 g of peak ground acceleration, both before and after retrofit.

4.2.3 Apply unit costs and benefits

Let U_i refer to the square-foot cost in Table 25. Then the cost of retrofit *i* for scenario *k*, denoted here by C_{ik}, is given by equation (26). Q_{ik} comes from equation (25).

$$C_{ik} = U_i \cdot Q_{ik} \tag{26}$$

Estimating benefits can be done using either RiskProfiler.ca or a less automated approach. The approach that builds on RiskProfiler.ca data is presented here.

Many of the mitigation measures listed in Table 25 allow one to approximate the post-retrofit building repair costs with RiskProfiler.ca by treating the retrofitted buildings as the same building type but with a higher code level. From building repair costs, one can then extrapolate property repair costs (i.e., buildings plus contents) and other monetary benefits (direct business interruption, indirect business interruption, and urban search and rescue).

Let us calculate mitigation benefits, *B*, using equation (27). In the equation:

L_0 = Property repair costs under as-is conditions, using the RiskProfiler.ca geopackage database, for a given earthquake scenario and a segment of the building stock to which the mitigation measure applies. For example, the database for the Cascadia subduction zone earthquake offers a table of damage data with asset loss under baseline conditions (in the file named "dsra_sim9p0_cascadiainterfacebestfault_indicators_b.gpkg" and field named "sL_Asset_b0").

L_1 = Property repair costs with retrofit, using the RiskProfiler.ca geopackage database, for the same earthquake scenario and building stock segment. For example, the same database table offers asset loss under retrofitted conditions (in field "sL_Asset_r1").

F_1 = Fraction of total monetary loss represented by property loss, as estimated by prior research such as Table 26.

D_0 = Deaths under as-is conditions, using the RiskProfiler.ca geopackage database, for the same scenario and segment of the building stock. For example, the database offers daytime (field "sC_CasDayL4_b0"), nighttime (field "sC_CasNightL4_b0"), and commute-hour (field "sC_CasTransitL4_b0") deaths under as-is conditions.

D_1 = Deaths with retrofit, using the RiskProfiler.ca geopackage database, for the same scenario and segment of the building stock. For example, the database offers daytime (field "sC_CasDayL4_r1"), nighttime (field "sC_CasNightL4_r1"), and commute-hour (field "sC_CasTransitL4_r1") deaths under retrofit conditions.

VSL = Value of a statistical life; $8.9 million in 2023, as discussed in section 2.1.3.

F_2 = Fraction of life-safety benefits represented by avoided deaths, as implied by prior research, such as Table 27.

$$B = \frac{\left(L_0 - L_1\right)}{F_1} + \frac{\left(D_0 - D_1\right) \cdot VSL}{F_2} \qquad (27)$$

Table 29 lists some common building types that, under earlier building codes, tended to exhibit seismic deficiencies. The table also lists common retrofit measures, a reasonable estimate of the square-foot unit costs (from section 4.1.5), and proxy parameter values to scale up from available loss outputs: property damage as a fraction of all monetary damage (F_1) and the acceptable cost to avoid fatalities as a fraction of the monetary value of all life-safety benefits (F_2).

These last two factors are taken from Multi-Hazard Mitigation Council (2019). This source does not examine earthquake braces and bolts for older woodframe buildings, so the F_1 and F_2 are taken from soft-story retrofit, which seems most similar in its relative effects on property loss and life-safety impacts. Similarly, retrofits for older reinforced concrete moment frames, unreinforced masonry, tilt-ups, and reinforced masonry make these buildings behave more like modern construction, so the most similar measure from Multi-Hazard Mitigation Council (2019) seems to be "adopt current code."

Table 29. Leading seismic retrofit measures for common building types

Building type	Retrofit	U ($/sf)	F_1	F_2	F_1 and F_2 most similar to
Older wood house	Earthquake brace and bolt	$7	60%	56%	Soft-story retrofit
Wood apartment building	Soft-story retrofit	$17	60%	56%	Soft-story retrofit
Nonductile concrete frame	Add shearwalls to openings	$250	50%	36%	Adopt current code
Unreinforced masonry	Brace parapets, bolt walls	$20	50%	36%	Adopt current code
Manufactured home	Add engineered tie-downs	$1.30	60%	23%	Engineered tie-downs
Tilt-up and reinforced masonry	Fix roof-to-wall connections	$79	50%	36%	Adopt current code

4.3 Results

4.3.1 Costs and avoidable losses in M9.0 Cascadia earthquake

Figure 25 shows the CanSRM1 map of estimated shaking in a magnitude-9.0 earthquake in the Cascadia subduction zone. Table 30 shows the quantity of buildings that would experience shaking at least 5% of gravity and, therefore, would potentially benefit from mitigation measures such as earthquake early warning systems and nonstructural retrofit.

The values in Table 30 are calculated using the detailed databases mentioned earlier in the geopackage files offered by RiskProfiler.ca. Rows in the table repeat the mitigation options listed in Table 29. The *N* column in Table 30 shows the number of buildings. The *Q* column shows the approximate area of those buildings in millions of square feet. The *C* column shows the approximate cost to retrofit the affected buildings, in millions of 2023 Canadian dollars. The column labelled $L_0 - L_1$ shows the estimate in RiskProfiler.ca of the reduction in property loss (building and content repairs) that retrofit would provide, in millions of 2023 Canadian dollars. The column labelled $D_0 - D_1$ shows the estimate of the reduction in fatal injuries in a daytime earthquake. (The mitigation measures provide the same or smaller safety benefits in a nighttime earthquake.) The *B* column shows the equivalent total dollar amount of avoidable losses, including building and content repairs, direct and indirect business interruption, urban search and rescue costs, and acceptable regulatory costs to avoid the deaths, injuries, and instances of post-traumatic stress disorder.

Table 30 shows that in the Cascadia earthquake, three of the measures would avoid more losses than the mitigation measure costs:

- Earthquake braces and bolts for older woodframe houses
- Soft-story retrofit for older woodframe apartment buildings
- Adding engineered tie-downs to older manufactured homes.

Implementing these three measures would cost about $4 billion but avoid $8 billion in an inevitable future Cascadia subduction zone earthquake. As with storms and fires, the costs and benefits are uncertain, within a factor of perhaps 1.5 times higher or lower.

Figure 25. Map of estimated ground shaking in an M9.0 Cascadia subduction zone earthquake scenario from RiskProfiler.ca.

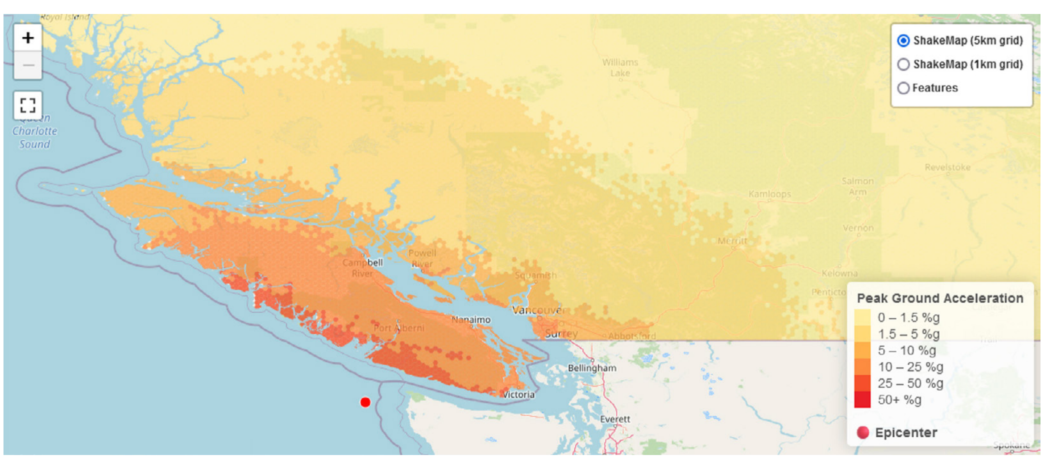


Table 30. Costs and avoidable losses for an M9.0 Cascadia subduction zone earthquake

Building type and common retrofit	Buildings *N*	Area *Q* (M sf)	Cost *C* ($ M)	Property benefit $L_0 - L_1$ ($ M)	Lives saved $D_0 - D_1$	Benefit *B* ($ M)	*B* > *C*
Older wood house: brace and bolt	54,834	177	$1,240	$1,656	0	$2,769	Yes
Wood apartment building: soft-story retrofit	8,940	183	$3,116	$3,081	1	$5,168	Yes
Nonductile concrete frame: add shearwalls	8,859	94	$23,535	$413	52	$2,114	No
URM: brace parapets, bolt walls	22,428	179	$3,586	$0	6	$148	No
Manufactured home: engineered tie-downs	13,904	26	$34	$236	0	$394	Yes
Tilt-up, reinforced masonry: roof-wall connections	19,326	259	$20,436	$1,158	15	$2,695	No

4.3.2 Costs and avoidable losses in M7.3 Leech River Fault earthquake

Figure 26 shows estimated shaking in the magnitude-7.3 earthquake on the Leech River Fault, and Table 31 includes the costs and avoidable losses. The table is organized like Table 30; see section 4.3.1 for an explanation of its contents. Table 31 shows that common retrofits for the same three building types seem to exhibit avoidable losses that exceed the costs:

- Retrofit older single-family woodframe buildings using earthquake braces and bolts
- Strengthen older woodframe apartment buildings using soft-story retrofit
- For older manufactured homes, add engineered tie-downs.

Figure 26. Map of estimated ground shaking in an M7.3 Leech River Fault earthquake scenario from RiskProfiler.ca.

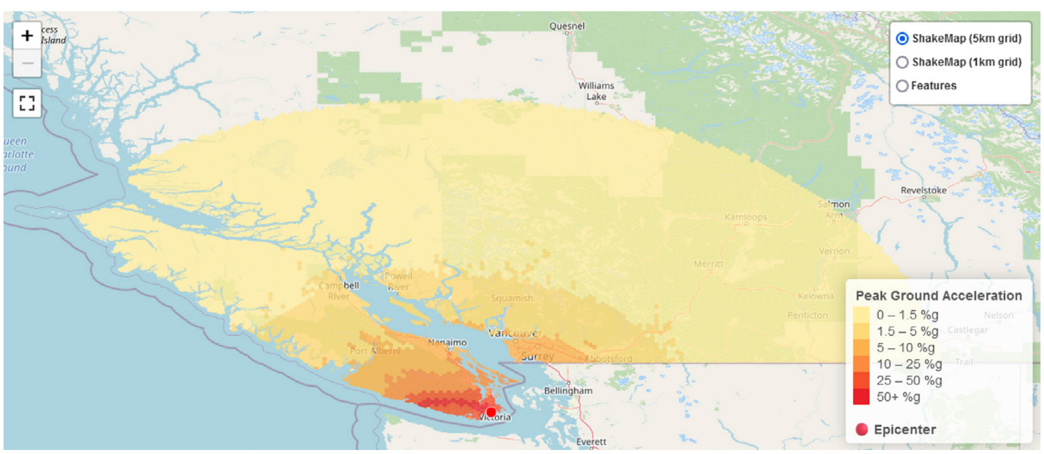


Table 31. Costs and avoidable losses for an M7.3 Leech River Fault earthquake

Building type and common retrofit	Buildings *N*	Area *Q* (M sf)	Cost *C* ($ M)	Property benefit $L_0 - L_1$ ($ M)	Lives saved $D_0 - D_1$	Benefit *B* ($ M)	*B* > *C*
Older wood house: brace and bolt	36,941	125	$873	$880	0	$1,471	Yes
Wood apartment building: soft-story retrofit	6,402	129	$2,192	$1,498	6	$2,601	Yes
Nonductile concrete frame: add shearwalls	6,377	68	$17,056	$168	22	$880	No
URM: brace parapets, bolt walls	16,510	134	$2,676	$0	8	$198	No
Manufactured home: engineered tie-downs	8,309	17	$22	$114	0	$191	Yes
Tilt-up, reinforced masonry: roof-wall connections	13,431	179	$14,104	$612	31	$1,995	No

4.3.3 Costs and avoidable losses in M7.0 Georgia Strait earthquake

Figure 27 shows estimated shaking in the magnitude-7.0 earthquake on the Georgia Strait fault, and Table 32 shows costs and avoidable losses. The table is organized like Table 30; see section 4.3.1 for an explanation of its contents. Like the previous two earthquake scenarios, this table shows that common retrofits for the same three building types seem to exhibit avoidable losses that exceed the costs:

- Retrofit older single-family woodframe buildings using earthquake braces and bolts
- Strengthen older woodframe apartment buildings using soft-story retrofit
- For older manufactured homes, add engineered tie-downs

Figure 27. Map of estimated ground shaking in an M7.0 Georgia Strait earthquake scenario from RiskProfiler.ca.

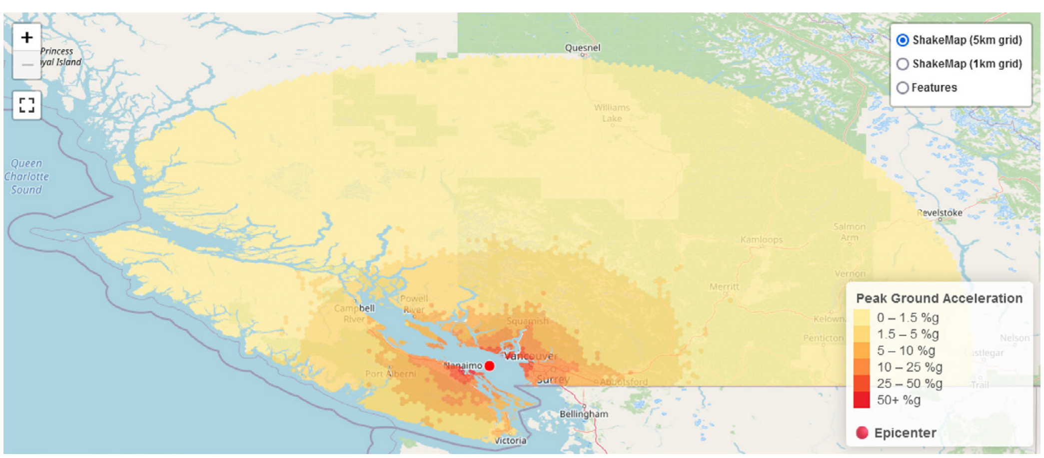


Table 32. Costs and avoidable losses for an M7.0 Georgia Strait earthquake

Building type and common retrofit	Buildings *N*	Area *Q* (M sf)	Cost *C* ($ M)	Property benefit $L_0 - L_1$ ($ M)	Lives saved $D_0 - D_1$	Benefit *B* ($ M)	$B > C$
Older wood house: brace and bolt	42,765	140	$977	$1,354	0	$2,265	Yes
Wood apartment building: soft-story retrofit	7,015	141	$2,393	$2,449	2	$4,127	Yes
Nonductile concrete frame: add shearwalls	7,138	76	$18,980	$269	19	$1,010	No
URM: brace parapets, bolt walls	18,816	152	$3,034	$0	2	$49	No
Manufactured home: engineered tie-downs	9,538	19	$25	$152	0	$254	Yes
Tilt-up, reinforced masonry: roof-wall connections	15,883	212	$16,762	$866	13	$2,059	No

4.3.4 Costs and avoidable losses in M7.1 Sidney earthquake

Figure 28 shows estimated shaking in a magnitude-7.1 Sidney earthquake, and Table 33 includes costs and avoidable losses. The table is organized like Table 30; see section 4.3.1 for an explanation of its contents. This table shows that common retrofits for two building types seem to exhibit avoidable losses that exceed the costs:

- Retrofit older single-family woodframe buildings using earthquake braces and bolts
- For older manufactured homes, add engineered tie-downs.

Soft-story retrofit of tuck-under parking for older woodframe apartment buildings costs slightly more than the losses it would avoid.

Figure 28. Map of estimated ground shaking in an M7.1 Sidney earthquake scenario from RiskProfiler.ca.

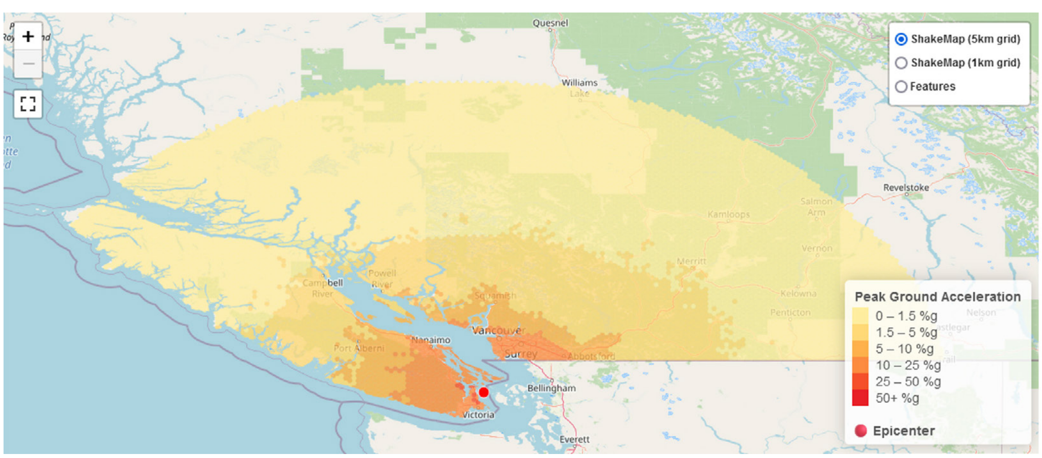


Table 33. Costs and avoidable losses for an M7.1 Sidney earthquake

Building type and common retrofit	Buildings *N*	Area *Q* (M sf)	Cost *C* ($ M)	Property benefit $L_0 - L_1$ ($ M)	Lives saved $D_0 - D_1$	Benefit *B* ($ M)	*B* > *C*
Older wood house: brace and bolt	49,917	165	$1,152	$975	0	$1,631	Yes
Wood apartment building: soft-story retrofit	8,432	172	$2,924	$1,528	0	$2,555	No
Nonductile concrete frame: add shearwalls	8,079	87	$21,628	$180	2	$411	No
URM: brace parapets, bolt walls	21,268	171	$3,418	$0	0	$0	No
Manufactured home: engineered tie-downs	10,715	22	$28	$126	0	$210	Yes
Tilt-up, reinforced masonry: roof-wall connections	17,843	239	$18,843	$680	0	$1,366	No

5. Conclusions

This study reinforces that natural hazard mitigation saves money and lives, and in many situations and for many mitigation measures, it saves more than it costs. This is true for all three types of disasters considered here: severe storms, wildfires, and earthquakes.

1. ***Severe storms***. Undertaking pluvial, fluvial, and wind retrofit before the 2021 November Rainstorm would have cost $1 billion but avoided $2.3 billion of the losses. Mitigation measures vary for the 12,400 affected buildings. Buildings subject to pluvial flooding would benefit from up to three basement flood-protection measures: proper soil grading, sewer backflow valves, and battery backup sump pumps. Buildings subject to fluvial flooding receive a mix of buyouts, elevations, equipment elevations, wet floodproofing, or dry floodproofing. Buildings subject to strong winds would benefit from stronger structural connections in accordance with CSA S520:22. Costs and benefits for these mitigation measures are uncertain. Table 34 lists the mitigation measures considered here and presents costs, benefits, retrospective benefit-cost ratios, and reasonable ranges of each.
2. ***Wildfires***. Had the Village of Lytton required buildings to comply with the *National Guide for Wildland-Urban Interface Fires* before the 2021 fire occurred and had all of the buildings complied by maintaining priority zones 1A to 2 (mostly relying on vegetation management within 30 m of the building perimeter), about $330 million in losses would have been avoided at a cost of about $1.7 million. Had the community affected by the Williams Lake wildfire retrofitted beforehand, it would have cost an estimated $110 million and saved $340 million. Again, Table 34 includes building counts and reasonable ranges.
3. ***Earthquakes***. Implementing three seismic retrofit measures in British Columbia would cost about $4.4 billion but avoid $8.3 billion in damage in an inevitable future Cascadia subduction zone earthquake. The three measures are earthquake braces and bolts for older woodframe houses with unbraced cripple walls, soft-story retrofit for older woodframe apartment buildings with tuck-under parking, and adding engineered tie-downs to older manufactured homes. Table 34 includes building counts, costs, benefits, and reasonable ranges for all four earthquakes considered here

Table 34. Recap of estimated retrospective costs and benefits

Event	Number of buildings needing mitigation	Cost 2023 $M (range)	Benefit 2023 $M (range)	Benefit-cost ratio (range)
2021 November Rainstorm	12,400 (8,400 for basement flood, 3,900 for fluvial flood, 100 for wind)	1,000 (700-1,500)	2,300 (1,500-3,500)	2 (1-5)
2021 Wildfires	100	1.7 (1.3-2.6)	330 (220-440)	170 (85-340)
2017 Wildfires	6,400	110 (80-160)	340 (230-460)	3 (1-6)
M9.0 Cascadia subduction zone earthquake	78,000 (55,000 cripple-wall houses, 9,000 soft-storey apartment buildings, and 14,000 manufactured homes)	4,400 (3,000-6,000)	8,300 (5,500-11,000)	2 (1-4)
M7.3 Leech River Fault earthquake	52,000 (37,000 cripple-wall houses, 7,000 soft-storey apartment buildings, 8,000 manufactured homes)	3,100 (2,100-4,200)	4,300 (2,900-5,800)	1.4 (1-3)
M7.0 Georgia Strait earthquake	59,000 (43,000 cripple-wall houses, 7,000 soft-storey apartment buildings, 9,000 manufactured homes)	3,400 (2,300-4,600)	6,600 (4,400-8,800)	2 (1-4)
M7.1 Sidney earthquake	61,000 (50,000 cripple-wall houses, 11,000 manufactured homes)	1,200 (800-1,600)	1,800 (1,200-2,400)	2 (1-3)

This study comes with important caveats. Here are four leading considerations.

1. This study presents estimates of losses that could have been avoided in a few past disasters and a few hypothetical future ones, without considering the prior chances that the event would occur. These are scenario benefits, rather than probabilistic benefits. One can divide the scenario benefits by the costs, producing something resembling a benefit–cost ratio. But because these are scenario benefits, not probabilistic benefits, one cannot compare them with benefit–cost ratios of past studies, like Multi-Hazard Mitigation Council (2019).
2. The estimated avoidable losses do not exceed the costs in cases considered here, at least as far as we are able to estimate the costs and benefits. On the other hand, we did not examine all common mitigation measures in all the disasters considered here. For example, we omit consideration of community flood protection with levees and enhancements to stormwater conveyance systems. Broadening our scope might reveal other cases where avoidable losses greatly exceed the mitigation costs.
3. Avoided loss estimates omit losses that one mitigation effort would avoid in other possible disasters. For example, considering the earthquake scenarios evaluated here, retrofit costs for many of the same buildings appear in all four scenarios, but the retrofit cost would only have to be borne once, not four times. In many cases, the same retrofit would avoid losses in all four earthquake scenarios.
4. Applying multiple mitigation measures could produce synergies. Maybe comprehensive mitigation produces benefits that exceed the sum of the benefits from individual do not provide alone. We have not attempted even to identify such synergies.

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Institute for Catastrophic Loss Reduction
Institut de prévention des sinistres catastrophiques

Toronto Office
30-34 Duncan Street
Toronto, Ontario, Canada
M5V 2C3

T 416-364-8677

London Office
Western University
Amit Chakma Building
Suite 4405
1151 Richmond Street
London, Ontario, Canada
N6A 5B9

T 519-661-3234

F 519-661-4273

info@iclr.org

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