Study of Impact and the Insurance and Economic Cost of a Major Earthquake in British Columbia and Ontario/Québec

October 2013

Commissioned by the Insurance Bureau of Canada

IBC BAC Insurance Bureau of Canada
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Contact Information

If you have any questions regarding this document, contact:

AIR Worldwide
131 Dartmouth Street
Boston, MA 02116-5134
USA
Tel: (617) 267-6645
Fax: (617) 267-8284

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1 Executive Summary

Earthquake in Canada, a new appreciation of risk

One of the most destructive natural disasters that Canada could experience is a major earthquake affecting a highly-populated area. British Columbia and the Ontario/Québec region are each at particular risk due to their large population density and elevated level of seismic activity. Recent events, such as the devastating earthquakes that struck Japan (M9.0 in 2011), Chile (M8.8 in 2010), New Zealand (M7.0 in 2010 and M6.1 in 2011), and Turkey (M7.1 in 2011) have highlighted the issue of insurance industry preparedness for such catastrophic events.

The most recent study of the economic impact of an earthquake in Canada was conducted by Munich Re in 1992[1]. Urban and infrastructure development, economic and population growth, advances in earthquake research and building codes, and changes to the Insurance Act in British Columbia over the last two decades have led to a revised understanding of the potential impact of a major earthquake. Furthermore, recent experience has shown that risks such as tsunami, liquefaction, and business interruption may not have been fully understood or taken into consideration when assessing earthquake risk in the past.

The study

AIR Worldwide (AIR) was engaged by the Insurance Bureau of Canada (IBC) to conduct a study of the impact and the insurance and economic costs of major earthquakes affecting British Columbia and the Ontario/Québec region. This massive undertaking would not have been possible without the valuable assistance of many partners and peer reviewers. Section 11 contains biographies of Drs Robert McCaffrey, Michael L. Lahr, Oh-Sung Kown, Adam Rose and Dan Wei, with whom we collaborated. Section 12 contains biographies of Drs. Keisuke Himoto, Stephane Mazzotti, Marie-José Nollet, and Geoff Thomas, each of whom provided a peer review.

This is the most comprehensive and all-inclusive study of its type yet done for Canada. It is intended to raise awareness and to serve as a valuable tool for the

[1] *A Study of the Economic Impact of a Severe Earthquake in the Lower Mainland of British Columbia*, the Munich Reinsurance Company of Canada, 1992.

insurance industry, government agencies, regulators, disaster preparedness organizations and the public in planning for, and mitigating, the risk from future earthquakes in Canada.

AIR modeled two particular events for the study, both attributable to established seismic sources and similar to earthquakes known to have taken place in the past—and therefore realistic scenarios. Having ascertained the likely ground motion across the target areas, AIR calculated probable levels of damage and their cost. In this report, these two scenarios are termed the *western scenario* and the *eastern scenario*. Unless otherwise stated, the unit of currency used in the report is the Canadian dollar.

The study is not a prediction of future events but a hypothetical exercise designed to indicate the scale of losses possible should major events strike at the present time. The earthquake rupture parameters used in this analysis represent only two of the many possibilities for events like them striking these regions in the future. The impact of the events chosen for the study and their projected loss costs can however be seen as good indicators for the likely outcome of similar events.

While the modeled events are realistic possibilities for British Columbia and the Ontario/Québec region they are not the worst-case scenarios that could happen in these two areas. Earthquakes of the magnitude modeled are low-frequency events in these locations, considered to have a 0.2% probability of occurring in any one year, but sufficiently threatening and devastating to warrant prudent planning and preparation now.

The scenarios

About 4,000 earthquakes are recorded in Canada each year. Most are small and not felt by humans. But some are large. In the past three centuries there have been at least 24 significant earthquakes that were widely felt in Canada. Figure 1 shows historic earthquakes in Canada with a magnitude greater than 5.0. These significant events are mainly concentrated in two regions, one off the west coast of British Columbia and the other in southeastern Canada, mainly in southern Québec and southeastern Ontario. Although these two seismic source zones cover only a small fraction of Canada by area, they impact about 40% of the national population.

According to studies by the Geological Survey of Canada and Natural Resources Canada, southwestern British Columbia, including the provincial capital, Victoria, and the Vancouver metropolitan area, falls in a high-risk area. There is at least a 30% chance that an earthquake strong enough to cause significant damage will strike this area in the next 50 years. In the east, the region from the St. Lawrence River Valley to the Ottawa Valley—an area including Québec City, Montreal, and Ottawa—is another high-risk area in which there is at least a 5-15% chance that a strong earthquake will strike in the next 50 years.

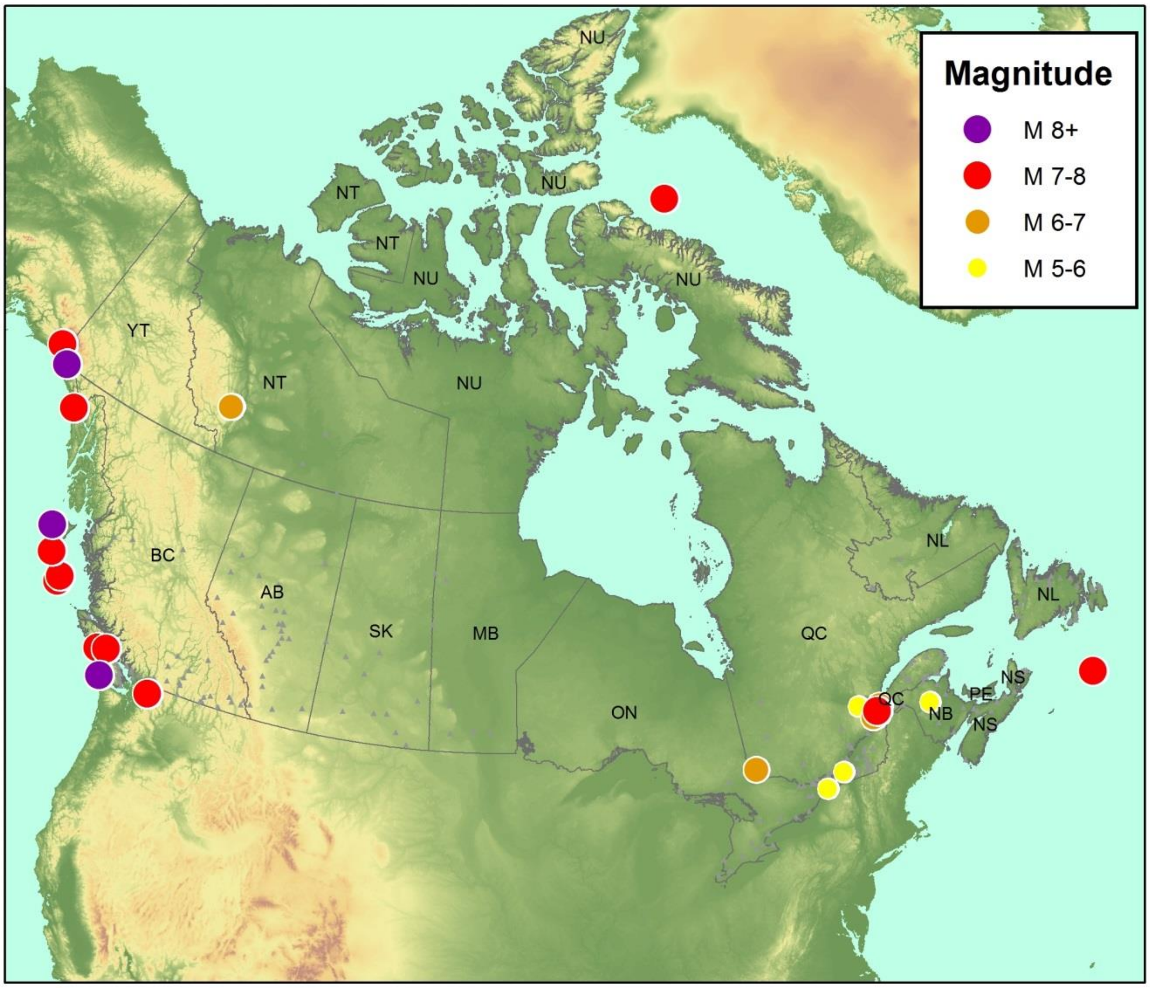


Figure 1: Significant historic earthquakes in Canada

This study selects two earthquake scenarios, one from each of the two higher-risk zones. A description of the method used to select the scenarios is found in Section 2.3 of this report. The scenario selected in the west seismic region is located in the Cascadia subduction zone, which has ruptured several times in recent geological history accompanied by great earthquakes, and last ruptured in 1700 in a magnitude 9.0 megathrust earthquake. The scenario selected in the southeastern seismic region is a magnitude 7.1 earthquake in the Charlevoix seismic zone. At least six or seven magnitude 5 or greater earthquakes are known to have occurred in the Charlevoix seismic zone (1663, 1791, 1860, 1870, and 1925). It is one of the most active seismic source zones in eastern North America.

1.1 The Western Cascadia Subduction Scenario

The first scenario studied in depth is the Western Cascadia Subduction Scenario, referred to through the remainder of this report as the *western scenario*. This earthquake happens on a weekday late in July. It is an extremely powerful event, with a magnitude of 9.0, occurring in the Cascadia subduction zone at the shallow depth of 11 km. The location of the rupture and the ground motion associated with it are shown in Figure 2. The epicentre location (Lat. 44.706, Lon. -124.569) is in the Pacific Ocean, approximately 75 km off the west coast of Vancouver Island, some 300 km from downtown Vancouver. The nature, size, and location of the event enable it to generate a modest tsunami.

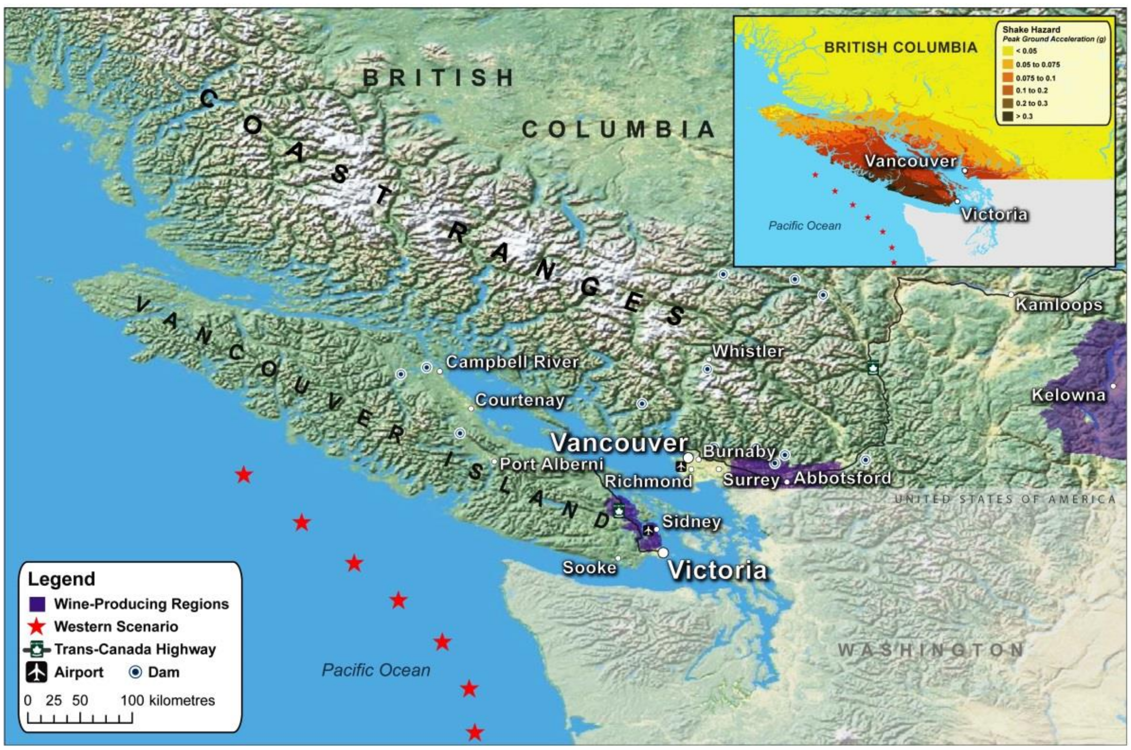


Figure 2: The location of the western scenario rupture is indicated by the red stars on this map

The earthquake is powerful enough to be felt over much of British Columbia and Washington State in the United States. The lower two thirds of Vancouver Island, being closest to the epicentre, would experience the strongest ground motion but much of the area outside the capital city of Victoria and its environs contains comparatively little insured property and low levels of insurance losses are anticipated. The greatest concentration of exposed assets in the region is the Metro Vancouver area, which experiences moderate shaking.

Anticipated damage

In this scenario, ground shaking is responsible for the majority of ground-up losses, but landslides, the tsunami, and fires following the rupture also contribute to the damage inflicted. The first tsunami wave is expected to reach Vancouver two hours after the earthquake. By then its height above tide level will have been reduced by its extended journey and its interactions with the intervening islands. Fires may start soon after the earthquake, or develop later as power supplies are resumed.

The nature of the ground motion associated with this type of earthquake can be particularly damaging to inadequately engineered tall buildings and bridges, and to pipelines. Unreinforced masonry buildings are particularly at risk. Damage to well-built modern buildings will be relatively slight, however.

Vancouver Island

Being closest to the epicentre of the event, the western side of Vancouver Island—and most particularly the southern half—would experience the strongest ground motion and the worst levels of damage to buildings and other property. We anticipate considerable damage to ordinary buildings in areas with the most violent ground motion, and severe damage to poorly built structures. Unreinforced masonry buildings will feel the worst effects, including widespread damage to chimneys and some partial collapses. The historic heritage and vintage buildings that give so much character to Victoria and Duncan for example, are particularly at risk. Victoria will be damaged by fires following the earthquake and some wood residential buildings near Esquimalt will suffer significant damage from the tsunami and landslides. Certain areas in Gordon Head, in the northern part of Victoria, may expect substantial landslide damage. Substantial to very heavy damage is expected in some areas along the Haro Strait, such as Cordova Bay, where most of the damage will be due to flooding from the tsunami. Generally, light to moderate damage is expected to commercial and industrial buildings.

Victoria International Airport is expected to sustain low to moderate levels of damage and no major service disruption is anticipated. The earthquake is however expected to cause slight to moderate damage to components of the Port of Victoria, through ground settlement affecting waterfront structures for example. Port Alberni at the head of the Alberni Inlet will experience severe shaking and ground failure as a result of the earthquake, which may lead to moderate damage to port facilities. Nanaimo, on the east coast of the island, will be hit hard by shaking and tsunami inundation. The extent of the damage anticipated is so large that the port may be out of use for many months.

Vancouver City

Residential buildings in Vancouver are mostly low-rise, with some mid-rise condominiums, and light damage is generally expected to these, and to commercial and industrial buildings. In coastal areas around the University of British Columbia tsunami may be a considerable contributor to losses to commercial and industrial property and business interruption in this vicinity may be several weeks. Substantial liquefaction damage may be observed in areas around the North Arm of the Fraser River and Sea Island.

Mid-rise commercial buildings in the south of New Westminster and north of Surrey and Delta may experience moderate damage, which may lead to downtime of more than a month in some cases. Part of this damage could be attributed to liquefaction. These communities are built on silty and sandy sediments that tend to amplify seismic waves, and as a result they will experience more powerful ground motion. Damage to higher buildings (eight or more stories) in these areas may be large, particularly the losses to contents. Inspection and repair in some of these buildings may take a few months. Government buildings around Richmond City Hall are expected to experience moderate damage. Most residential buildings in Richmond are low-rise and moderate damage is expected to these also. Some residential buildings in west Richmond and near the Fraser River are expected to experience substantial tsunami damage. Also commercial buildings in southern areas such as Gilmore (south of Richmond Country Club) and Paramount (Stevenston Harbor), substantial tsunami damage is expected.

As a result of ground shaking and liquefaction, some roads will be damaged and impassable, water supply and other buried services will be compromised, and many bridges will be closed temporarily. Most of the major roadways in and around Vancouver may experience only slight damage and closure of more than a few hours is not expected. However, damage to bridges may lead to the closure or rerouting of many highways and local roads. Road access to Vancouver from the north via the Lion's Gate and Ironworker's Memorial (Second Narrows) Bridges should be unaffected, but access to Vancouver from the east will be impaired. The Port Mann Bridge on Route 1 for example, is expected to be functional but with some minor disruption—repairs might take a few days. Road travel between

Richmond and Vancouver to the north and Delta and Surrey to the south is also likely to be impaired. Road access to Vancouver Airport will be cut off during the first few critical days after the earthquake as all of the bridges leading to it are impacted. Sea Island, on which Vancouver International Airport is situated, is at moderate risk for liquefaction—a likely source of damage to the runways. Buildings such as terminals, towers, and hangars are expected to sustain slight to moderate damage. Only slight damage is expected to occur however at Abbotsford International Airport. While damage to port facilities in and around Vancouver Harbor itself will probably be slight, damage to facilities in south Richmond and north of Delta and Surrey (around the Fraser River) will be greater due to liquefaction and flooding.

Modeled losses

The study modeled both total economic loss and insured loss. Total economic loss includes direct losses to property and infrastructure, and indirect losses due to supply chain interruptions, infrastructure network disruptions and other problems related to interconnectivity between economic sectors. Table 1 summarizes the economic and insured losses for the western scenario.

Table 1: Summary of losses inflicted by western scenario

Direct and Indirect Loss				
Peril	**Property**	**Infrastructure**	**Public Assets**	**Total**
Shake	48,639	1,044	1,333	51,016
Tsunami	4,208	91	65	4,364
Fire Following	519	0	14	534
Liquefaction and Landslide	5,250	753	83	6,086
Total Direct Loss	**58,617**	**1,888**	**1,495**	**62,000**
Indirect Impact				12,744
Total Direct and Indirect Loss				**74,744**
Insured Loss				
Shake				17,078
Tsunami				1,117
Fire Following				337
Liquefaction and Landslide				1,899
Total Insured Loss				**20,431**

All figures are in millions and include demand surge, or post event inflation.

Infrastructure and public asset values are shown with no distinction between all property and insured values because market penetration rates could not be determined from available data.

Indirect Impact reflects the midpoint estimate.

Table 2 summarizes the indirect losses to infrastructure for the western scenario with resilience, without resilience, and at the midpoint.

Table 2: Western scenario, infrastructure indirect losses from various sources

Source of Impact	Without Resilience	With Resilience	With Resilience – Midpoint
Building Damages	18,612	3,802	11,207
Oil Pipeline Disruption	34	4	19
Gas Pipeline Disruption	396	13	205
Water Supply Disruption	564	32	298
Power Supply Disruption	671	86	379
Telecom System Disruption	852	49	450
Air Ports Disruption	83	41	62
Sea Ports Disruption	111	55	83
Roads Disruption	44	11	27
Railroads Disruption	18	9	14
Total	**21,385**	**4,103**	**12,744**

All figures are in millions

Figure 3 shows the proportion of loss associated with each type of insurance coverage (left) and with each line of business (right).

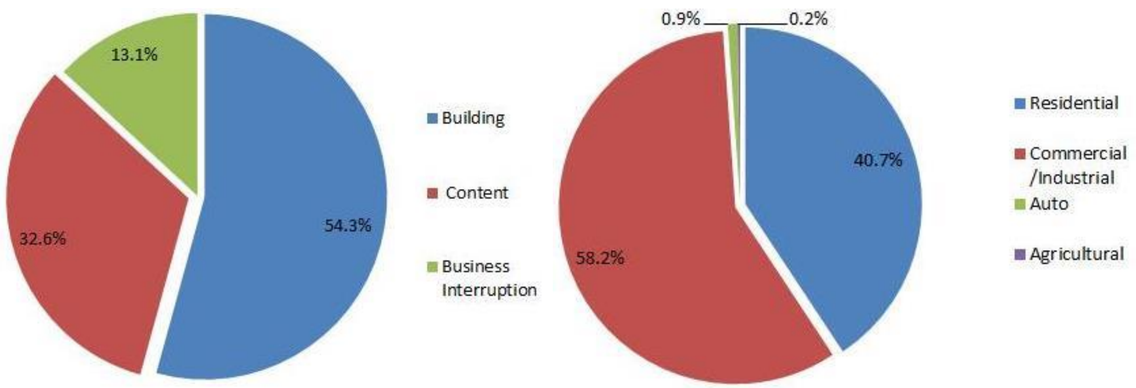


Figure 3: Western scenario direct loss by coverage (left) and by line of business (right)

1.2 The Eastern Charlevoix Crustal Scenario

The second scenario in this study, the Eastern Charlevoix Crustal Scenario, is referred to through the remainder of the report as the *eastern scenario*. It occurs early in December, and is a powerful earthquake, with a magnitude of 7.1, occurring at the shallow depth of 10 km. The location of the epicentre (Lat. 47.245, Lon. -70.470) is beneath the St. Lawrence River, about halfway between Bai-Saint-Paul on the north bank and Montmagny on the south, and almost 100 km north east of Québec City. The location of the event and the ground motion associated with it are shown below in Figure 4. Tsunami is not an issue with this inland event.

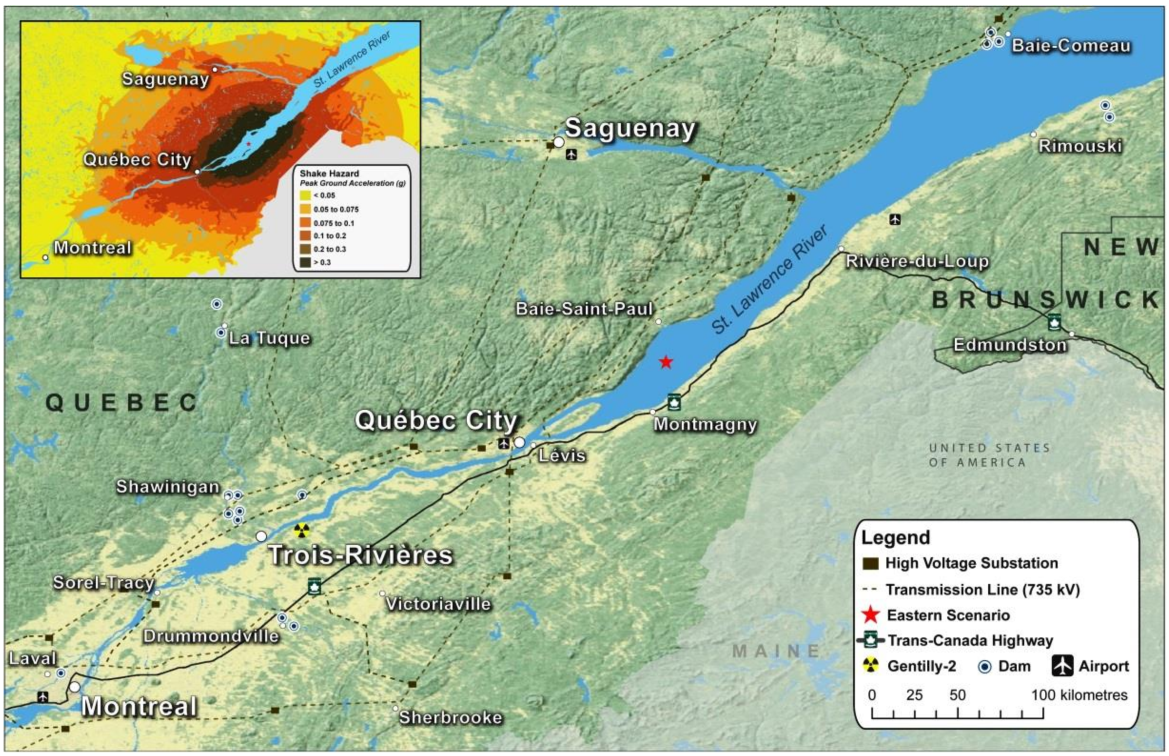


Figure 4: The location of the eastern scenario rupture is indicated by the red star on near the centre of this map

The earthquake is powerful enough to be felt over much of Ontario, Québec, New Brunswick, Nova Scotia, and parts of the United States. The western scenario models a magnitude 9 event—a much more powerful earthquake than this—with its epicentre some 300 km from Vancouver. But the eastern scenario earthquake, although weaker, is felt more strongly since it occurs closer to Québec City. As a result, the city experiences a degree of shaking similar to that felt in Vancouver due to the western scenario.

Anticipated damage

Ground shaking is responsible for the vast majority of losses to all property and infrastructure in this scenario. Because the epicentre of the earthquake is so close to it, Québec City and its environs experiences more violent shaking than Vancouver does in its scenario. Modern engineered structures should perform well, but poorly-built masonry buildings in particular will experience serious damage. The historic unreinforced masonry buildings that are so prevalent in Québec City's upper and lower towns for example, are particularly at risk.

The strongest and most damaging shaking from the earthquake will be experienced in the rural communities along the north and south banks of the St. Lawrence River within a radius of about 50 km of the epicentre. In addition to commercial properties, residential buildings, particularly the unreinforced masonry structures in the city of Beaupré, may suffer very heavy damage, or even total destruction. Damage of this nature will be widespread and will extend as far as Saint-Tite-de-Caps and across the river to Montmagny, Berthier-sur-Mer and Cap-Saint-Ignace. The bridges crossing Rivière Montmorency on Route 138 (Boulevard Sainte-Anne) and Route 360 (Avenue Royale) are expected to suffer extensive damage.

Québec City

Commercial buildings in and around the Place Fleur de Lys are likely to suffer moderate to extensive damage due to the severe ground shaking. The highway bridges crossing the St. Charles River on Route 440 (Autoroute Dufferin-Montmorency) and the highway and railway bridges on Route 136 (Boulevard Jean Lesage) as well as the one on Route 175 (Autoroute Laurentienne) are likely to suffer moderate to extensive damage. The closure of these bridges, if required, will significantly hamper the traffic and transportation between Québec City and the populated districts of La Cite'-Limoilou. Damage to high-rise establishments in the Québec City area is expected to be light and residential buildings in downtown Québec will mainly suffer light to moderate damage.

In Old Québec damage in the areas surrounding the Parliament buildings is expected to be light to moderate, and damage to the mid-rise steel and concrete buildings will be light. The earthquake is however expected to cause moderate structural and non-structural damage to the historic buildings in this area. While most of the anticipated damage will be due to ground shaking some fire following incidents are also likely to contribute to the losses.

Port and rail infrastructure is not expected to be significantly damaged, but the greatest infrastructure loss will be experienced by the electricity and telecommunications sector. Power is expected to be out for a few days in Québec City and in many of the most developed parts of the metro area, but communities to the east along the St. Lawrence River will face much longer outages.

Most of the major roadways in and around Québec City may experience only slight damage due to settlement or offset of the ground, and no significant closures are expected. However, further to the east, between Baie-Saint-Paul and La Malbaie, moderate damage to local roads will be widespread Many bridges will have high degrees of damage which will need considerable closure and repair time. Most seriously, the two bridges spanning the St. Lawrence River will be severely impacted, and may be closed to traffic for a considerable amount of time.

Structures such as terminals, towers, and hangars at Jean Lesage International Airport, located about seven miles southwest of Québec City, are expected to sustain minor to moderate damage. Runways may experience minor to moderate ground settlement or buckling of the tarmac surface. Despite moderate damage of this nature no major disruption or loss of functionality is anticipated at the airport. The earthquake is however expected to cause widespread damage in the Port of Québec, both directly from ground shaking and from liquefaction. The greatest damage will likely occur in and around the Basin Louise, in which moderate to severe damage may put port facilities out of service for one or two weeks.

Modeled losses

The study modeled both total economic loss and insured loss. Total economic loss includes direct losses to property and infrastructure, and indirect losses due to supply chain interruptions, infrastructure network disruptions, and other problems related to interconnectivity between economic sectors. Table 3 summarizes the economic and insured losses for the eastern scenario.

Table 3: Summary of losses inflicted by the eastern scenario

Direct and Indirect Loss				
Peril	**Property**	**Infrastructure**	**Public Assets**	**Total**
Shake	44,915	1,891	1,354	48,159
Fire Following	706	0	19	726
Liquefaction and Landslide	302	67	5	374
Total Direct Loss	**45,922**	**1,958**	**1,378**	**49,259**
Indirect Impact				11,336
Total Direct and Indirect Loss				**60,595**
Insured Loss				
Shake				11,543
Fire Following				628
Liquefaction and Landslide				56
Total Insured Loss				**12,228**

All figures are in millions and include demand surge, or post event inflation.

Infrastructure and public asset values are shown with no distinction between all property and insured values because market penetration rates could not be determined from available data.

Indirect Impact reflects the midpoint estimate.

Table 4 summarizes the indirect losses to infrastructure for the eastern scenario with resilience, without resilience, and at the midpoint.

Table 4: Eastern scenario, infrastructure indirect losses from various sources

Source of Impact	**Indirect Loss w/o Resilience**	**Indirect Loss with Resilience**	**Indirect Loss with Resilience – Midpoint**
Building Damages	13,997	5,224	9,610
Oil Pipeline Disruption	50	5	28
Gas Pipeline Disruption	240	8	124
Water Supply Disruption	385	20	203
Power Supply Disruption	1315	156	735
Telecom System Disruption	738	36	387
Air Ports Disruption	32	16	24
Sea Ports Disruption	163	82	123
Roads Disruption	61	11	36
Railroads Disruption	97	36	67
Total	**17,078**	**5,594**	**11,336**

All figures are in millions

Figure 5 shows the proportion of loss associated with each type of insurance coverage and with each line of business.

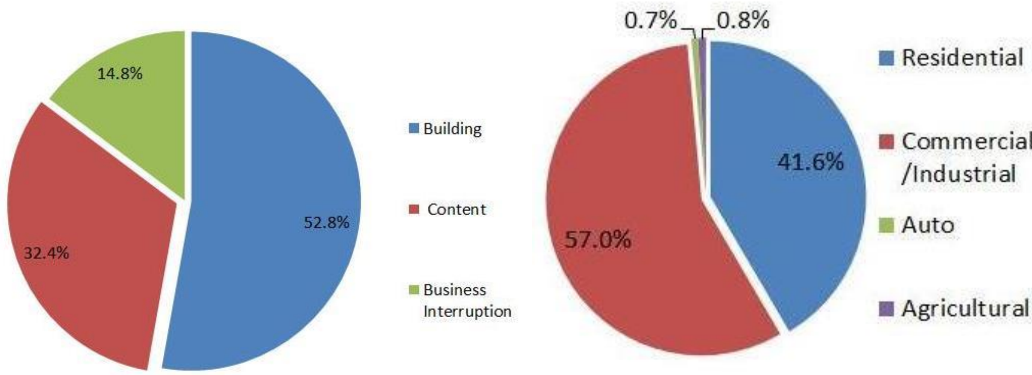


Figure 5: Eastern scenario direct loss by coverage (left) and by line of business (right)

2 Introduction

2.1 Overview of Project

This project concerns a study to provide a detailed description of the impacts of a major earthquake in British Columbia and Ontario/Québec. The project fell into three phases, starting with an analysis of the earthquake hazard in the regions to enable AIR to identify several scenarios that met the criteria set for the study. After narrowing down to two viable scenarios in each region and through discussions with the IBC, AIR recommended one scenario in each region. Next, these scenarios were evaluated by the IBC, who approved a single scenario in each region to be the subject of the study. AIR then conducted a full analysis of each these two final scenarios to produce the findings in this report.

This massive undertaking would not have been possible without the valuable assistance of many partners and peer reviewers. Section 11 contains biographies of Drs Robert McCaffrey, Michael L. Lahr, Oh-Sung Kown, Adam Rose and Dan Wei, with whom we collaborated. Section 12 contains the peer reviews by Drs. Keisuke Himoto, Stephane Mazzotti, Marie-José Nollet, and Geoff Thomas, each of whom provided a peer review.

Throughout the study, AIR has worked closely with the IBC and we have been appreciative of their deep knowledge of the issues relating to earthquake risk which face Canada, its citizens and public officials as well as the insurance industry, and their dedication to producing a report that will become a timely and useful earthquake risk management tool.

2.2 Development of Probabilistic Risk Analysis

In the context of this study, a probabilistic risk analysis is the process of estimating the risk of a very large earthquake impacting Canada. The risk level can be defined by the probability that an earthquake of a certain magnitude will occur. It can also be defined as the probability of an earthquake causing a certain size loss. The selection of the appropriate scenario in each region began with a separate probabilistic analysis for events and loss for British Columbia and for Ontario/Québec, acknowledging the markedly different sources of seismic risk, surface geology conditions and tectonic settings of these regions. A catastrophe model is the best tool for identifying credible, likely scenarios for a study of this nature because it combines the science underlying earthquake risk with knowledge and information about vulnerability of structures to this peril as well as actuarial techniques to arrive at the insured perspective.

One of the primary components of the model is a catalog of potential earthquake events, ranging from small to extremely large and catastrophic. This collection of events, or stochastic catalog, depicts thousands and thousands of possible and realistic potential years of seismic activity in Canada. Just like in history, many years in the stochastic catalog have very small earthquake occurrences, and occasionally a year has a huge earthquake (such as 1946 when the great Vancouver Island earthquake happened). The stochastic catalog captures the best scientific assessment of the true underlying seismic risk in the country. Therefore analyzing Canadian risks in the model produces the full range of possible earthquake losses from the various types of earthquakes. From the model output, it is possible to understand the probability associated with different levels of loss. The term used to describe this concept (i.e. the full range of potential levels of loss and the associated probabilities of meeting or exceeding this level of loss in a given year) is an exceedance probability (EP) curve.

After these probabilistic analyses were completed, AIR proposed scenarios for both regions by separating out the results of the probabilistic analyses at different sites to identify the dominant earthquake sources contributing to loss for the provinces of interest.

2.3 Scenario Selection

The scenario selection phase of the project involved a period of interaction and knowledge sharing with the IBC to communicate the scientific basis and technical details of the proposed scenarios. It also included an evaluation of stress test scenarios used by the Office of the Superintendent of Financial Institutions (OSFI) during its 2012 reviews. Based on all information available and AIR's recommendations, the IBC accepted the recommended scenarios for further analysis.

The primary feature of each selected scenario is that they are geophysically representative earthquake events for a given seismic source and have a probability of occurrence that is roughly 1-in-500 years. A secondary consideration when selecting the scenarios involves the loss levels associated with the scenario event. At the end of the probabilistic analysis and scenario selection processes, AIR chose scenarios for each province that represented a 500 year seismic recurrence and produced ground up loss levels within a targeted range of loss values The targeted loss values represent roughly a 0.2% probability of being met or exceeded in a given year.

Given the population and property distribution in these provinces, the scenarios selected are necessarily close to concentrations of insured property such as Vancouver, B.C., and Québec City, Québec, for example.

2.4 Scenario Analysis

Finally, AIR began the scenario analysis phase using comprehensive updates to its existing Earthquake Model for Canada. These included updates to the shake and fire following components, as well as new liquefaction, landslide, and tsunami components. The damage estimation and local earthquake intensity components, including soil conditions, were updated as well. AIR's property inventory was updated and enhanced to include Canada's infrastructure and reflect current industry policy conditions.

The model calculates direct loss to residential, commercial, and industrial buildings and property, automobiles and agricultural buildings. It also estimates direct business interruption to properties direct and indirect losses from infrastructure are critically important from an economic point of view, so we have modeled them as well.

All components of the model underwent review by external peer reviewers who are eminent scientists in their respective fields. The peer review reports are included in Section 12 of this document, Appendix—Peer Review Reports.

This final Earthquake Report contains a description of the scenario selection process and a detailed descriptive narrative of the impact of the major earthquake in each region. It also includes estimates of economic and insured losses.

2.5 Explanation of Modeled Perils

Now that we have discussed the selection of the scenarios it will be valuable to understand the different ways in which an earthquake can damage property. This section contains an introduction to the different physical aspects of an earthquake event.

An earthquake is the rapid relative displacement of the rock on either side of a fracture, or fault, within the solid earth. Elastic strain energy that has been stored in the rocks is suddenly released. Some of the energy released dissipates as friction along the fault. The rest is transferred to seismic waves that radiate outward in all directions from the initial point of rupture and cause ground motion at the earth's surface.

The severity of an earthquake can be measured in a variety of ways and places. These include measurements of what occurs on the surface, where ground motion can damage structures and infrastructure. Other measurements enable seismologists to infer what happened at the point within the earth where the rupture initiated, known as the hypocenter.

The current practice among earth scientists and engineers is to use the word "magnitude" to characterize the energy released at an earthquake's hypocenter, and the word "intensity" to refer to the observed effects of an earthquake at the surface.

While the magnitude of an earthquake is independent of the location at which measurements are made, intensity is a function of the distance from the rupture, the intervening geology, and local site conditions such as the type of soil underneath the structure. The same event is experienced differently in different locations.

Ground shaking

The ground shaking in an earthquake can range from barely perceptible trembling to violent shaking, depending on the magnitude of the event, on the distance from the rupture to the affected site, the geological characteristics of the region, and local site conditions.

Damage caused by ground shaking

The most immediate and obvious damage resulting from earthquakes is that caused to buildings and infrastructure by ground shaking and displacement. The damage is caused in various ways by waves of vibrations radiating out through the ground from the epicentre of the event in complex patterns influenced by the varied geological conditions of the area.

Each earthquake is a unique event, and its effects will be experienced differently in diverse parts of the affected area and by individual structures. Figure 6 shows an example of typical damage to a reinforced concrete structure caused by ground motion.

Figure 6: Damage to a reinforced concrete structure caused by shaking, Chile, 2010

The strength of the shaking felt varies in relation to the energy released and the distance from the epicentre. All things being equal, the shaking produced by a magnitude 7 earthquake is half as strong 13 km from the epicentre, a quarter as strong at 27 km, and an eighth as strong at 48 km away[2]. Some earthquakes cause shaking for only a moment or two, while others can persist for a minute or more. Most produce aftershocks of some form and these may continue to occur for several hours or even sporadically for years. Areas of soft soil will generally amplify the waves and shake longer than areas of solid rock. The more shaking is experienced, the more damage occurs.

Violent ground motion will move a building's foundation from side to side and impart that motion to the rest of the building. The higher a building, the more

[2] http://www.iris.edu/hq/files/programs/education_and_outreach/retm/tm_100112_haiti/BuildingsInEQs_2.pdf

flexible it generally is, and the higher up its upper stories are the more they will move. Individual buildings will react to ground motion in different ways depending on their height, form of construction, condition and other factors. When the motion exceeds the building's ability to absorb it, damage occurs.

Each building is able to vibrate back and forth to some degree at a particular rate and therefore has a natural frequency. Resonance (high amplitude continued oscillation) occurs when the frequency of the seismic waves experienced corresponds closely to the natural frequency of the building, and it may cause severe damage. Small buildings are particularly affected by rapid high-frequency shaking and large or high-rise buildings by slow low-frequency shaking.

When Mexico City was impacted by an offshore magnitude 8.1 earthquake in 1985 for example, the majority of short and tall buildings remained standing in the most devastated areas. About 60% of the collapsed or seriously damaged buildings however, were medium-height structures (6-15 stories)—their resonance frequency coincided with the frequency range amplified most in the subsoils during that particular quake.

The design codes that govern construction in developed countries like Canada have evolved as understanding of earthquakes, and buildings' performance during them, have improved. The codes are intended principally to save lives rather than to ensure the survival of the structures.

Modern reinforced concrete or steel-framed buildings in areas at risk are generally built to codes intended to ensure that the structures do not collapse during an earthquake and trap their occupants. Older buildings constructed to less effective codes will not perform as well as newer ones.

Some forms of construction, particularly older buildings of traditional unreinforced masonry (stone, brick or concrete blocks) or wooden structures not tied to their foundations, generally perform poorly. Typical damage to an unreinforced masonry building is shown in Figure 7.

Figure 7: Damage to an unreinforced masonry structure, Christchurch, New Zealand, 2010

Post-Event Losses

As well as costs directly related to debris removal and reconstruction, which can be inflated by demand surge (premium rates charged temporarily for labor and materials in short supply), businesses and individuals face other expenses after an earthquake. People may need to stay in a hotel while their home is repaired for example, or take time off work because they can't get to their place of employment or need to spend time with contractors.

Business interruption can be a major loss. It can take businesses some time to return to full operation because of their own or, or their suppliers' and/or client's post-earthquake issues. Some businesses, such as offices, can relocate, but others, such as hotels, often cannot. For both businesses and individuals damage must be assessed, repair costs negotiated with contractors, and building permits obtained.

All of this takes time. And it may be some while before contractors are available to do the work, which will of course take yet more time.

Liquefaction

When an earthquake strikes an area that is saturated with groundwater, the shaking can cause the soil to lose its stiffness due to increased pore water pressure, and behave like a heavy liquid. When this happens, the soil loses its capability to support structures.

Figure 8: Evidence of liquefaction seen in New Zealand's 2010 Christchurch earthquake

Buildings can suddenly tilt or even topple over as the ground beneath them becomes liquefied. Pipelines and ducts can surface as the liquefied soil shifts, and buried utility lines can break. Figure 8 shows liquefaction damage to a heritage building caused by the earthquake in Christchurch, New Zealand.

If the saturated soil lies underneath a dry crust, the ground motion can crack the top dry soil allowing the liquefied sand to erupt through the cracks, creating sand boils. Sand boils can spread through utility openings into a building and damage the building or its electrical system.

Liquefaction is more likely in areas with loose coarse grained soils that have poor drainage and are saturated with water. An example would be loose sands, which are found along riverbeds, beaches, dunes, and other areas where sands have accumulated. A prime example is the Fraser River Delta area in Vancouver, where the municipality of Richmond in particular is susceptible to damage from liquefaction.

The AIR Earthquake Model for Canada includes a liquefaction component covering the areas of highest exposure concentration in British Columbia, Ontario, and Québec.

Landslides

Earthquake triggered landslides and slope failures represent major seismic hazards and pose a significant threat to both human life and property. Earthquake triggered landslides cause loss of life and destroy structures, roads, lifelines and pipelines. Therefore they have a direct impact on the social and economic life of the hazard region.

Figure 9: A massive landslide in Beichuan, China, triggered by the 2008 Sichuan earthquake

A major landslide caused by an earthquake, and some of the damage it caused, are shown in Figure 9. It is well documented that earthquake triggered landslides have caused hundreds of thousands of deaths and substantial economic losses.

The main objective of regional earthquake-triggered landslide hazard analysis is to evaluate the location of the areas where landslides can be triggered by future earthquakes. The susceptibility of an area to earthquake-triggered landslides can be assessed based on the potential ground motion, and the composition and structure of local geology. It is important to note that landslide is a secondary hazard. Although landslide damage to a particular structure may be severe, its contribution to the total damage caused by the earthquake is relatively small.

Fire following earthquake

Earthquakes that occur in built-up regions can cause fires as a result of building and contents damage from the ground shaking. A building damaged by fire after the 2010 earthquake in Christchurch, New Zealand, is shown in Figure 10.

Figure 10: Fire damage as a result of the earthquake in Christchurch, New Zealand, 2010

The risk of fires following earthquakes is tied to the building density and the level of ground motion, among other factors. Fires which start in the aftermath of a large earthquake can grow unchecked and spread to adjoining properties, causing significant damage.

Disrupted communication systems may delay fire reporting, simultaneous ignitions may overwhelm local fire department resources, and ground motion can cripple the water system that supplies fire hydrants. The earthquake ground motion location and strength directly affects the number and location of ignitions, level of water system damage, and the time required for fire engines to reach the site of each fire in the event. Damage from fire following is explicitly modeled by AIR using a stochastic model.

Tsunami induced inundation

A tsunami is a series of waves caused by the displacement of a large volume of water, and they can occur due to earthquakes or other disturbances below water including volcanic eruptions, landslides, glacier calvings, and meteorite impacts. Specific to earthquakes, tsunamis form due to the vertical displacement of the seafloor, which displaces water above the deformed area from its equilibrium position. Figure 11 illustrates the process of tsunami creation and propagation. How high, how rapidly, and how much water it lifts depends on the rupture characteristics of the event, including the earthquake magnitude, how abruptly the slip occurs, and how deep it is under the ocean floor.

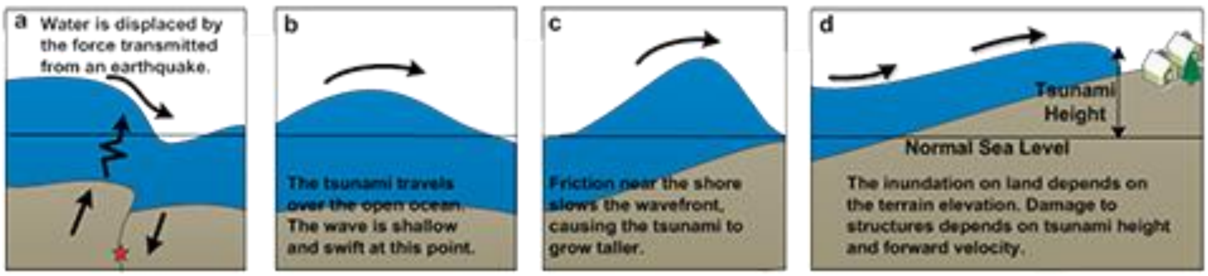


Figure 11: Tsunami generation and movement (Adapted from the Tokyo Metropolitan Government)

Once initiated, the mound of displaced water propagates outward in all directions, potentially traveling thousands of kilometres and impacting locations far removed from the initial earthquake rupture. Typically the wavelength (or horizontal dimension) of the water is much longer than the depth of the ocean; for this reason, the tsunami wave is considered a shallow wave (e.g., Figure 11b). This type of wave moves very fast over deep water, as its propagation speed is proportional to water depth. Early on and (typically) over deep water, its height (or amplitude) is fairly shallow owing to its long wavelength. Because of the long wavelength and small height, mariners on the deep ocean do not typically feel a tsunami wave passing below, even though it is moving at great speed.

As the wave moves into shallower water, the speed decreases, and the wave begins to feel the effect of bottom friction, leading to a decrease in wavelength because the back of the wave moves faster than the front. As the wavelength decreases the water has to go somewhere and it goes up, increasing the wave height.

Tsunami damage can be significant at coastal locations which feature exposure at low elevation, while coastal regions with steeper coastlines, rougher terrain and higher elevations are less prone to tsunami damage. The presence of coastal flood defenses, such as seawalls, can significantly reduce tsunami damage if they are of sufficient height and remain structurally sound during the tsunami. The background tide condition also plays a critical role in determining how far a tsunami is able to penetrate inland and how deep the flooding is, especially in areas with a large tidal range of similar magnitude to the water rise from the tsunami itself.

2.6 Earthquakes in Canada

Between 3,000 and 4,500 earthquakes occur in Canada every year, but most of them are too slight to be noticed. On average, an earthquake large enough to be felt happens somewhere in the country every week. Earthquakes powerful enough to cause insured losses typically strike decades apart, and most of the areas they are likely to occur in are either offshore or remote and largely unpopulated. In such locations they cause little damage and few casualties. Truly catastrophic earthquakes take place much more rarely still.

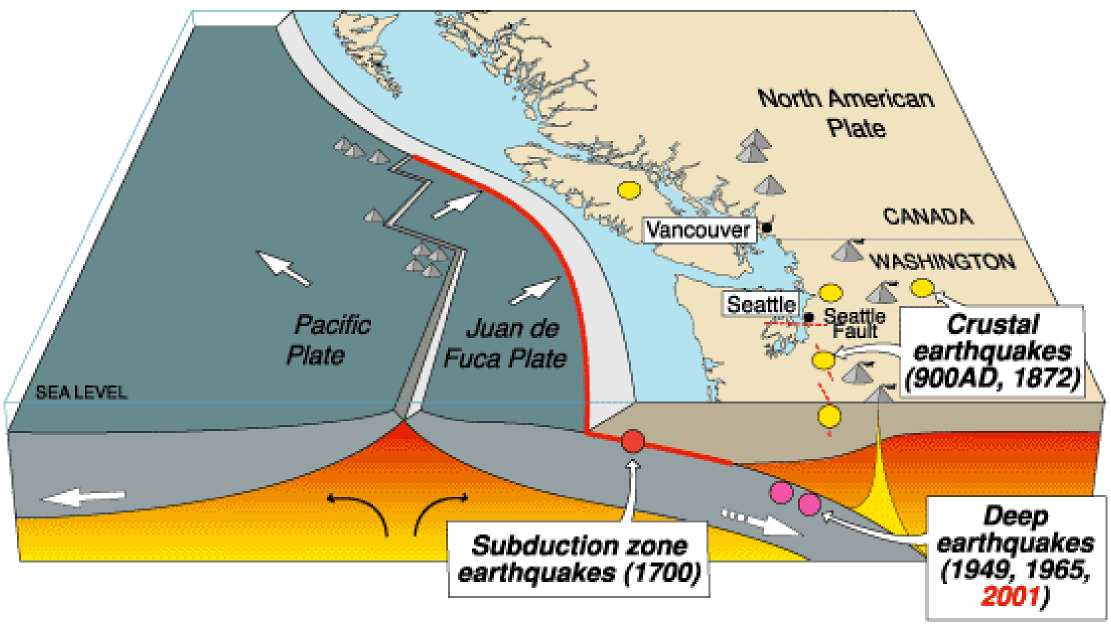
Nevertheless, it is important to bear in mind that extremely powerful earthquakes have occurred in, or close to, Canada. Furthermore, earthquakes strong enough to inflict serious damage today have impacted the highly-populated and developed regions selected for this study—and are likely to do so again, sooner or later. A recent study of earthquakes on the west coast of Canada for example noted that major events have occurred there irregularly every 500 years or so, and that the last took place about 300 years ago[3].

The tectonic plates that form the earth's crust are continually moving towards each other, moving apart and/or slipping past each other. They move very slowly, usually just a few millimetres each year, but the stresses their interactions generate build up over time until the friction holding the slabs together can no longer be contained. The sudden release of energy as the plates spring apart is what makes the earth quake.

The west coast of Canada is part of the circum-Pacific seismic belt, popularly known as "the Ring of Fire," which marks the rim of the Pacific Ocean. It is one of the few regions of the world to exhibit all three of the major types of plate motion

[3] Giant earthquakes beneath Canada's West coast, R.D. Hyndman et al, http://www.nrcan.gc.ca/earth-sciences/energy-mineral/geology/geodynamics/earthquake-processes/8595

that cause significant seismic activity (see Figure 12). Off the west coast of Vancouver Island, the Juan de Fuca plate and the Pacific plate are spreading apart along the Juan de Fuca ridge. Further east, the Juan de Fuca plate is converging with and subducting (sliding) beneath the North American plate to form the Cascadia subduction zone. Immediately north of this area is the Queen Charlotte fault, an active transform fault in which the plates are moving sideways in relation to one other. This is Canada's equivalent of the San Andreas Fault, and in 1949 it was the site of the nation’s largest recorded earthquake—a magnitude 8.1 event.



	Source	Affected area	Max. Size	Recurrence
● (red)	Subduction Zone	W.WA, OR, CA	M 9	500-600 yr
● (pink)	Deep Juan de Fuca plate	W.WA, OR,	M 7+	30-50 yr
● (yellow)	Crustal faults	WA, OR, CA	M 7+	Hundreds of yr?

Figure 12: Earthquake sources in the Cascadia subduction zone (United States Geological Survey)

The Cascadia subduction zone can produce powerful earthquakes that affect a wide geographic area and give rise to tsunamis. These types of earthquakes tend to create long-period seismic waves that are particularly damaging to tall buildings, bridges, and pipelines. In addition, cities such as Vancouver, B.C. are located within basins whose sedimentological characteristics amplify these long period seismic waves, rendering these waves even more damaging to buildings and infrastructure. The city of Richmond, which is situated on silty and sandy sediments, is highly susceptible to liquefaction, which can significantly exaggerate building and infrastructure damage (as was observed in the recent Christchurch, New Zealand, earthquake).

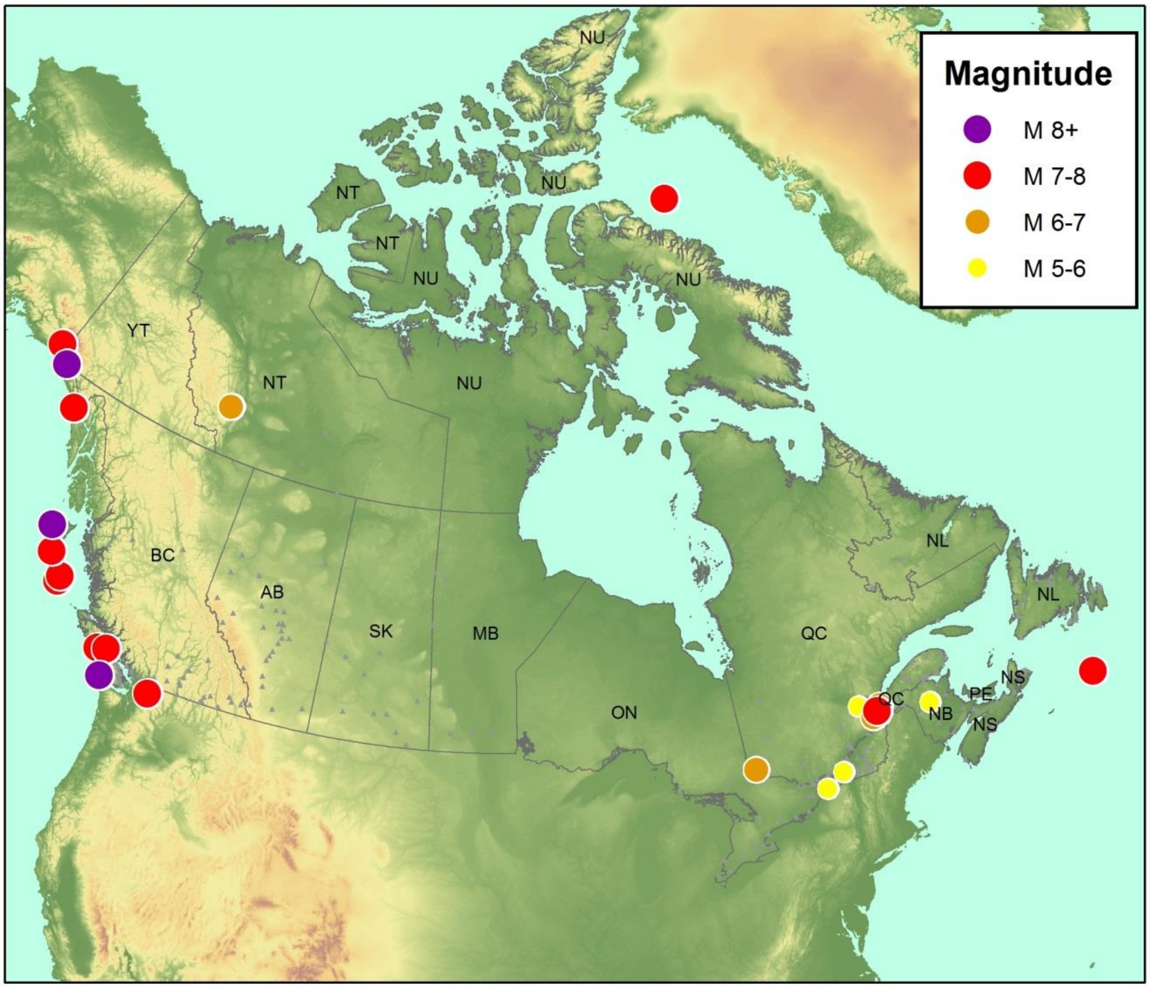


Figure 13: Canadian earthquakes of magnitude 5.0 or greater since 1700

Seismicity in eastern Canada is very different. The causes of earthquakes there are not well understood and because of this uncertainty we are unable to offer an explanatory graphic for the eastern scenario to match Figure 12 above. Unlike plate boundary regions where the rate and size of seismic activity can be directly correlated with plate interaction, eastern Canada is located in a stable continental region upon the North American Plate. Seismic activity seems to be related to regional stress fields, with earthquakes concentrated in regions of crustal weakness. Eastern Canada has a relatively low rate of earthquake activity, yet large and damaging events have occurred in this region in the past. The historical seismicity of Canada (all earthquakes of magnitude ≥ 5.0 since 1700) is shown in Figure 13 above. Figure 14 and Figure 15 below provide more detailed views of the historical earthquake activity in British Columbia and in the Québec area respectively.

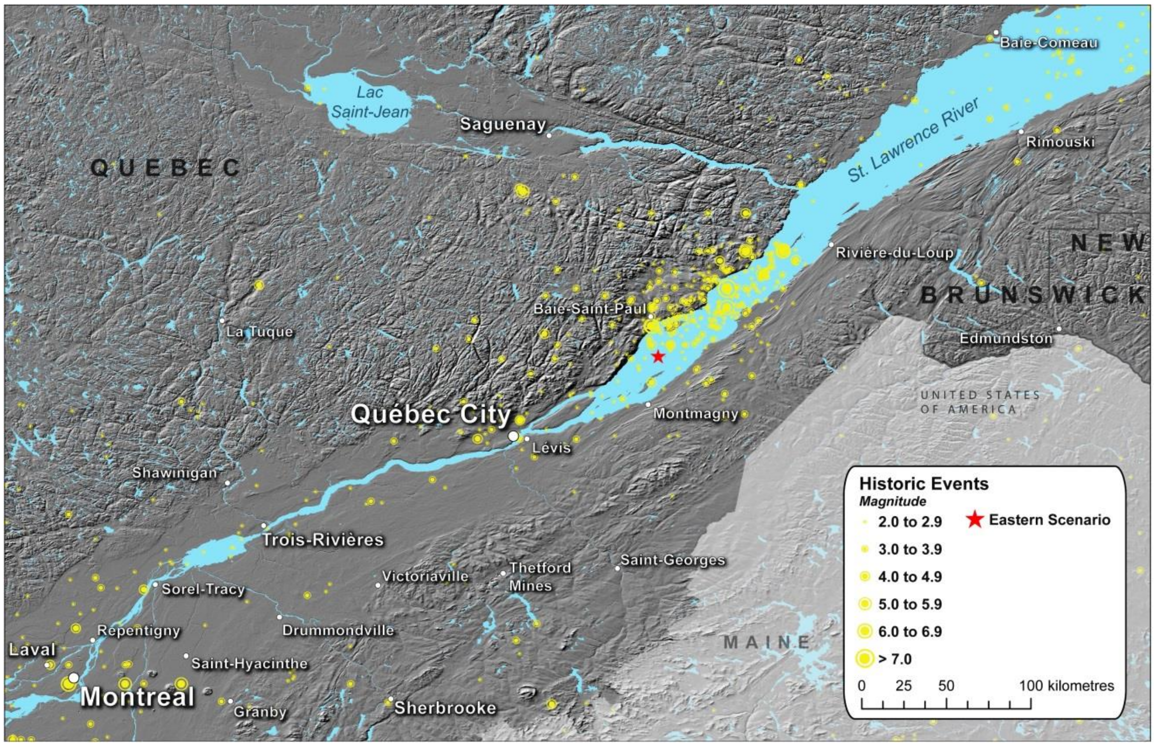


Figure 14: Historical earthquakes in the Québec area

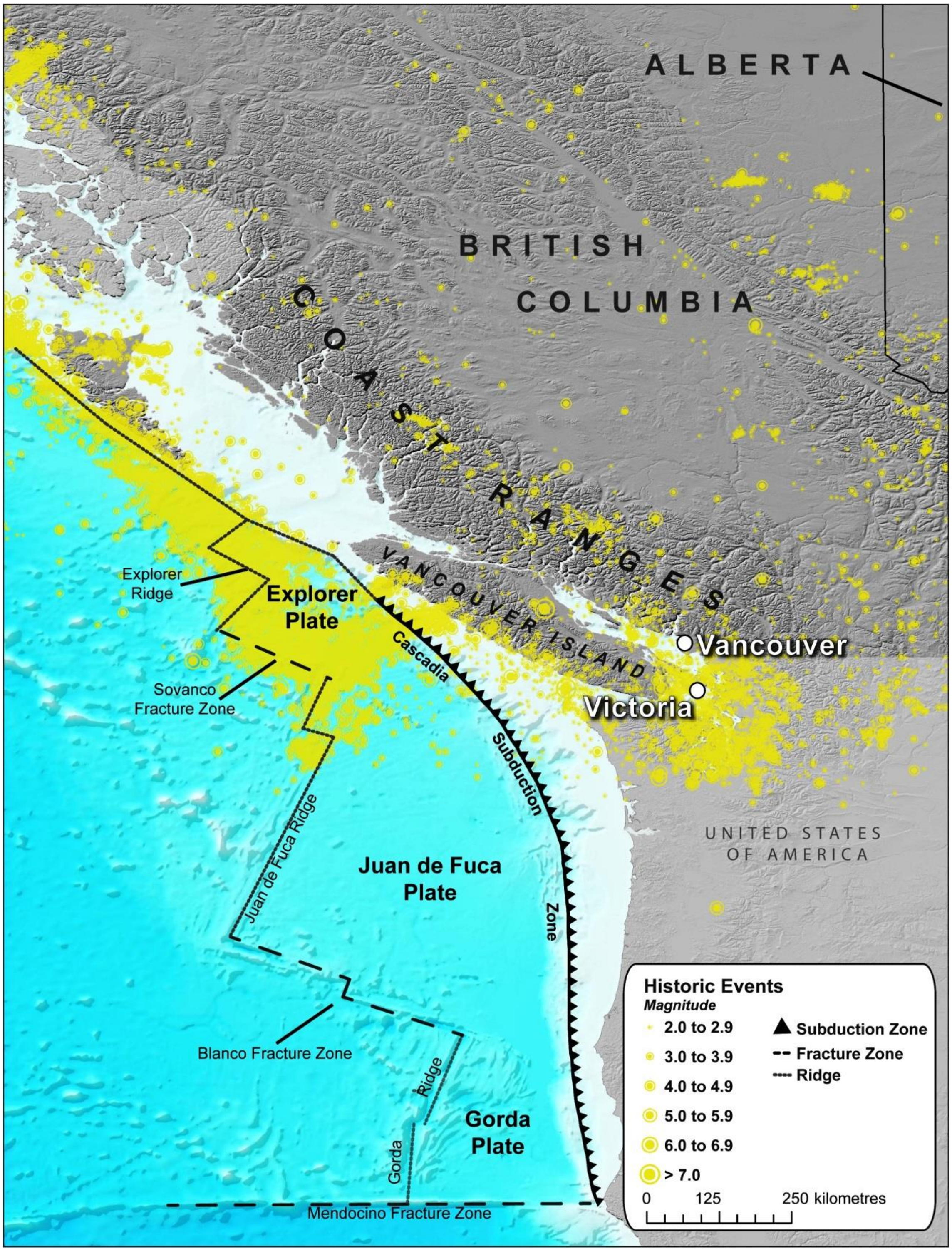


Figure 15: Historical earthquakes in British Columbia

2.7 The AIR Earthquake Model for Canada

AIR was the first company to develop catastrophe modeling technologies as an alternative to the actuarial or "rule of thumb" approaches that the insurance industry had previously relied upon for the estimation of potential losses from catastrophe events.

Overall, AIR currently maintains 38 catastrophe models worldwide, 17 of which are earthquake-specific. One of these is the AIR Earthquake Model for Canada, which was first released in 1997 and was updated in 1999, 2002, 2005, and 2008. It has been comprehensively updated once more for this study.

AIR catastrophe models are computer software—complex systems of algorithms which expresses mathematically the fundamental physical characteristics of catastrophic events. They are built on extensive research into the nature of the perils concerned and use scientific data collected and cross-verified from many different sources. The most important sources for this study were the Geological Survey of Canada and the United States Geological Survey (USGS).

The software takes information about real or hypothetical events and uses it to calculate the damage likely to be sustained by property in the locations exposed to those events so insurance losses can be estimated from the results. Massive amounts of data are used for the calculations, which it can take powerful modern computers several days to complete.

3 Exposure

The presence of humans and the structures and objects they interact with on a daily basis drive the loss estimates from the earthquake scenarios. Once the scenario in each region was selected, the next step in the modeling process was to see how the earthquake scenario affects the exposed risks (or exposures) to yield loss estimates. In this section we explain in detail the exposures in Canada which have been modeled for this analysis. Further information on the data sources used to develop these exposures is included in Section 15 of this report.

3.1 Development of the Property and Infrastructure Inventory

AIR developed an inventory of all properties and infrastructure at risk and their corresponding replacement values in Canada. A comprehensive understanding of the properties and infrastructure at risk is essential as a significant portion of earthquake losses result from physical damage to property and infrastructure. This inventory was split into two pieces: the property inventory, which was further split into buildings and automobiles, and the infrastructure inventory. The structure of the inventory can be seen in Figure 16.

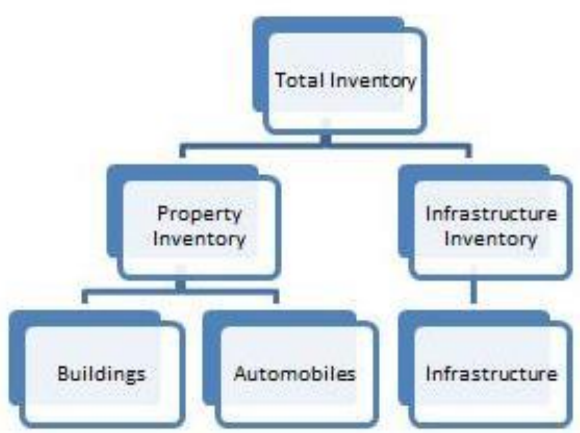


Figure 16: Inventory of all properties and infrastructure

To compile the building inventory, detailed data was gathered from a host of sources including government and private vendors. This data included not only building counts, but also additional information on construction costs as well as the physical characteristics of the buildings including structural type, height classifications (stories per building), and floor area. This additional information was important as it was used to assess the buildings' potential vulnerability and/or susceptibility to earthquake damage as well as to determine the costs of the resulting property damage.

The primary sources of information that were used to derive the building counts were high resolution census data and business registries including ProCan B2B which were obtained through a private vendor (GEOGRAFX© Digital Mapping Service). Counts of businesses were obtained from these business registries along with their corresponding North American Industry Classification System (NAICS) codes which provide information about the type of business activity at each location. Data from government reports such as the motor vehicle surveys from Natural Resources Canada were used to develop the motor vehicle counts.

Figure 17: The Lion's Gate Bridge, Vancouver (Dbrustad, Wikimedia Commons)

Information on infrastructure, which typically refers to the basic physical systems that support society such as: roads, bridges such as the Lion's Gate Bridge in Vancouver seen in Figure 17, water supply and others, was collected in addition to the building and automobile property counts. The CanVec dataset, which was produced by Natural Resources Canada and distributed by GeoGratis, was the primary source of information for infrastructure. Additional regional datasets, such the Canadian Airport Charts diagrams from NAV CANADA and the Technical and Administrative Frequency Lists (TAFL) from Industry Canada, were also used.

3.2 Occupancy Descriptions

The data, as described above, was used to group the properties and infrastructure into the following occupancy classes. For the purpose of analysis, the property inventory was further grouped into aggregated categories of residential, commercial/industrial, public, automobile and agriculture, as noted in Table 5. Infrastructure types are shown in Table 6.

Table 5: Property types

Property Type	Aggregated Type	Description
Single-family home	Residential	Single unit detached dwellings usually occupied by a single family. Also excludes mobile homes.
Mobile home	Residential	Mobile/manufactured homes.
Apartment	Residential/Commercial*	Multi-unit housing.
Public building	Public	Government establishments engaged in justice, public order, and safety; also includes offices of executives, legislative bodies, general government offices and facilities.
Health care facility	Public	Establishments including medical, surgical and other health services such as clinics, laboratories, and hospitals.
Educational facility	Public	Institutions engaged in instruction at primary and secondary level, as well as those providing higher-level academic or technical instruction.
Commercial establishment	Commercial/Industrial	Establishments involved in a commercial trade other than public administration, health care, or education; includes retail and wholesale trade, repair services, professional services, religious organizations, entertainment, lodging, dining, corporate offices, and others.

Property Type	Aggregated Type	Description
Industrial establishment	Commercial/Industrial	Establishments involved in an industrial trade including manufacturing, chemical processing, construction, high technology, mining, and others.
Industrial facility	Commercial/Industrial	Complex, high-value industrial sites, often with extensive machinery, including large-scale manufacturing, refining and smelting, and others.
Automobile	Automobile	Residential and commercial vehicles including passenger cars, motorcycles, vans, and a variety of small and large trucks including semi-trailers.
Agricultural building	Agriculture	Buildings associated with an agricultural holding and used for agricultural purposes, such as storage of grain or livestock.

*Apartment buildings were aggregated to either residential or commercial/industrial depending on the size of the building. The building values for larger apartment buildings were included in commercial/industrial, while the building values for smaller apartment buildings were included in residential. The content values (value of the residents' belongings) were included in residential.

Table 6: Infrastructure types

Infrastructure Type	Description
Road	Roadways such as highways, thoroughfares and paved local roads; also includes bridges and tunnels associated with roadways.
Railway	Railway tracks including freight and passenger lines as well as public transportation systems; also includes bridges and tunnels associated with railways.
Port	Port structures such as wharves for major industrial ports; also includes equipment such as cranes and facilities directly associated with the port.
Airport	Airport runways and tarmacs for international and large regional airports; also includes terminals and facilities directly associated with the airport.
Electric power	Transmission and local distribution lines for electric power supply.
Natural gas	Transmission and local distribution pipelines for natural gas supply.
Oil	Transmission pipelines for oil supply.
Water systems	Transmission and local distribution pipelines for potable water supply.
Communication systems	Cell phone towers, antennas, and rooftop structures that support antennas.

3.3 Structural Types and Height of Buildings

Data obtained from census information, government reports, engineering studies, building codes and other such surveys were used to classify buildings by structural type and height. The proper classification of buildings by structural type is important because differences in building materials, quality, and design all have a significant impact on building vulnerability. The lightweight materials and high energy-absorbing qualities of wood-frame, for example, make those structures relatively less likely to collapse during an earthquake than heavier, less ductile, unreinforced masonry buildings, all else being equal.

The general construction and height classifications assigned to the properties in the building inventory are provided in Table 7 and Table 8 below. Please note the structural types displayed in these tables are grouped by material type and that the actual structural types assigned to the buildings in the building inventory are more detailed. There are, for example, various types of concrete such as reinforced concrete shear wall (without moment resisting frame, or MRF) and pre-cast concrete assigned to the properties in the building inventory. These more detailed structural types were considered when the damage to the buildings was calculated to better capture the level of damage and amount of loss. The distribution of buildings by property type, height category and material type can be seen below for British Columbia (Table 7) and Québec (Table 8).

Table 7: Building distribution by height and material type, British Columbia

Property type	Height	# of buildings	Wood	Masonry	Concrete	Steel	Light metal
Single-family homes	1 - 3 stories	1,173,922	91%	9%	0%	0%	0%
Apartments	1 - 3 stories	20,404	78%	18%	3%	1%	0%
	4 - 7 stories	6,522	0%	27%	69%	4%	0%
	>7 stories	680	0%	0%	97%	3%	0%
Public buildings	1 - 3 stories	2,329	36%	48%	9%	7%	0%
	4 - 7 stories	720	0%	15%	70%	15%	0%
	>7 stories	75	0%	0%	32%	68%	0%
Health care facilities	1 - 3 stories	3,938	37%	46%	10%	7%	0%
	4 - 7 stories	1,418	0%	14%	72%	14%	0%
	>7 stories	191	0%	0%	21%	79%	0%

Property type	Height	# of buildings	Wood	Masonry	Concrete	Steel	Light metal
Educational facilities	1 - 3 stories	2,182	41%	44%	9%	6%	0%
	4 - 7 stories	532	0%	12%	76%	12%	0%
	>7 stories	49	0%	0%	22%	78%	0%
Commercial establishments*	1 - 3 stories	136,986	48%	38%	7%	5%	2%
	4 - 7 stories	38,574	0%	12%	75%	13%	0%
	>7 stories	5,233	0%	0%	21%	79%	0%
Industrial establishments	All heights	37,515	26%	57%	8%	7%	2%

*Agricultural buildings are included with commercial establishments for the purpose of this table.

Table 8: Building distribution by height and material type, Québec

Property type	Height	# of buildings	Wood	Masonry	Concrete	Steel	Light metal
Single-family homes	1 - 3 stories	2,049,134	65%	35%	0%	0%	0%
Apartments	1 - 3 stories	136,060	45%	37%	10%	8%	0%
	4 - 7 stories	42,860	0%	26%	58%	16%	0%
	>7 stories	954	0%	0%	82%	18%	0%
Public buildings	1 - 3 stories	3,313	23%	55%	11%	9%	2%
	4 - 7 stories	947	0%	62%	8%	30%	0%
	>7 stories	26	0%	15%	27%	58%	0%
Health care facilities	1 - 3 stories	7,035	22%	52%	13%	11%	2%
	4 - 7 stories	2,026	0%	64%	7%	29%	0%
	>7 stories	46	0%	0%	17%	83%	0%
Educational facilities	1 - 3 stories	3,263	24%	54%	11%	10%	1%
	4 - 7 stories	827	0%	67%	5%	28%	0%
	>7 stories	9	0%	0%	22%	78%	0%
Commercial establishments *	1 - 3 stories	203,633	33%	47%	9%	8%	3%
	4 - 7 stories	47,560	0%	67%	6%	27%	0%
	>7 stories	1,015	0%	3%	18%	79%	0%
Industrial establishments	All heights	53,749	16%	61%	7%	12%	4%

*Agricultural buildings are included with commercial establishments for the purpose of this table.

3.4 Building Floor Area

Floor area plays an important role in the valuation of properties as it provides critical information on the relative size of buildings. Data from the census in combination with information from the Natural Resources Canada energy surveys were used to develop the floor area for the residential properties, measured in square metres.

With respect to commercial/industrial, public, and agricultural buildings, estimates of floor area were not explicitly provided. Information gathered from the energy surveys relating to the typical sizes of business grouped by activity was used together with data from the business registries, which included the number of businesses and workers by business activity, to derive the floor area estimates.

An example of the type of floor area data available is shown in Table 9 below. These data were used in the development of the floor area estimates for single family homes. Variations in floor area exist by property type and geographic area.

Table 9: Residential property floor area

Floor Area (m^2)	Percent of Properties
56 or less	8%
56-93	27%
93-139	33%
139-186	17%
186-232	8%
232 or more	7%

3.5 Values by Occupancy and Coverage Type

Replacement value represents the cost to rebuild a structure in the event that it is damaged and needs to be replaced. The replacement value of a property excludes the value of the land on which it is built. For buildings, replacement values were calculated by multiplying the floor area estimates by construction costs, which are usually expressed in terms of a unit cost per square metre. These costs vary by occupancy, construction type, height, and location. The variation in costs by location accounts for regional differences in labor and material costs.

AIR obtained construction cost estimates from Xactware® to use in the valuation of the building inventory. Estimates were provided through Xactware's 360Value product, which provides component-based replacement cost estimates that account for all material and labor components needed to rebuild a particular structure.

Additional sources were used in the valuation of the commercial/industrial, public, and agricultural properties. Cost estimates were obtained from construction cost guides and reports published by companies such as Altus Group and BTY Group. These reports provide a comprehensive view of the construction market and costs throughout Canada.

In addition to the building values, estimates of appurtenant structures, contents and direct BI (additional living expenses [ALE] for residential, or business interruption [BI] for commercial/industrial, public and agriculture) are also included in the building inventory. The contents value for residential properties, for example, represents personal belongings while the contents value for business properties consists of values for fixed equipment, internal fixtures, and inventory. The value for contents is calculated as a percentage of the building replacement value, with the percentages varying by occupancy type.

Appurtenant structures are structures that are not physically attached to the principal building such as separate garages, sheds, and other structures. Most property insurance contracts, such as homeowner's insurance policies, typically include coverage for appurtenant structures.

ALE coverage can help to reimburse policy holders for costs incurred in addition to normal living expenses when a loss occurs and makes their residence uninhabitable. This may include payments for the cost of a hotel, food, and other expenses. In terms of commercial/industrial, public, and agriculture, BI reflects costs associated with loss of net income, temporary relocation expenses as well as other ongoing expenses such as employee payroll. For commercial/industrial, public and agriculture, the contents and BI proportions varied by occupancy classification. The percentages of ALE and BI exposure values were calculated as a proportion of the combined building and contents replacement value.

Motor vehicle valuations were done using both market value estimates of automobile prices along with information from the National Accounts provided by Statistics Canada. The values of motor vehicles depreciate over time as the vehicles age. The age distributions were used to develop the depreciated values for the residential vehicles and to essentially derive the current value of the residential vehicle stock. Statistics Canada provided a national estimate of the value of commercial vehicles in the Capital Stock section of the National

Accounts. The accounts included current estimates of the depreciated values of the commercial vehicles.

The costs used in the valuations of the various types of infrastructure were based on data obtained from published reports and provincial data and the values were benchmarked against the National Accounts, which provided capital stock by province and by asset type, such as pipelines, bridges, trestles, overpasses, and different types of roads.

To value each of the infrastructure categories listed in Table 6, unit costs were multiplied by the size of the structure (including area and/or length) depending on the type of infrastructure. For example, the cost per lane per kilometre of road was multiplied by the length of road and the number of lanes to derive the value. This unit cost varied depending on the attributes of the type of the road, such as highway, thoroughfare, or local road. Unit costs for road bridges and tunnels are significantly higher.

A similar valuation process was used for railways, oil pipelines, natural gas pipelines, water pipelines, and electrical transmission lines, where unit costs were provided by kilometre and varied by attribute type as listed under the descriptions in Table 6.

Telecommunications infrastructure cost estimates are based on a cost for each tower and antenna located at the site. Where antennas attach directly to a building without the presence of a tower, a cost was given to each structural support and antenna located on the building.

To value airports, the total size of the runways was calculated using the maps of the tarmacs from the CAC manual. In addition to the cost of the runways, the terminals were valued separately and added to the total cost of the airport. The values for the airports do not include value for the businesses already accounted for in the property inventory, such as vendors located inside the terminals.

A similar process was used for the valuation of large ports, involving the use of port maps and aerial imagery to derive the area of the port locations. The cost for the ports includes value for the port structures such as wharves and also includes costs for equipment such as cranes and facilities directly associated with the port.

Once the replacement values for properties and infrastructure were derived, they were benchmarked against insurance industry data and information on fixed assets and other economic variables. Table 10 to Table 13 provide a summary of the replacement values by occupancy type for British Columbia and Québec.

Table 10: All property values in British Columbia*

Property Type	Building or Structural Value	Appurtenant Structures Value	Contents Value	Additional Living Expense/BI
Residential	437,533	27,651	327,007	90,453
Commercial/Industrial	420,400	-	223,843	155,898
Automobiles	48,262	-	-	-
Agriculture	5,548	-	1,585	792
Public	20,642	-	9,672	7,578

** Excludes the value for land.*

All figures are in millions.

Table 11: All property values in Québec*

Property Type	Building or Structural Value	Appurtenant Structures Value	Contents Value	Additional Living Expense/BI
Residential	559,290	28,026	435,780	118,387
Commercial/Industrial	781,397	-	436,432	294,121
Automobiles	81,867	-	-	-
Agriculture	13,351	-	3,814	1,907
Public	35,497	-	17,000	13,123

**Excludes the value for land.*
All figures are in millions.

Table 12: All infrastructure values in British Columbia

Infrastructure Type	Value
Roads	172,836
Railways	22,048
Ports	4,456
Airports	6,475
Electric power	13,955
Natural gas	70,052
Oil	8,772
Water systems	15,786
Communication systems	117

All figures are in millions.

Table 13: All infrastructure values in Québec

Infrastructure Type	Value
Roads	246,865
Railways	16,596
Ports	3,870
Airports	9,124
Electric power	28,080
Natural gas	13,449
Oil	1,558
Water systems	46,491
Communication systems	186

All figures are in millions.

3.6 Insurance Industry Policy Terms and Market Penetration

Information pertaining to standard industry policy terms such as limits and deductibles was also incorporated into the properties inventory. A limit is the maximum amount of loss that the insurer pays, while a deductible is the amount of loss that the policyholder pays before the insurance takes effect. Data for policy conditions were collected from an extensive review of insurance policy data which varied by region and occupancy type. Local insurers, reinsurers, and brokers provided data for a variety of property types and geographic resolutions, including aggregated and location-level data split by residential, commercial, industrial, agricultural, and automobile property types. In total, these sources represented over 70% of the Canadian insurance market. In addition, third-party research such as the latest reports from AXCO Insurance Information Services reports provided a broad view of the industry, including current data and information on market trends.

In addition to policy terms, market penetration rates are important in determining the impact of a major disaster on the insurance industry. Market penetration rates are measures of the total value of insured property in relation to the value of all property. For instance, a rate of 50% would indicate that only half of all property value is insured. The market penetration rates for earthquake insurance in Canada were derived from the insurance policy data mentioned above. Market penetration rates vary by peril and by occupancy, and tend to be higher in areas of high earthquake risk, such as in British Columbia. Generally speaking, commercial and industrial market penetration rates tend to be higher than residential rates. The following tables display the insurance terms and the market penetration rates used in British Columbia and Québec for this report by aggregated property type. Information on deductibles and limits by property type is provided in Table 14 while market penetration rates and the corresponding insured values are included in Table 15. In calculating the insured values the limit is applied first followed by the market penetration rate for a certain property type and location, the result is the insured values as seen in Table 15.

Table 14: Insurance terms

Property type	Location	Deductible*	Limit**
Residential	*British Columbia*		
	Vancouver Metro	*10%*	*100%*
	Victoria Metro	*8%*	*100%*
	Rest of British Columbia	*8%*	*100%*
	Québec		
	Montreal Metro	*5%*	*100%*
	Québec Metro	*5%*	*100%*
	Rest of Québec	*5%*	*100%*
Commercial/ Industrial	*British Columbia*		
	Vancouver Metro	*10%*	*80%*
	Victoria Metro	*7.5%*	*80%*
	Rest of British Columbia	*7.5%*	*80%*
	Québec		
	Montreal Metro	*5%*	*80%*
	Québec Metro	*5%*	*80%*
	Rest of Québec	*5%*	*80%*
Agriculture	*British Columbia*		
	Vancouver Metro	10%	80%
	Victoria Metro	7.5%	80%
	Rest of British Columbia	7.5%	80%
	Québec		
	Montreal Metro	5%	80%
	Québec Metro	5%	80%
	Rest of Québec	5%	80%
Auto	All locations	CAD 500	100%

*A deductible is the share of loss that the policyholder agrees to pay out-of-pocket before the insurance company pays the remainder of a claim. A deductible may either be a flat amount or a percentage of the total value, depending on the policy.
**A limit is the maximum amount that the insurer will pay over a given period of time or over the life of the policy. A limit can either be a flat amount or a percentage of the total value, depending on the policy. Please note that the 80% limit for commercial and agriculture does not apply to BI or to large apartment buildings. The limits remain at 100% for BI and large apartment buildings.

Table 15: Market penetration rates by province and by aggregated property type

Property type	Location	Total value	Market penetration rate*	Insured value***
Residential	British Columbia			
	Vancouver Metro	394,963	55%	217,229
	Victoria Metro	69,611	70%	48,728
	Rest of British Columbia	418,070	40%	167,228
	Québec			
	Montreal Metro	488,065	5%	24,403
	Québec Metro	140,663	2%	2,813
	Rest of Québec	512,755	2%	10,255
	Total Canada	**5,763,131**	*****	**551,384**
Commercial / Industrial	British Columbia			
	Vancouver Metro	453,345	85%	330,942
	Victoria Metro	61,414	85%	44,772
	Rest of British Columbia	285,382	85%	205,421
	Québec			
	Montreal Metro	815,601	60%	420,391
	Québec Metro	175,297	60%	90,022
	Rest of Québec	521,052	60%	267,028
	Total Canada	**6,361,275**	*****	**3,266,503**
Auto**	British Columbia			
	Vancouver Metro	20,326	100%	20,326
	Victoria Metro	3,776	100%	3,776
	Rest of British Columbia	24,159	100%	24,159
	Québec			
	Montreal Metro	35,869	100%	35,869
	Québec Metro	10,006	100%	10,006
	Rest of Québec	35,991	100%	35,991
	Total Canada	**364,574**	**100%**	**364,574**

Property type	Location	Total value	Market penetration rate*	Insured value***
Agriculture	British Columbia			
	Vancouver Metro	2,581	85%	1,799
	Victoria Metro	121	85%	84
	Rest of British Columbia	5,223	85%	3,641
	Québec			
	Montreal Metro	4,372	60%	2,151
	Québec Metro	3,435	60%	1,690
	Rest of Québec	11,265	60%	5,545
	Total Canada	**111,949**	*****	**50,576**

All figures are in millions

*Market penetration rates are measures of the total value of insured property in relation to the value of all property, which vary by geographic area and property type.

**Automobiles were assumed to have an earthquake market penetration rate of 100%. Although there is a small percentage of automobiles without insurance, these tend to be low-valued automobiles which do not represent a significant portion of the overall value of the automobile stock.

Please note that values for the public properties are not included in the table above, but they can be found in the preceding all property tables, which are Table 10 and Table 11. The values are shown with no distinction between all property and insured values because market penetration rates could not be determined from available data.

3.7 Resolution of Property and Infrastructure Inventory

The total property and infrastructure inventory was developed at a 1 km^2 grid resolution[4]. In assembling the building inventory, individual building locations were aggregated to a resolution of 1 km^2 to obtain grid-level totals. In areas where information was available at a lower resolution than 1 km^2, the property and infrastructure inventories were modeled at the 1 km^2 grid using auxiliary information such as high resolution datasets on land use, impervious surface area, slope, elevation, regional data and road networks.

Figure 18 below illustrates the total value of the property inventory at the 1 km^2 grid resolution in a small area of North Vancouver, British Columbia. The zoom-

[4] This is in fact an estimate. The size of the model's grid cells are 1/120° x 1/120°, which means that the dimensions of each grid cell vary with latitude. For example, at a latitude of 45 degrees, the model's grid cells are each 0.93 km wide (latitude direction) and 0.66 km high (longitude direction), yielding an area of 0.61 km^2.

in to the highlighted area shows the outlines of the individual buildings within a single 1 km² grid area. When the values for the properties in this 1 km² grid area are added together, they result in a single total value, which in this case is represented by the yellow category on the legend.

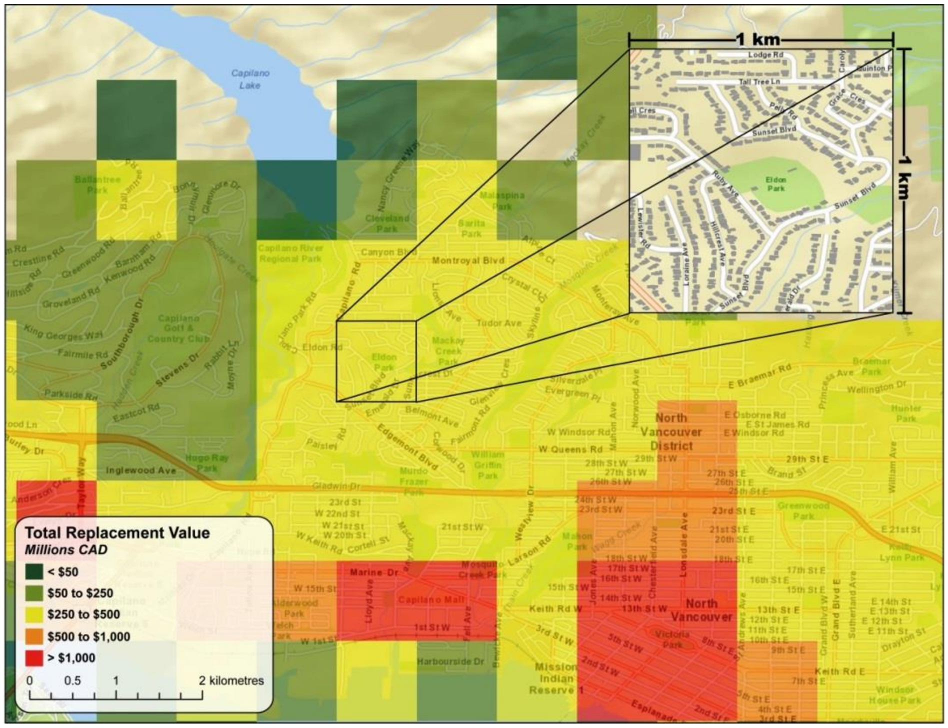


Figure 18: Example of a 1 km² grid cell used for modeling property and infrastructure inventories

4 Scenario Selection

The earthquake scenarios described in Sections 6 and 7 of this report were selected by AIR in accordance with two criteria set by the IBC:

- Each selected earthquake scenario should exhibit a recurrence period (i.e. interval of time elapsed since a comparable event) of about 500 years;
- The ground up loss estimate for each selected earthquake scenario should exhibit a 500-year return period (0.2% exceedance probability) in the affected region.

To identify earthquake scenarios that meet these criteria, AIR conducted a comprehensive probabilistic hazard and loss analysis using an updated version of the AIR Earthquake Model for Canada. Specifically, AIR first generated a pool of 100,000 years of simulated earthquakes within Canada[5]. Next, AIR examined the ground motion footprints of events in this scenario pool, along with correlations among these footprints and uncertainties in ground motion estimation, to ensure that the simulated earthquakes inflict realistic ground shaking. Ground up loss estimates were used in addition to other physical considerations to yield a more stable scenario selection. (The ground up losses are not influenced by policy conditions and insurance penetration rates, which can change over time.) Finally, AIR selected two scenarios from this pool that best fit the IBC criteria described above. Details of this process are described in the section that follows.

Generating a pool of earthquake scenarios

AIR generated a pool of 100,000 years of scientifically sound and realistic stochastic earthquake events (termed the *stochastic catalog*), using different techniques for regions of Canada with different seismicity. These regions, or *seismic zones*, are defined on the basis of historical earthquake data obtained from the GSC and from the United States Geological Survey (USGS)[6]. The seismicity of each zone is captured by several factors, such as the frequency of earthquakes of

[5] Although AIR used several data sources during the development of this pool of 100,000 years of earthquake scenarios, key data were obtained from a historical earthquake catalog compiled by the Geological Survey of Canada (GSC), which was provided to AIR by the GSC in 2012.
[6] AIR conducted extensive internal studies to evaluate the impact of differences in seismicity parameters and the earthquake modeling approach used by the GSC (e.g. a cluster-based approach) and the USGS (a smoothed seismicity approach) for seismic zones of Canada located close to the Canadian-U.S. border. Based on these results, AIR was able to develop seismicity models for each zone that are consistent with the GSC approach, as well as the USGS approach.

given magnitude that occur within the zone (which is termed the *magnitude-frequency distribution* of the zone), earthquake depth, earthquake location, and rupture mechanisms of faults within the zone. Historical values of selected parameters—such as earthquake depth and location—are randomized to account for uncertainty before they are used to create corresponding values for stochastic earthquake events.

However, it should be noted that, for western Canada, which is much more seismically active than the remainder of the country, a kinematic model—which takes account of the crustal movement patterns that produce rock deformation—was used to complement the seismicity assessed using the source zones.

In addition, because the seismicity of eastern Canada is relatively low, a 100,000-year stochastic catalog may not capture the full range of earthquakes that is scientifically feasible for the region. This is particularly true for large magnitude events. To address this issue, AIR first created a 1,000,000-year stochastic catalog to evaluate the effect of earthquake location and other characteristics on regional loss. By examining the exceedance probability (EP) curve of events comprising this 1,000,000-year catalog, AIR was able to produce a 100,000-year stochastic catalog that appropriately captures the probability of large magnitude earthquakes in eastern Canada.

Modeling ground motion for the scenario pool

A critical component of AIR's probabilistic hazard and loss analysis for selecting earthquake scenarios is the calculation of ground motion (and its associated uncertainties) for the scenario pool. To achieve this goal, AIR used empirical ground motion prediction equations (GMPEs), which relate the degree of ground shaking at a particular site to several characteristics of the earthquake (such as its magnitude and depth) and characteristics of the site itself (such as soil conditions). In this project, the most up-to-date suite of GMPEs was used to estimate ground motion from earthquakes produced by all tectonic environments in Canada—including active continental margins, stable continental regions and subduction zone environments—allowing AIR to account for their unique surface ground motion characteristics.

It is important to note that the AIR probabilistic loss analysis method used in the scenario selection process accounts for uncertainty in ground motion calculation. While some uncertainty is random and can be corrected for in the damage estimation component of the model[7], other sources of uncertainty are more worrisome as they can cause the calculated ground motion from a scenario to be artificially high or low (and thus cause a scenario to incorrectly appear more or less damaging, respectively) due to spurious correlations in ground motion across a region. To correct for these correlations, AIR had to devise a new methodology based on analyzing the impact of ground motion from certain scenarios on insurance portfolios.

Selecting two final scenarios from the pool for further analysis

After the 100,000-year stochastic catalog of simulated earthquakes for Canada as a whole was finalized, and the ground motion of these simulated events was modeled, regional loss analyses were conducted. The results of these analyses were used to construct exceedance probability curves for regions of Ontario/Québec and British Columbia. First, events of the stochastic catalog with loss estimates that exhibited a 0.2% exceedance probability (500-year return period) were identified. Next, seismicity information for each of these events was considered, to identify simulated earthquakes with a recurrence interval of about 500 years. The two events described in this report—the eastern Charlevoix crustal scenario and the western Cascadia subduction zone scenario—best fit these criteria.

[7] Information about the model's damage estimation component is available in Section **Error! Reference source not found.**.

5 Scenario Analysis

Section 6 and Section 7 of this report contain detailed descriptive narratives of the impact of the scenario earthquake in each region. They also include estimates of economic and insured losses in each of the following sub-categories:

- Ground shaking/earthquake shock
- Ensuing fire and possible conflagration
- Flooding/inundation (tsunami)
- Liquefaction
- Landslides

The types of economic losses included in this analysis are:

- Direct damage to buildings and loss of contents
- Indirect economic loss resulting from the damage to buildings and loss of contents
- Direct and indirect losses resulting from damage to public infrastructure

The types of insured costs included are:

- Insured loss to commercial and residential buildings
- Insured loss to automobiles
- Insured losses to infrastructure
- Indirect insured losses resulting from damage to buildings and loss of contents
- Indirect insured losses resulting from damage to public infrastructure

Maps accompanying the analyses that follow show the ground motion intensity for each scenario measured both by peak ground acceleration and by a measurement scale known as the Modified Mercalli Intensity scale (MMI). Over the years, various parameters have been used to describe or measure the severity of earthquake ground motion. Peak ground acceleration is the largest increase in ground velocity recorded by a particular seismic station during an earthquake, i.e., the most powerful shake felt at each location. It is an objective measurement of one aspect of an earthquake made by scientific instruments.

Before the use of modern instruments, MMI was more commonly used to describe the severity of earthquake ground shaking based on human observations. MMI is a subjective descriptive measure of seismic intensity on a scale of I-XII from low to high. In Canada and the U.S., MMI is still used to represent the seismic intensity observed by people experiencing an earthquake. Table 16 gives an abbreviated description of typical examples of how each MMI is experienced.

Table 16: An abbreviated description of the MMI scale

MMI	Description
I	Not felt except by a very few under especially favorable conditions.
II	Felt only by a few persons at rest, especially on upper floors of buildings.
III	Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibrations similar to the passing of a truck. Duration estimated.
IV	Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.
V	Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.
VI	Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.
VII	Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken.
VIII	Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned.
IX	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.
X	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent.
XI	Few, if any (masonry) structures remain standing. Bridges destroyed. Rails bent greatly.
XII	Damage total. Lines of sight and level are distorted. Objects thrown into the air.

MMI ground motion is determined based on semi-quantitative reports from people who felt the earthquake or the degree of building damage observed in earthquake affected areas. Assignment of a seismic intensity for a location based on descriptions of damage relies on the observer's subjective judgment, however it is often very useful to aid in understanding the nature of the ground motion experienced in an earthquake.

Figure 19: Fallen shelf unit and fixtures reflecting typical damage in a domestic setting from intensity VI on the MMI scale, Chile, 2010

The MMI scale ranges from Intensity I, at which ground motion is barely perceived by humans, to Intensity XII, at which buildings are generally collapsed. Figure 19 illustrates minor damage from shaking matching intensity VI on the MMI scale experienced in a home during the 2010 earthquake in Chile. The MMI is not used in AIR's earthquake model to calculate losses, but we have used it to inform the descriptive narrative in this report and present MMI maps to show the impact of the events in a more "intuitive" manner.

5.1 Special Modeling Considerations

Fire following earthquake

To assess the potential of fire following from any given earthquake, the variability of fire behavior and environmental conditions needs to be considered. Our fire following model accounts for this uncertainty by allowing for variation in each component: ignition location and number, wind speed, success of fire suppression, and fire severity.

Our model simulates fire following behavior 50 times for each earthquake, with each of the 50 simulations representing one possible outcome of the model and one view of the fire following risk from the earthquake. The average of these 50 simulations is the final view of fire following risk for a given event. The average of the 50 fire following simulations highlight which areas are most at risk to fires following earthquakes while also showing that a wide area surrounding the highest risk locations is also at risk to some fire following induced losses.

In addition to providing the average view of fire following risk we analyze the results of each of the 50 simulations and select one simulation with a loss that is close to the average loss from the 50 simulations. The selected simulation results give a view of what the loss footprint would look like for a single fire following scenario. A fire following scenario tends to have more isolated and intense areas of loss when compared to damage footprint of the average which has wide spread low and moderate losses.

Specification of background tide when tsunami occurs

Tsunami events can occur at any time of day, and therefore can occur during any portion of the tidal cycle at a given location. The background tide condition strongly influences the severity of a given flooding event, especially in areas which have a large background tidal fluctuation, much like a hurricane or other meteorological phenomenon. Given the fact that the British Columbia area experiences tidal fluctuations of several metres, it is therefore important to consider the background tide when simulating tsunami events.

To investigate the influence of tide on the scenario, three separate simulations were conducted. The first featured zero tide height, which is consistent with the tsunami event occurring at a time when the tide is near average. Given the pattern of tides, it is more likely that the tide will be closer to neutral height than it is to very low or very high during a tsunami event. The second and third simulations feature tide specifications at the time of highest or lowest tide for the Vancouver area. In this manner, the range of loss due to different tide conditions was considered.

Non-modeled loss sources

Scenario loss estimates account for insured damage to residential and commercial property, including buildings, appurtenant structures, outbuildings, contents, additional living expenses and direct business interruption. Losses to infrastructure are also included, but not the contents. Economic damage estimates also include indirect business interruption.

The losses included in this report exclude potential losses from several sources. While this is not a complete list, the major sources of non-modeled losses include:

- Loss from levee or dam failures (see further discussion below);
- Loss adjustment expenses;
- Debris removal;
- Hazardous waste removal;
- Loss inflation or deflation due to political pressure;
- Claims under personal or commercial liability coverages;
- Medical payments to others;
- Extra contractual obligations;
- Release of pollutants, contaminants or biological agents;
- Strikes, riots or civil commotion;
- Nuclear reaction, radiation or radioactive contamination;
- All liability arising by contract, operation of law, or otherwise from participation or membership, whether voluntary or involuntary, in any insolvency fund;
- Damage to growing and/or standing crops;
- Credit and/or financial guarantee insurance (policies of insurance or reinsurance guaranteeing payment of indebtedness or financial credit, or cost of repossession);
- Mold;

• Commercial inland marine, ocean marine, recreational marine and pleasure boat;

• Share of any losses or assessments from property residual markets, including cat pools established to make property insurance available to persons reasonably unable to procure such insurance in the voluntary market.

- Losses from extra-contractual obligations

The losses reflect AIR's default assumptions about post-event inflation, or demand surge. The demand surge assumption reflects economic inflation only. It does not account for other factors that may increase insured losses in the aftermath of a catastrophe, such as those listed above or insurance-to-value issues.

Levees and dams

Sections of British Columbia, including the Vancouver area, feature levee defense structures that would be an important factor in mitigating tsunami damage. The tsunami model calculates probabilistic levee failure due to the tsunami wave itself, although in simulations featured here there was no failure of levees. The tsunami modeling strategy does not, however, consider the potential for levee structures to be damaged by the ground motion itself. In other words, failure of levee defense structures due to the earthquake ground motion could potentially increase tsunami damage. In addition, failure of dam structures due to the shake motion is not modeled.

Nuclear power

Losses associated with nuclear power plants and facilities are not modeled.

Human life

Losses associated with human life, such as personal accident coverage, are not modeled.

6 The Western Scenario

6.1 Event Description

The earthquake that is the focus of the western scenario originates off the west coast of British Columbia, but it is strong enough to be felt on land as much as 700 km from the rupture. The area impacted includes the whole of Vancouver Island and an arc of the mainland radiating some 400 km inland from Vancouver and 600 km north west along the coast. This domain includes the capital of British Columbia, Victoria, the whole of the Metro Vancouver area and the communities along both shores of the Strait of Georgia, at the southern tip of Vancouver Island and to the east of Vancouver.

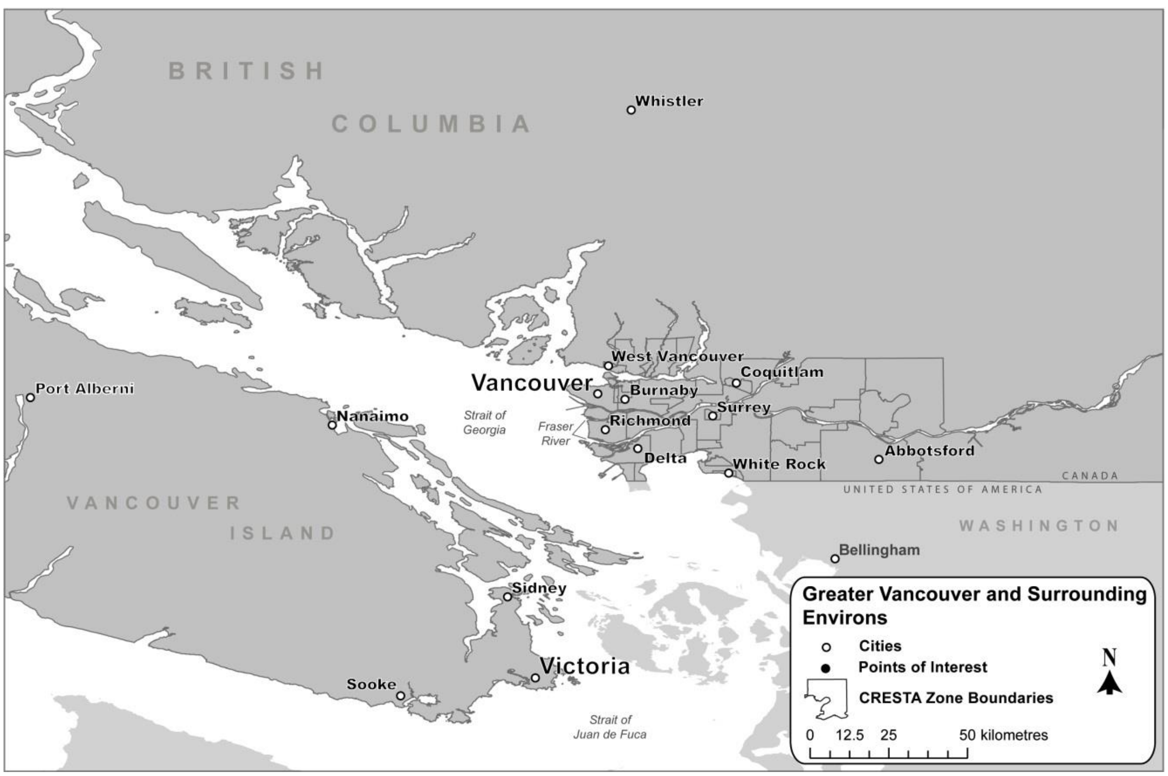


Figure 20: The principal municipalities in the western scenario region

The defining feature of this mountainous coastal region is the Strait of Georgia, which separates Vancouver Island from the mainland, and the greatest concentration of population and property in the region is the Metro Vancouver area. The city of Vancouver itself lies mostly on the western portion of the Burrard Peninsula with the Burrard Inlet, which provides its principal harbor, to the north. It shares the peninsula with several municipalities to the east. To the south, Richmond, Delta and Surrey occupy the sedimentary plain formed in the delta of the Fraser River. The entire Metro Vancouver area extends further still, and encompasses a total of 22 municipalities, one electoral area and one treaty First Nation.

Figure 21: Vancouver from Grouse Mountain. Port facilities on the Burrard Inlet face the concentration of high-rise development that marks Vancouver City. In the background Vancouver International Airport can be seen in the Fraser River delta (Adam Lindsay, Wikimedia Commons)

Vancouver is one of Canada's youngest cities and, with its focus on high-rise residential and mixed-use development, one of the most densely populated in Canada. It owes its success to the superb natural harbor that it provides in these sheltered waters. It is the western focus of transcontinental railroad and highway routes and Canada’s gateway to the Pacific. Port Metro Vancouver is Canada’s largest port and handled international trade worth more than CAD 186 billion in 2012. Vancouver International Airport, the second busiest in the country, is a major connection to Asia.

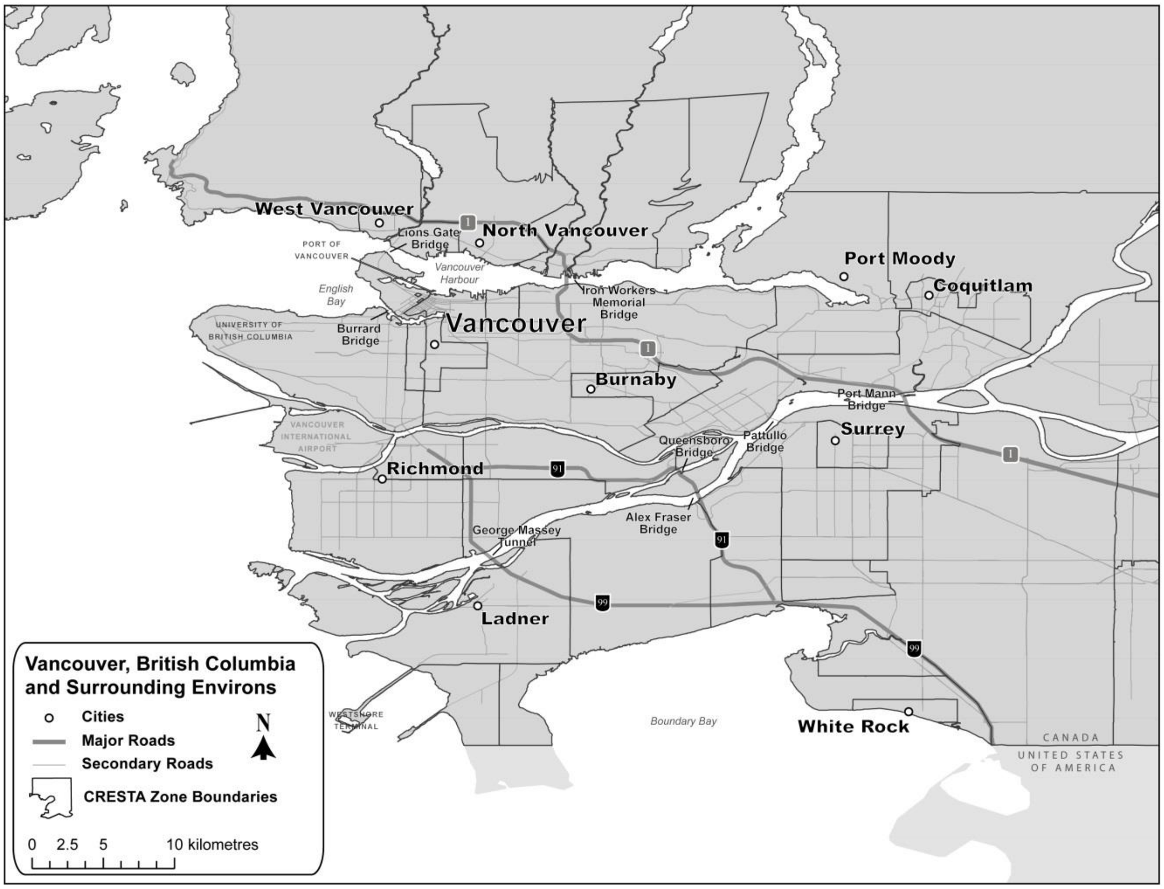


Figure 22: The Metro Vancouver area

Dubbed the world's most livable city many times, Vancouver is home to support services, manufacturing industry and more than half of the province's office space. As well as corporate headquarters and professional firms, it boasts growing software and biotechnology sectors, thriving tourism and a flourishing film industry. With less than 10% of its land useful for grazing or cultivation, British Columbia's principal economic activities are logging and mining, and much of their output passes through Vancouver. In the milder south-central part of the province more than 200 wineries have been established, and there are several more on Vancouver Island's drier and less rugged east coast.

The scenario event

The western scenario earthquake occurs on a weekday late in July. This is the high tourist season in the region, and the weather is likely to be very pleasant. Temperatures will be warm but comfortable, probably rising to the low to mid 20s. Any cloud cover is likely to clear rapidly and since rain is typically experienced on only seven days in July there is a low probability of some precipitation falling—this is the least rainy month in a city famous for its rain. Typical July wind speeds vary from 2 km/h to 20 km/h and rarely exceed 30 km/h. Winds are most likely to come from the west, and least likely to come from the north. This scenario has been assigned a wind speed of 19 km/h, well within the usual range experienced.

The time of day at which the earthquake occurs is not significant from the perspective of insured losses, and is therefore not considered in this exercise. A significant earthquake coinciding with rush hour would however be expected to result in an elevated number of personal accident claims, but these fall outside the scope of this study.

The western scenario event is an extremely powerful earthquake, with a magnitude of 9.0. It is strong enough to be felt over a very wide area, including much of British Columbia and Washington State in the United States. It occurs at the shallow depth of 11 km. The location (Lat. 44.706, Long -124.569) is out in the Pacific Ocean, approximately 75 km off the west coast of Vancouver Island, some 300 km from downtown Vancouver. The nature, size and location of the event enable it to generate a tsunami.

Anticipated damage

A few seconds, perhaps a minute, of strong shaking can feel like a very long time. After the shaking people in these municipalities may experience a rolling motion, much like being at sea. They will find it difficult to stand or walk and drivers will be very aware of the ground motion. Standing water will be turbid with mud and waves will likely form on ponds. Fire alarms and sprinkler systems can be activated in buildings, and car alarms may be triggered. Structures will creak, windows may crack or break, and lights and power may go off almost immediately.

The upper floors of high-rise or a multi-storey buildings will sway more and shake less than lower buildings do, resulting in more toppled furniture and contents damage. In addition to items falling off walls and shelves, hanging objects may quiver and some furniture will be broken. Well designed and built buildings will perform well, but poorly-built masonry buildings will be damaged. Weak chimneys are likely to break off at the roof line, plaster and some loose bricks, stones, tiles, cornices and unbraced parapets and porches will fall. Some cracks will appear in better-built masonry buildings.

In this scenario, ground shaking is responsible for the majority of ground-up losses, but landslides, the tsunami and fires following the rupture contribute to the damage inflicted.

Figure 23: Damage to a residential structure in L'Aquila Italy, 2009

The first wave from the tsunami created by the earthquake strikes the closest part of Vancouver Island about 30 minutes after the rupture. As it travels outwards from the epicentre it impacts the entire west coast of the island. When the southward moving portion reaches Victoria about 45 minutes after the earthquake it still has a peak wave height of 1 – 2.5 m above the level of the tide at that time. The first wave is expected to reach Vancouver two hours after the earthquake. By then its height above tide level will have been further reduced by its extended journey and its interactions with the intervening islands.

After the earthquake several fires will probably develop across the area as fuel comes into contact with sources of ignition. These fires may start soon after the earthquake, or develop later as power supplies are resumed.

Vancouver Island

Being closest to the epicentre of the event, the western side of Vancouver Island—and most particularly the southern half—would experience the strongest ground motion and the worst levels of damage to buildings and other property. A few locations on the west coast of Vancouver Island may experience shaking as strong as level IX on the MMI scale (see Table 16 for a description of the levels on the MMI scale), but much of the southern part of the island will experience shaking somewhere between levels VII and VIII. The Metro Victoria area, the 15th most populous Canadian metro region and home to almost half of the island's population, will experience ground motion similar to that felt in Vancouver, as discussed in the next section.

Figure 24: Victoria and its environs

We anticipate considerable damage to ordinary buildings in areas with the most violent ground motion, and severe damage to poorly built structures. Frame houses will move on their foundations if not bolted down and some loose panel walls will be thrown out. Chimneys, towers and elevated tanks will likely twist and fall. Unreinforced masonry buildings will feel the worst effects, including widespread damage to chimneys and some partial collapses. The historic heritage and vintage buildings that give so much character to Victoria and Duncan for example, are particularly at risk.

Residential buildings in Victoria are mostly low-rise, and moderate damage to them is generally expected. For wood buildings with moderate shake damage, large cracks around corners and window openings may be observed. Large and extensive cracks may be seen in many partition walls. Some mid- to high-rise condominiums in downtown Victoria will be damaged by fires following the earthquake. Additional living expenses may be required for several days. Some wood residential buildings near Esquimalt will suffer significant damage from landslides and certain areas in Gordon Head, in the northern part of Victoria, may expect substantial landslide damage. Substantial to very heavy flooding damage from the tsunami is expected south of Esquimalt and near Sooke Harbor. Similar levels of tsunami-related flood damage are anticipated in some areas along the Haro Strait, such as Cordova Bay.

Generally, light to moderate damages are expected to commercial and industrial buildings. For reinforced concrete buildings with light shake damage, cracks in columns and beams are expected. A few ceiling tiles might fall down. In downtown Victoria, ground shaking is the major cause of losses. In some areas, landslide and fire following also contributes substantially. Business interruption may be a few months. In some locations around Victoria Harbor, tsunami is expected to be the major cause of loss. Business interruption due to damage from multiple perils may continue for a few months.

Victoria International Airport, one of the busiest airports in B.C. in terms of the number of passengers, is expected to sustain low to moderate levels of damage as a result of the earthquake. Damage to buildings at the airport is expected to be light, but some masonry commercial buildings in the area are expected to have moderate damage such as cracks in the walls and falling plaster. Moderate losses to the contents are also expected from items falling from shelves, damage to electronic equipment, etc. Repair and reconstruction of moderately damaged masonry buildings like these can take more than a month. No significant damage is expected in the runways and tarmac, and therefore no major service disruption is anticipated.

The earthquake is expected to cause some slight to moderate damage to various components of the Port of Victoria. We anticipate considerable ground settlement affecting waterfront structures, with several piles broken and damaged. Some cranes and cargo handling equipment may experience derailment due to unequal changes in surface levels. Moderate damage to some buildings in the port area is anticipated in the form of diagonal cracks across wall panels in wood or masonry buildings and small cracks or splitting at bolted connections in wood buildings. Considerable disruption and toppling of contents is anticipated. As a results of the damage in the port, service may be cut for several days.

Buildings and facilities in the area on the Canadian Forces Base – Esquimalt may sustain moderate to extensive damage from ground shaking and tsunami. Ground failure is also likely to cause damage to some buildings in the area. Restoration may take up to two months for some hard hit buildings, mainly due to tsunami damage.

Vancouver Island infrastructure

Beyond Metro Victoria, which is home to a significant IT and technology industry, the island's economy is largely concerned with forestry, tourism and fishing. There is also a flourishing winery industry located mostly in the vicinity of Victoria and Duncan on the southeastern tip of the island. The commercial losses anticipated in these areas are generally at the lower end of the range. Damage to the island's infrastructure, particularly to the roads and bridges, could prove to be of greater significance to its economy. Damage to roads in and around Victoria is expected to be slight. Some local roads along the slopes on the southern coast of the Vancouver Island (e.g. near Sooke and Esquimalt) may experience extensive damage partly due to landslide. Closure of for a few weeks is likely in these roads.

Port Alberni at the head of the Alberni Inlet will experience severe shaking and the ground failure as a result of the earthquake, which may lead to moderate damage to port facilities. Considerable ground settlement and several broken piles are expected in water front structures and some cranes and cargo handling equipment may be derailed. In addition to minor structural damage to buildings some disruption and toppling of contents is anticipated. At this level of damage, the port may be out of service for several days. Nanaimo, on the east coast of the island, will be hit hard by shaking and the tsunami inundation. Extensive damage is expected in the port from the failure of many piles, extensive sliding of piers, and significant ground settlement causing extensive cracking of pavements in the waterfront structures. Considerable damage to equipment and the toppling or total derailment of cranes are likely to occur. Significant damage to equipment and facilities can be attributed to tsunami inundation. The extent of the damage anticipated is so large that the port may be out of use for many months.

The Swartz Ferry Terminal in North Saanich, about 20 miles north of Victoria, is in an area likely to experience moderate to extensive damage from ground shaking and tsunami inundation. A few buildings on the slopes may experience some landslide damage as well. Damage to commercial and industrial facilities in the ferry area may render them inoperable for a considerable amount of time. While some masonry buildings in the area may take two to three months for full restoration some steel and reinforced concrete buildings may require more than one month for full restoration.

To the north of Tofino on the west coast there are large areas at moderate risk of landslides, and additional areas of high risk; some landslides will occur. The airport at Tofino for example is likely to experience moderate to extensive damage from ground shaking and, to some extent, from landslide. The runways may be damaged by moderate to considerable ground settlement or heaving of the surface and there could be moderate to substantial damage to buildings in the area. Tsunami damage would also be expected at Tofino's airport, which will be flooded and may be out of service for several weeks.

In addition, the coast in this area would experience the most severe effects of the tsunami. This is however, an area with low exposure, and relatively low levels of insurance loss are anticipated. Small towns on the western shores of Vancouver Island, such as Tofino or Ucluelet, being in the direct path of the tsunami wave, benefit from sheltering effects of the western side of the spit of land on which they are built. The local elevation of these towns also keeps them relatively safe from major damage in the tsunami.

Vancouver City

The greatest concentration of exposed assets in the region is of course the Metro Vancouver area, which for the most part experiences moderate shaking. Everyone in the Metro area will feel this shaking, and many people will be frightened by it. Walking will be difficult during the ground movement, trees and bushes will be seen to shake and heard to rustle. Inside buildings books and ornaments will jiggle off shelves, pictures will fall from walls and even heavy pieces of furniture will move or topple. Damage to well-built modern buildings however, will be relatively slight. Some window glass will break, weak plaster will be damaged and some older and/or poorly built masonry buildings will develop cracks.

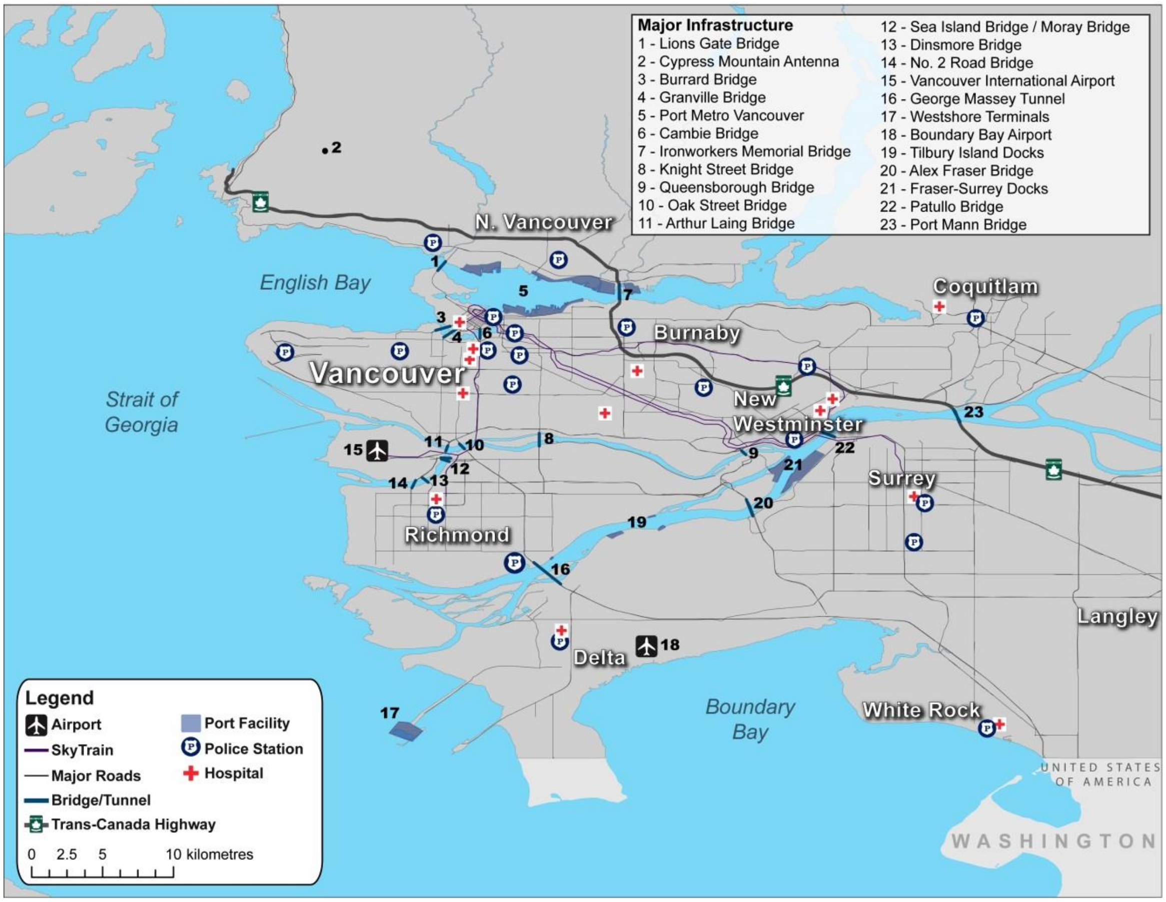


Figure 25: Key infrastructure in Vancouver City

Granville Island, located in False Creek directly across from Downtown Vancouver, is a major tourist destination. Most of the commercial structures on this island are of wood and may only experience some light damage and may sustain moderate damage leading to business interruption for perhaps a few weeks. Moderate damage in masonry commercial buildings may be widespread, and could consist of cracks in walls and falling plaster. Considerable contents movement and damage is also likely. Damage in unreinforced masonry buildings may need up to a month for repair and restoration. Damage is mainly from ground shaking, but in wood construction (Residential and Commercial) some incidents of fire following earthquake may also contribute. The eight-lane Granville Street Bridge, which straddles the island, is expected to experience slight damage and will remain operational. No major closure is expected after the initial inspection.

At the University of British Columbia, on the western tip of the peninsula on which Vancouver sits, damage in general is expected to be light to moderate. Moderate damage in masonry buildings may involve cracks in many walls, failure in the connection of panels to structural frames, and falling ceiling tiles and fixtures—even the partial collapse of ceilings at a few locations. Depending on the extent of the moderate damage some buildings may be out of service for repair and restoration a few weeks. Damage in steel and reinforced concrete buildings is expected to be slight. Ground failure may contribute to the damage in this area.

The area around the Vancouver General Hospital hosts a large number of medical buildings. These are of different construction and heights. Usually buildings for medical use are designed and constructed with a higher degree of engineering considerations, as required by design codes and standards. This is particularly true for buildings designed to modern codes (e.g. buildings built after 1985). Better design and construction reduces the seismic vulnerability of buildings and contents in these facilities. The scenario earthquake is expected to cause some light damage to these buildings in this area. Some older masonry buildings may experience light to moderate damage in the form of cracks in main walls and partition walls, and falling plaster, ceiling tiles and fixtures. Reinforced concrete and steel buildings are expected to sustain light structural damage and some non-structural and content damage. Several days of downtime is expected for some buildings, mainly those of masonry construction.

Residential buildings in Vancouver are mostly low-rise, with some mid-rise condominiums. Light damage to residential buildings is expected in this area. Some buildings near the Coal Harbor, English Bay and Chinatown might suffer light to moderate damages from tsunami. Moderate to substantial liquefaction damage is expected in the south part of Vancouver, including Iona Island and areas along the North Arm Fraser River. Moderate to substantial damage from tsunami (and ground shaking) is likely to occur in the buildings south of Roche Point and Windsor Park in North Vancouver.

Generally, light damage is expected to commercial and industrial buildings. For steel moment resisting frame buildings with light damage some members may suffer large deformations at connections. In coastal areas around the University of British Columbia tsunami may be a considerable contributor to losses to commercial and industrial property. Business interruption may be several weeks. Substantial liquefaction damage may be observed in areas around the north arm of the Fraser River and Sea Island. Mid-rise commercial buildings in the south of New Westminster and north of Surrey and Delta may experience moderate damage, which may lead to downtime of more than a month in some cases. Part of this damage could be attributed to liquefaction. Damage to higher buildings (eight or more stories) in these areas may be large, particularly losses to contents. Inspection and repair in some of these buildings may take about a few months.

Richmond, Delta and Surrey

To the south of Vancouver City, the municipalities of Richmond, Delta and Surrey will be worse hit. These communities, either side of the Fraser River, are built on silty and sandy sediments that shake more than the rock on which Vancouver itself is constructed. As a result, these municipalities experience more powerful ground motion generally described as strong shaking. Because they are built on the coarse-grained soils deposited by the Fraser River, these municipalities are more prone to damage from liquefaction. This peril is responsible for 6.6% of the entire economic loss anticipated from the western scenario, but much of that damage is concentrated in a few vulnerable areas.

Government buildings around Richmond City Hall are expected to experience moderate damage. Liquefaction contributes significantly to the damage expected in this area. Masonry buildings are expected to sustain moderate damage, and some may be out of service for repair and restoration for more than a month. Steel, reinforced concrete and wood frame structures may be out of service for several weeks.

Most residential buildings in Richmond are low-rise and moderate damage is expected. For masonry building with moderate shake damage, fairly large pieces of plaster may fall for example, some chimneys may partially collapse and some window frames may need realignment. Liquefaction damage in Richmond is expected to be high. Some mid- and high-rise condominiums might be closed for several days due to shake and liquefaction damage. Some buildings in west Richmond and near the Fraser River are expected to experience substantial tsunami damage.

Generally moderate damage is expected to commercial and industrial buildings. For steel braced buildings with moderate shake damage a few braces or connections may have indications of reaching their ultimate capacity, exhibited by buckled races, cracked welds, or failed bolted connections. Although ground shaking dominates losses in most cases, liquefaction will cause significant loss in many locations. Moderate damage is expected in the mid-rise buildings in and around the city centre and in the Golden Village area. Damage in the high-rise buildings is expected to be lower. In these locations liquefaction becomes the major cause of loss. Downtime may vary from a few weeks to a few months. In the west of Richmond and in southern areas such as Gilmore and Paramount, substantial tsunami damage is expected.

Infrastructure

As a result of ground shaking and liquefaction, some roads will be damaged and impassable, water supply and other buried services will be compromised and many bridges will be closed temporarily. All bridges will require inspection prior to being reopened and the most strategic bridges will receive priority. Less significant structures will be closed for some while until inspection engineers are free to turn their attention to them. Damaged bridges, like the one in Chile seen in Figure 26 will require repairs, which in some cases may keep them closed for years, but these will not necessarily need to be carried out immediately.

Figure 26: Earthquake damage to a road overbridge, Chile, 2010

Most of the major roadways in and around Vancouver may experience only slight damage, such as slight settlement (a few inches) or distortion of the ground. Closure of more than a few hours is not expected for these roads. However, damage to bridges may lead to the closure or rerouting of many local and highway roads. The interaction of infrastructure elements like these cannot be easily represented without detailed modeling of the traffic system. Therefore the qualitative damage descriptions presented here addresses each transportation component separately, and interactions are not accounted for.

Road access to Vancouver from the north via the Lion's Gate and Ironworker's Memorial (Second Narrows) Bridges should be unaffected because neither bridge is expected to be damaged. We expect all bridges to be closed temporarily for inspection after the event, but do not anticipate issues that would delay the reopening of these particular structures. Access to Vancouver from the east will however be impaired. The Port Mann Bridge on Route 1 is expected to be functional with some minor disruption—repairs might take a few days. The longest bridge closure anticipated in this analysis is that for the Patullo Bridge, which was built in 1936. Repairs to its moderate damage may take a few weeks.

Road travel between Richmond and Vancouver to the north and Delta and Surrey to the south is also likely to be impaired. Moderate damage, involving several inches of settlement or offset of the roads is expected in Richmond, Delta and Surrey because of liquefaction. Furthermore, all of the bridges communicating between these municipalities and Vancouver will be affected. The Oak Street Bridge is expected to sustain slight to moderate damage due to ground shaking and liquefaction. Slight damage is only cosmetic, and may include minor cracking and spalling to the abutments, hinges, and/or minor cracking to the deck. At the moderate damage level cracks are more severe and settlement of the approaches is also likely due to liquefaction. Full restoration and repair may take up to three weeks. Both sections of the Knight Street Bridge, which straddles Mitchel Island, are expected to sustain moderate damage, repairs to which may take a few weeks.

The Queensborough Bridge, which connects Vancouver and Richmond on route 91A over the North Arm of the Fraser River, may be closed early for a few days for initial inspection and repairs. It will suffer damage from ground shaking and liquefaction, and full restoration may take a few weeks. Moderate to extensive damage due to ground shaking and liquefaction is expected to the Alex Fraser Bridge, which spans the Fraser River and connects Delta to Annacis Island. It may be closed for inspection and initial repairs in the few days after the event but full-scale repairs may take several weeks. The George Massey Tunnel is a road tunnel under the Fraser River, connecting the City of Richmond to the north with the Corporation of Delta to the south. Only slight damage, such as minor cracking of the tunnel liner or slight settlement of the ground at a tunnel portal is anticipated. The tunnel will require no more than cosmetic repair and is expected to be operational after initial inspection.

Figure 27: Vancouver International Airport is on an island in the delta of the Fraser River, at risk of liquefaction damage and accessible chiefly via vulnerable road bridges (Alejandro Erickson)

Most importantly, road access to Vancouver Airport will be cut off during the first few critical days after the earthquake as all of the bridges leading to it are impacted. The Arthur Lainge Bridge for example, the major connection between the airport and the city of Vancouver, is expected to suffer moderate damage. Damage at this level may result in moderate cracking and spalling to columns, which remain structurally sound. Abutments may move less than two inches. The bridge may need to be closed to traffic for a few days for inspection and initial repair. Full restoration may take a few weeks. The Canada Line rail service to Vancouver Airport will likely also be disrupted.

Sea Island, on which Vancouver International Airport is situated, is at moderate risk for liquefaction—a likely source of damage to the runways. Structures such as towers, storage facilities, office buildings and hangars are modeled as commercial entities but the tarmac and terminals are modeled as airport infrastructure. In addition to losses to insured commercial property at their locations, infrastructure at the region's airports is anticipated to sustain more than CAD 300 million in damage from shake and liquefaction, corresponding to 17% of the total infrastructure loss in this scenario.

At Vancouver International Airport, buildings such as terminals, towers and hangars are expected to sustain slight to moderate damage. Typical damage to reinforced concrete buildings at this moderate level consists of cracks in the columns and beams of frames, and in structural walls. Cracks in partition and infill walls are also expected, as well as falls of brittle cladding and plaster. Steel structures that experienced deformation may develop major cracks in some welded connections or exhibit broken bolts or enlarged bolt holes at bolted connections. Areas of tarmac will be moderately damaged, characterized by some minor ground settlement or heaving of the runway surface. Some sections of runway may be out of service for a few days, but restoration of some masonry structures at the airport area may take a few months.

Only slight damage is expected to occur however at Abbotsford International Airport. Runways may experience some minor ground settlement or heaving of the surface, and some commercial buildings and their contents could sustain light damage. The airport is expected to remain functional, with no disruption in service.

Port facilities in the Vancouver area are likely to be hit by different degrees of damage. While damage in and around Vancouver Harbor itself will probably be slight, damage to facilities in south Richmond and north of Delta and Surrey (around the Fraser River) will be greater due to liquefaction and flooding.

Slight damage in the Vancouver Harbor ports may include minor ground settlement, minor cracks in the piles and cracks on the wharf surface. Some unanchored crane and cargo handling equipment may experience derailment or misalignment without any major structural damage to the rail mount. Minor repair and adjustments may be required before these become operable again. Anchored equipment is expected to remain functional.

Moderate damage in ports near Richmond, Delta and Surrey areas due to liquefaction will likely include considerable settlement and cracking of piles, the notable derailment of cranes and cargo handling equipment, and wall cracking in the port facility buildings. Liquefaction damage is particularly notable in port areas in Annacis Island and North Delta. Damage from tsunami inundation is expected at some smaller ports near Tilbury Island and Sunbury in Delta. An increased level of debris in the water contributes to the damage to buildings and automobiles around these ports. Service in some of the ports in Vancouver area may be disrupted for one to two weeks.

Water supply will be impacted to some extent across the entire Metro Vancouver area, with damage in various locations ranging from none to more than CAD 100,000 in some 1 km^2 cells. The greatest concentration of liquefaction damage at the highest level to structures and to buried services is likely to be in Richmond and Delta, with additional pockets in locations adjacent to the Fraser River further inland. Wastewater services will probably be similarly impacted.

Cell phone service is likely to experience significant disruption in the short term, due to a dramatic increase in the volume of calls throughout the affected region immediately after the event. In Richmond, Delta and Victoria service may be impacted for longer because some towers may be out of service for a few days. Fortunately power outages are likely to be few and brief, with Richmond, Delta, Victoria and Duncan, the most affected communities, mostly experiencing a brief period without power. Gas production and distribution will be impacted in Vancouver and Burnaby and along the Fraser River in Surrey, with a particular concentration of losses to property in central Richmond and Delta.

A few days after the earthquake power and communications will have been restored to most municipalities, and all fires will have been extinguished. For most of these communities the familiar routines of life will be beginning to return, except that damage to roads and the continued closure of key bridges will significantly impair road travel for some time to come. In most respects, the worst-hit municipalities are likely to be Richmond and Delta. In addition, numerous blockages to lifelines over a large area caused by landslides and shake damage would disrupt economic activity and restrict access to the Metro Vancouver area as a whole.

Exposure in the region affected by the western scenario

Figure 28 shows population per 1 km^2 grid in the region impacted by the western scenario. At the end of 2012, there were an estimated 4.6 million people living in British Columbia according to British Columbia's statistical website, BC Stats.

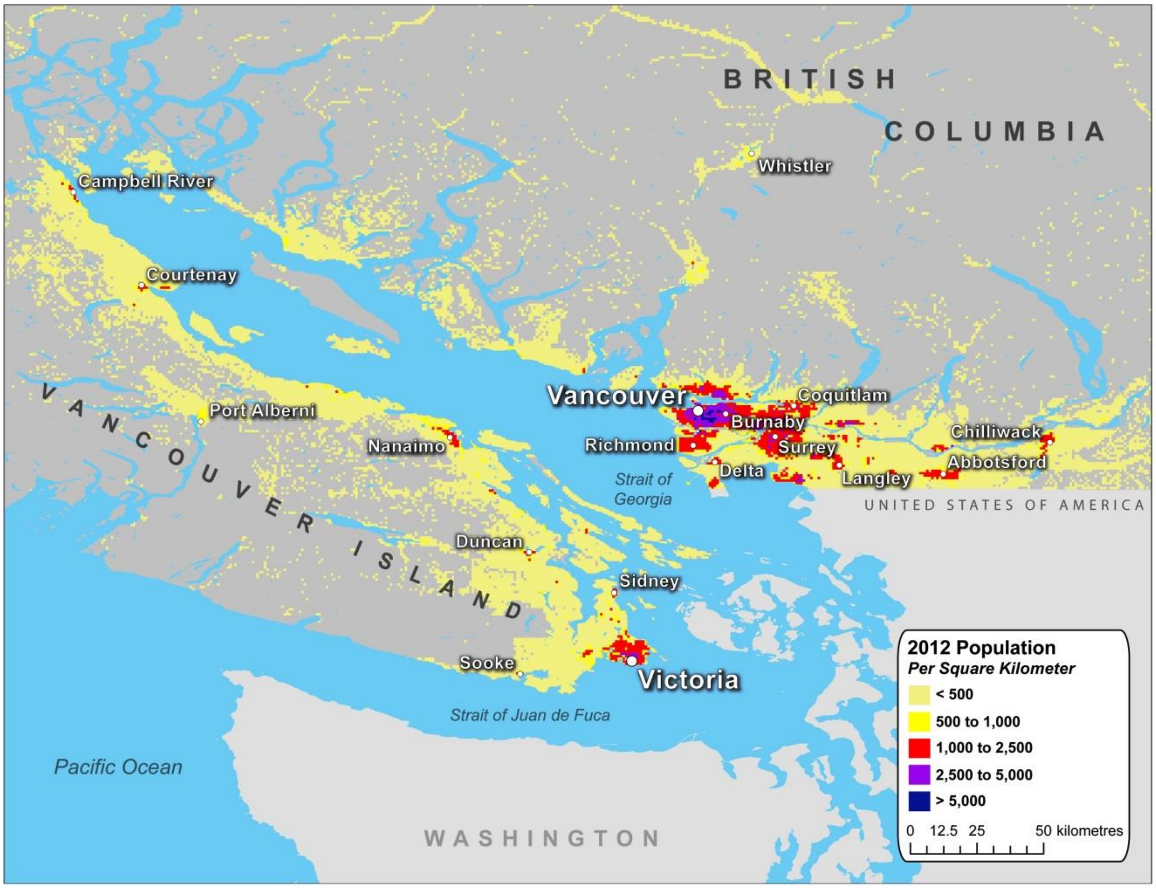


Figure 28: Population distribution in the western scenario region

It is clear from the population density map given in Figure 28 that large concentrations of population are centred in and around the cities of Vancouver and Victoria. In fact, roughly half of the population of British Columbia lives in Metro Vancouver, which is the third largest metropolitan area in Canada. In addition, well over 300,000 people live in the Victoria metropolitan area. Both of these areas would be affected by the western scenario.

The large concentrations of population in Vancouver and Victoria have brought along with them correspondingly large proportions of property and infrastructure exposure which would be vulnerable in the event of the western scenario. Damage to even a small percentage of these exposures could still result in great loss. However, it is not enough to look at the overall value of exposure in this area, as it is the distribution by property type, geographic location and the presence of earthquake insurance that would determine how the damage would be felt, and by whom.

The following maps show residential, commercial, and infrastructure values at 1 km^2 in the at-risk areas surrounding the western scenario. The maps showing "all property" display all of the exposure value that is at risk, whether it is insured or not. The "insured" maps show only the values of the property that is covered by earthquake insurance policies. The difference between the two maps is the amount of exposure that would not be covered by insurance in the event of an earthquake, which is sometimes very great.

For the purpose of these maps, agricultural buildings and industrial establishments and facilities are included with commercial exposure. Public properties are also included in the total all property commercial maps but these properties are not included in any of the insured maps in this section.

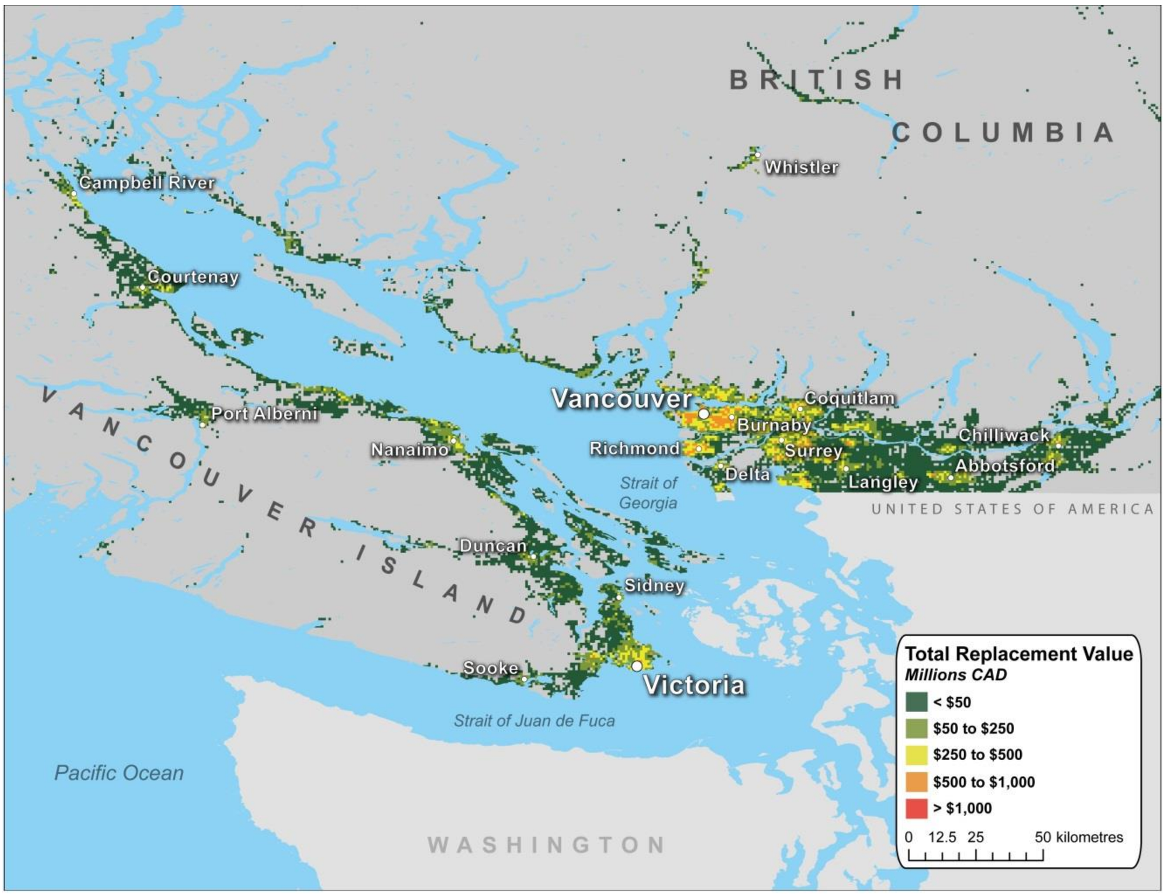


Figure 29: All residential property values, western scenario

Figure 29 above and Figure 30 below compare the values of all residential property and insured exposure surrounding the western event. The percentage of residential homes and apartment residences with earthquake insurance is much higher in this region than in eastern Canada, but there is still a large amount of residential exposure without any earthquake insurance. This pattern is perhaps most apparent in downtown Vancouver, where there is a high concentration of apartments.

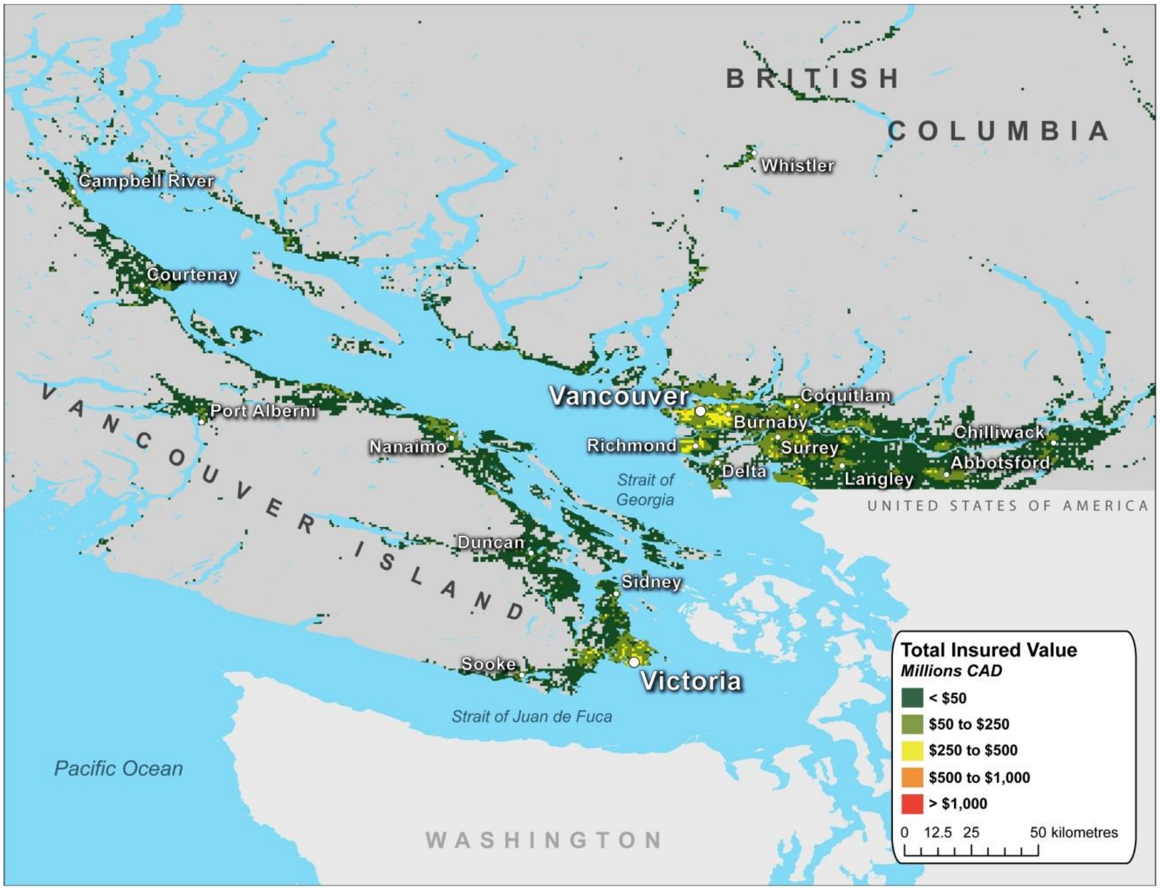


Figure 30: Insured residential values, western scenario

Commercial establishments tend to be more concentrated in downtown areas, with large numbers of high-rise buildings clustering nearer to the city centres. Industrial establishments are often grouped in distinct industrial parks throughout a general metropolitan area.

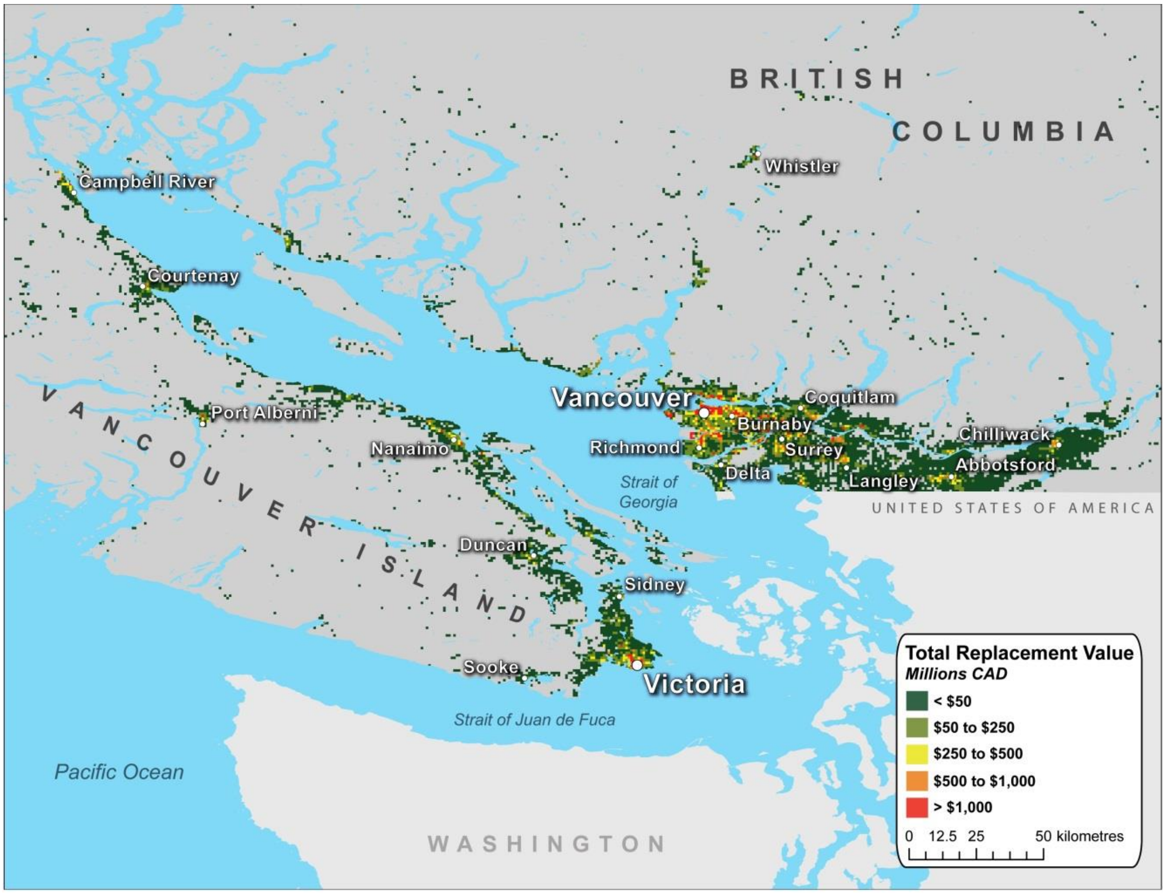


Figure 31: All commercial/industrial property values, western scenario

This pattern is apparent in Figure 31 and Figure 32, which show all commercial and industrial property and insured exposure values surrounding the western event.

Overall, businesses tend to have much higher take up rates for earthquake insurance than residential homes and apartment residences, leading to a much less noticeable difference between the insured and all property maps for commercial when compared to residential (Figure 29 and Figure 32). In addition, the percentage of businesses with earthquake insurance is larger here than anywhere else in Canada.

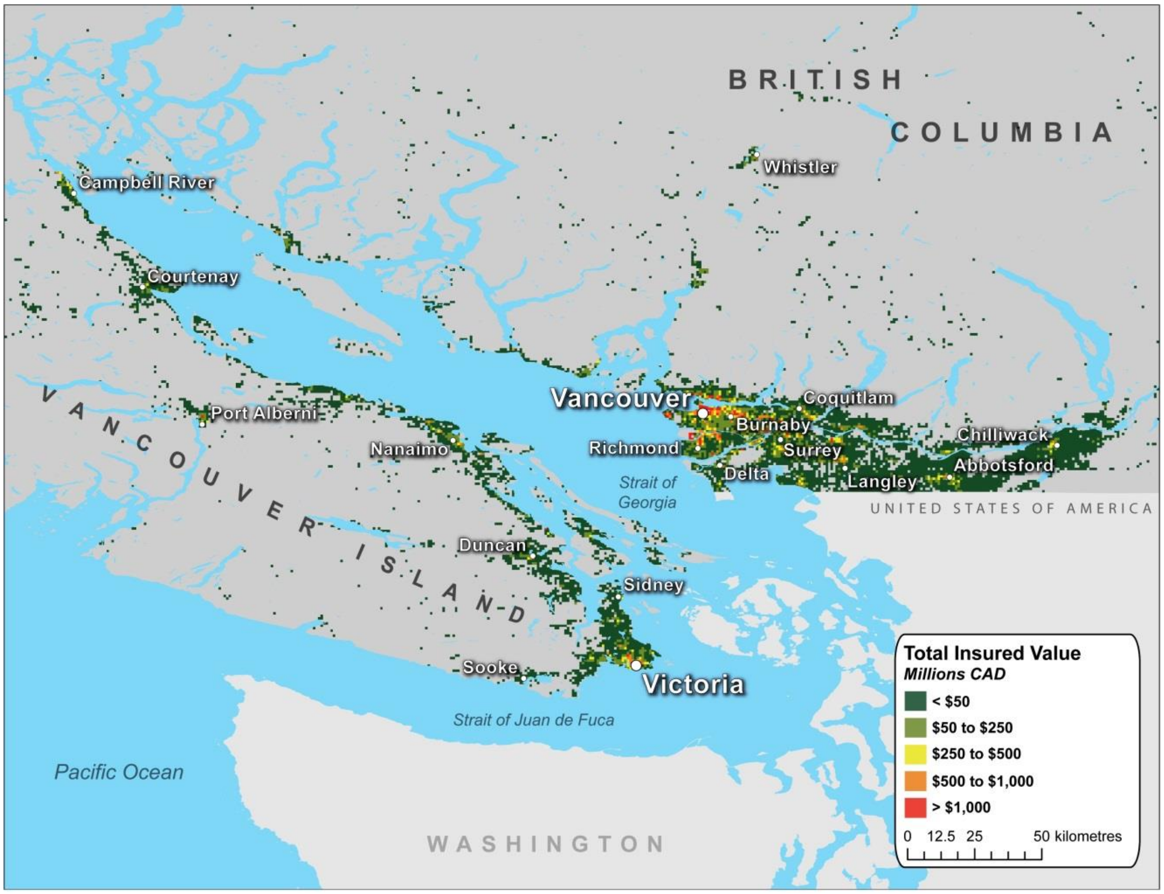


Figure 32: Insured commercial/industrial values, western scenario

Next, in Figure 33 and Figure 34, the total insured and all property values (commercial/industrial, residential, agriculture and auto combined) are shown for the western scenario. The concentration of exposure in the Metro Victoria and Vancouver areas is very evident.

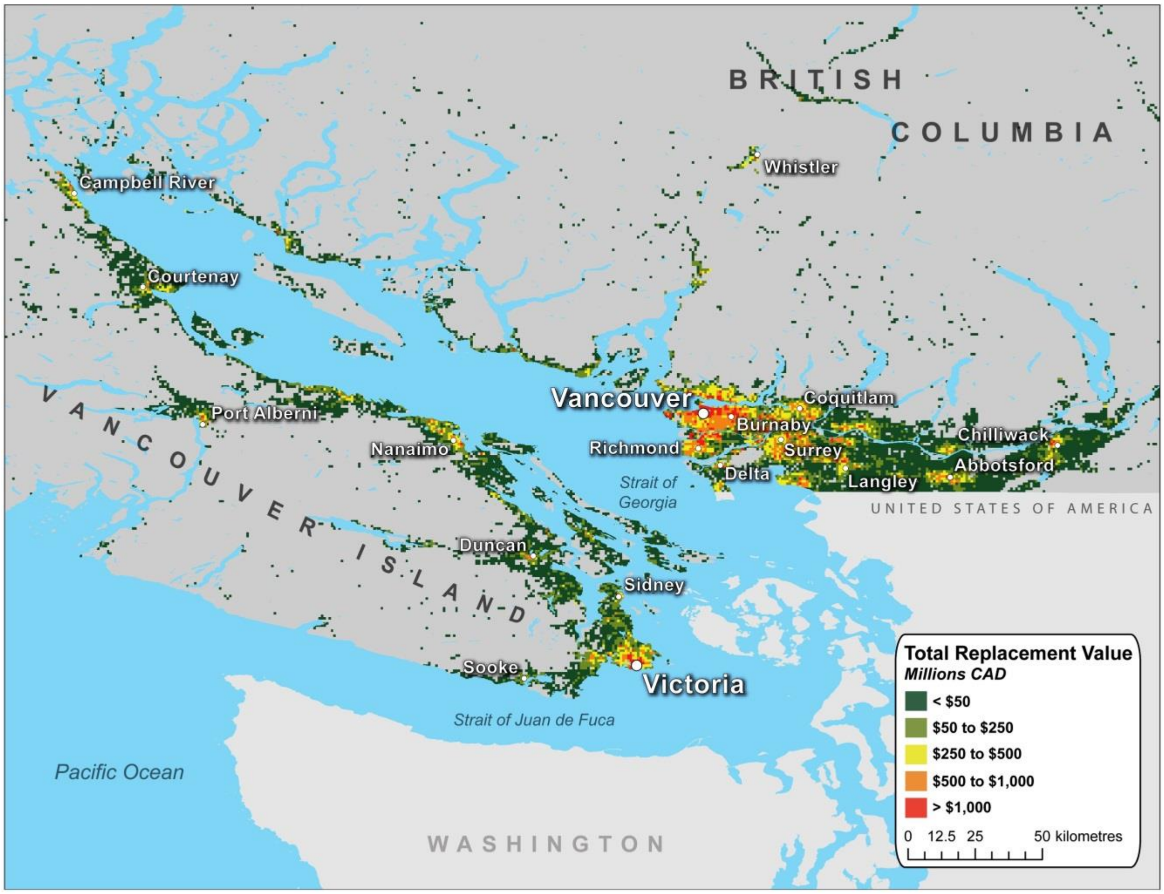


Figure 33: Total all property value, western scenario

Figure 33 shows the total value of all property in the principal portion of the western scenario region, whether it is insured or not. The concentration of property and population along the shores of the Strait of Georgia, on the southern tip of Vancouver Island, and to the east of Vancouver itself is clearly visible.

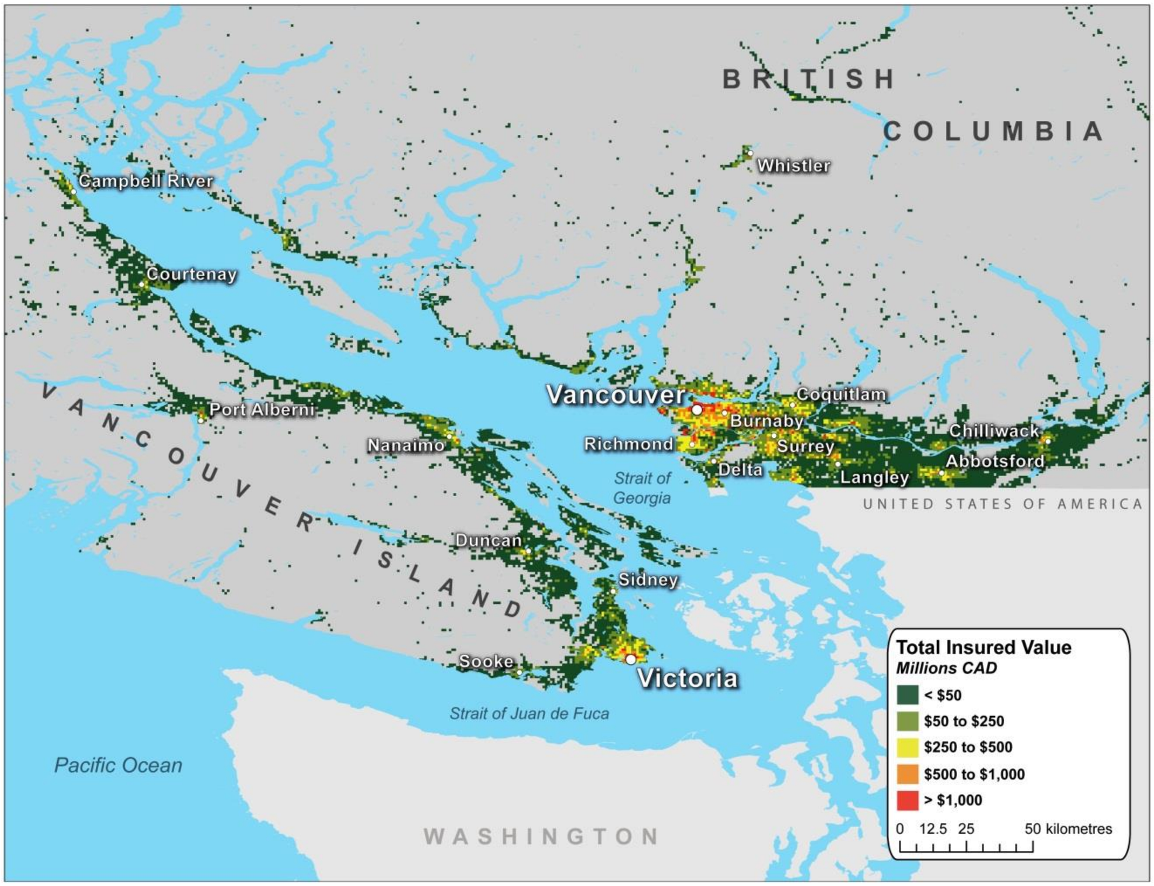


Figure 34: Total insured property value, western scenario

The total insured values for the region shown in Figure 34, when contrasted with the values for all property shown in Figure 33, reveal the value currently uninsured.

Looking more closely at the total insured property value in Figure 35 one can see the highest concentrations of insured risk in and around Vancouver and Victoria more clearly.

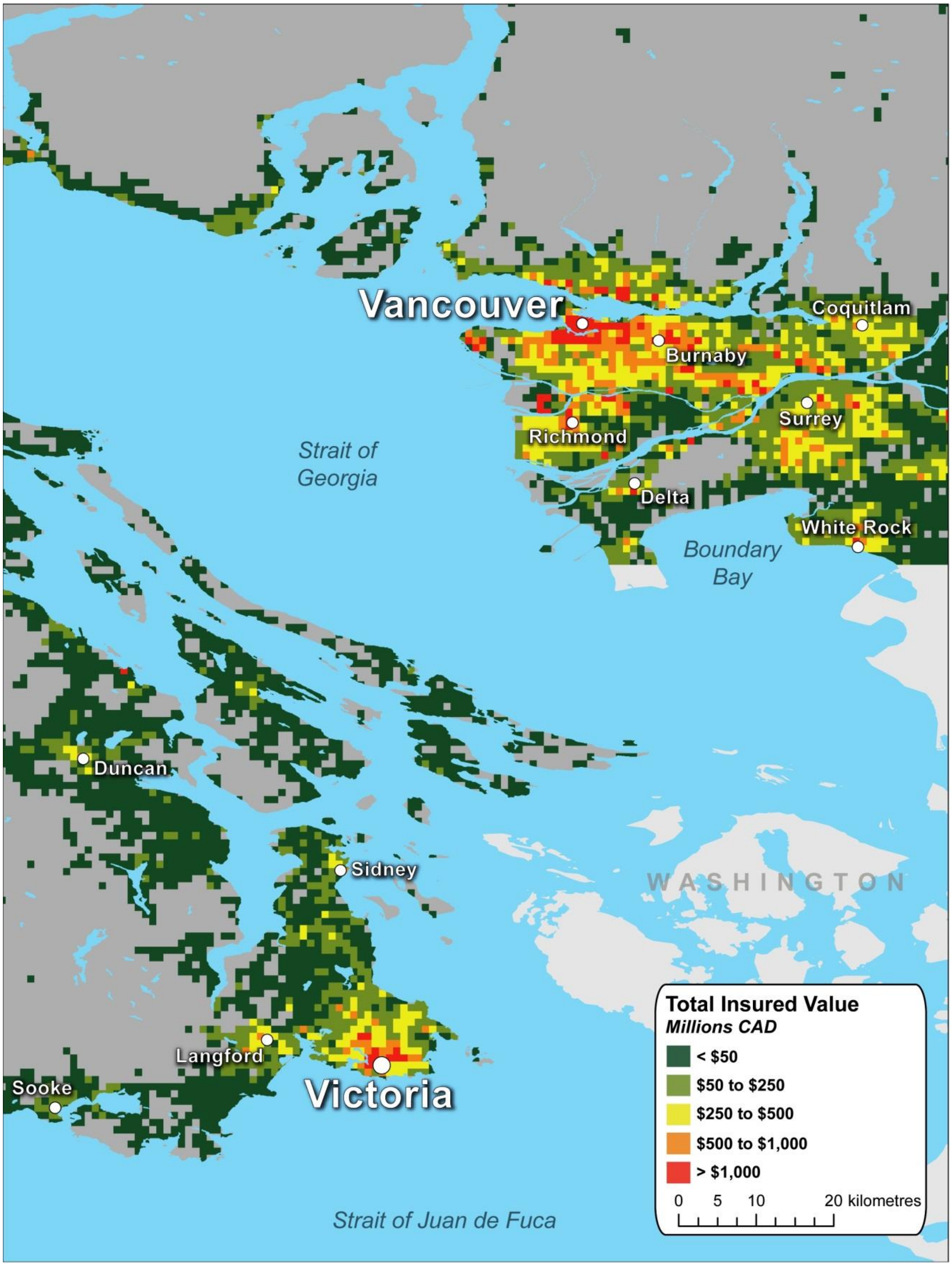


Figure 35: Total insured property value map for Vancouver and Victoria

The total infrastructure values are shown in Figure 36. Infrastructure can be privately, publicly, or self-insured, but the prevalence of each of these types of insurance could not be determined from available data. For this reason, market penetration rates, which are measures of the total value of insured property in relation to the value of all property, could not be determined, and so the infrastructure values are shown with no distinction between all property and insured values.

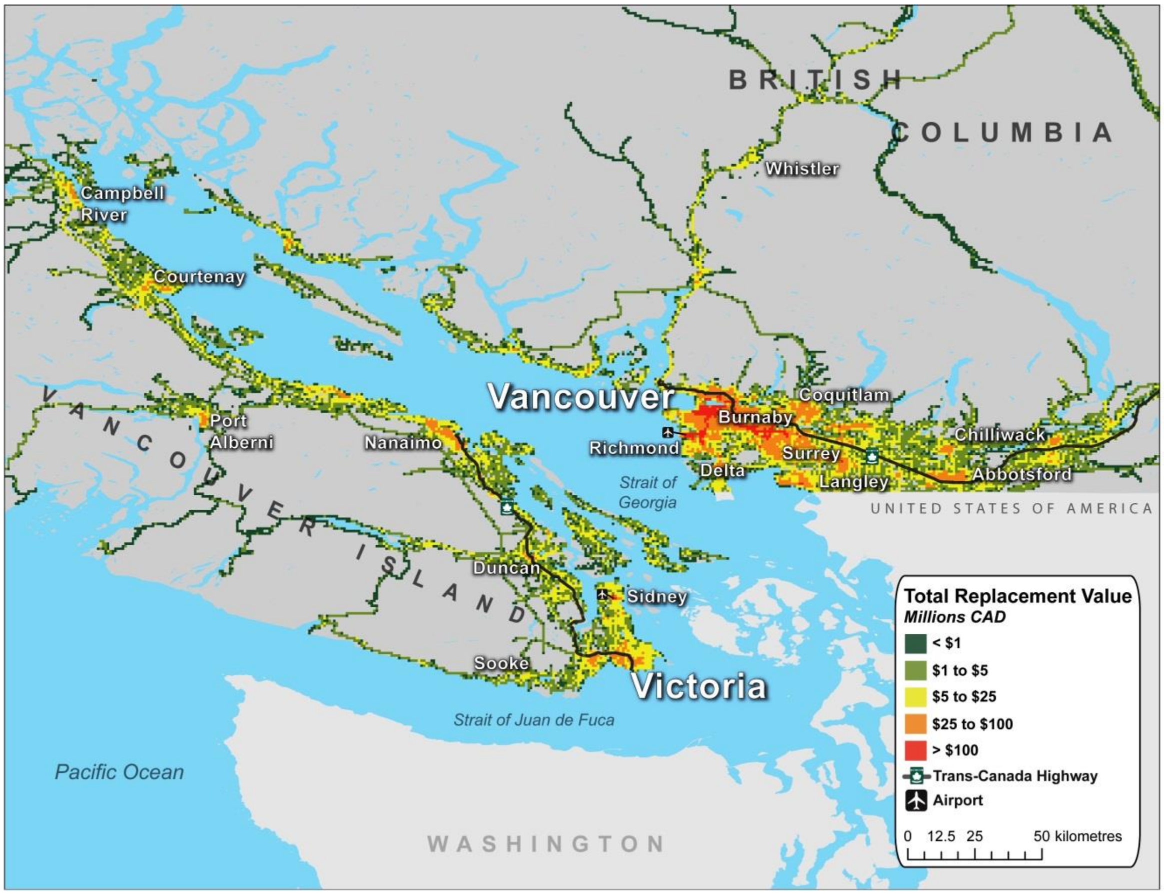


Figure 36: Total infrastructure value, western scenario

The most readily apparent patterns in the infrastructure map are the road and railway networks, with the railways being especially visible radiating southeast from downtown Vancouver. There is also a large concentration of value around Vancouver and Victoria International Airports, as well as the port areas surrounding Vancouver Harbour.

Hazard

In the following sections, we describe the various aspects of the scenario hazard; that is, the various ways by which the hypothetical earthquake would cause damage and loss. Earthquake hazard includes ground shaking, liquefaction, landslide, fire following earthquake and tsunami.

Ground shaking

The selected scenario for British Columbia has a magnitude 9.0. The epicentre is located in offshore to the west of Vancouver Island. The detailed rupture parameters for this event are listed in Table 17.

Table 17: Detailed rupture parameters for the western scenario

Magnitude	Epicentre Latitude	Epicentre Longitude	Depth	Rupture Length	Rupture width
9.0	44.706	-124.569	11 km	840 km	122 km

An earthquake can generate seismic waves of various frequencies or periods. Buildings and infrastructure respond to seismic waves of different frequencies differently, depending on their structural characteristics and height.

The AIR earthquake model uses several accelerations—including peak ground acceleration (PGA,) and 0.3 second and 1 second spectral accelerations (measures of seismic wave intensity)—to define the spectrum of ground motion at each location, to calculate the damage to different types of structures, and to calculate the local impact of secondary hazards such as liquefaction and landslide.

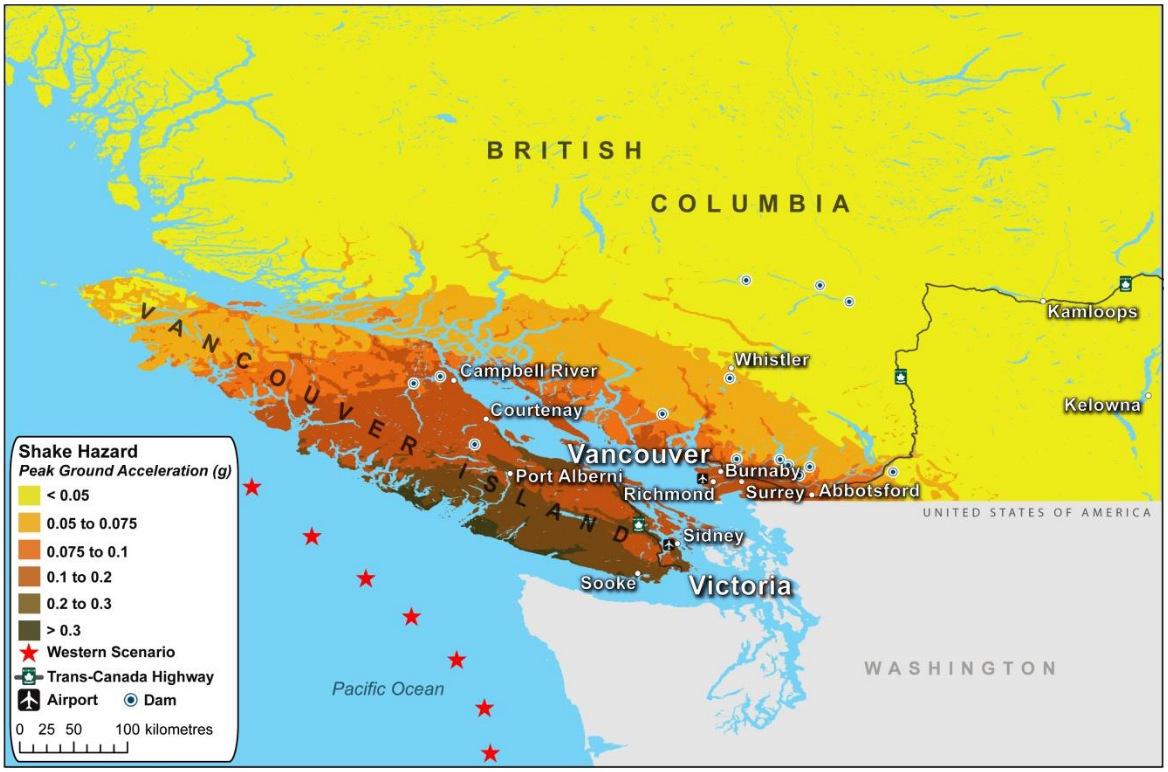


Figure 37: Ground motion intensity (peak ground acceleration) field from the western scenario. Each red star represents the centre of a fault patch ruptured during the earthquake

Figure 37 above shows the ground motion intensity field expressed as peak ground acceleration (PGA; note that PGA is expressed in units of g, the gravitational constant). The highest PGA exceeding 0.3 g is expected to impact southern Vancouver Island close to the rupture source. The ground motion intensity decays with distance from the rupture source.

Both Vancouver and Victoria are expected to experience a PGA of 0.1 to 0.3 g. Delta and Richmond may experience higher ground motion than the surrounding areas because they are situated on the soft sediments of the Fraser delta, which tend to amplify ground motion.

Figure 38: MMI Map from the western scenario. Each red star represents the centre of a fault patch ruptured during the earthquake

Figure 38 provides another view of the shake hazard, this time using the MMI scale. As mentioned in Section 5, the MMI scale describes the intensity of the earthquake in more descriptive terms.

Figure 39 below shows a more detailed MMI map for Vancouver and Victoria. As can be seen in Figure 39 the shaking intensity is as high as MMI VIII in some regions in Delta, Richmond and Victoria. At this intensity extensive damage to unreinforced masonry buildings can be expected, including partial collapse. Some masonry walls will fall, and chimneys and monuments may twist and topple. Victoria of course, is one of the oldest cities in the Pacific Northwest and is known for its many historic unreinforced masonry buildings.

A large area covering Surrey, Burnaby and Coquitlam and Vancouver Island experience MMI VII. Recalling Table 16, at these intensity levels, significant damage is expected especially in poorly built buildings (such as unreinforced masonry buildings) and slight to considerable damage in the moderate and well-built structures is anticipated.

The total value of all property in the same area is given below in Figure 40. Examining the exposure distribution along with the intensity footprints clearly shows that there is a large accumulation of value at risk in the regions with large shakings, thus significant losses are expected in these areas.

Similarly, Figure 41 below shows the ground motion by peak ground acceleration which is well correlated with the damage in infrastructure. Figure 42 shows the value of infrastructure in the region.

Putting together the exposure at risk and the ground motion footprint indicates that significant damage and loss to infrastructure is possible in the north of Richmond and in Burnaby, Coquitlam and Victoria. Moreover, high PGA values in Richmond and Delta, which are susceptible to ground failure, increase the possibility of damage due to liquefaction.

Figure 39: MMI map for Vancouver and Victoria

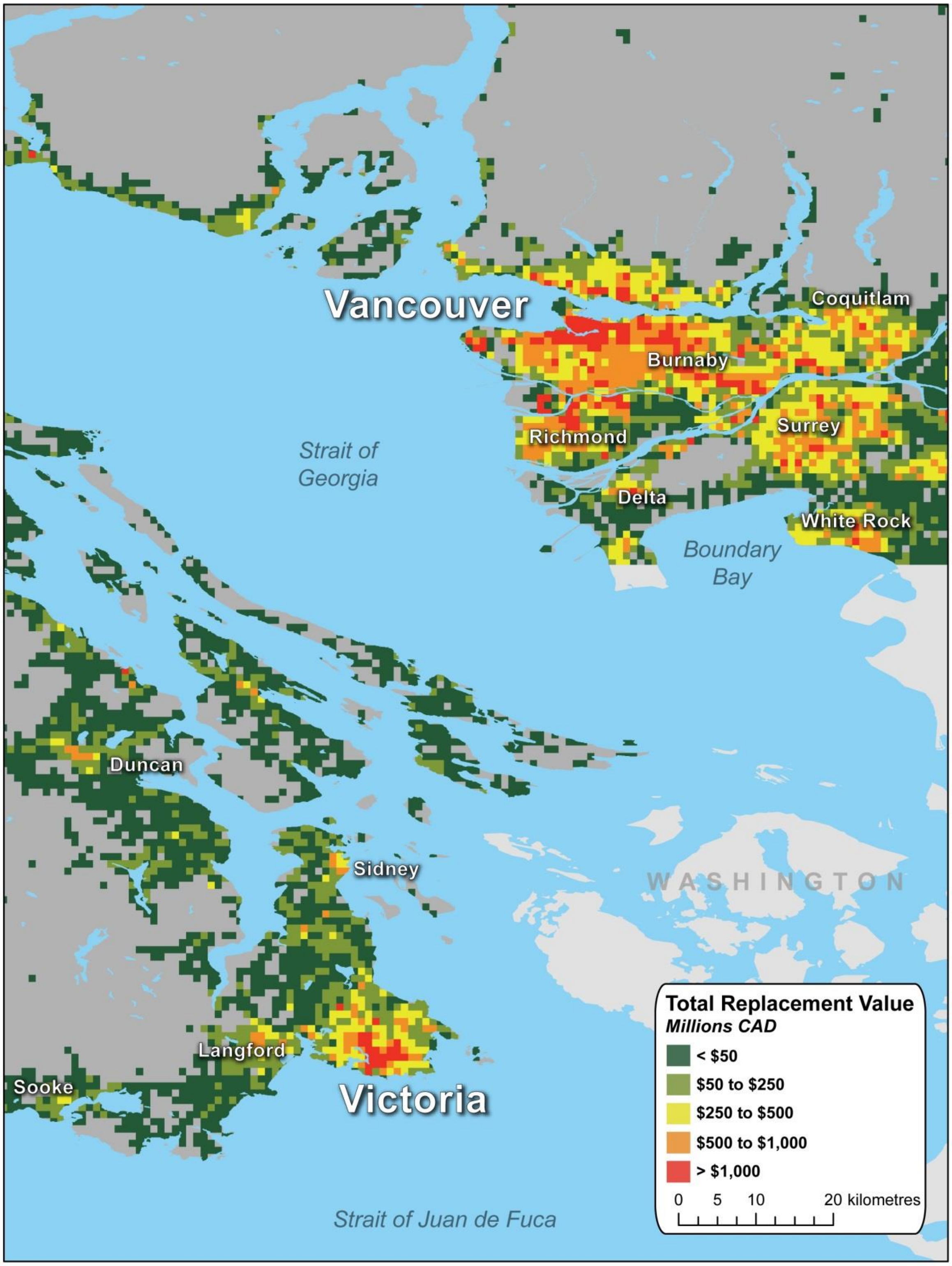


Figure 40: Total all property value, Vancouver and Victoria

Figure 41: Ground motion intensity (peak ground acceleration) field for Vancouver and Victoria

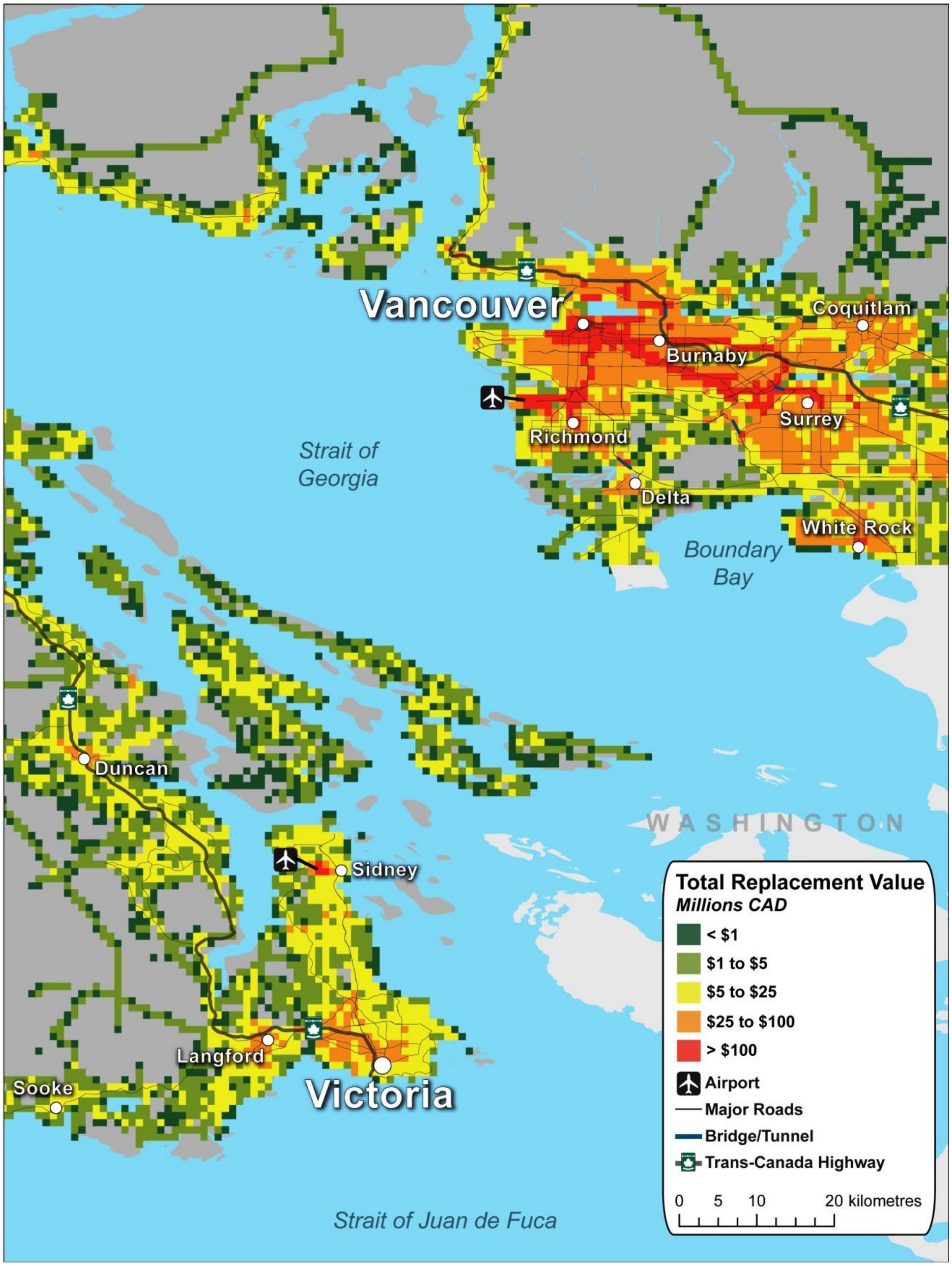


Figure 42: Total infrastructure value, Vancouver and Victoria

Liquefaction

The western scenario earthquake is expected to cause liquefaction damage in the areas overlying the young saturated Holocene sediments of the Fraser River Delta (the Holocene is the geological epoch from approximately 12,000 years ago to the present). The prediction of liquefaction damage requires the determination of liquefaction susceptible soils, groundwater levels and ground shaking intensity. A liquefaction hazard map based on these parameters is created for the scenario event and it can be seen below in Figure 43.

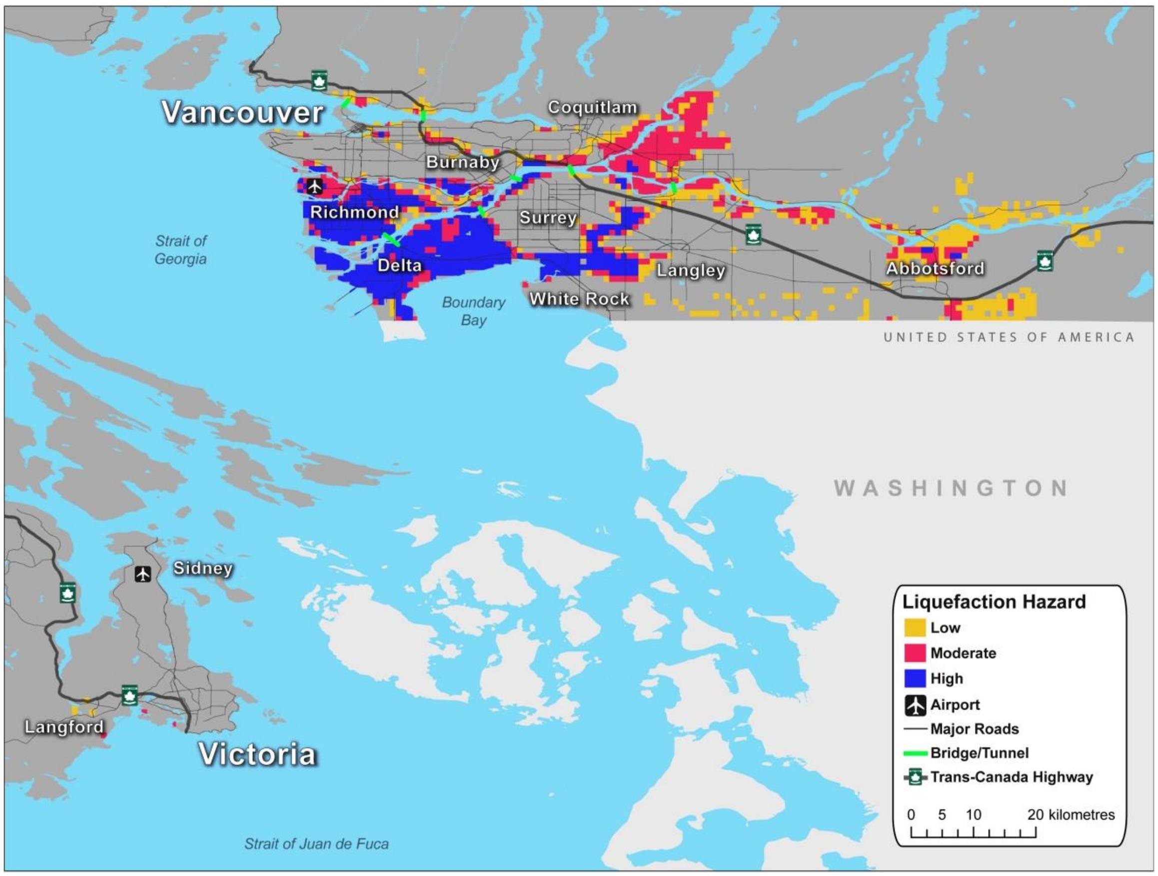


Figure 43: Liquefaction hazard map for the western scenario

In the areas with moderate to high liquefaction hazard as seen in the liquefaction hazard map, the damage will be associated with ground shaking and the failure of ground due to liquefaction. Liquefaction damage is expected in Delta, Richmond and portions of Burnaby, Surrey, Port Coquitlam, Pitt Meadows, Maple Ridge and Abbotsford due to the loose granular sediments, high water table, and long duration ground shaking. The western scenario earthquake is expected to have a long duration of ground shaking because of its large magnitude. The longer duration events induce further liquefaction due to the accumulation of higher pore water pressures with increased shaking. Liquefaction causes solid ground become temporarily softened and produces permanent ground displacements.

These permanent ground displacements cause substantial damage to buildings and lifelines. Buildings may settle, tilt, or slide due to the failure of underlying ground. Most of the low- and medium-rise buildings in the Metro Vancouver area have preloaded sand fill foundations. Some of the medium- to high-rise buildings are constructed on pile foundations. The liquefaction hazard will be reduced by these improved foundations. On the other hand, buildings with weaker foundations could experience higher damage due to unequal changes in surface levels.

Liquefaction induced ground failure also has a great impact on lifelines such as roads, railways, bridges and buried pipelines. The transportation network in the lower mainland area contains roads, freeways, bridges and tunnels in the moderate and high liquefaction hazard areas. Large settlements of loose saturated sand can bend rail tracks, rupture the road surfaces and damage bridge foundations and tunnels. Liquefaction may also damage the airport runaways by uneven settlement. The underground and the surface piping in the moderate and high liquefaction hazard areas will also be affected. Some of the dykes surrounding the Fraser Delta region to prevent flooding during high tides may be affected by liquefaction.

Little liquefaction damage is expected in the highlands of the greater Vancouver area including Vancouver City, thanks to the less susceptible soils and lower groundwater levels there. In the greater Victoria area liquefaction damage is expected only in several artificial fill locations along the shoreline.

It is important to note that the regional approach adopted in this study can provide reasonable estimates of liquefaction damage, but predicting site-specific liquefaction effects requires site-specific geotechnical data.

Landslide

The western scenario event is expected to trigger landslides in the south of Vancouver Island and the southern coast mountains of British Columbia. Landslide hazard maps for the western scenario can be seen in Figure 44 and Figure 45. Landslide hazard refers to the landslide potential as a function of soil/rock type, topography and ground shaking intensity. The main highways, rail lines and energy transmission lines in high landslide hazard areas would be blocked and damaged by landslides during the earthquake. Even though the western scenario event might not trigger landslides in the Vancouver and Victoria urban areas, possible blockages to lifelines would interrupt economic activity.

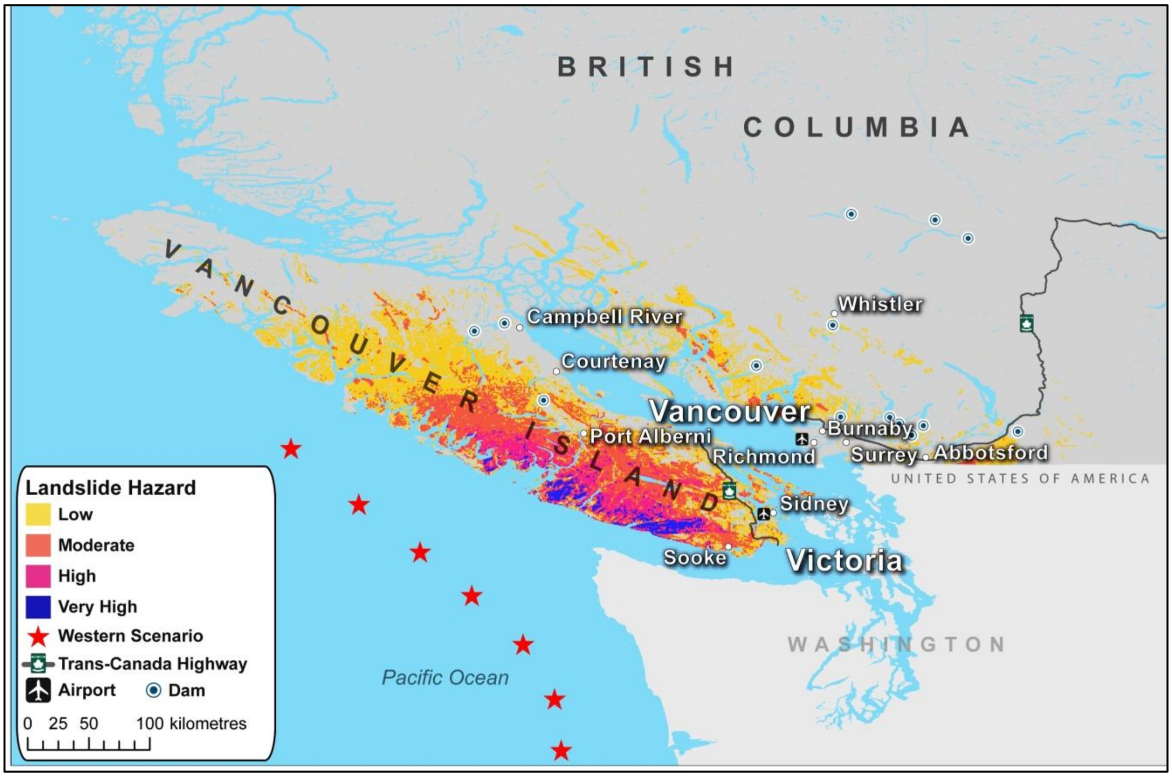


Figure 44: Landslide hazard map for the western scenario

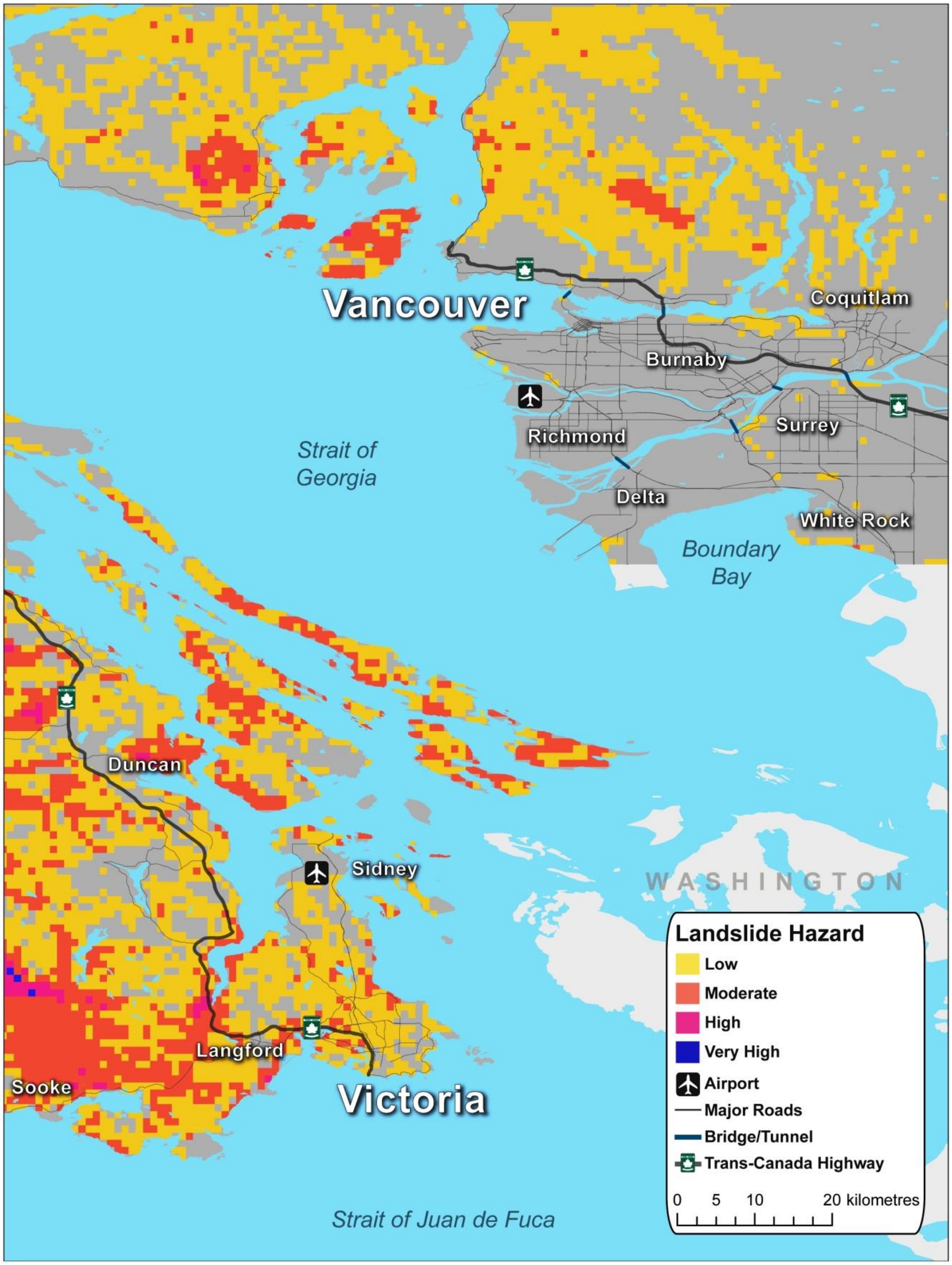


Figure 45: Vancouver and Victoria area landslide hazard map

Fire following earthquake

Earthquakes that occur in built-up regions can cause fires as a result of damage to buildings from the ground shaking. The risk of fires following earthquakes is tied to the building density and level of ground motion, among other factors. The western scenario is a large subduction zone event that generates moderate ground motion throughout a large area in British Columbia (see Figure 37 and Figure 38). The major locales impacted by fire following are the Metro Vancouver and Victoria areas. A wind speed of 19 km/h is selected for the scenario based on local climatic data. Below is the assessment of the risk of fires following this earthquake. The assessment suggests that locally intense fires, capable of spreading through multiple buildings and occasionally from city block to city block, will challenge first responders throughout the Vancouver and Victoria regions.

Built environment

Most of the single family houses in British Columbia are of wood frame construction, with combustible exterior siding. Following a large earthquake, a fire ignition has the potential to grow and rapidly spread between such houses. Non-combustible buildings, like those with glass and steel or concrete exteriors commonly used for commercial properties and apartments, tend to have a lower risk of fire spread, but they are not completely free of risk. For example, fire in a nearby building could penetrate a non-combustible building through the building’s windows, as was seen in the fires following the 1995 Kobe earthquake in Japan.

Most of the buildings in the urban centre of Vancouver are within close proximity of other structures, raising the risk of fire spreading from one building to another. Homes and other structures in the suburban and rural regions have greater spacing between building faces, and this hampers fire spread.

Figure 46: A heritage wood frame house in Victoria, British Columbia (World Housing Encyclopedia)

Ground motion

The strongest ground motion occurs on the sparsely developed, western side of Vancouver Island, which has limited risk of fires following earthquakes due to the low building densities. Still, the ground motion experienced in the more densely populated areas of Metro Vancouver and Victoria is strong enough to ignite a significant number of fires following the earthquake.

Ignitions

Immediately following the ground shaking, several fires will ignite. Ignitions are most likely to come from overturned items on heating elements, electrical short circuits and broken gas mains. Commercial buildings may be unoccupied, which can allow fires to grow unattended for an extended period.

Figure 47: A large fire burning in the port of Odaiba following the 2011 Sendai earthquake and tsunami in Japan (Hikosaemon)

The first hours after the earthquake will pose the greatest challenge to first responders, as this will coincide with the peak in the number of simultaneous fires. However, given the level of suppression resources and the scattered spatial distribution of ignitions in this scenario, many of the initial fires could be controlled before additional, delayed ignitions occur (see Table 18 for the ignition timeline). The timeline of ignitions caused by the earthquake throughout the entire affected region does not include fires that were ignited from nearby burning city blocks, and only includes fires that started independently as a result of the earthquake. Most delayed ignitions are a result of power restoration in an area where electrical systems have been damaged. In total, the ground shaking from the earthquake will cause fires on 55–65 city blocks in the two days that follow the earthquake.

Almost 50% of the earthquake induced ignitions occur in the Metro Vancouver area, while only about 10% of the ignitions occur in the Victoria area. A handful of ignitions are concentrated in the central business district of Vancouver, where ignition risk is increased due to overhead power lines being in close proximity to mid- and high-rise buildings. The Burnaby area experiences a high number of ignitions when compared to the Metro Vancouver area. Other ignitions are scattered throughout the affected area in small communities. The small communities are less likely to see simultaneous ignitions, but a fire that ignites may involve several buildings on a block, or even consume the entire block.

Table 18: Timeline of fire ignitions

Time since earthquake	Cumulative primary ignitions
20 minutes	12
1 hour	24
3 hours	48
10 hours	54

Spread

A range of fire sizes can be expected to follow this earthquake, from single-building to multi-block fires. On average, each fire is expected to last around three hours. The duration of these fires suggests that they typically involve several average buildings or a single large building on each affected city block.

Although the wind speed for this scenario is 19 km/h, the average wind speed for the region affected by this earthquake is less, around 11 km/h, based on historical data. Some of the 55-65 primary fires that were ignited by the earthquake subsequently ignite fires on neighboring city blocks. Fires will ignite on a total of nearly 100 city blocks throughout the affected area and burn a total of 1.5 to 2.5 million square feet of building floor area. The moderate wind speed of 19 km/h and the availability of sufficient suppression resources compound to mitigate the loss incurred from this event, which could potentially have a much greater impact if conditions created an environment more susceptible to fire risk.

Suppression

Given the history of fire following in other earthquake prone population centres such as San Francisco and Los Angeles, California; or Kobe, Japan; the City of Vancouver has constructed the Dedicated Fire Protection System (DFPS) to be prepared for fires resulting from an earthquake similar to the scenario presented here. The DFPS is an auxiliary water system designed to withstand strong ground shaking and it will protect the central business district of Vancouver. The system was designed to amend the established water system which has major transmission lines that are at high risk of damage due to liquefaction. The DFPS resources have never been put to the test, but their design was based on other existing systems that have performed successfully under earthquake conditions.

Outside the area protected by the DFPS, water supply will be the main concern in mitigating the fires started after the earthquake. The areas at the most risk of liquefaction, which can cause severe damage to water systems and reduce or completely eliminate water flow, lie entirely outside the area protected by the DFPS, namely in the Richmond area. Victoria is not expected to sustain much liquefaction, but water pipes may still be damaged by the ground shaking.

Severe cases of water supply damage were observed in the 1994 Northridge earthquake and these forced fire departments to use swimming pools and other alternatives as water sources (Scawthorn, et al, 2005). If there were to be a critical water system failure in the Vancouver area, fires could grow uncontrolled and damage a much greater area such as in the 1995 Kobe earthquake (Scawthorn, et al, 2005).

A secondary factor in successfully suppressing fires after a strong earthquake will be the preparedness of the fire companies to operate at full capacity following such an event. Most fire companies in the area have plans and procedures for this type of scenario, but have little actual experience.

Other factors can lead to exacerbated damage from fires following the earthquake. Some fire stations may sustain structural damage, such as happened in the 1906 San Francisco earthquake where 10 fire stations sustained serious damage (Scawthorn, et al, 2005). Luckily, in 1906 San Francisco, no engines were disabled, but the possibility remains that fire station damage might cause the engines they house to be inaccessible. Additionally, some streets may be impassable due to debris blocking the roads, as was observed in the 1995 Kobe earthquake (Scawthorn, et al, 2005), and this would force engines to find an alternative route. Communication systems may be out of service or flooded, hindering the ability of residents to report a fire, such as happened in the 1995 Kobe earthquake (Thomas, 2005) and 1989 Loma Prieta Earthquake (Scawthorn, 1992). Inconveniences like these increase the time elapsed before fire engines arrive, and allow a fire to grow larger before suppression begins. In the 50 simulated outcomes that were modeled, an interaction of several of these situations was captured, including both damaged fire stations and delayed fire reporting resulting in losses that were more than three times the average for this scenario.

It is unlikely that a major conflagration would develop under these conditions, since fire engines will likely outnumber ignitions in all of the affected regions, and winds do not complicate any suppression efforts. However, the isolated areas of damage may be acute.

(Note that, in the fire following earthquake figures that follow, the diamonds represent loss for a single fire following scenario, while the squares, or colored pixels, represent average loss for fire following earthquake.)

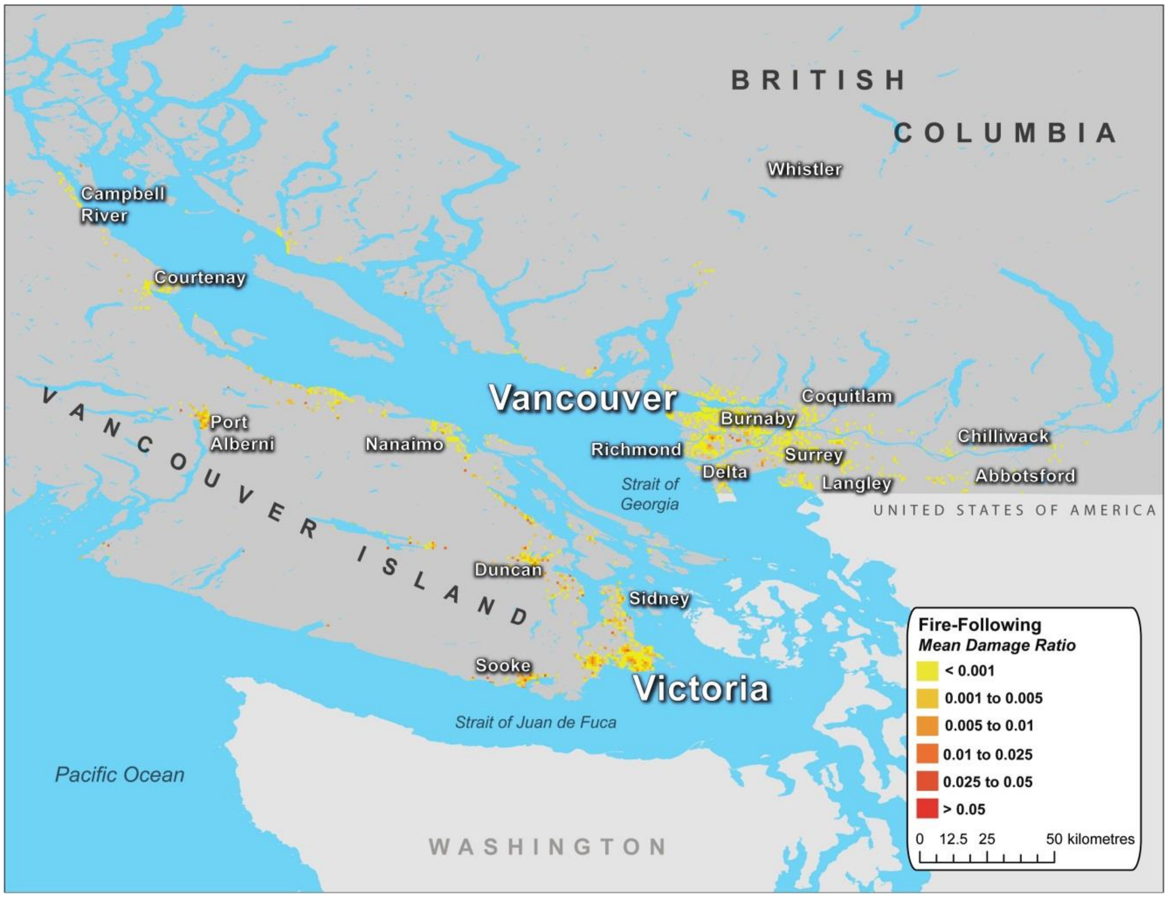


Figure 48: Average fire following damage ratio distribution for the full extent of the western scenario region

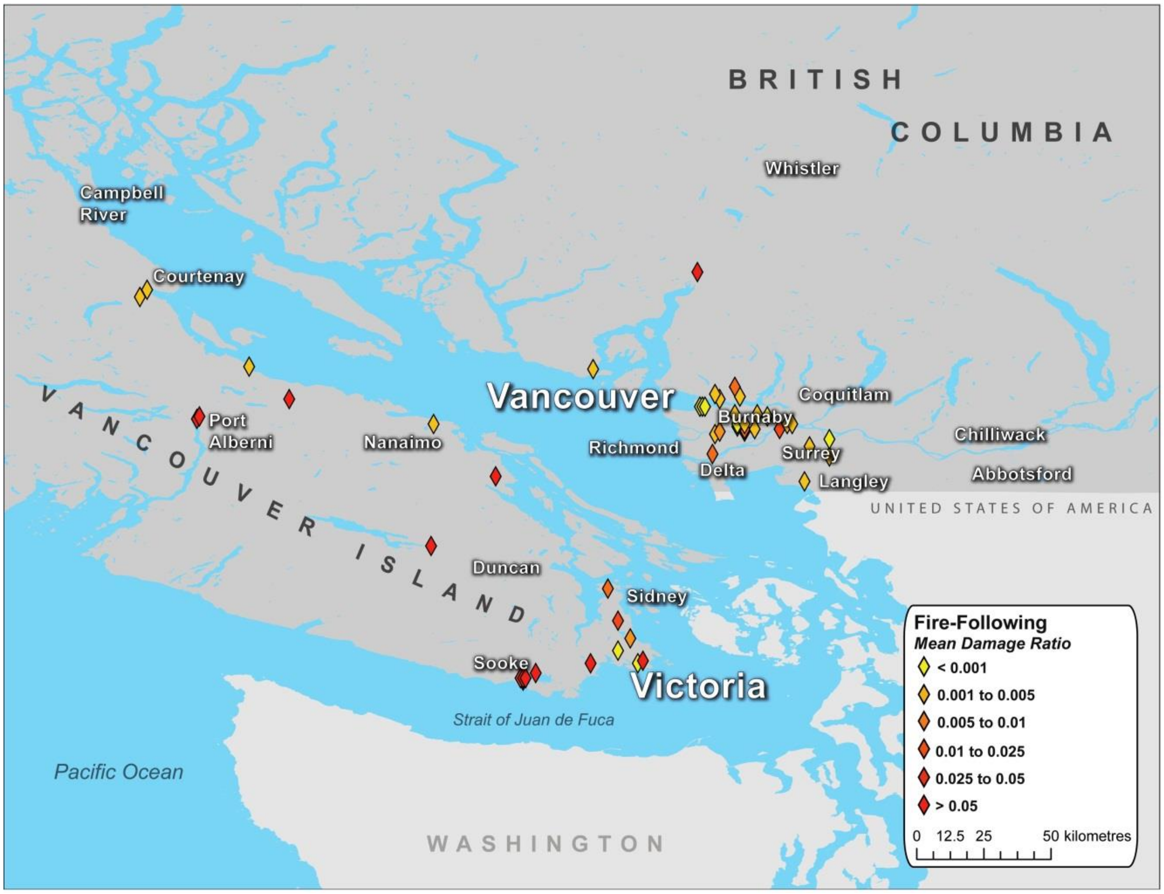


Figure 49: One possible distribution of fire following damages in the western scenario

The damage footprint depicted in Figure 48, based on the average results of 50 fire simulations, does not indicate a more extensive fire spread footprint on average. Rather, it simply identifies the area affected by the western scenario with significant fire following loss potential. The loss footprint is greater than in Figure 49, which shows the results of a single fire simulation, because the average footprint accounts for variability of ignition location and other parameters. The result is a map which highlights areas at risk for fire following damage from the earthquake scenario in this case study.

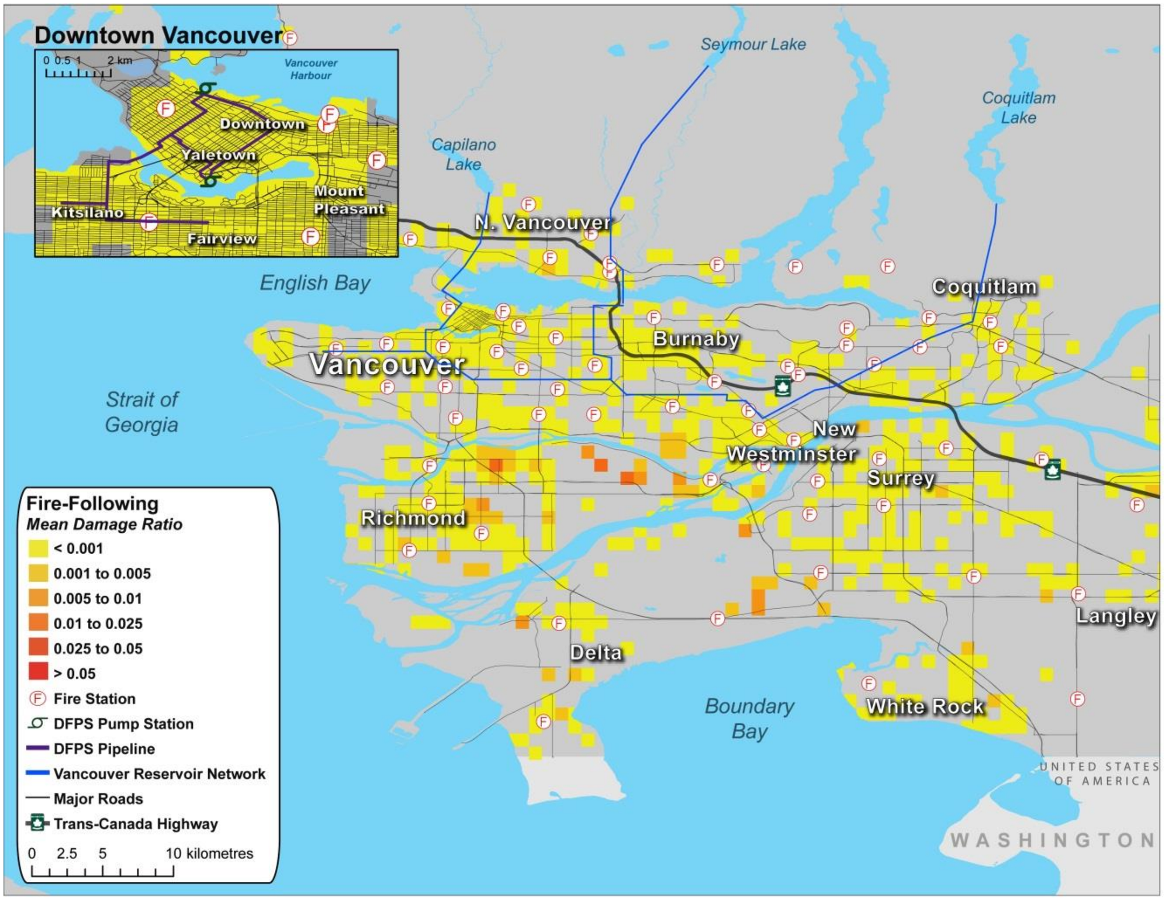


Figure 50: Average fire following damage ratio for the Vancouver area

Figure 50 shows the average fire following damage ratio for the Metro Vancouver area, and identifies areas with significant fire following loss potential. The locations of fire stations and DFPS infrastructure are indicated on this map.

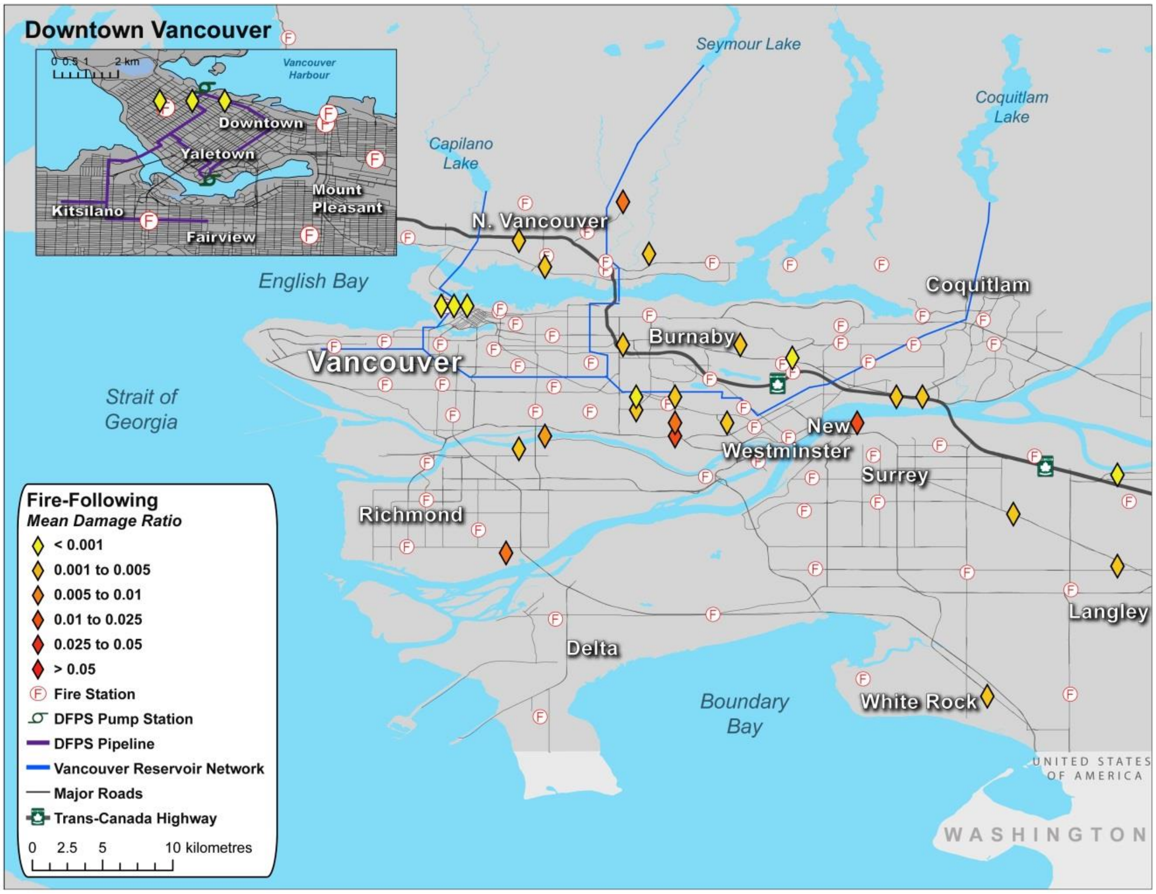


Figure 51: One possible distribution of fire following damages in the Metro Vancouver area

Figure 51 shows the results of just one of many single fire simulations, each of which produced a different distribution of possible incidents, and each of which contributed to the average determined.

The average fire following damage ratio distribution for the Victoria area is given in Figure 52, and one possible distribution of fire following damages can be seen in Figure 53.

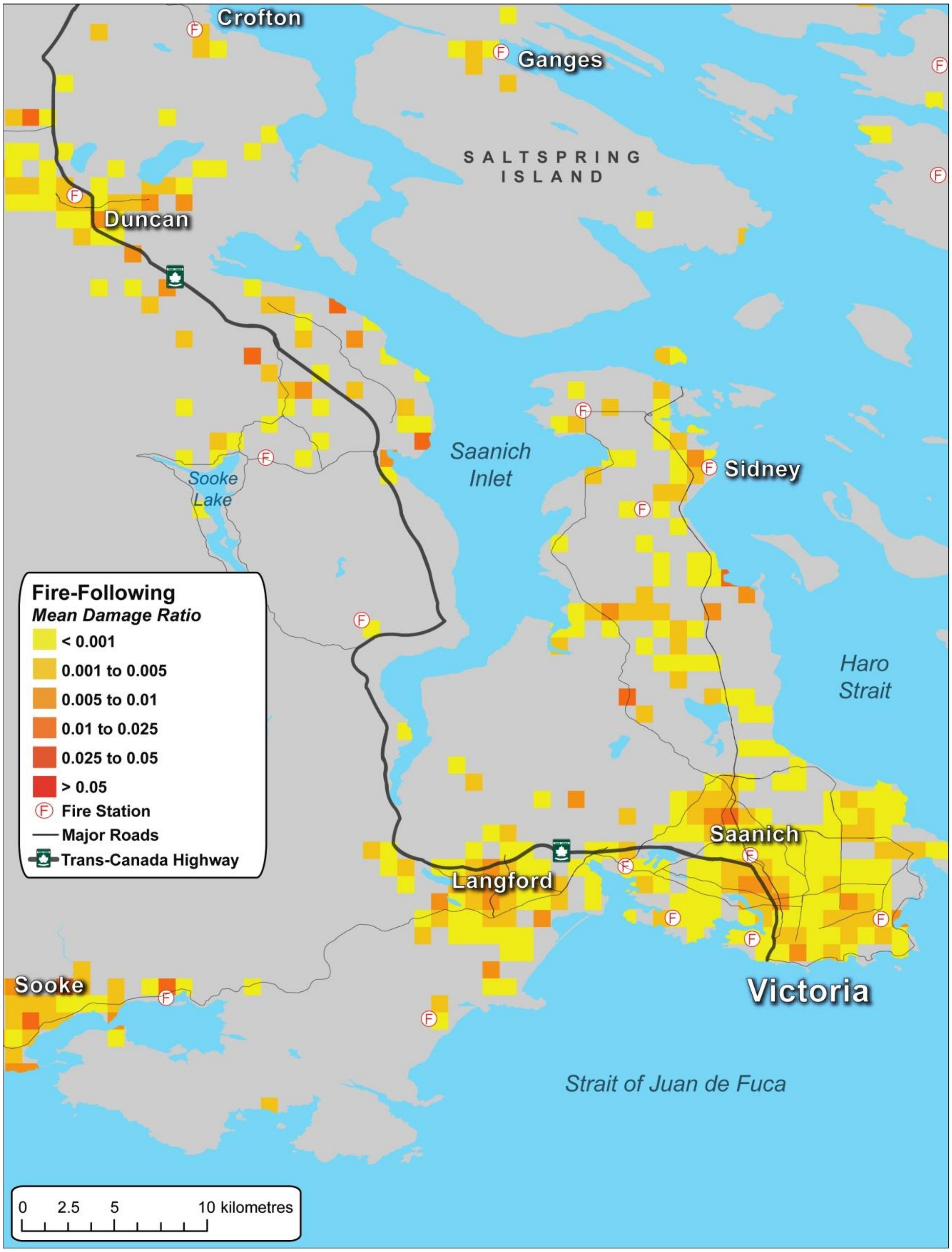


Figure 52: Average fire following damage ratio distribution in the Victoria area

Figure 53: One possible distribution of fire following damages in the Victoria area

Tsunami

The western scenario is a large subduction zone event that is able to displace a significant volume of water and create a tsunami that impacts a long stretch of coastline. Figure 54 shows the initial water displacement, in metres, from the tsunami model, along with the location of the fault segments used in initialization.

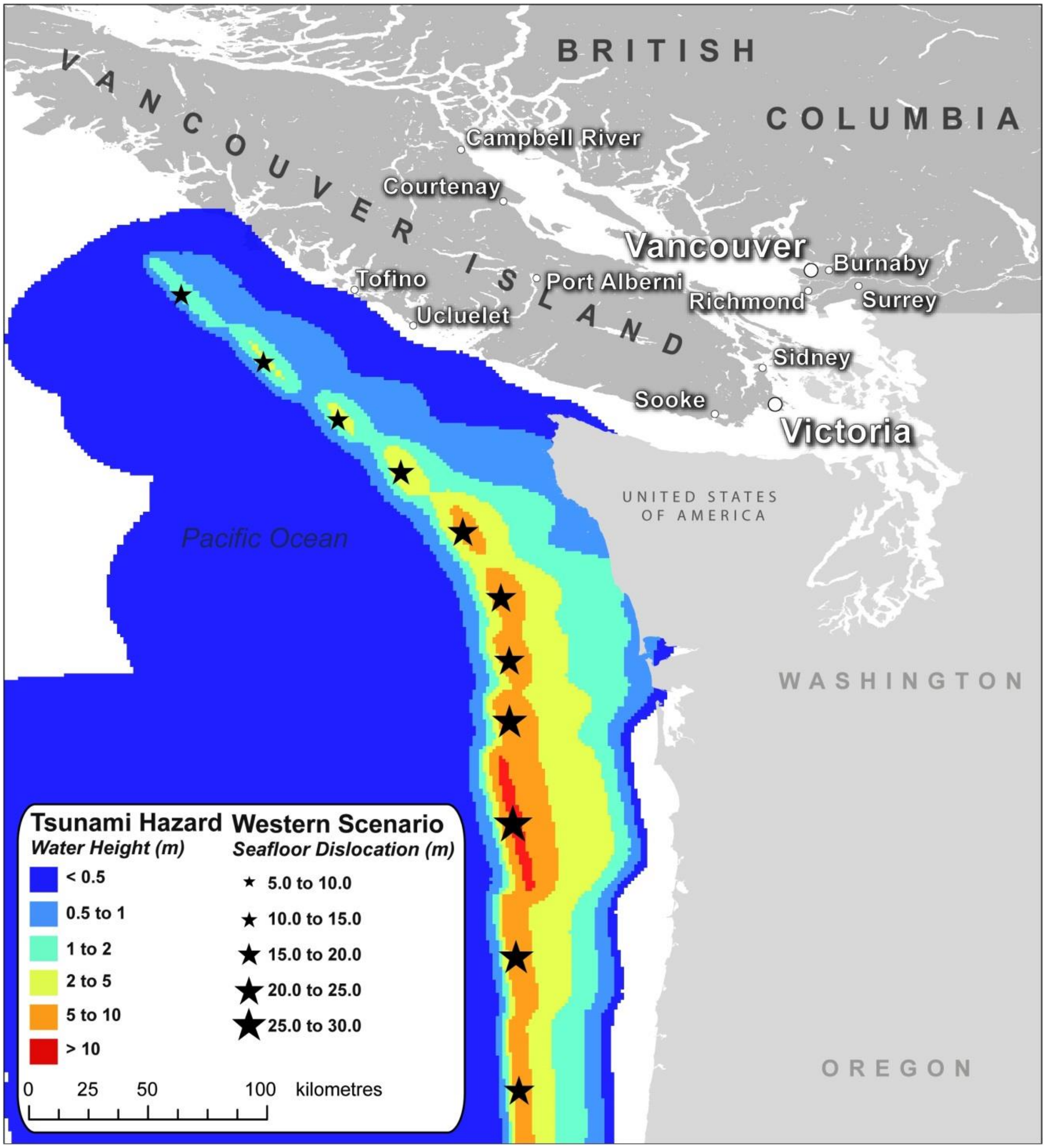


Figure 54: Initial water displacement (m) due to the western scenario earthquake and location of fault segments (stars)

The maximum water displacement is 12 m, with large areas exhibiting displacement of 2.5 m or more. A summary graphic showing the arrival time of the tsunami wave is presented (Figure 55) and should serve as a reference as the time evolution of the tsunami is traced in the next two paragraphs. The western scenario was evaluated for tsunami using several different tidal conditions, including neutral (i.e. no tide) tide, low tide in Vancouver, and high tide in Vancouver. Since the tide in the Vancouver area can vary by several metres, it can thus impact tsunami damage significantly. The output shown in Figure 55 and Figure 56 and the accompanying descriptions are without consideration of the local tide; the tsunami occurring at high (low) tide would have a higher (lower) total water level than that shown in this discussion. The tidal phase does not alter the timing of the tsunami wave, and interpretation of the increase in water height due to the tsunami is easier in the absence of the background spatially-varying tide condition.

The next few paragraphs describe the progression of the tsunami from the point at which it reaches Canada.

Roughly 30 minutes after the earthquake rupture the tsunami wave slams into the coast of British Columbia with a large area of the coast being impacted by a tsunami wave of greater than 1.0 m. At this time the leading edge of the tsunami wave is forced to channel through the strait of Juan de Fuca which, being devoid of islands and other blockages, allows the tsunami to pass through with relatively little impediment (although some of the wave energy is absorbed by the coast).

By 60 minutes after rupture the tsunami wave has continued to move up rivers in Southwest British Columbia, reaching a significant distance inland from the coast. The leading edge of the tsunami wave has passed almost entirely through the Strait of Juan de Fuca, and is rapidly approaching the city of Victoria.

By 90 minutes after rupture, the tsunami wave has moved through the Strait of Juan de Fuca and has impacted Victoria. The wave is now in the process of interacting with many small islands, which will all tend to absorb energy and reduce the intensity of the tsunami wave as it tries to propagate past them. Peak wave height is still in the range of 1 – 2.5 m which could cause damage to low lying coastal areas.

By 120 minutes after rupture the tsunami wave has completely wrapped around the city of Victoria, with its western sections facing a tsunami height of 1 – 2.5 m. The tsunami wave has reached Boundary Bay to the south of Vancouver, although the wave has been significantly reduced in height due to interaction with the numerous islands found to the south of Vancouver.

By 150 minutes after rupture the tsunami wave has reached to northern Vancouver as well, with heights (generally 1.0 m or less) that are again modest compared to earlier values. To the south of Vancouver, in an area extending from Bellingham to White Rock water levels above the background tide of 1.0 – 2.5 m are found over a widespread area.

170 minutes after rupture the wave continues to propagate to the north of Vancouver, although the maximum height above the background tide has been further reduced to 0.5 – 0.75 m. Throughout the entire tsunami event, numerous reflections and higher-frequency fluctuations in water height are evident, as the wave hits land, is reflected and interacts with other portions of the tsunami wave.

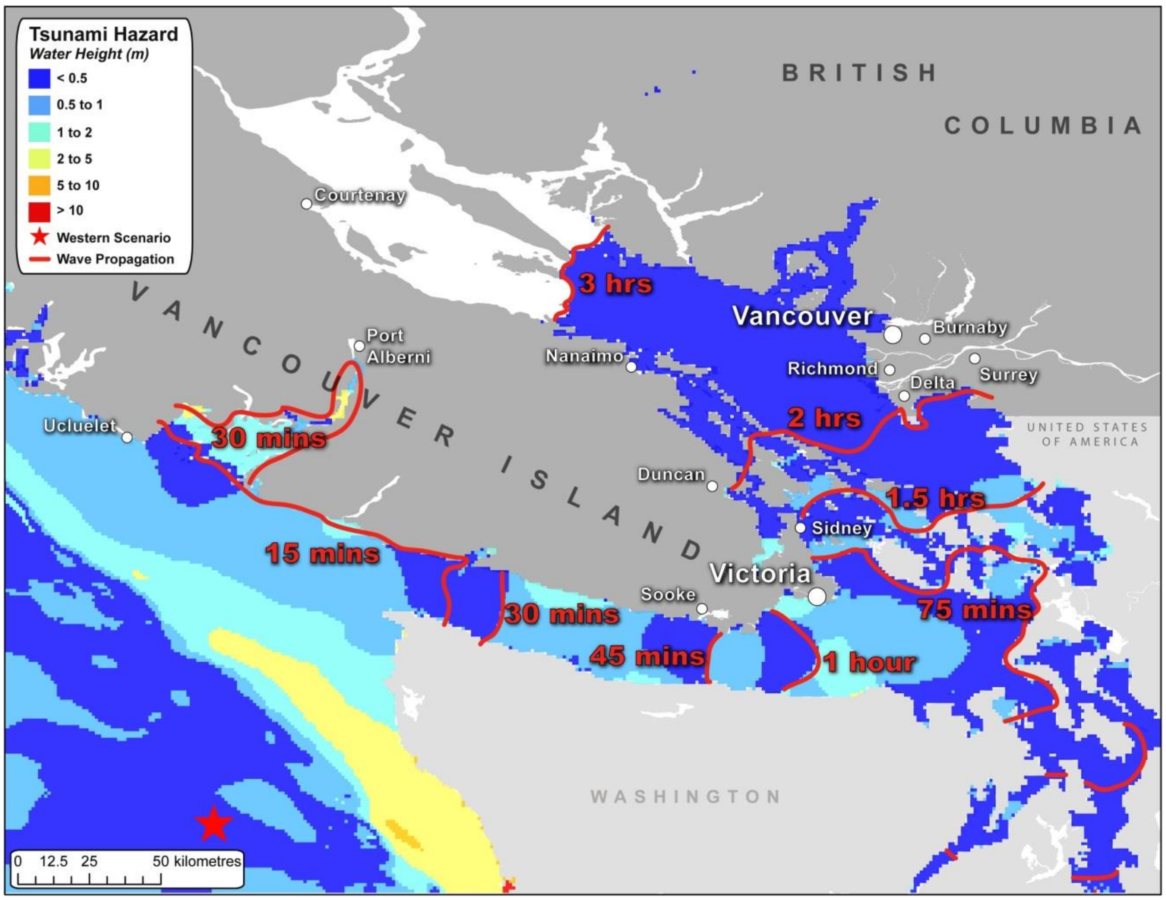


Figure 55: Tsunami timeline and wave height

Increases in water height due to the tsunami of > 5 m are found along the Washington coast and over isolated sections of Vancouver Island (Figure 56). Tsunami heights of up to 2.5 m are found near the city of Victoria while, as previously described, attenuation leads to maximum heights near the city of

Vancouver being around 1 m except just south of the city where isolated areas of up to 2.5 m are found.

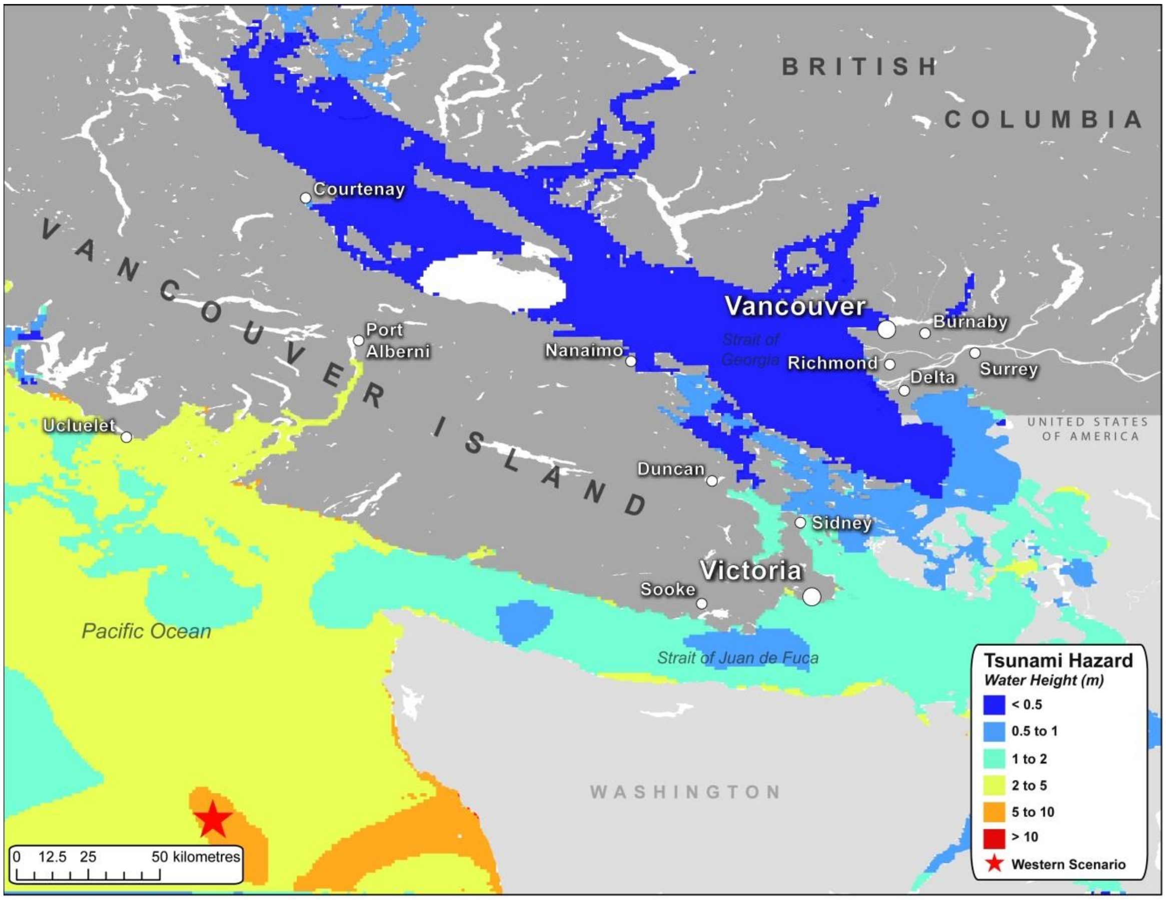


Figure 56: Maximum water height above background tide

Vulnerability to and damage from the western scenario.

After looking in depth at the various hazards accompanying a large earthquake, the next important consideration is how the earthquake will affect structures. This section explores the vulnerability of the buildings and the damage that ensues.

Information from AIR's industry exposure database, along with a literature review of the building stock of British Columbia, reveal the construction mix and expected seismic performance of buildings in the region. Key information about the vulnerability of buildings in British Columbia to earthquake ground shaking is provided in the section that follows.

Rapid population growth in British Columbia is associated with the increased value of insured property in the province. In fact, the 2011 census indicates that British Columbia is the third fastest growing province in Canada (data available from Statistics Canada). With a 7% growth since 2006, the population in the province was about 4.4 million in 2011. More than 85% of the population resides in urban areas. The total number of private dwellings in the 2011 census was 1,945,365, of which the most common types are single family detached houses and apartment buildings.

Most residential buildings in British Columbia are of wood construction (AIR's IED, 2012; Ventura et al., 2005; Onur et al., 2005, Ventura and Kharrazi, 2002). In fact, wood construction of residential buildings is particularly common in southwestern British Columbia, in the Metro Vancouver and Victoria regions, which are particularly at risk from the effects of the western scenario. The small remaining proportion of residential buildings is often of masonry construction. Commercial and industrial buildings, however, are most often reinforced concrete and steel structures, though some are made of wood or masonry.

A typical single family house of wood construction in Canada consists of a timber frame with horizontal wood plates forming the floors and vertical wood plates used as internal and external walls. The ground floor normally includes a platform of joists covered with plywood supported on a concrete foundation directly using some anchor bolts or indirectly with cripple walls. The roof structure consists of prefabricated trusses covered with sheathing and roof tiles. According to Ventura and Kharazi (2002), three distinct age classes can be identified for these buildings in Canada: pre-1940, 1940-1980, and post-1980. These age classes correspond to changes in wood production technology that affected the seismic performance of these buildings. For example, the 1940-1980 class reflects a shift in sheathing products from boards to panels such as plywood with a resultant change in wall performance. Some popular construction styles in this age class are the post-and-beam homes of the 1950s, the "Vancouver Special" of the late 1950s to the mid-1960s and the "monster homes" of the 1980s.

The majority of multi-unit residential buildings up to four stories in southwestern British Columbia are of wood construction. These buildings have numerous interior load-bearing walls and their exterior walls are clad with wood or brick veneer or metal. Prior to the late 1960s and early 1970s, these buildings were usually constructed without underground parking. After the 1970s, however, most of the multi-unit wood construction in the province includes an underground concrete parking level.

Wood construction in the commercial and industrial sector often includes one or two story buildings. Commercial buildings are usually clustered in retail areas while industrial structures are often individually located on large lots. Their exterior walls are wood frame, with cladding of wood or vinyl siding, plaster, brick veneer, and metal. Large buildings of this type are usually divided into segments by masonry fire walls (Ventura et al., 2005).

Wood construction has historically performed well in earthquakes. The satisfactory behavior of wood structures is attributed to their light weight and high material strength. Nail connections in wood frame construction allows more flexibility and thus provides more energy absorption capability during earthquake shaking. Attachment of sheathing and finishes to wood joists and studs using numerous connections provides more redundancy in transferring earthquake forces to the base. Furthermore, the interaction of structural panels with the wood frame provides some shear wall-like effects and improves seismic behavior. According to the Canadian Wood Council, a typical shortcoming in wood constructions is the existence of weak or soft first stories, often due to the use of the space as garage or storage area. Weak connections to the foundation, the use of cripple walls, and weak and/or heavy chimneys are other possible weaknesses observed in wood construction.

While unreinforced masonry (URM) construction is common only in the older parts of Vancouver and Victoria, reinforced masonry is very common throughout British Columbia especially for commercial, institutional and industrial buildings. Many of the URM buildings have been recently seismically retrofitted. URM buildings up to three stories were commonly used for commercial and industrial buildings until the early 1970s. Mid–rise URM buildings up to six stories were also common for commercial and industrial buildings prior to 1940.

URM buildings rely on the masonry walls to resist both gravity and lateral loads and are known to have performed poorly in the past earthquakes around the world. Since 1973 the National Building Code of Canada (NBCC) required that all the masonry buildings in seismically active areas (which includes almost all of BC) be built with reinforcements.

The seismic performance of reinforced masonry buildings is notably improved compared to URM. Although the walls generally perform well in this type of construction, the connection of the floors to the walls is usually the weak point, especially in pre-1985 buildings. Reinforced masonry buildings with storefront openings and and/or flexible diaphragms tend to be damaged due to torsional effects. Nonstructural and glazing (window) damage are examples of other common problems in these buildings.

While reinforced concrete moment resisting frames are not very common in British Columbia, concrete frames with infill walls and concrete frames with shear walls are common in institutional, commercial and industrial buildings. Concrete frames with masonry infill (in pre-1950 office buildings) are not designed for seismic forces and do not perform well in earthquakes. However, those built after 1985 generally behave well. Nonstructural damage and damage to cladding are examples of known problems in these types of buildings, when they are exposed to earthquake ground shaking.

Steel construction is also very common for industrial buildings. In particular, steel frames with concrete walls have been used commonly for low-rise industrial buildings after 1970s and mid-rise institutional buildings as well as office towers. These types of buildings rely on both steel frames and concrete shear walls (mainly located around the elevator shafts or stair case or along the building perimeter) in resisting the lateral loads, and perform well in earthquakes. Post 1985 buildings of this type perform much better, especially if the walls are distributed. Damage in these buildings is often caused by torsional effects.

Damage in the non-structural components is another form of typical damage in these buildings. While steel moment-resisting frame and steel braced frame structures are not very common in British Columbia, steel frame with concrete infill walls are common for offices and light industrial buildings built before 1950s. They usually perform well in earthquakes even though most of these pre-1950 buildings were not designed for seismic forces. Those with irregularity in plan and height are prone to significant damage due to torsional effects. Non-structural damage and falling of brick walls are other modes of failure in these buildings.

The impact of seismic design codes on vulnerability in British Columbia

In general, seismic performance of engineered buildings is closely connected with the stringency of the construction codes to which they are designed. Strictness of seismic design requirements provides an implicit measure for assessing the seismic vulnerability of buildings. In Canada, guidelines to determine design forces (gravity, seismic, wind, snow, etc.) are defined in the codes published by the National Building Code of Canada (NBCC). Requirements for seismic detailing for different structure types are set in the design standards published by the Canadian Standard Association (CSA).

Seismic design codes are usually established in the wake of devastating earthquakes, and evolve with the accumulation of new knowledge of hazards and the performance of buildings. The first Canadian regulation for earthquake resistant building was published by NBCC in 1941. Since its publication, the code has been revised significantly several times to reflect the latest research findings. Design philosophy has also transformed from allowable stress design to ultimate strength design and ideas of performance based design. In the section that follows, we provide an overview of the evolution of seismic design codes of Canada.

The NBCC 1941 code was based on the 1935 Uniform Building Code (UBC 1935). The first seismic zonation map was introduced in the 1953 version of the NBCC code. The NBCC 1953 zoning map delineated four zones based on the locations of large historical events. Most of Canada was assigned zone 0 (with no need for seismic consideration). The zone with the largest design forces (zone 3) included regions such as southern and western parts of British Columbia in the west, and the St. Lawrence Valley in the east of Canada. Building design was based on working stress.

The code was updated in 1960 and 1965 to consider torsional effects and to add the "importance factor." However, the seismic zoning map of the NBCC 1953 was retained. The design philosophy underlying the NBCC 1965 was based on working stress design, but ultimate strength design was permitted for concrete structures as an alternative based on the American Concrete Institute (ACI) 1963. The first fully probabilistic seismic zoning map was introduced in the 1970 version of the NBCC code. This zoning map was based on the peak ground acceleration with 100 year return period (exceedance probability of 0.01) and demonstrated four seismic zones with respect to design base shear calculations. NBCC 1970 introduced the period-dependent structural flexibility factor, and also considered higher mode effects through a concentrated force at the top of the structure. The NBCC 1970 is considered a major update in the code evolution.

The code was updated again in 1975, 1977 and 1980; however, the seismic zoning map was unchanged. In 1975 a foundation factor was introduced to account for soft soil effects. Moreover, dynamic analysis was presented as an alternative procedure. A change in the seismic response factor in NBCC 1980 resulted in some increase in the design forces for low- and mid-rise buildings while decreasing the design forces of taller buildings (period greater than 1.0 second). A new seismic zoning map went into effect in the 1985 version of the NBCC code based on the hazard with a 10% probability of exceedance in 50 years (475 year return period). The map presented peak ground acceleration and peak ground velocity. Some refinements were also made in the design base shear formula.

The next edition of the code (NBCC 1990) used the same seismic zoning of NBCC 1985, but involved changes in the design base shear formula. An update in 1995 offered additional force modification factors and a new formula for building period and torsional eccentricities. The zoning map of NBCC 1985 was still used in NBC 1995. A milestone in the code evolution was represented by the introduction of the Uniform Hazard Spectrum (UHS) approach in the 2005 version of NBCC. In this approach, which was adopted from NEHRP 1997 in the U.S., design forces were calculated using site-specific response spectral acceleration with an exceedance probability of 2% in 50 years (2,475 year return period). The formula for determining design base shear was significantly modified as well. The code also incorporated two types of force modification factor, one related to ductility (reflecting energy dissipation capability) and another related to overstrength (reserve strength beyond yielding).

The most recent version of the code, namely, the NBCC 2010, is essentially the same as NBCC 2005 except for a minor reduction in the low period hazard and a slight increase in the long period hazard in zones with low seismic activity such as Toronto. The minimum design base shear was also updated. A comparison of design factored base shear for various structures in Vancouver and Montreal shows an overall increasing trend from 1970 to 2005 (Mitchell et al., 2010).

Although Vancouver and Victoria were among the first cities to adopt building codes, they did not adopt the first version of the NBCC when it was published in 1941. While the seismic provisions of NBCC were incorporated into the building bylaws of Vancouver in 1963, the city did not adopt the NBCC in entirety until after 1973. In general, buildings built before 1970 in British Columbia are known to have no seismic consideration. Figure 57 shows the seismic hazard map of Canada in the NBCC 2010 (in terms of spectral acceleration at 0.5 second). As the figure shows, southwestern British Columbia exhibits the highest hazard; therefore, the buildings in this region are expected to be designed to high standards against earthquake forces.

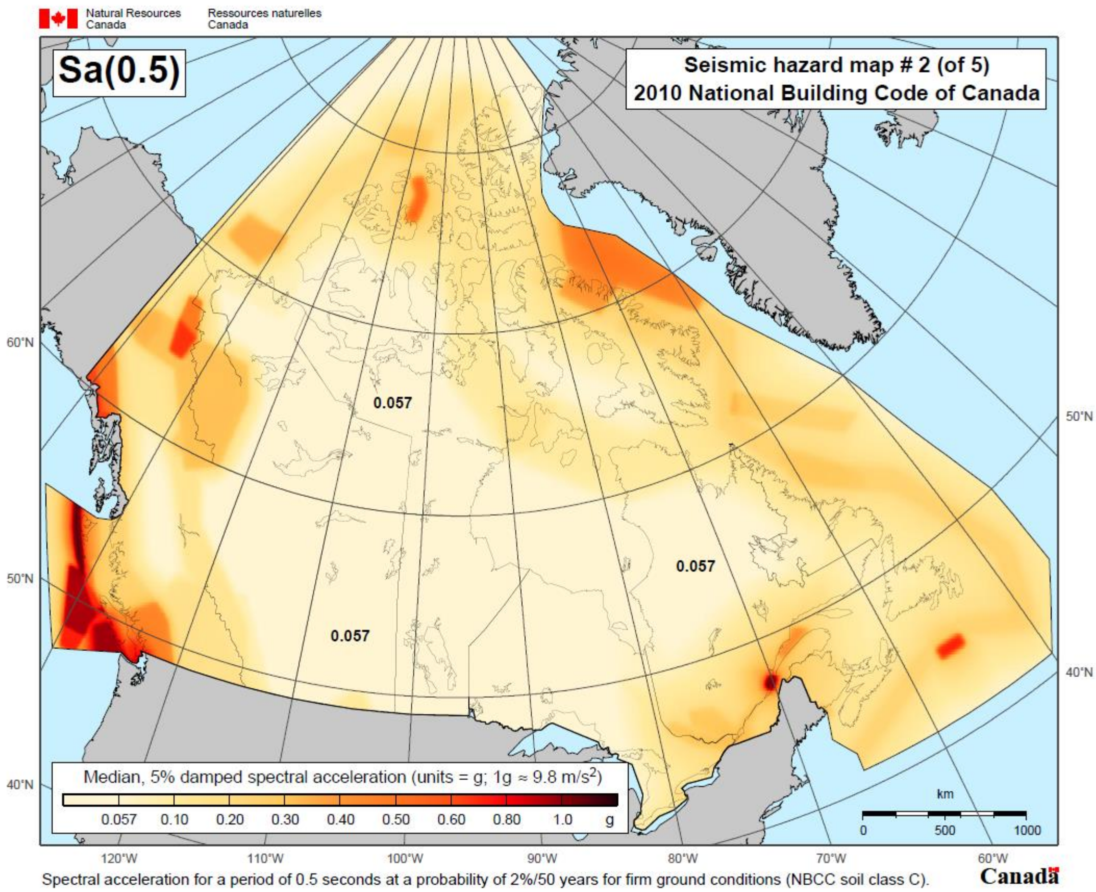


Figure 57: Seismic hazard map of Canada from the 2010 NBCC

6.2 Estimated Economic and Insured Losses

Economic losses

This section details the estimated economic and insured losses that will result from the western scenario. Economic losses include both direct and indirect losses due to damage to buildings and contents, as well as both direct and indirect losses resulting from damage to infrastructure. Direct and indirect losses can contribute to the economic losses from the western scenario. These are described in detail below.

Direct losses

Direct losses are those inflicted by the damage in property and infrastructure. Direct business interruption, which refers to the immediate reduction or cessation of economic production in a damaged property or a property cut off from at least one of its utility lifelines, is also presented in the context of direct losses.

The event causes a total of CAD 62,000 million in direct economic losses to properties and infrastructure of the British Columbia. Out of this total, CAD 60,112 million is inflicted on the properties and the remaining CAD 1,888 million on the infrastructure.

It must be noted that the losses shown above comprise the losses due to damage to buildings, their contents and the direct business interruption due to the immediate reduction or cessation of production in the damaged property or the loss of service. Indirect losses due to interconnectivity between the economic sectors and the infrastructure are excluded from the above numbers and are presented separately in the following section. Table 19 below provides a summary of direct all property losses by peril and by coverage. Figure 58 shows the proportion of each coverage to the total losses.

Table 19: Summary of all direct property losses by coverage

	Building	Contents	Direct BI	Total	Contribution of Peril
Shake	25,543	18,067	6,363	**49,972**	83.1%
Tsunami*	2,623	1,181	469	**4,273**	7.1%
Fire Following	311	147	76	**534**	0.9%
Liquefaction and Landslide	4,148	213	971	**5,332**	8.9%
Total	**32,625**	**19,608**	**7,879**	**60,112**	
Contribution of coverage	54.3%	32.6%	13.1%		

All figures are in millions and include demand surge.

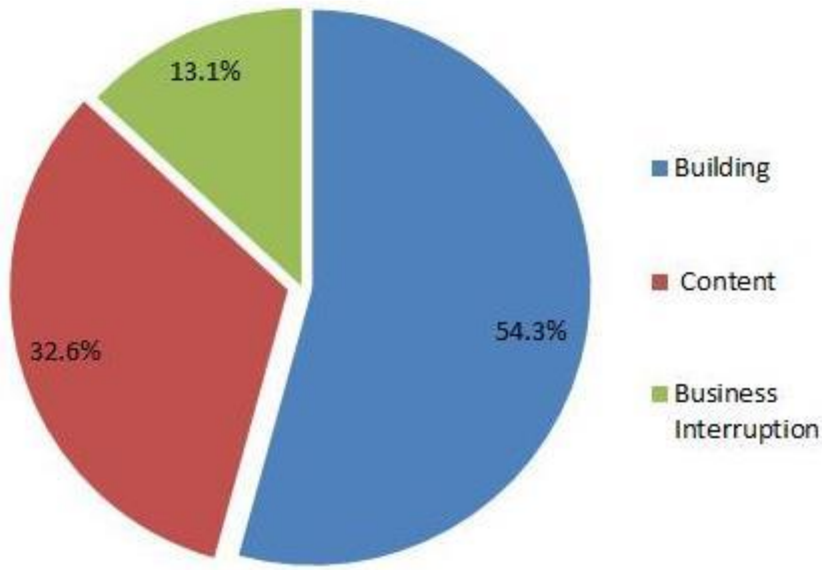


Figure 58: Contribution of each coverage to all direct property losses

Below in Table 20 we give a summary of all property losses by peril and by line of business, and in Figure 59 the proportion of each line of business to the total losses is shown. Table 21 gives a summary of western scenario all infrastructure losses by category.

Table 20: Summary of all direct property losses by line of business

	Residential	Commercial/ Industrial	Auto	Agriculture	Total	Contribution of Peril
Shake	19,451	30,219	199	102	**49,972**	83.1%
Tsunami	2,417	1,614	238	5	**4,273**	7.1%
Fire Following	214	307	12	1	**534**	0.9%
Liquefaction and Landslide	2,378	2,839	78	37	**5,332**	8.9%
Total	**24,461**	**34,979**	**527**	**145**	**60,112**	
Contribution of line of business	40.7%	58.2%	0.9%	0.2%		

All figures are in millions and include demand surge.

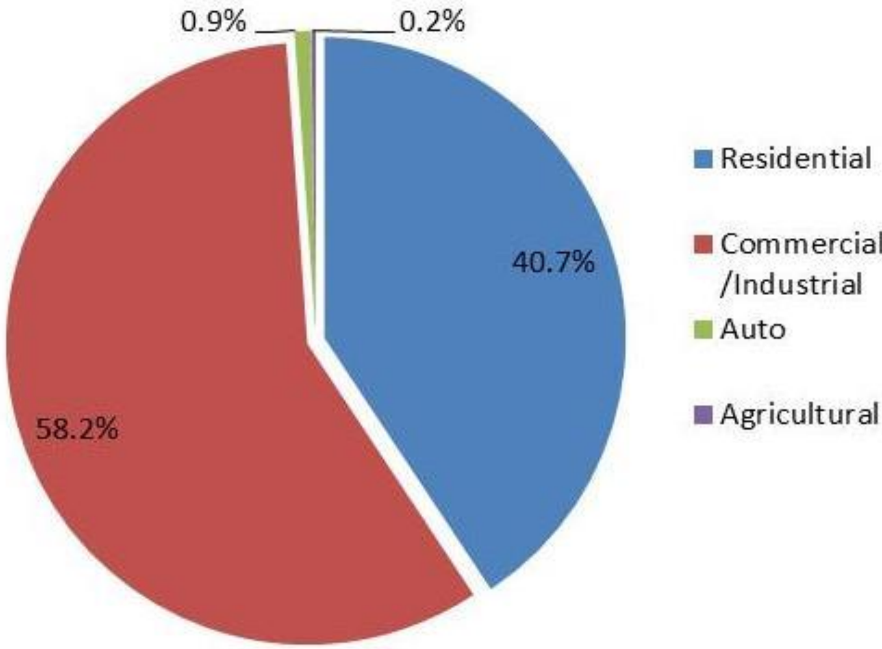


Figure 59: Contribution of each line of business to all direct property losses

Table 21: Summary of all infrastructure losses by category

	Transportation		Airport	Port	Pipelines			Electric/ Telecom	Total	Contribution of Peril
	Road	Rail			Gas	Oil	Water			
Shake	260	64	241	173	40	0	21	246	**1,044**	55.3%
Tsunami*	62	2	0	17	0	0	1	10	**91**	4.8%
Fire Following	0	0	0	0	0	0	0	0	**0**	0.0%
Liquefaction & Landslide	256	26	77	71	186	1	90	44	**753**	39.9%
Total	**578**	**92**	**318**	**261**	**226**	**1**	**112**	**300**	**1,888**	
Contribution of Category	30.6%	4.9%	16.8%	13.8%	12.0%	0.1%	5.9%	15.9%		

All figures are in millions and include demand surge.

Indirect losses

Indirect losses are losses due to interruption in supply chains, infrastructure, and interconnectivity of economic sectors. Indirect losses are estimated by thoroughly analyzing the ripple effects associated with the supply chain or customer chain of a directly affected business. Indirect loss calculation accounts for the impact of both property and infrastructure loss on the overall economy of the region by different sectors. Note that the sectors used here correspond to those defined in the North American Industrial Classification System (NAICS).

In this study, the indirect loss impacts are estimated for electricity, natural gas, oil, and water utilities, telecom systems, and transportation networks such as railroads, airports, sea ports, and roads, using an input-output (I-O) model. I-O analysis is a static, linear model of all purchases and sales between sectors of an economy based on the technological relationships of production (Rose and Miernyk, 1989). The I-O model was developed by Nobel laureate Wassily Leontief and is the most widely used tool for economic impact analysis. It has been used extensively to analyze the economic impacts of earthquakes and other natural hazards (see, e.g., ATC, 1991; Shinozuka et al., 1998; Rose and Lim, 2002; and Gordon et al., 2007; FEMA, 2008).

The resilience of a network—its ability to maintain functionality following a disruption—has a significant impact on the total indirect losses. Although there are many strategies a business or utility could use to stay operational after a disruption, the four most critical[8] resilience tactics are taken into account in this study:

- Conserving critical materials or utilities during production;
- Accounting for production processes that are effectively insulated from disruptions in utilities (e.g., much of agricultural production does not require electricity)
- Recapturing lost production by having employees work overtime or extra shifts
- Re-routing flights, ships, trucks, and so on, to ensure that freight arrives on schedule, in spite of damage to the transportation network

In this study, indirect losses for each scenario are presented with a range that shows the upper bound (with no resiliency), lower bound (considering all applicable resiliencies), and midpoint estimate (considering all applicable resiliencies, but these resiliencies are not necessarily implemented effectively, as might be expected in the aftermath of a major earthquake). It must be noted that

[8] Note that all of these strategies represent static resiliency, in which continued functionality after a disruption is achieved without repair and reconstruction. In addition, note that according to published studies, the effects of these four resiliency tactics greatly outweigh the effects of other resiliency tactics that are not included here. For a full discussion of resiliency types, see the report *Analysis of Indirect Economic Impacts of the Earthquake Scenarios in British Columbia and Quebec*, by D. Wei, A. Rose, and M. Lahr, which is included as an addendum.

in estimating the total indirect losses for each sector of economy, adjustments are made to avert the double counting of the impact of different disruptions.

The total indirect losses in the western scenario are CAD 21,385 million without resilience (upper bound) and CAD 4,103 million with all the sources of resilience (lower bound), and CAD 12,744 million with resilience measures implemented "realistically" (midpoint). Table 22 shows the indirect losses from various sources with and without resilience after the adjustments for potential double counting. The table also shows the midpoint indirect loss estimate.

As can be seen in the table, indirect losses associated with the loss of building property have the highest contribution to the total indirect losses both with and without resilience. Furthermore, a comparison of the results with and without resilience indicates that if all sources of resilience are fully effective the indirect losses can be reduced significantly (on average 82% in this scenario). However, actual implementation of resilience is likely to fall short of this potential due to problems in management, unforeseen interdependencies in business operations, and supply-chain conditions that hinder a business from resuming operations even if its facilities have been completely repaired or reconstructed. Therefore the actual indirect loss falls between the upper bound and lower bound of the losses presented here with the midpoint estimate of CAD 12,744 million considered to be the most likely.

Table 22: Indirect losses to infrastructure from various sources

Source of Impact	Without Resilience	With Resilience	With Resilience – Midpoint
Building Damages	18,612	3,802	11,207
Oil Pipeline Disruption	34	4	19
Gas Pipeline Disruption	396	13	205
Water Supply Disruption	564	32	298
Power Supply Disruption	671	86	379
Telecom System Disruption	852	49	450
Air Ports Disruption	83	41	62
Sea Ports Disruption	111	55	83
Roads Disruption	44	11	27
Railroads Disruption	18	9	14
Total	**21,385**	**4,103**	**12,744**

All figures are in millions.

The total losses shown in Table 22 can be further broken down to the losses by each sector of economy. Table 23 and Table 24 show the indirect losses in each sector of economy from various sources of disruption respectively without and with resilience effects. It should be noted the numbers in these tables are before the adjustment for potential double counting.

Table 23: Sectorial indirect losses by various impact sources without resilience

Sector	Building	Oil	Gas	Water	Power	Tele-com	Air Ports	Sea Ports	Roads	Rail-roads	Total Output Losses
Crop & Animal Production	111	1	6	9	11	13	1	7	1	1	161
Forestry & Logging	228	1	13	18	22	27	1	11	2	1	323
Fishing, Hunting & Trapping	5	0	0	1	1	1	0	1	0	0	9
Support Activities for Agriculture & forestry	32	0	2	3	4	5	0	2	0	0	49
Mining and Oil & Gas Extraction	349	2	25	36	43	54	5	20	3	4	541
Utilities	190	1	11	16	19	24	0	0	1	0	260
Construction	2,072	6	65	93	111	141	0	43	7	1	2,539
Manufacturing	2,014	7	80	114	136	172	23	61	17	8	2,631
Wholesale Trade	806	3	33	47	56	71	7	15	5	1	1,045
Retail Trade	1,538	4	47	68	80	102	10	0	5	2	1,856
Transportation & Warehousing and Transportation Margins	1,194	5	60	85	101	128	23	49	11	6	1,662
Information & Cultural Industries	814	2	28	39	47	59	6	12	4	2	1,012
Finance, Insurance, Real Estate & Rental & Leasing	2,618	11	131	187	222	282	32	0	13	4	3,500
Professional, Scientific & Technical Services	1,127	4	40	57	68	87	8	0	3	1	1,396
Administrative, Waste Management & Remediation Services	508	2	21	29	35	44	4	0	2	1	645
Educational Services	96	0	2	3	4	5	0	0	0	0	111
Health Care & Social Assistance	556	2	20	29	35	44	2	0	2	0	690
Arts, Entertainment & Recreation	276	1	9	13	16	20	4	0	1	0	339

Sector	Building	Oil	Gas	Water	Power	Tele-com	Air Ports	Sea Ports	Roads	Rail-roads	Total Output Losses
Accommodation & Food Services	810	3	29	41	48	61	13	0	3	0	1,007
Other Services (Except Public Administration)	711	1	16	22	26	33	0	0	1	0	811
Operating, Office, Cafeteria & Laboratory Supplies	416	2	25	35	42	54	0	0	0	0	574
Travel, Entertainment, Advertising & Promotion	561	2	27	38	46	58	0	0	0	0	733
Non-Profit Institutions Serving Households	211	1	13	18	21	27	2	0	1	0	294
Government Sector	1,369	8	89	126	150	191	25	0	7	3	1,968
Total	**18,612**	**68**	**793**	**1,128**	**1,342**	**1,704**	**166**	**221**	**87**	**37**	**24,158**

All figures are in millions.

Table 24: Sectorial indirect losses by various impact sources with resilience

Sector	Building	Oil	Gas	Water	Power	Tele-com	Air Ports	Sea Ports	Roads	Rail-roads	Total Output Losses
Crop & Animal Production	30	0	0	1	2	1	0	4	0	0	39
Forestry & Logging	63	0	1	2	4	2	1	5	0	1	78
Fishing, Hunting & Trapping	1	0	0	0	0	0	0	0	0	0	2
Support Activities for Agriculture & forestry	9	0	0	0	1	0	0	1	0	0	11
Mining and Oil & Gas Extraction	21	0	0	0	1	0	2	10	1	2	37
Utilities	52	0	1	1	4	2	0	0	0	0	60
Construction	197	0	0	2	3	2	0	22	2	1	228
Manufacturing	114	0	0	1	2	1	12	31	4	4	169
Wholesale Trade	121	0	1	2	6	3	4	8	1	1	145
Retail Trade	226	0	1	2	8	5	5	0	1	1	250
Transportation & Warehousing and Transportation Margins	849	3	5	16	41	28	12	25	3	3	983
Information & Cultural Industries	32	0	0	0	1	0	3	6	1	1	44
Finance, Insurance, Real Estate & Rental & Leasing	320	1	2	5	17	11	16	0	3	2	378
Professional, Scientific & Technical Services	135	0	1	2	5	3	4	0	1	1	152

Sector	Building	Oil	Gas	Water	Power	Tele-com	Air Ports	Sea Ports	Roads	Rail-roads	Total Output Losses
Administrative, Waste Management & Remediation Services	60	0	0	1	3	2	2	0	0	0	68
Educational Services	40	0	0	0	1	1	0	0	0	0	42
Health Care & Social Assistance	228	0	2	4	10	4	1	0	1	0	250
Arts, Entertainment & Recreation	113	0	1	2	5	3	2	0	0	0	127
Accommodation & Food Services	333	1	3	8	15	9	6	0	1	0	375
Other Services (Except Public Administration)	355	0	1	3	10	5	0	0	0	0	375
Operating, Office, Cafeteria & Laboratory Supplies	52	0	1	1	3	2	0	0	0	0	59
Travel, Entertainment, Advertising & Promotion	68	0	1	1	4	2	0	0	0	0	75
Non-Profit Institutions Serving Households	87	0	1	2	6	3	1	0	0	0	101
Government Sector	296	1	3	7	21	11	12	0	2	2	354
Total	**3,802**	**8**	**26**	**64**	**173**	**97**	**83**	**111**	**22**	**18**	**4,403**

All figures are in millions.

Direct losses to infrastructure constitute 3% of the total direct losses experienced in this scenario. This ratio for indirect losses rises to 12%. Considering both direct and indirect losses, the contribution of infrastructure to the total economic loss is 5%. It must be noted that estimating the contribution of infrastructure losses to total losses is subjected to large uncertainties.

Similar studies for different regions have shown a wide range for the contribution of infrastructures, which depend on many factors such as the socio-economic situation of the region under study, the selected scenario and the damage estimation approach, to name a few. In studies such as the 2008 ShakeOut Scenario (a magnitude 7.8 earthquake from San Andreas Fault in southern California) and the Munich Re (1992) study of the lower mainland of British Columbia direct property losses from infrastructure contribute to 1-8 % of total losses (lower numbers correspond to the ShakeOut scenario). When indirect economic losses are accounted for these numbers can be larger (8-25%).

Insured losses

Insured losses, which are estimated from economic losses, reflect the level of earthquake insurance purchased in an area, as well as insurance policy conditions. For information about the insurance penetration and policy condition assumptions that affect the insured losses presented in this report, see Section 3.6.

Insured losses from the western scenario amount to a total of CAD 20,431 million. The losses are determined using the latest policy conditions and the best estimates of the take up rates in the areas as discussed in Section 3.6.

Typically insurance policies having earthquake as a covered peril utilize two deductibles, one for the non-earthquake loss event (this is the standard policy deductible), and another for the earthquake loss event. In calculating the insured losses shown in this report, in the case where there is only an earthquake loss, we have used the earthquake deductible. When there is only a fire following earthquake loss, we have used the standard policy deductible. If there is both earthquake and fire following loss, then we have used the highest deductible, which is standard practice in the industry.

Insurance company reactions to recent changes in legislation in British Columbia have resulted in evolving policy conditions. For this reason, we ran a sensitivity test using the policy deductible where there is both fire and earthquake loss, the resulting insured loss would be 44% higher.

It must be noted that the infrastructure losses have no contribution to the total insured losses presented here. Infrastructure can be privately, publicly, or self-insured, but the prevalence of each of these types of insurance was unable to be determined from available data. For this reason, market penetration rates, which are measures of the total value of insured property in relation to the value of all property, could not be determined.

Table 25 below provides a summary of all insured property losses by peril and by coverage, and Figure 60 indicates the proportion of each coverage to the total losses shown and Figure 63 shows the proportion of losses attributable to each coverage.

Table 25: Summary of insured property losses by peril and coverage

	Building	Contents	Direct BI	Total	Contribution of Peril
Shake	9,024	5,671	2,383	**17,078**	83.6%
Tsunami	739	203	175	**1,117**	5.5%
Fire Following	206	90	41	**337**	1.6%
Liquefaction and Landslide	1,465	59	374	**1,898**	9.3%
Total	**11,433**	**6,023**	**2,974**	**20,431**	
Contribution of Coverage	56.0%	29.5%	14.6%		

All figures are in millions and include demand surge.

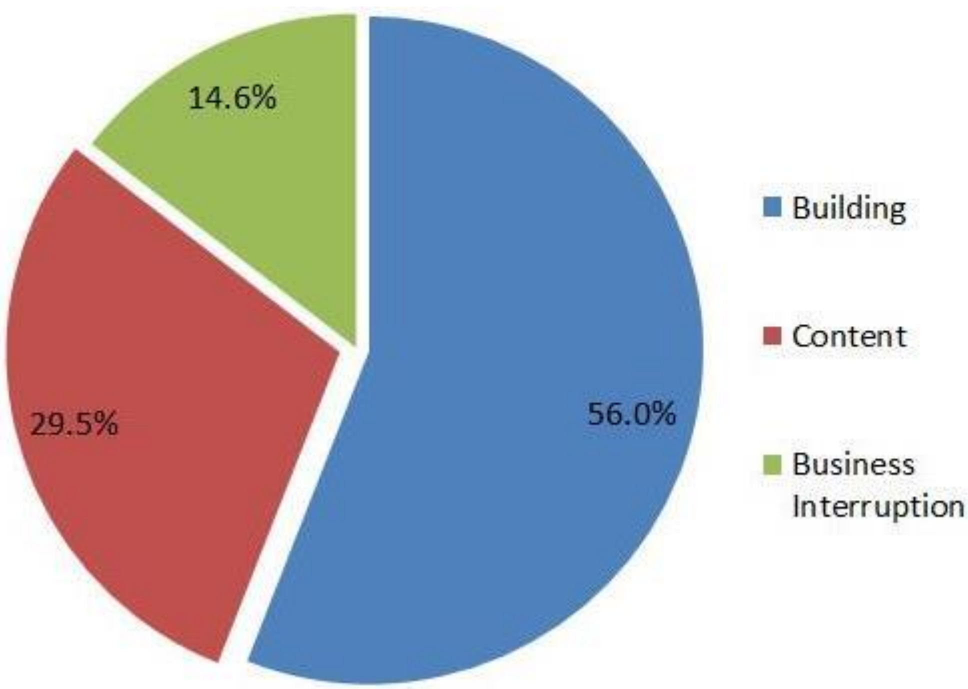


Figure 60: Contribution of each coverage to total insured property losses

Table 26: Summary of insured property losses by line of business

	Residential	Commercial/ Industrial	Auto	Agricultural	Total	Contribution of Peril
Shake	4,154	12,784	102	38	**17,078**	83.6%
Tsunami	-	901	213	3	**1,117**	5.5%
Fire Following	147	182	8	0	**337**	1.6%
Liquefaction and Landslide	556	1,276	51	16	**1,898**	9.3%
Total	**4,856**	**15,144**	**373**	**58**	**20,431**	
Contribution of Line of Business	23.8%	74.1%	1.8%	0.3%		

All figures are in millions and include demand surge.

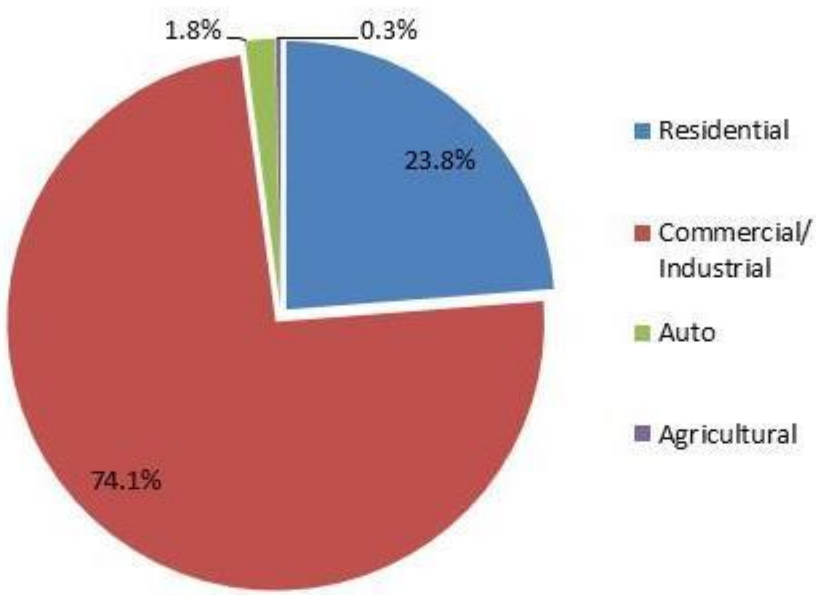


Figure 61: Contribution of each line of business to total insured property losses

The automobile losses shown in Table 26 above include losses from the earthquake covered under automobile insurance policies. In British Columbia, the Insurance Corporation of British Columbia (ICBC) provides all mandatory automobile insurance policies as well as the vast majority of the optional policies which cover earthquake. The amount of insured automobile losses for the western scenario is shown in

Table 27 below, which draws a distinction between the losses covered by the ICBC and those covered by private insurers.

Table 27: Summary of insured automobile losses by insurer

	ICBC	Other Insurers	Total
Insured Loss	**336**	**37**	**373**
Contribution of Insurer	90.0%	10.0%	

All figures are in millions.

Commercial/Industrial losses are depicted in the next three figures. Figure 62 indicates the total losses for the region as a whole, Figure 63 shows losses for the Vancouver area and Figure 64 illustrates losses in and around Victoria.

Figure 62: Western scenario region insured commercial losses

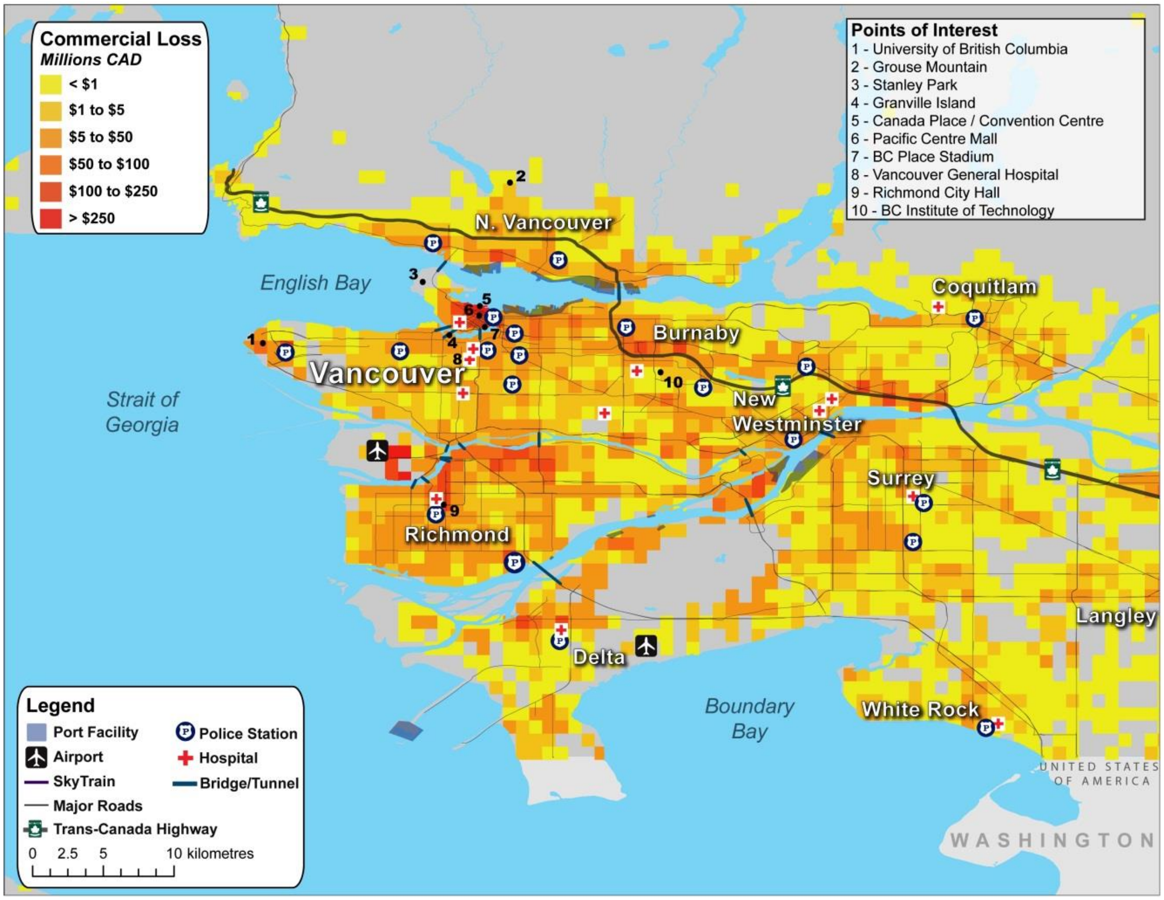


Figure 63: Vancouver insured commercial losses

Areas with high-value losses can be seen scattered through the region with conspicuous concentrations in downtown Vancouver, north Richmond and among the industrial properties on Annacis Island in the Fraser River. Equally conspicuous are the losses associated with commercial property at Vancouver International Airport, which are additional to the losses to infrastructure at the facility recorded in Table 28.

The losses in the Metro Victoria shown below in Figure 64 are similarly concentrated centres of population, particularly downtown Victoria itself where commercial losses reflect the value of development along Highway 1 and Highway 17.

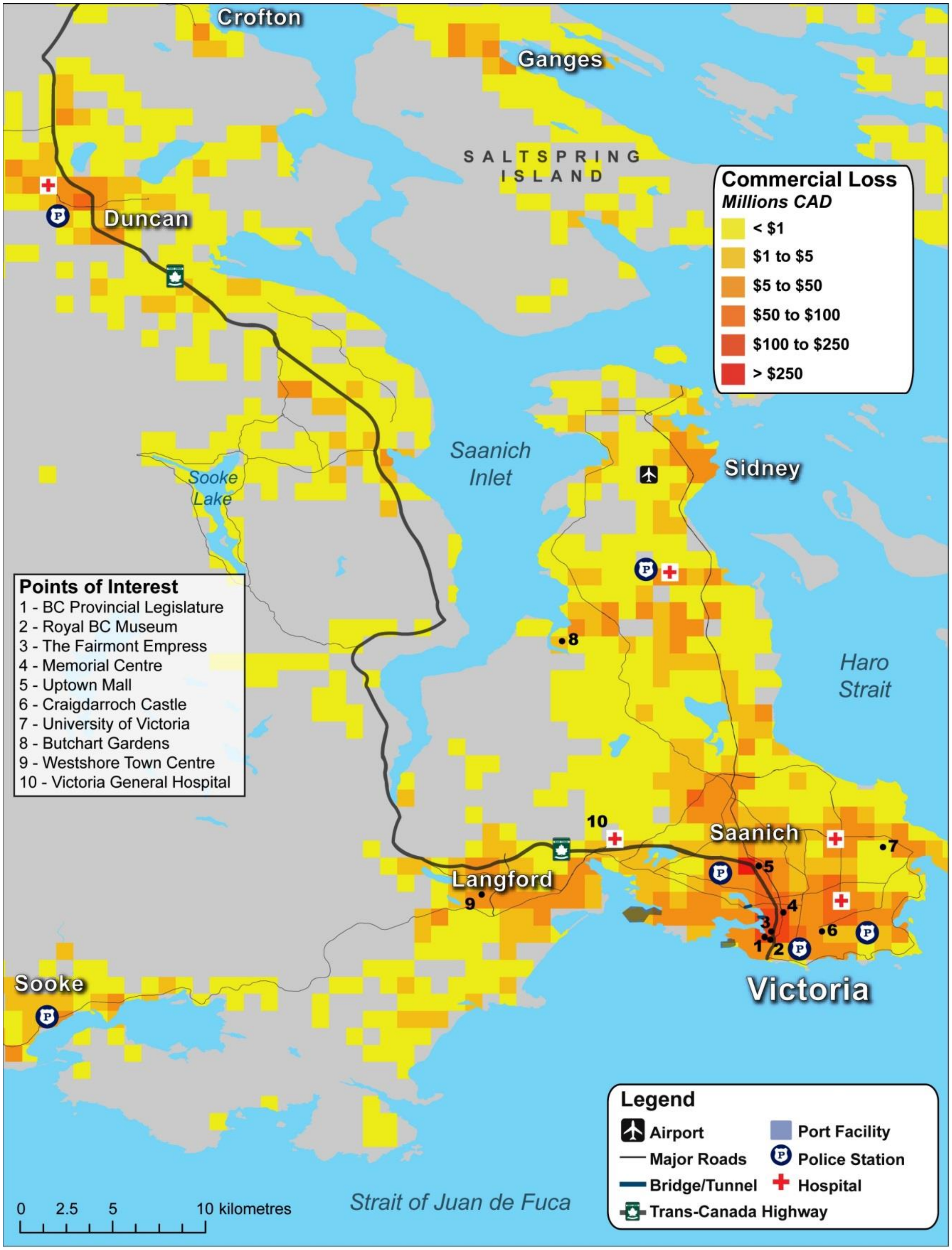


Figure 64: Victoria commercial losses

Residential losses are addressed in the following three figures. Losses for the entire region are shown in Figure 65, those for the Vancouver area are given in Figure 66 and Victoria losses are indicated in Figure 67.

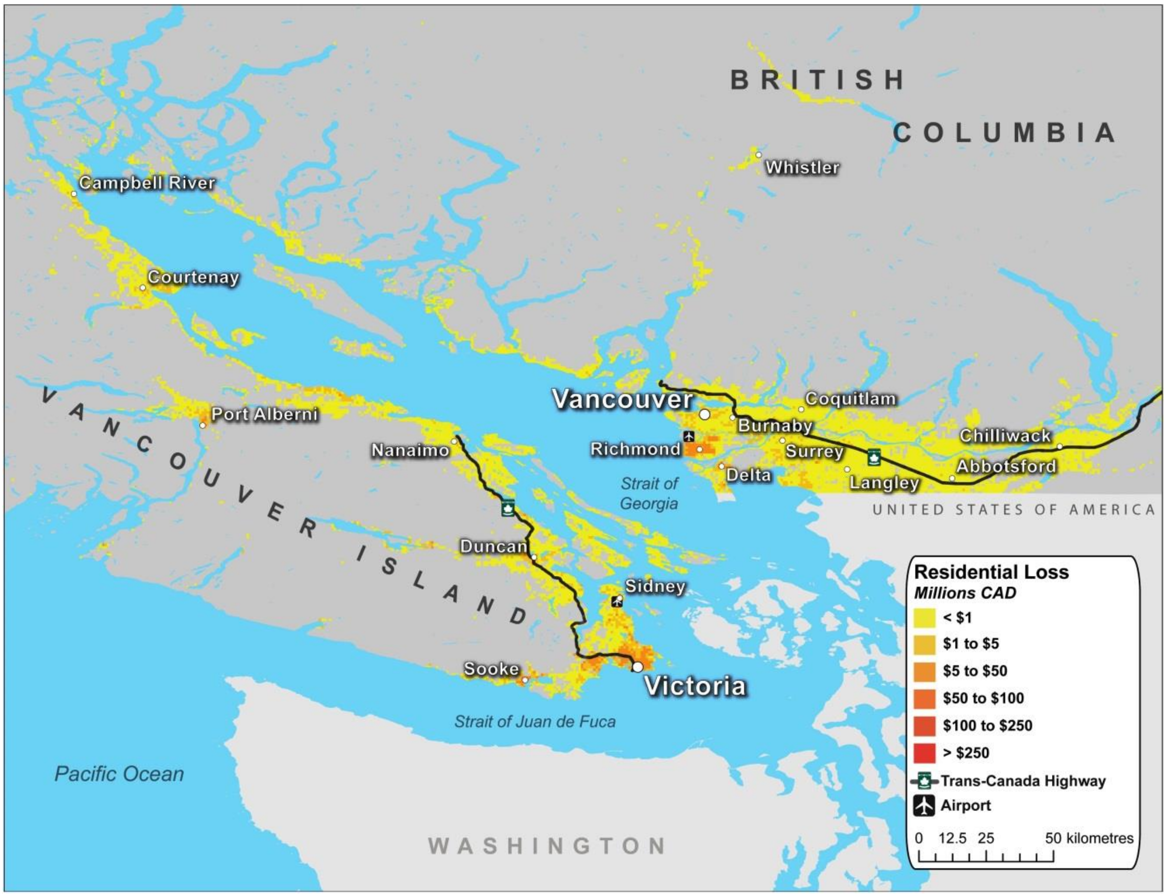


Figure 65: Western scenario region residential losses

Figure 65 above illustrates how losses to residential properties follow the distribution of population seen in Figure 28.

Communities are located principally along the shores of the Strait of Georgia and to the east of Vancouver, with the highest concentrations of both population and property value being located in the Metro Victoria and Vancouver areas. Elsewhere in the region affected by the earthquake the population density and distribution of insured residential property are very low.

The residential losses seen in Figure 65 reflect both the increased density and the enhanced value of insured property in the centres of population. In general, the highest losses per km^2 are seen in the principal municipalities of the region.

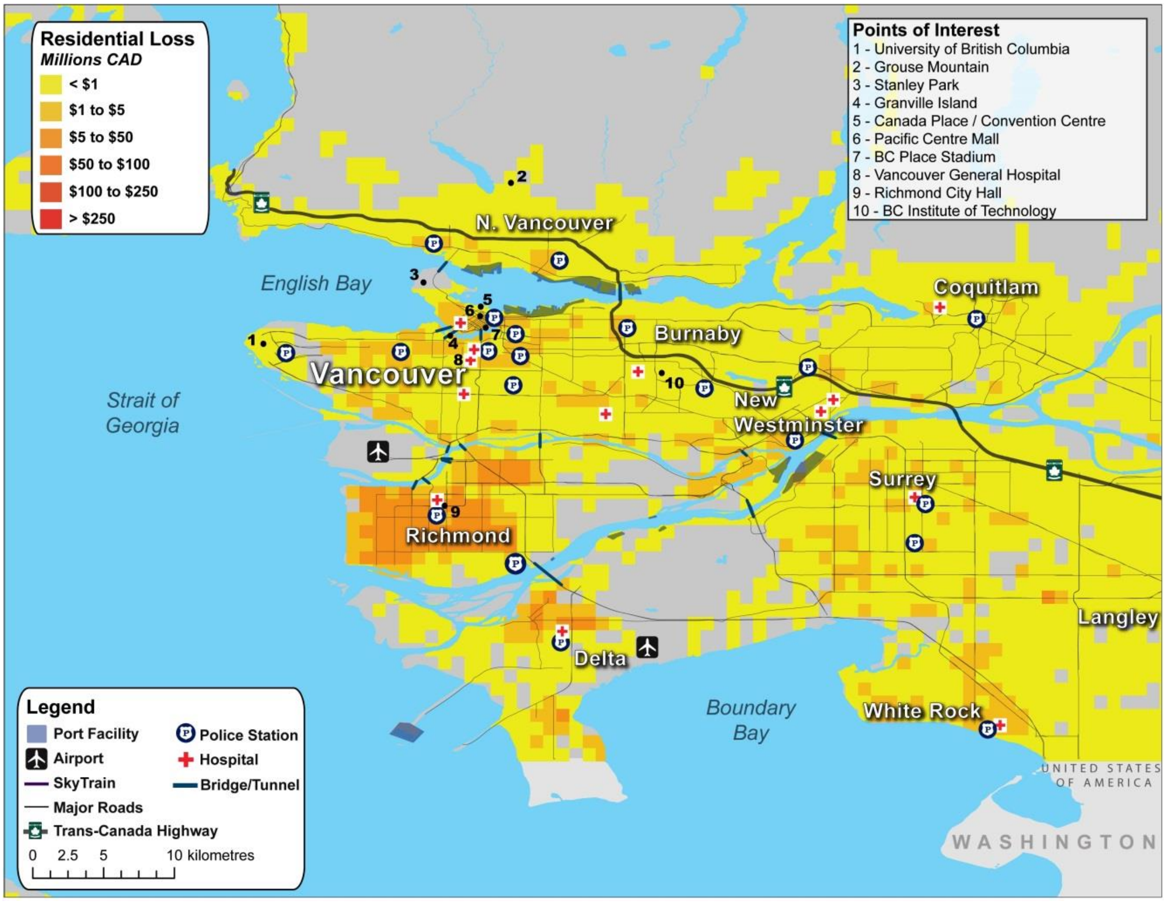


Figure 66: Vancouver residential losses

Residential losses are evident throughout most of the Metro Vancouver area. The elevated level of loss in Vancouver itself reflects the carefully-planned high density development that contributes so much to its famed livability. Elevated levels of loss in Richmond reflect both the degree of shaking experienced and the higher level of liquefaction hazard in the area.

Pockets without loss are evident, and some of these reflect the areas that host many parks and preserved open spaces. The large loss-free space in Delta for example is formed principally by the 40 km^2 of Burns Bog—the largest domed peat bog on the west coast of North America—which occupies a quarter of Delta.

Residential losses are similarly seen throughout most of the Metro Victoria area (Figure 67), with elevated levels of loss evident in the more developed urban locations.

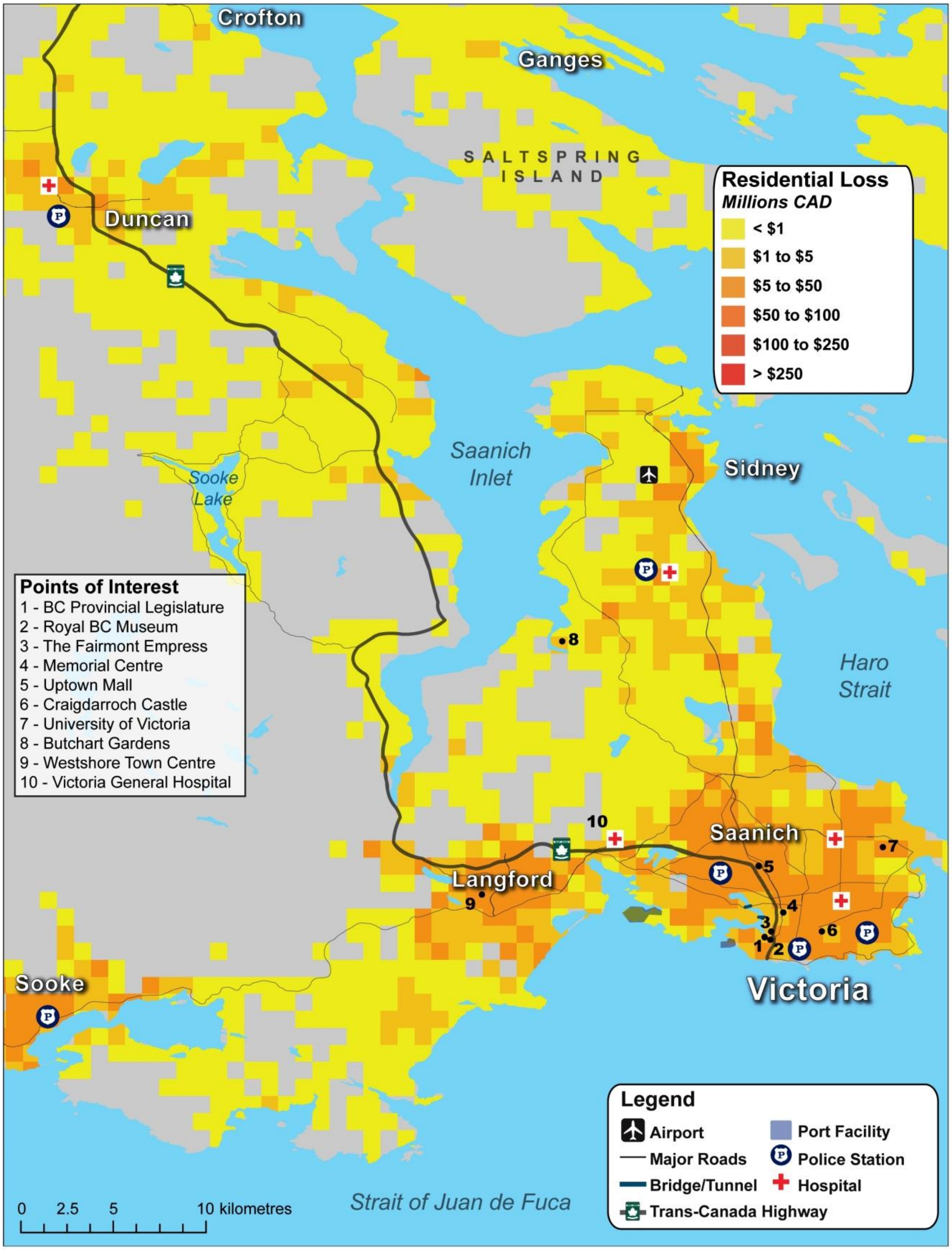


Figure 67: Victoria residential losses

Infrastructure

Losses to infrastructure across the region are outlined in Figure 68. Greater detail for the Vancouver area is given in Figure 69 and for the Victoria area in Figure 70.

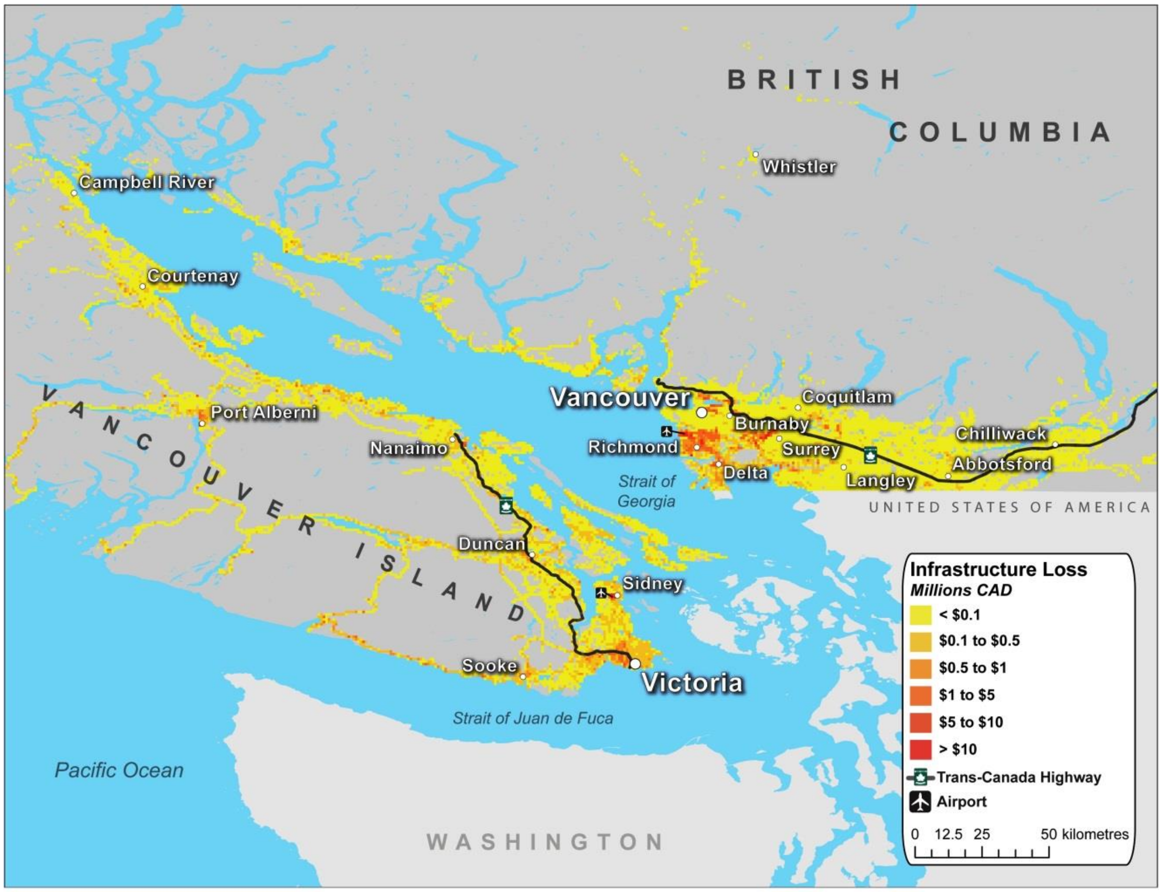


Figure 68: Losses to infrastructure in the western scenario region

Infrastructure in the region follows the development of the communities within it. It is the arteries that supply them with essential services such as power, water and communications and the roads, railroads and bridges that connect them. It is the lifelines that enable them to function and their economies to prosper.

Figure 68 shows low levels of loss throughout the region's communities. Losses to roads on Vancouver Island, which experiences stronger shaking than the rest of the region, stand out particularly. Damage to roads is the most significant of the categories of loss contributing to the total infrastructure losses for the region noted in Table 28.

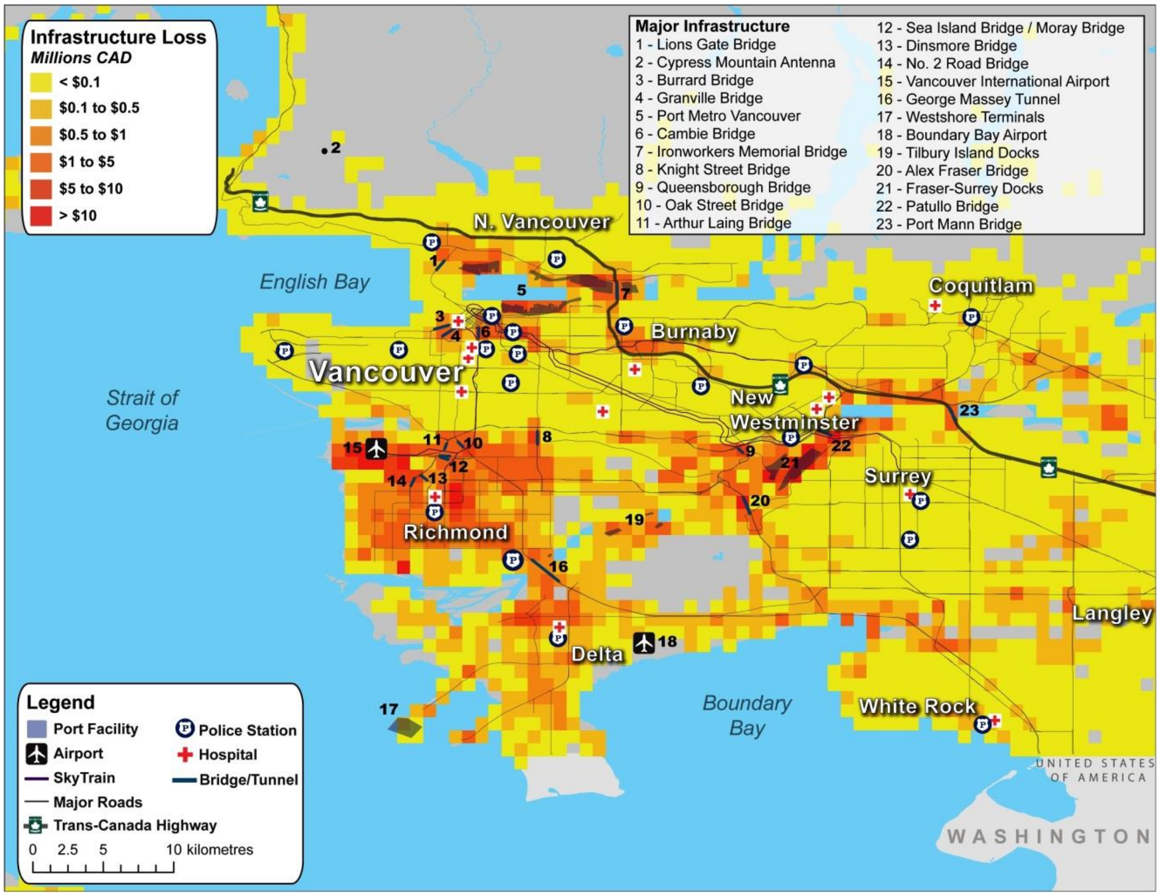


Figure 69: Losses to infrastructure in the Metro Vancouver area

The losses to infrastructure in the Metro Vancouver area noted in Figure 69 show a generally low level of loss with occasional pockets of higher loss. An elevated level of losses can be seen in Richmond, which is subject to a higher degree of liquefaction risk to which roads and pipelines are particularly vulnerable. As well as damage to bridges in the area, significant losses at Vancouver International Airport are seen. These principally reflect liquefaction damage to runways, and are in addition to the losses to commercial property at the site noted in Figure 63.

Infrastructure losses in the Metro Victoria area show a similar general distribution of low level losses with occasional pockets of slightly higher losses. The most conspicuous high level losses are those associated with Victoria International Airport.

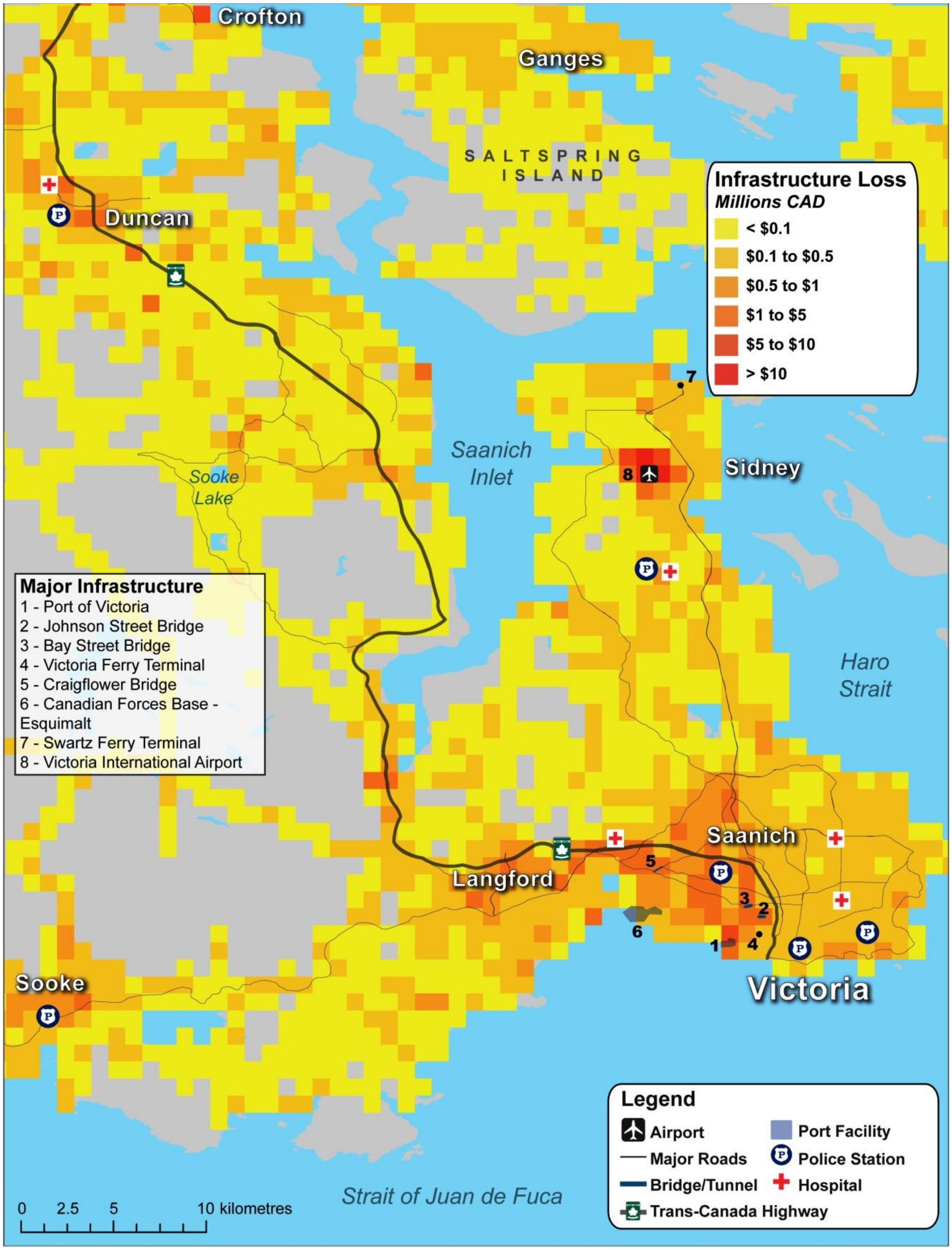


Figure 70: Victoria infrastructure losses

The contribution of each infrastructure type to total losses is shown in Table 28, and the proportion of losses attributable to each infrastructure type is given in Figure 71.

Table 28: Contribution of each infrastructure type to total losses

Type	Direct Loss	Contribution of Type
Transportation- Road	578	30.6%
Transportation-Rail	92	4.9%
Airport	318	16.8%
Port	261	13.8%
Pipeline-Oil	1	0.1%
Pipeline-Water	112	5.9%
Pipeline-Gas	226	12.0%
Electrical Transmission System	296	15.7%
Telecommunication System	4	0.2%
Total	**1,888**	

All figures are in millions.

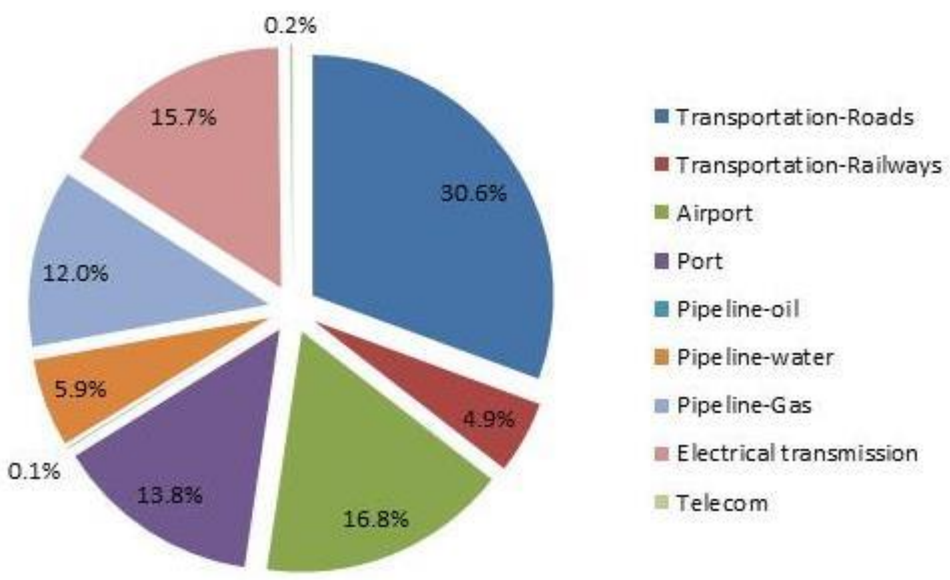


Figure 71: Contribution of each infrastructure type to total losses

Public buildings

Table 29 below gives a summary of all ground up losses to public buildings by category and by coverage.

Table 29: Total ground up losses to public buildings

LOB	Type	Building	Content	Direct BI	Total	Contribution of Type
Commercial	Healthcare	325	189	124	**637**	42.6%
	Government	230	128	88	**445**	29.8%
	Education	183	106	70	**358**	23.9%
Industrial	Public Utility Facilities	17	25	13	**55**	3.7%
Total		**755**	**448**	**295**	**1,495**	
Contribution of Coverage		50.5%	30.0%	19.7%		

All figures are in millions.

7 The Eastern Scenario

7.1 Event Description

The earthquake that is the focus of the eastern scenario originates in the St. Lawrence River Valley almost 100 km north east of Québec City, the greatest concentration of population and property in the region. People at a distance of 800 km from the epicentre of the event, and in some cases farther, will be able to feel it indoors. The affected region includes the more heavily populated areas along and to the south of the St. Lawrence River, the communities around Saguenay, parts of New Brunswick, eastern Ontario, Nova Scotia and northern New England, and a considerable swath of the lightly populated surrounding area.

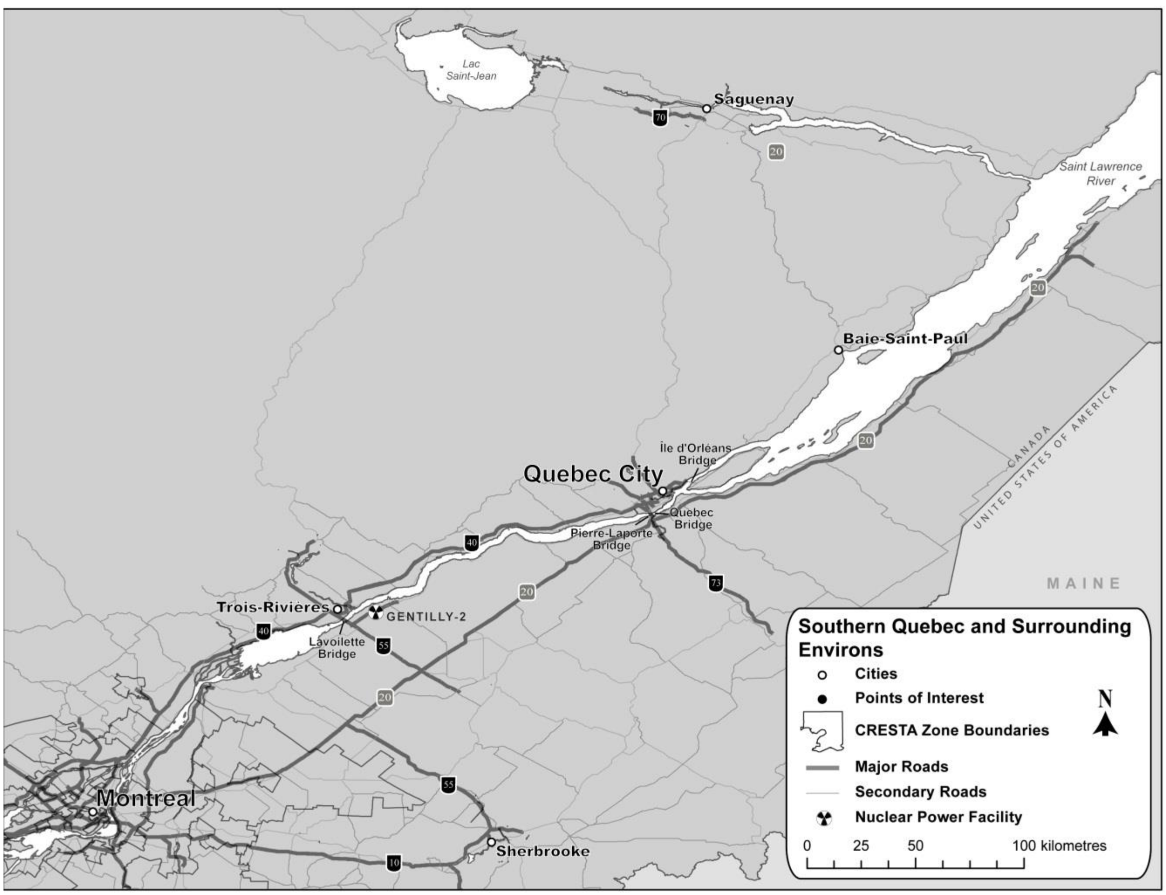


Figure 72: Principal municipalities in the eastern scenario region

The region is bisected by the St. Lawrence River, beneath which the earthquake originates. The St. Lawrence Lowlands follow the river northeastward towards Québec City, which is close to the scenario region's centre and marks the transition of the river into a wider tidal estuary. The Laurentian Highlands to the north and the Notre Dame Mountains to the south accompany the river until it discharges into the Gulf of St. Lawrence.

Figure 73: The historic upper and lower town districts of Québec City, with port facilities in the foreground (Datch 78, Wikimedia)

The mention of Québec City conjures up images of the picturesque historic stone-built upper and lower town areas. Because of its many attractions Québec City is a popular tourist destination and it possesses a world class tourism infrastructure. It is also the provincial capital and home to Québec's National Assembly and government ministries. The service sector dominates its economy, but the city also accommodates many corporate headquarters, has a strong manufacturing sector and has become a major centre for the life sciences industry. Its location on the St. Lawrence River affords it deepwater port facilities significant both for freight and cruise traffic.

Upstream and to the west of the city, extending away from the epicentre of the earthquake, lies the densely populated Québec City–Windsor Corridor—the most heavily-industrialized region of Canada. The earthquake will be experienced in Trois Rivieres only at level VI on the MMI scale, and at level V in Montreal (see Table 16 for a description of the levels on the MMI scale). Damage to nuclear installations, like the decommissioned power plant at Gentilly near Trois Rivieres, is not modeled by AIR.

The scenario event

This earthquake occurs early in December, and average high temperatures in Québec will struggle to reach -5 degrees Celsius. There is likely to be substantial cloud cover and the probability that some form of precipitation will be experienced that day is 73%. That precipitation is likely to be light or moderate snow. Typical wind speeds vary from 0 km/h to 28 km/h and rarely exceed 42 km/h. This scenario has a wind speed of 28 km/h, which is well within the expected range. Winds are most likely to come from the west or the east.

As with the western scenario, the time of day at which the earthquake occurs is not significant from the perspective of insured losses, and is therefore not considered in this exercise. A significant earthquake coinciding with rush hour would however be expected to result in an elevated number of personal accident claims, but these fall outside the scope of this study.

The eastern scenario event is a powerful earthquake, with a magnitude of 7.1, which occurs at the shallow depth of 10 km. The location of the epicentre (Lat. 47.245, Lon. -70.470) is beneath the St. Lawrence River, about halfway between Bai-Saint-Paul on the north bank and Montmagny on the south.

Anticipated damage

In this scenario, ground shaking is responsible for the vast majority of ground-up losses, and being an inland event, a tsunami is not generated. The western scenario models a much more powerful magnitude 9 event, the epicentre of which is about 300 km from Vancouver. But because the epicentre of the eastern scenario earthquake is so close to it, Québec City and its environs experience more violent shaking than Vancouver does in its scenario. Afforded a rating of VII on the MMI Scale, the strong to very strong shaking experienced in and around the city will make it difficult to stand or walk, and will affect the steering of cars. For an explanation of the MMI scale, its intensity levels and a description of their impacts, see Table 16.

Modern engineered structures should perform well, but poorly-built masonry buildings in particular will experience serious damage as chimneys, loose plaster, cornices, bricks and tiles, upper walls and parapets fall. Cracks will develop even in some better-built masonry structures. The historic unreinforced masonry buildings that are so prevalent in Québec City's upper and lower towns for example, are particularly at risk.

The St. Lawrence Valley

The strongest and most damaging shaking from the earthquake will be experienced in the rural communities along the north and south banks of the St. Lawrence River within a radius of about 50 km of the epicentre. In these areas shaking will correspond to level VIII. Liquefaction and landslide will contribute significantly to the anticipated damage along the St. Lawrence River.

Figure 74: Earthquake damage when a house is not bolted to foundation (J.K. Nakata, U.S. Geological Survey)

The area near the ski resort of Mont-Sainte-Anne in the city of Beaupré, about 40 km northeast of Québec City, includes several temporary lodging and apartment buildings as well as low-rise commercial buildings. Extensive damage is expected in the resort and nearby areas. It must be noted that in addition to ground shaking, landslide can also contribute to the total damage in this region.

Substantial damage to wood buildings in the resort, which are mainly lodgings, may include large diagonal cracks across wall panels, loosened or even broken diagonal rod braces, slippage or splitting at bolted connections, and permanent lateral movement of floors and roofs. Moreover, cracks in foundations, slippage of structures over their foundations and partial collapse of "soft-story" configurations, if present, are other types of expected damage. Damage in masonry buildings (both URM and reinforced masonry) is likely to be very heavy. Serious failure of walls, partial structural failure of roofs and floors, or even near collapse, is anticipated. The extent of damage in the masonry buildings will be so large that it can render these buildings out of service for several months.

Substantial damage is also anticipated in reinforced concrete and steel buildings in Saint-Ferréol-les-Neiges along Route 360. Many steel brace and other structural members will have exceeded their yield capacity, resulting in significant permanent lateral deformation of the structure. Some structural members or connections will exceed their ultimate capacity, and this will be apparent from braces that have buckled or broken, buckled flanges, broken welds, or failed bolted connections. Anchor bolts at columns may be stretched. The partial collapse of portions of structures is possible due to the failure of critical elements or connections. Because of the severity of their damage, these buildings may be out of service for repair and reconstruction for more than three months.

Ground failure, in particular landslide, is expected to make a large contribution to damage in these areas, especially in the elevated areas near the river in Sainte-Anne-de- Beaupré. The severity and extent of damage can significantly impact the businesses in this region.

In addition to commercial properties, residential buildings in the above regions, particularly the URM buildings in the city of Beaupré, may suffer very heavy damage, or even total destruction. Damage of this nature will be widespread and will extend as far as Saint-Tite-de-Caps and across the river to Montmagny, Berthier-sur-Mer and Cap-Saint-Ignace.

Saguenay

Residential and commercial buildings in both Saguenay (see Figure 75) and Port Alfred will experience negligible to light damage. Damage to wood frame structures will include small cracks at the corners of door and window openings and wall-ceiling intersections. Hairline cracks in a very few walls may be found in some damaged masonry constructions. Business interruption may last a few days while many others will not suffer service disruption.

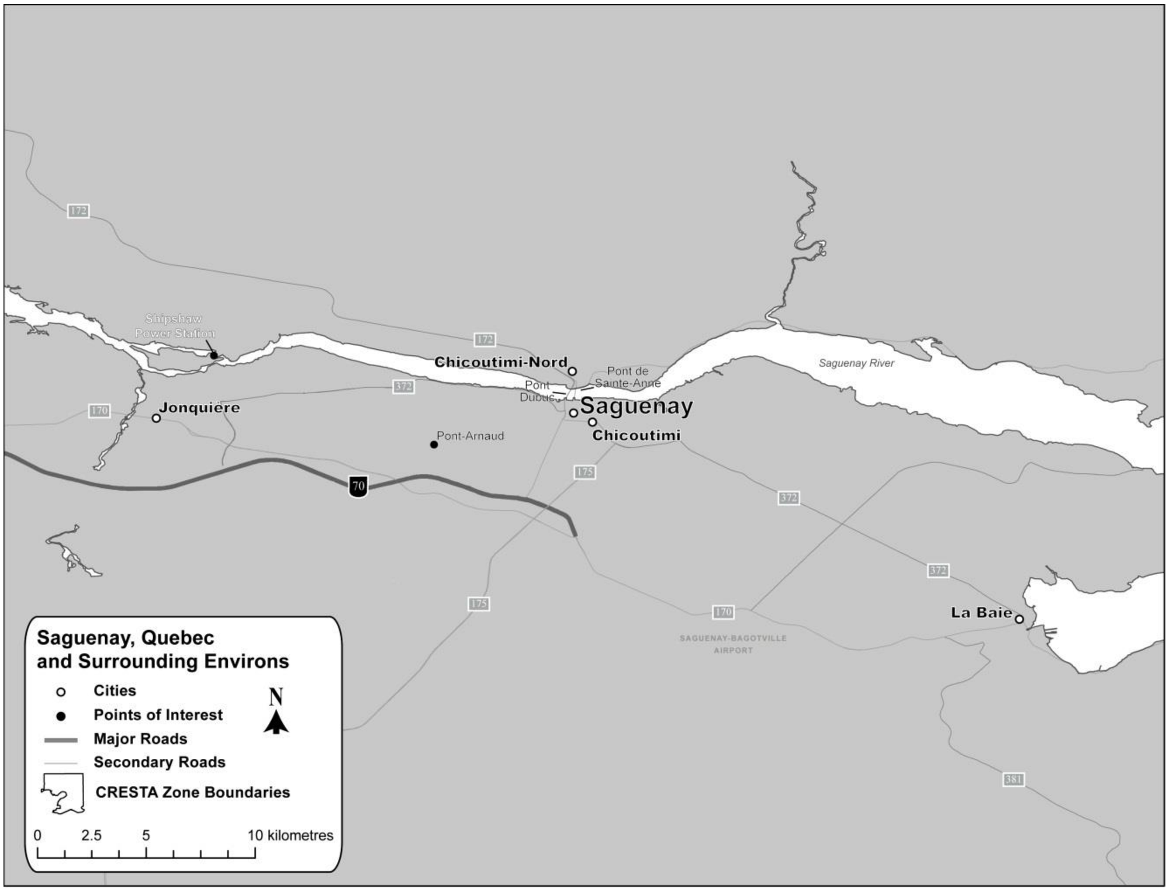


Figure 75: Communities in the vicinity of Saguenay

Parc de la Chute Montmorency

Parc de la Chute-Montmorency is the site of a large waterfall—the Montmorency Falls—located about 12 km from Québec City on the boundary between the borough of Beauport, Québec City, and Boischatel. The commercial establishments in this area and in the nearby towns are expected to suffer moderate damage in the earthquake. While moderate damage to the reinforced concrete and steel buildings may cause less than a week of business interruption for repair and reconstruction, more extensive damage to masonry (specifically URM) will result in extended disruption (as long as three months).

Residential properties in the nearby towns of Boischatel and Chute-Montmorency, which are mainly low-rise buildings, may also sustain moderate damage. Buildings of wood with masonry veneer may experience cracks at the corners of door and window openings and at the bolted connections. Some partitions may require the replacement of gypsum board or other finishes. Repair time for these buildings is anticipated to be less than a week. However, masonry buildings in this area will be more seriously damaged, with wider cracks in columns, beams and structural walls as well as damage to ceilings and exterior wall panels. Some reinforced masonry buildings may require up to a month for repair while unreinforced masonry buildings may be unusable for up to two months for repair and reconstruction.

The bridges crossing Rivière Montmorency (Montmorency River) on route 138 (Boulevard Sainte-Anne) and route 360 (Avenue Royale) are expected to suffer extensive damage. Repair and reconstruction of these bridges may take several months and can severely impact the transportation in the communities across the river. Complete destruction of masonry constructions will occur on the Isle d'Orleans. Serious failure of walls and the partial structural failure of roofs and floors are expected in many buildings.

Québec City

Commercial buildings in and around the Place Fleur de Lys are likely to suffer moderate to extensive damage due to the severe ground shaking. In some masonry buildings damage to the structure and contents will be significant enough to take the properties out of service for several weeks for repair and restoration. Light to moderate building and contents damage to reinforced concrete, steel and wood buildings in the area may also lead to a few weeks of downtime for repair in each case.

The highway bridges crossing the St. Charles River on route 440 (Autoroute Dufferin-Montmorency) and the highway and railway bridges on route 136 (Boulevard Jean Lesage) as well as the one on route 175 (Autoroute Laurentienne) are likely to suffer moderate to extensive damage from ground shaking in the earthquake. At these levels of damage structural damage in some elements will be considerable. It will require both thorough inspection and a lengthy repair and reconstruction process, which may require three to four months. The closure of these bridges, if required, will significantly hamper the traffic and transportation between Québec City and the populated districts of La Cite'-Limoilou.

Also the bridge on highway 440 crossing Saint-Vallier Street may sustain moderate damage and can be closed for inspection and initial repair for a few days. Full repair and reconstruction damage may take more than a month.

Damage to high-rise establishments in the Québec City area is expected to be light. These buildings are expected to be operational after initial inspection. Residential buildings will mainly suffer light to moderate damage in downtown Québec. Moderate damage will occur to unreinforced masonry buildings causing many cracks in walls. The disruption of use of homes may continue for a few weeks. Some mobile homes with moderate damage may be uninhabitable for several days. Some wood constructions will suffer slight damage without any interruption to their use.

Around downtown Québec the severity of building damage will vary. In Sillery, reinforced masonry constructions will mostly suffer light damage such as cracks in walls or the falling of fairly large pieces of plaster. It may take less than a week to restore the use of those buildings. Moderate to substantial damage will occur to residential buildings in Beauport. Some buildings of wood construction with masonry veneer may lose functionality for a few weeks. Structural damage will include large diagonal cracks across shear wall panels; extensive slackening of diagonal rod braces and/or broken braces; and permanent lateral movement of floors and roofs.

Damage to healthcare facilities in the Québec City area will vary also. Ground shaking will cause some light to moderate damage to the Hôtel-Dieu de Québec, a teaching hospital affiliated with Université Laval's medical school located in the center of Québec City. The damage will likely consist of cracks in walls and fallen plaster and chimneys, as well as cracks in partition walls, doors and window frames, and fallen ceiling tiles. In addition to damage to structural elements, damage to building contents is likely to be prevalent. The extent of the damage may make some parts of the hospital inoperable for a few weeks. Full repair and reconstruction may even take up to two months.

The Centre Médical Berger is the largest professional building in Québec. There are several medical centers in the vicinity, such as the Hôpital Du Saint-Sacrement (the primarily psychiatric hospital) and the Jeffery Hale Hospital. The medical facilities in this area are epected to suffer light to moderate damage. Most of the health care units in buildings with light damage will be available for use immediately, but some units may be out of service for up to two months for complete repair and reconstruction.

Only light damage is anticipated to the Hôpital Laval. While most of its units are expected to remain operational, some repair and reconstruction may take a few days. Moderate damage is expected at the Centre Hospitalier Affilié Universitaire De Québec - Hôpital De L'Enfant-Jésus. Structural, non-structural and contents damage may be prevalent in some buildings. Some parts of the hospital may be out of service for repair and reconstruction for three or four months.

Light to moderate damage is likely at the Hôtel-Dieu de Lévis on the opposite bank of the St. Lawrence River. Some parts of the hospital may be out of service for a few weeks for repair, but most of the units are expected to be operational after initial inspection.

Old Québec

One of the features that makes this area such a major tourist destination is Old Québec (Vieux-Québec), which contains a number of historic buildings built in the 17th and 18th centuries. Old Québec, which has been designated a World Heritage Site by UNESCO, consists of the Upper Town and the Lower Town. Within its fortifications, which are unique in North America, the Upper Town contains many significant buildings. Among these are the Hôtel de Ville, the Hôtel-Dieu de Québec teaching hospital, the Sanctuaire Notre-Dame-de-Sacré-Coeur and the famous Château Frontenac.

Damage in the areas surrounding the Parliament buildings is expected to be light to moderate. Damage in the mid-rise steel and concrete buildings will be light. No significant downtime is anticipated in these buildings; after initial inspection possible repair may take less than a week. However, moderate damage to masonry buildings will lead to a longer downtime, and the repair and reconstruction may take more than two months. No considerable damage, except minor content disruption, is expected in high-rise steel and concrete buildings in this area.

Historic buildings are typically of masonry construction, often unreinforced. These buildings are characterized by heavy stone or brick walls and wood floors. Although this form of construction makes them attractive to tourists, it makes them particularly vulnerable to earthquakes. The heavy weight of the material used in these buildings combined with the aged and weak connections between walls, floors and foundations renders them seismically vulnerable unless they have been strengthened. Typical damage to these buildings during a moderate earthquake includes the dislodging and falling of the parapets, chimneys, and gable ends. In more severe ground motion walls, floors, roofs, porches and stairs may fail and interior structural supports may partially, or totally, collapse. Large diagonal cracks may appear, upper stories may collapse and poorly anchored wood frame buildings may slide off their foundations.

Seismic retrofit can significantly improve the performance of historic buildings. Such retrofit and strengthening of historic buildings, albeit constrained by the preservation of the historic character, can be achieved through the reinforcement of structural elements. Such reinforcement can include adding anchored ties, reinforced mortar joints, braced frames or moment-resisting frames, shear walls and horizontal diaphragms.

The scenario earthquake is expected to cause moderate structural and non-structural damage to the old buildings in this area. For masonry buildings this may entail cracking of many walls, the falling of large pieces of plaster and the partial collapse of chimneys. The falling of ceiling tiles and light fixtures may be extensive. Damage to old concrete buildings, typically with unreinforced masonry infill walls, is expected to be light to moderate. Damage may be in the form of cracks in beams, columns and structural walls and wider cracks in the infill walls and cladding, as well as mortar falling from the joints of wall panels. The inspection, repair and reconstruction process may lead to more than a month of downtime in these buildings.

Figure 76: The Rue du Petit-Champlain, Vieux-Québec (Jeangagnon)

The historic area around the Quartier du Petit-Champlain in the Lower Town is an old commercial district where several art and craft shops as well as the Rue du Petit-Champlain Mural are located. This area is also home to the Musée de la civilisation. Commercial buildings in this area mainly low-rise masonry structures. Moderate damage, as described before, is expected in this area also. Downtime of a few weeks to one month is likely for these buildings. Damage in some mid-rise masonry buildings may be more extensive and could render them out of service for as long as two months. While most of the anticipated damage in this area will be due to ground shaking some fire following incidents are also likely to contribute to the damage.

Infrastructure

Port and rail infrastructure is not expected to be significantly damaged, but the greatest infrastructure loss will be experienced by the electricity and telecommunications sector. Power is expected to be out for a few days in Québec City and in many of the most developed parts of the metro area. (Beauport, Charlesbourg, les Rivieres, Sainte-Foy-Sillery-Cap-Rouge etc.). Communities to the east along the St. Lawrence River will face outages lasting for many days. Cell phone service may be unreliable for a few days immediately after the event, more as a result of the volume of calls attempted than because of damage to the infrastructure. Some of the damaged towers should be operational within a few days, but others, particularly in Québec City and to the east may be down for a few weeks. Some towers in Charlesbourg and Beauport to the north could be out for several weeks.

Roads, pipelines and tunnels in the area will mostly be out of service for a few days, but there will be some locations where they will be closed for a few weeks. Most of the major roadways in and around Québec City may experience only slight damage due to slight settlement or offset of the ground. No significant closure (of more than a few hours) is expected for these roads. However, further in the east, between Baie-Saint-Paul and La Malbaie, moderate damage to local roads will be widespread. Moderate damage to roads involves several inches of settlement or offset of the roads. Part of the damage in the elevated roads along the riverbank could be attributed to landslides.

Many bridges will have high degrees of damage which will need considerable closure and repair time. Downtime of these bridges affects the local roads and highways in these regions; however, the model does not take into account such interaction. All bridges will require inspection prior to being reopened and the most strategic bridges will receive priority. Less significant bridges will be closed for some considerable time until inspection engineers are free to turn their attention to them. Many of the bridges giving access to Québec City from the north could be out of service for several weeks.

The Pont de L'Isle D'Orléans—the island's only road access—is likely to experience extensive to complete damage due to both severe ground shaking and liquefaction. This damage may be in the form of significant residual movement at connections, damage to anchorage and cables, the collapse of decks or the tilting of the substructure due to foundation failure. At this level of damage, major disruption in service is anticipated. The full restoration (if possible) may take several months.

Figure 77: Québec and Pierre-Laporte Bridges, seen from the northern end in winter (Blanchardb at en.wikipedia)

More seriously still, the only bridges to span the St. Lawrence River will be severely impacted. The Pont Pierre Laporte is expected to experience moderate to extensive damage in the form of significant residual movement at connections and damage to the anchorage or to steel members and connections. This extent of damage will require a few months for a full restoration, and as a result the bridge may be closed to traffic for a considerable amount of time. The Pont de Québec carries both a highway and a railroad. Both are expected to experience moderate damage and full restoration is likely to take several weeks.

Structures such as terminals, towers and hangars at Jean Lesage International Airport, located about seven miles southwest of Québec City, are expected to sustain minor to moderate damage. Typically, this would include small cracks at corners of door and window openings and wall-ceiling intersections. Cracks may become evident in the walls of some masonry buildings, in columns and beams of frames, and in structural walls of reinforced concrete buildings. Some ceiling tiles may move or fall from the suspended ceilings. Runways at the airport may experience minor to moderate ground settlement or buckling of tarmac surface. Despite moderate damage of this nature no major disruption or loss of functionality is anticipated in the airport. Some buildings may need a few days to be fully functional after the event.

The earthquake is expected to cause widespread damage in the Port of Québec, both directly from ground shaking and from liquefaction. The greatest damage will likely occur in and around the Basin Louise, in which moderate to severe damage is anticipated to port facilities. In the facilities southwest of Basin Louise the damage is expected to be less. Due to the extent of damage, some parts of the port facility (in the Basin Louis) may be out of service for one to two weeks.

Buildings in the port area are expected to have moderate damage, which in masonry structures will include cracks in the walls and connections, ceiling tiles, and parts of ceilings and fixtures falling. Equipment may move considerably and pipes may develop leaks at a few locations. Steel and reinforced concrete structures are also expected to develop slight to moderate levels of damage. Some steel members may exhibit observable cracks in welded connections or deformations in bolted connections. Moderate damage in reinforced concrete buildings may be in the form of cracks in columns and beams of frames and structural walls. Some masonry buildings in the port area may need up to a month for repair and restoration.

Damage in other ports such as Becancour and Trois-Rivieres is expected to be slight and should not hamper operations. The largest port in Québec, located in Montreal, will not be affected by this scenario.

Several hospitals and educational establishments in the six arrondissements that comprise Québec City may experience some damage, as may City Hall, police headquarters, the Museum of Fine Arts of Québec and other landmark structures. The government buildings around City Hall are expected to experience light to moderate damage. Damage in wood, reinforced concrete and steel structures will be the range of light damage which may need repair and restoration taking a few days. Masonry buildings are expected to sustain moderate damage, and some may be out of service for repair and restoration for several weeks.

Exposure in the region affected by the eastern scenario

At the end of 2012 there were an estimated 8.1 million people living in Québec. Of these, 3.8 million people lived in the Montreal metropolitan area, which is the second-largest metropolitan area in Canada. In addition, over 1.2 million people lived in the Ottawa-Gatineau metropolitan area and well over 750,000 people lived in the Québec City metropolitan area, which is the most densely populated area affected by the eastern scenario.

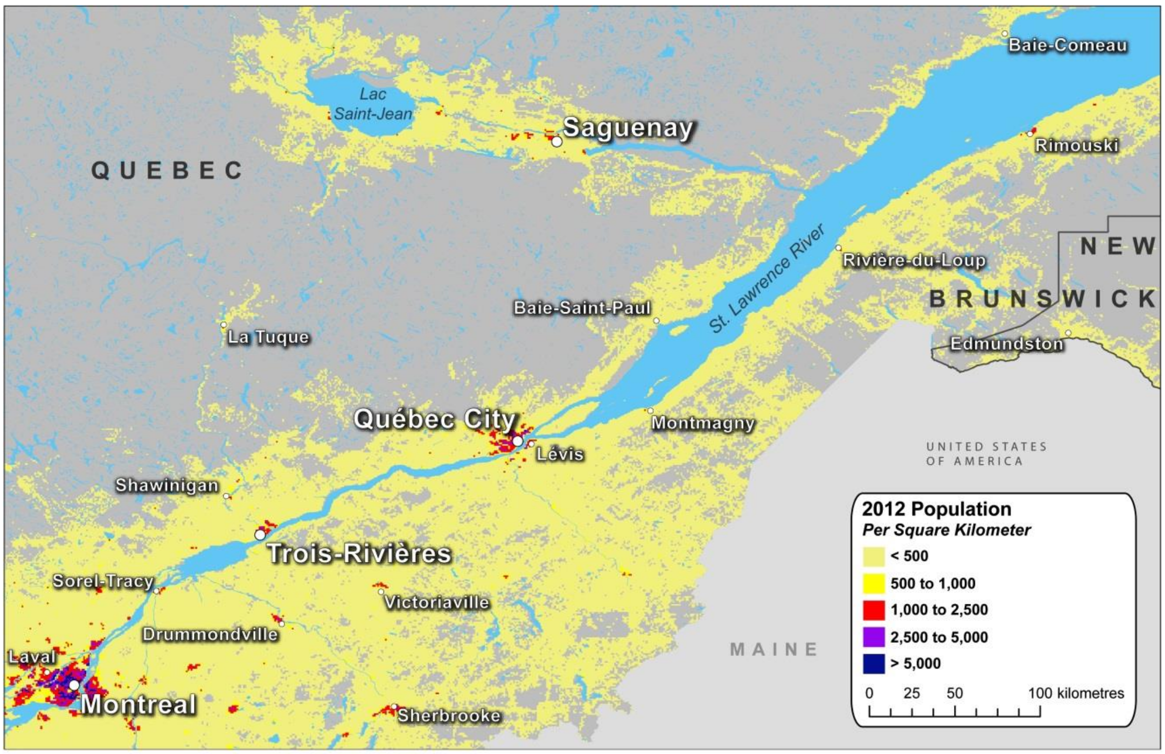


Figure 78: Population density, eastern scenario

Figure 78 shows population per 1 km2 grid cell surrounding the eastern scenario. Though Québec City is not the largest population centre in the region, it is nevertheless a highly concentrated metropolitan area that would suffer significant impact from a large earthquake in the Charlevoix region.

Québec City has a notable stock of property and infrastructure exposure which would be vulnerable in the event of the eastern earthquake scenario and potentially result in great loss. However, it is not enough to look at the overall value of exposure in this area, as it is the distribution by property type, geographic location and the presence of earthquake insurance that would determine how the damage would be felt, and by whom.

The following maps show the total value of all residential property and the total insured residential, commercial and infrastructure values at 1 km^2 grid cells in the at-risk areas surrounding the eastern earthquake scenario. The all-property maps display all exposure value that is at risk, while the insured maps show only the value that is covered by an earthquake insurance policy. The difference between the two maps is the amount of exposure that would not be covered by insurance in the event of an earthquake, which is sometimes very great. For the purpose of these maps, agricultural buildings and industrial establishments and facilities are included with commercial. Public properties are also included in the total all-property commercial maps but these properties are not included in any of the insured maps in this section.

Figure 79 and Figure 80 below compare residential all-property and insured exposure surrounding the eastern event.

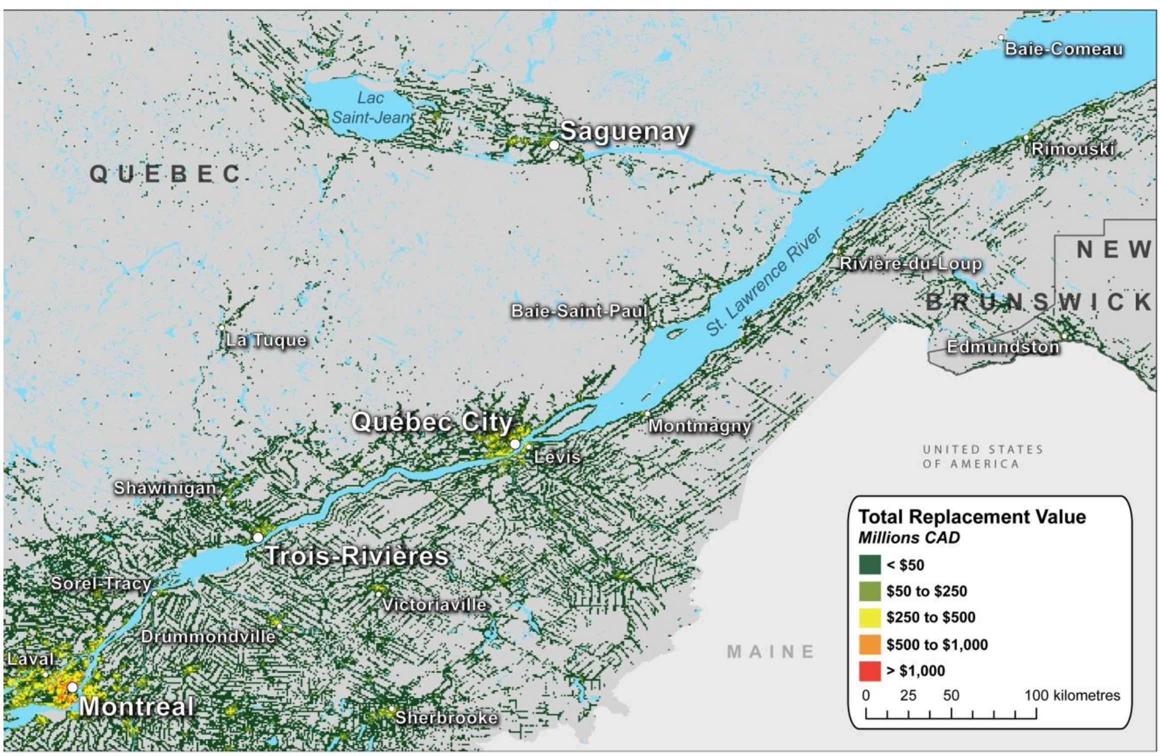


Figure 79: All residential property values, eastern scenario

Echoing the distribution of population in the area, concentrations of residential value are evident in the larger communities of the region such as Saguenay and Trois-Rivieres. They are particularly apparent in Québec City.

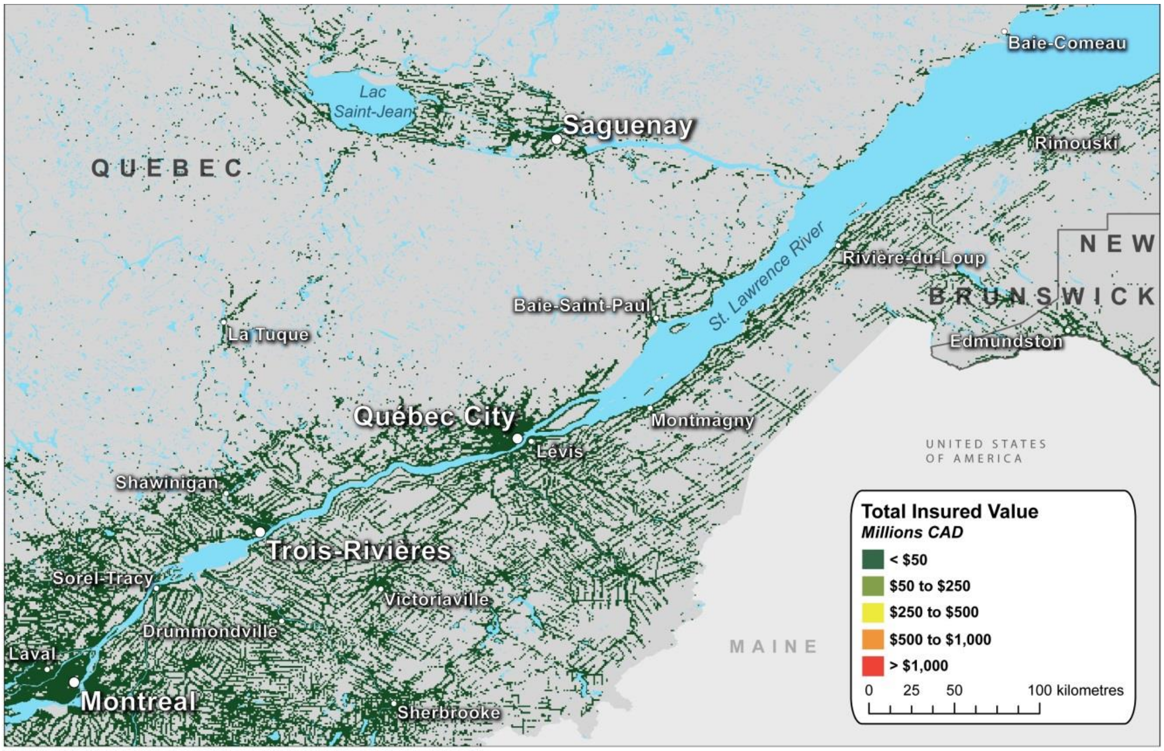


Figure 80: Insured residential values, eastern scenario

Comparing Figure 79 and Figure 80, it is evident that the percentage of residential homes and apartment residences with earthquake insurance is very low in this region. This low percentage of insurance coverage means that there is a large amount of value in the all-property map that would not be covered by insurance in the event of a large earthquake. This situation could have potentially devastating financial consequences for many homeowners.

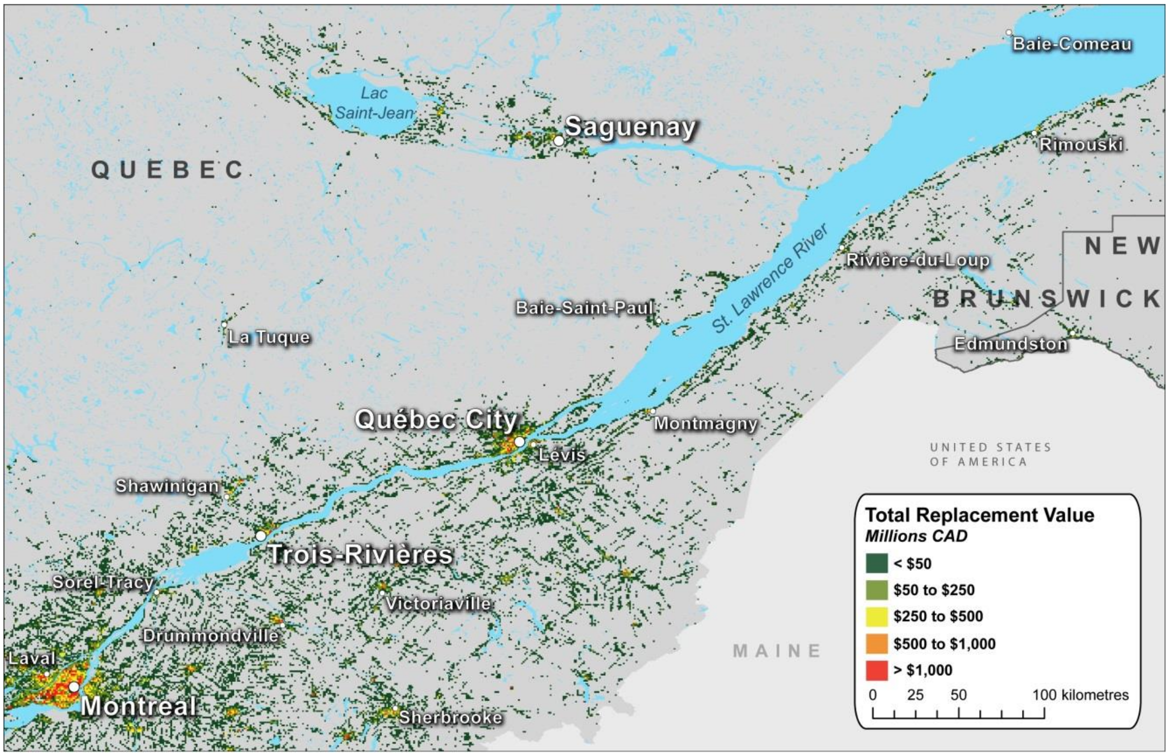


Figure 81: All commercial/industrial property values, eastern scenario

The commercial and industrial all-property and insured values surrounding the eastern scenario are shown above in Figure 81 and below in Figure 82.

The pattern echoes the distribution of population within the region. The concentration of exposure is divided into a few distinct pockets in and surrounding downtown Québec City, with a high concentration near the city centre and several high-valued industrial or commercial areas spreading out to the west.

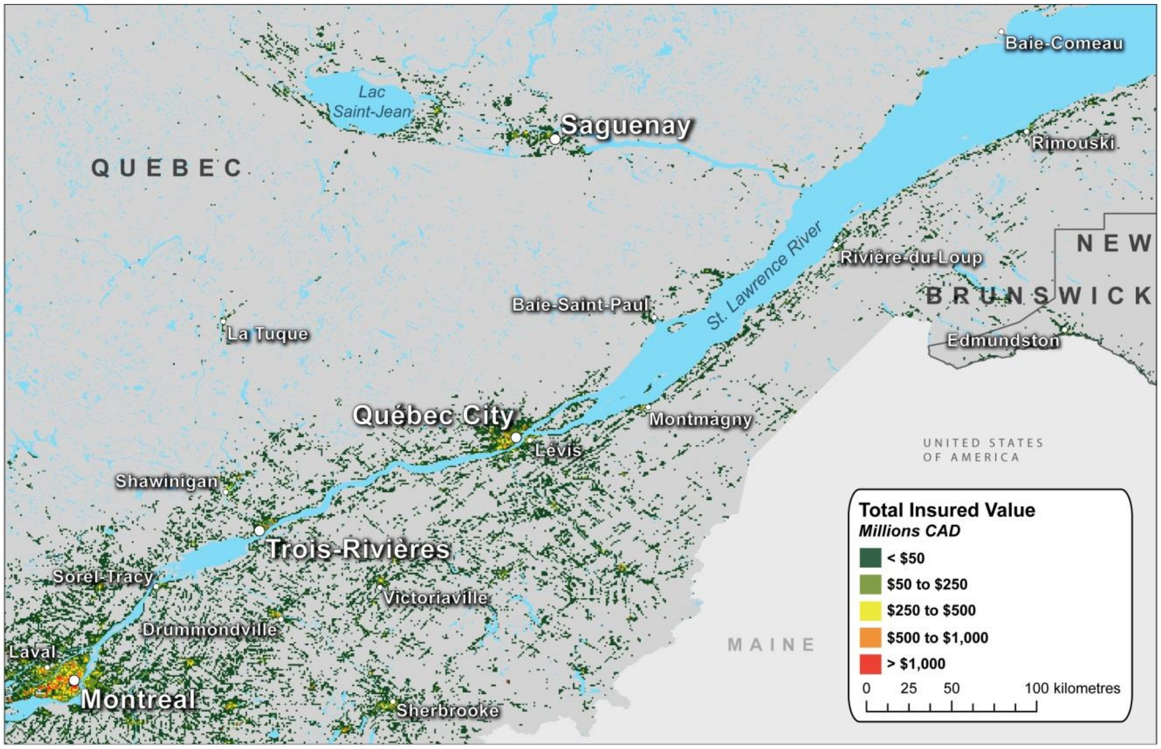


Figure 82: Insured commercial/industrial values, eastern scenario

It will be noted that much of the commercial exposure in the region does not carry earthquake insurance.

Though the ratio of businesses with and without earthquake insurance is not as low as that for residential policies in this region, it is still lower than the corresponding ratio of insured businesses in the region surrounding the western scenario.

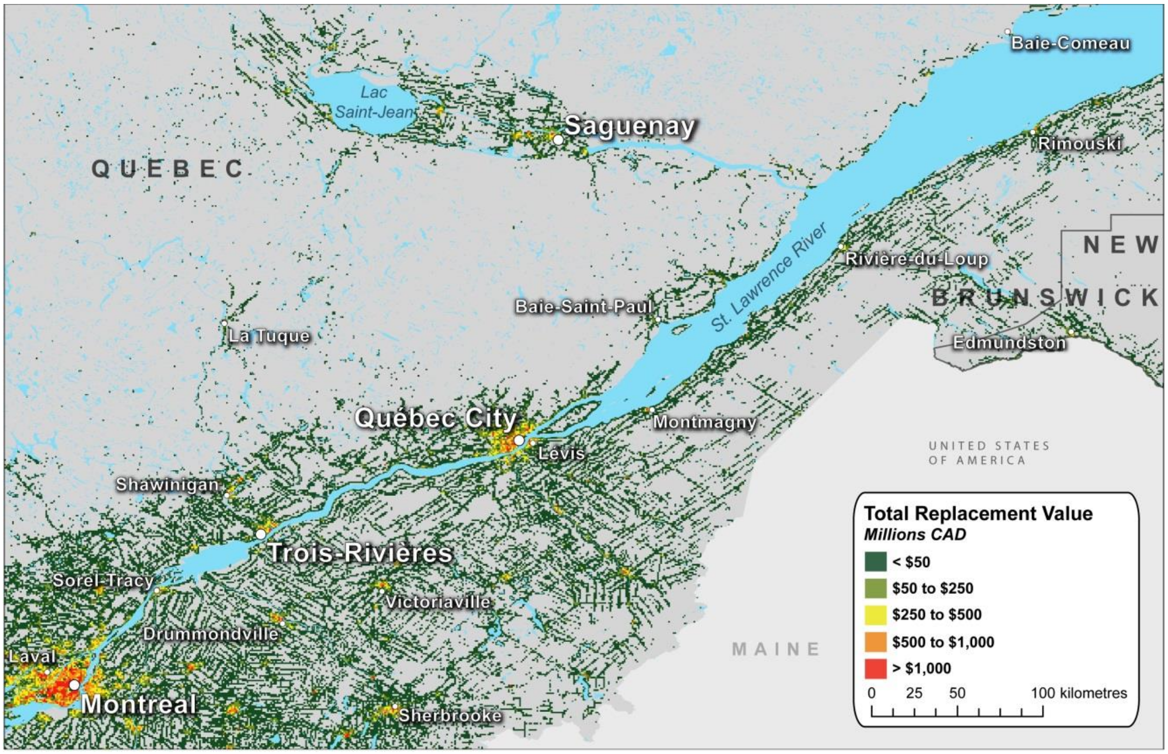


Figure 83: Total combined value for all eastern scenario commercial, industrial, residential, agriculture, and auto property

In Figure 83 above and Figure 84 below, the total all property and insured values (commercial, industrial, residential, agriculture, and auto combined) are shown for the eastern scenario region. Figure 84 shows the total all property values for Québec City and its environs in greater detail.

The concentration of property value within the major centres of population is immediately apparent.

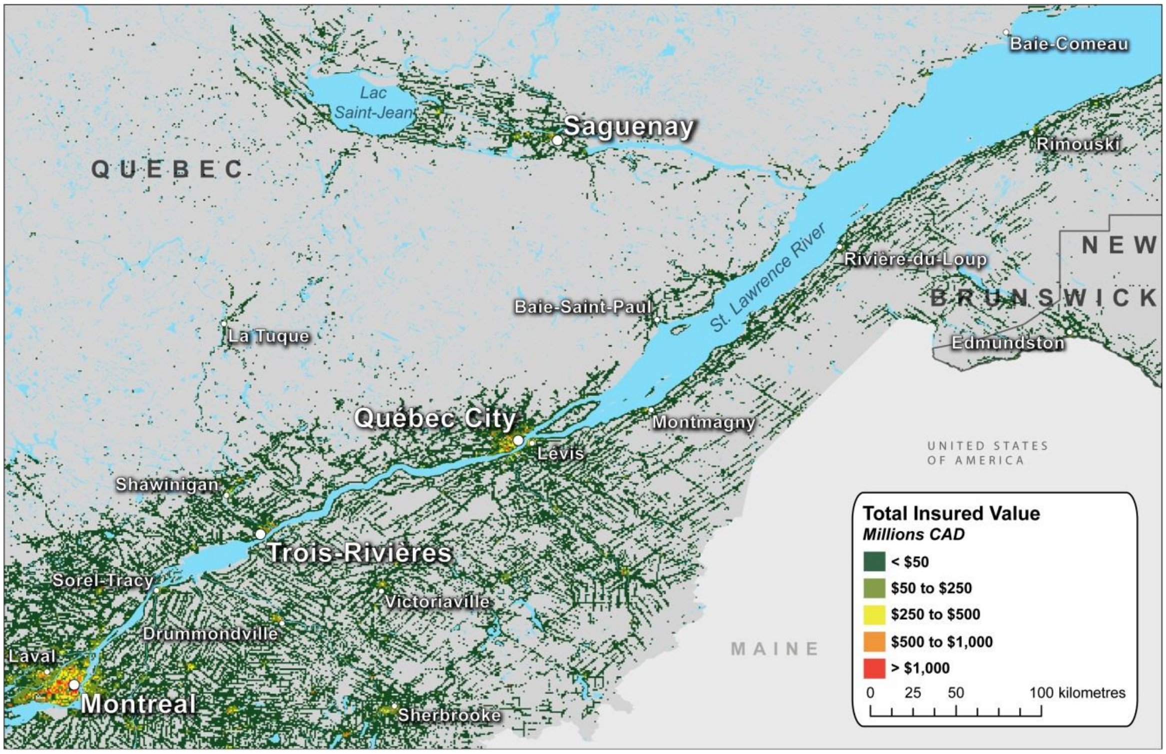


Figure 84: Total insured value for all eastern scenario

A comparison of Figure 83 and Figure 84 shows that much of the insurable property in the eastern scenario region does not have earthquake insurance.

The total infrastructure values are shown in Figure 85. Infrastructure can be privately, publicly, or self-insured, but the prevalence of each of these types of insurance was unable to be determined from available data. For this reason, market penetration rates, which are measures of the total value of insured property in relation to the value of all property, could not be determined, and so the infrastructure values are shown with no distinction between all property and insured values.

The most readily apparent patterns in the infrastructure map are the road and railway networks. There are also clusters of value surrounding airports and ports, notably Jean Lesage International Airport on the western edge of Québec City, and a large port area on the eastern, river-facing side of the city.

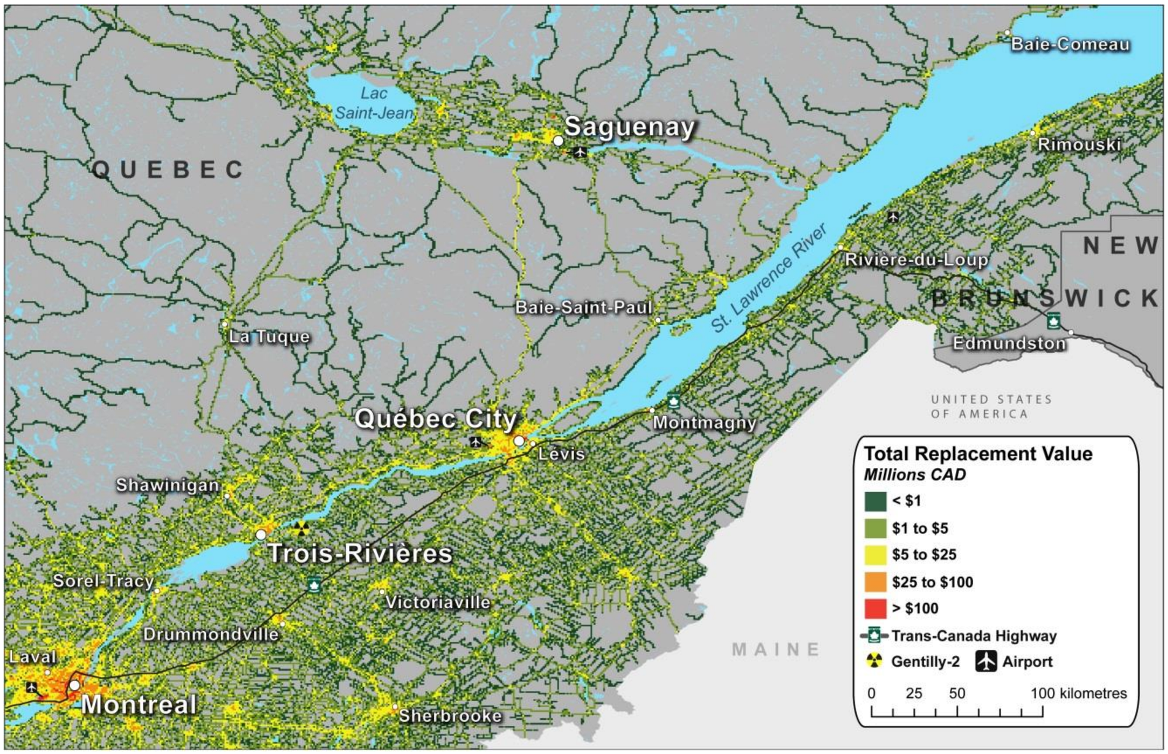


Figure 85: Total infrastructure value, eastern scenario

Figure 86 below shows the infrastructure value for the Québec City area in greater detail. The concentration of value in the city centre and at bridges spanning the St. Lawrence River (the Pont de Québec and Pierre Laporte Bridge) is clearly seen.

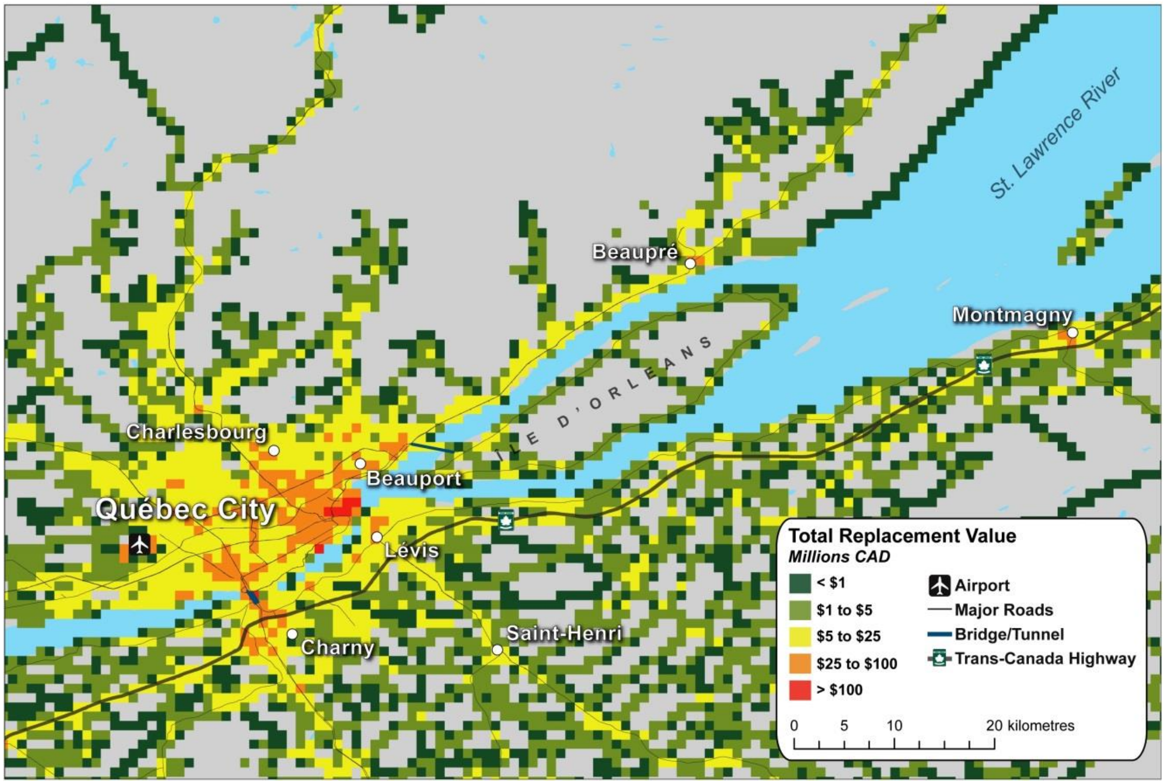


Figure 86: Québec City area, total infrastructure values

Hazard

In the following sections, we describe the various aspects of the scenario hazard; that is, the various ways by which the hypothetical earthquake would cause damage and loss. Earthquake hazard includes ground shaking, liquefaction, landslide, and fire following earthquake.

Ground shaking

The selected scenario in eastern Canada has a magnitude 7.1. The epicentre is located about 75 km east of Québec City. The detailed rupture parameters for this event are listed in Table 30 below.

Table 30: Detailed rupture parameters for the eastern scenario

Magnitude	Epicentre Latitude	Epicentre Longitude	Depth	Rupture Length	Rupture width
7.1	47.245	-70.470	10 km	53.8 km	20.5 km

An earthquake can generate seismic waves of various frequencies or periods. Buildings and infrastructure respond to seismic waves of different frequencies differently, depending on their structural characteristics and height. The AIR earthquake model uses several measurements of ground motion—including PGA, 0.3 second and 1 second spectral accelerations—to define the spectrum of ground motion at each location, to calculate the damage to different types of structures, and calculate the local impact of secondary hazards such as liquefaction and landslide.

Figure 87 below shows the ground motion intensity field for the region expressed as peak ground acceleration (note that PGA is expressed in units of g, the gravitational constant) and Figure 88 shows the Québec area in detail. The highest PGA, with values exceeding 0.3 g is expected to impact the towns along the St. Lawrence River in the epicentral area.

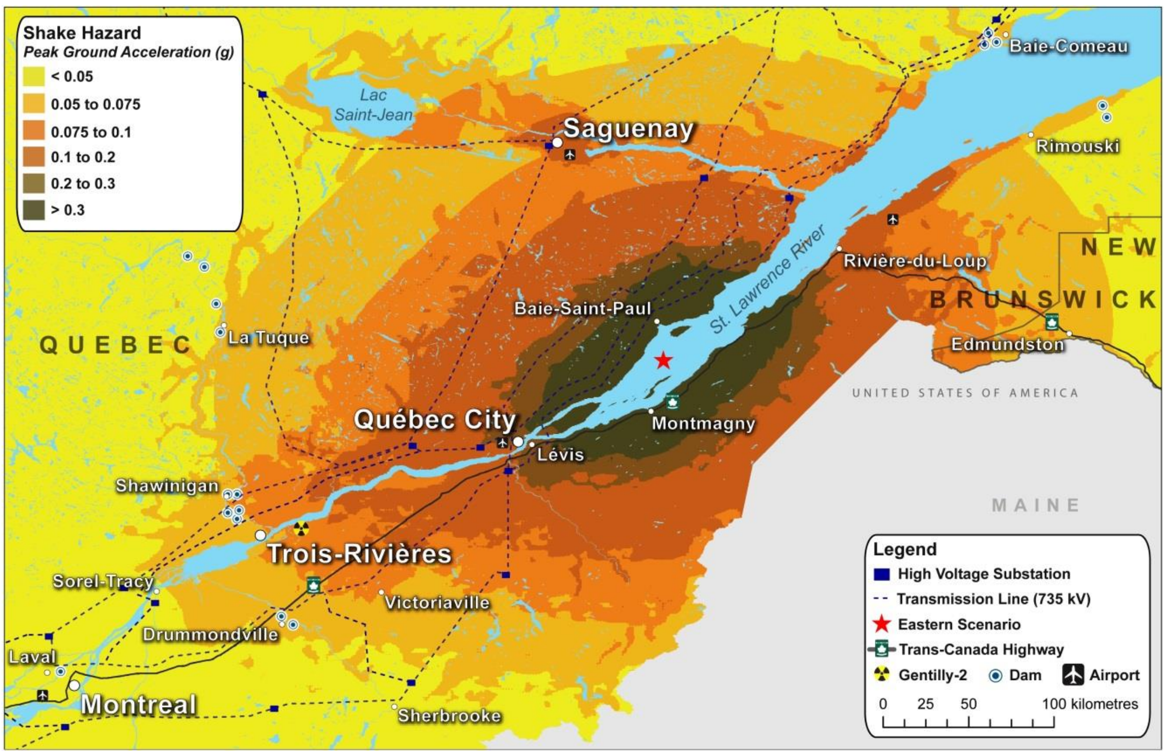


Figure 87: Ground motion intensity (peak ground acceleration) field from the eastern scenario. The red star represents the epicentre of the earthquake

Figure 87 clearly shows how the ground motion intensity associated with an earthquake decays the further away from the rupture source it is experienced. While more intense ground motion is expected closer to the epicentre along the banks of the St. Lawrence River to the east, Québec City is expected to experience a PGA of 0.2 to 0.3 g. Saguenay, a city north of epicentre, may also experience moderately high ground motion because of soft soil conditions in the area.

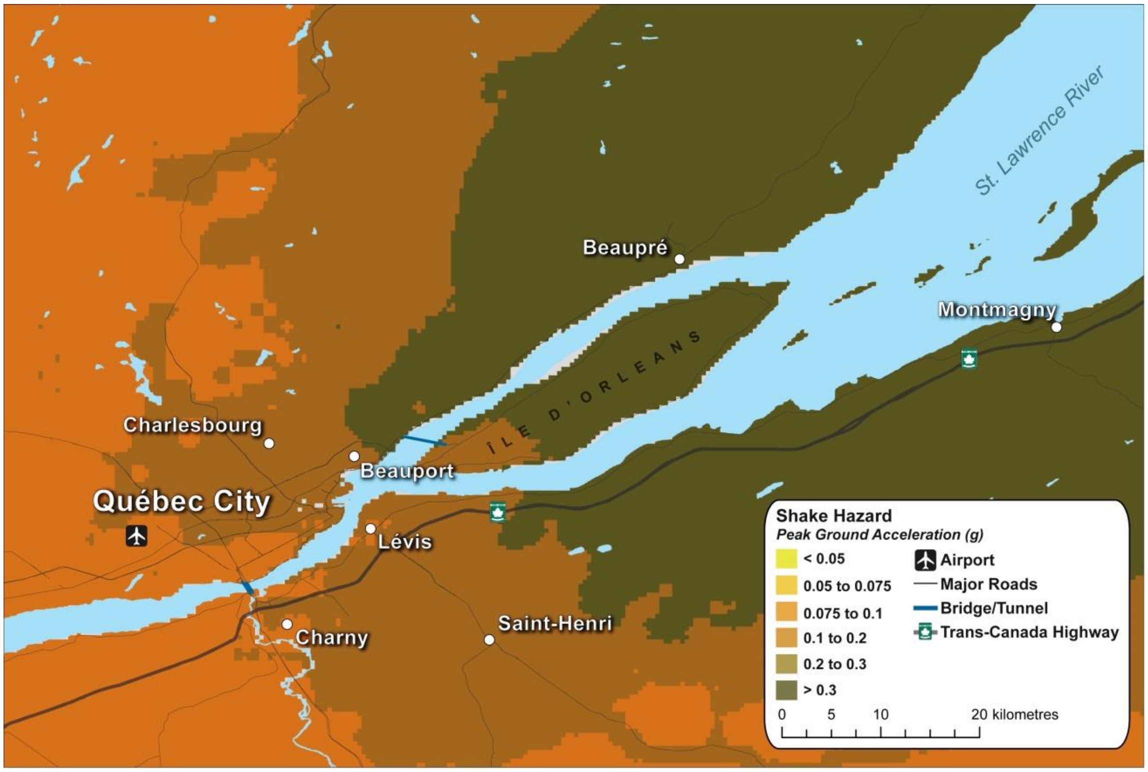


Figure 88: Ground motion intensity (peak ground acceleration) field in the Québec City area

The ground motion intensity in Montreal, about 300 km from the epicentre, may be lower, but residents in Montreal would readily perceive ground shaking from this event.

Figure 89 below shows the MMI field for the region calculated from the model and Figure 90 shows the Québec area in detail. The MMI scale is a descriptive or semi-quantitative scale, ranging from I to XII, that is generally used to measure observed ground motion intensity based on felt reports and observed building damage[9]. Therefore, its correlation with the more quantitative ground motion

[9] More information about the MMI scale is available from the Canadian Geological Survey http://www.earthquakescanada.nrcan.gc.ca/info-gen/scales-echelles/mercalli-eng.php) and the United States Geological Survey (http://earthquake.usgs.gov/learn/topics/mercalli.php).

intensity measures such as PGA or spectral accelerations that can be measured by instruments is very rough. For a description of the MMI levels see Table 16.

The MMI map below therefore mainly provides a more intuitive but rough view of the ground motion intensity footprint. The estimated MMI in Québec City is VII, which would be expected to cause damage to a considerable number of properties. Montreal will experience an MMI of V.

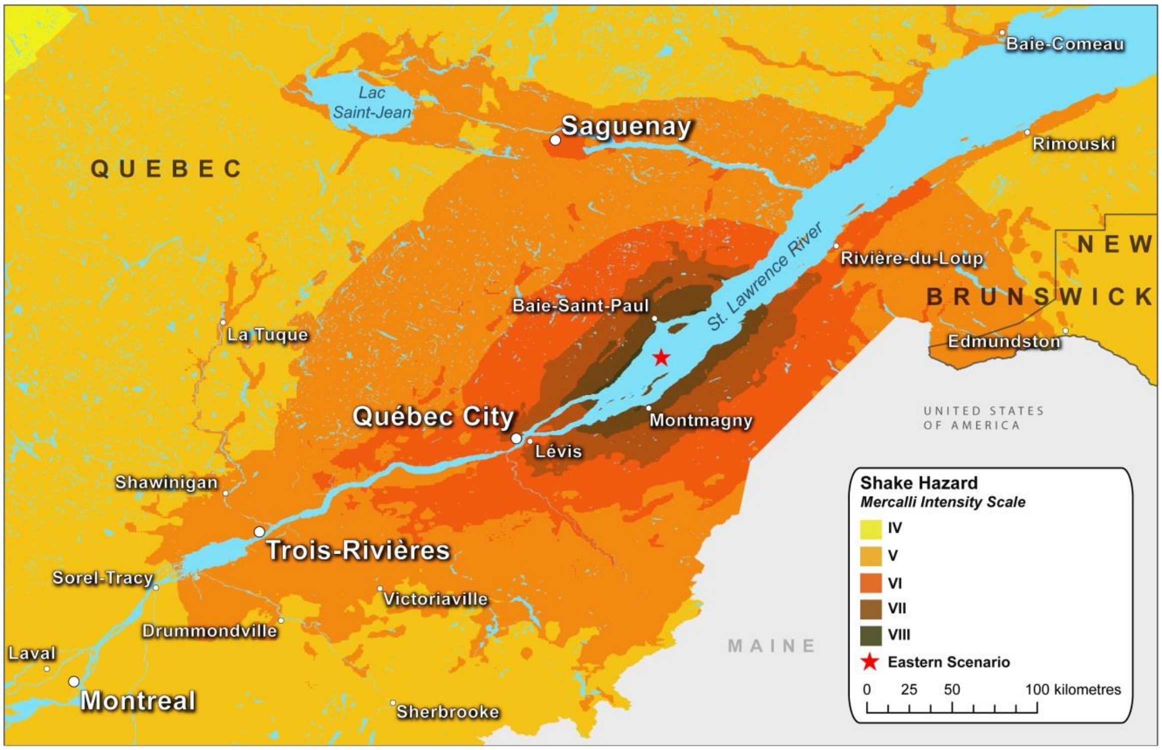


Figure 89: MMI map from the eastern scenario. The red star represents the epicentre of the earthquake

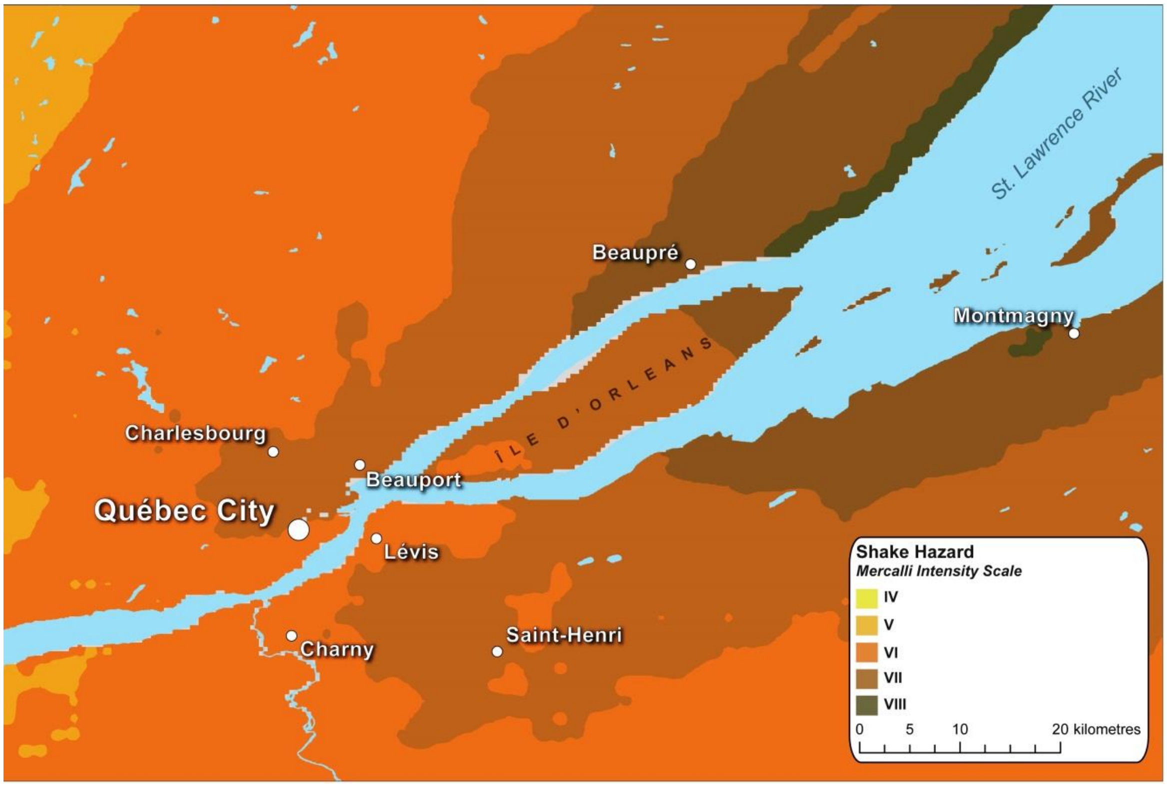


Figure 90: MMI field for the Québec City

Liquefaction

The younger sedimentary soils deposited by the rivers in and around Québec City are susceptible to liquefaction damage, although to a lesser degree than seen in the western scenario. The liquefaction hazard map for the eastern scenario event can be seen in Figure 91. Very little liquefaction damage is expected in the Québec City area for this scenario event.

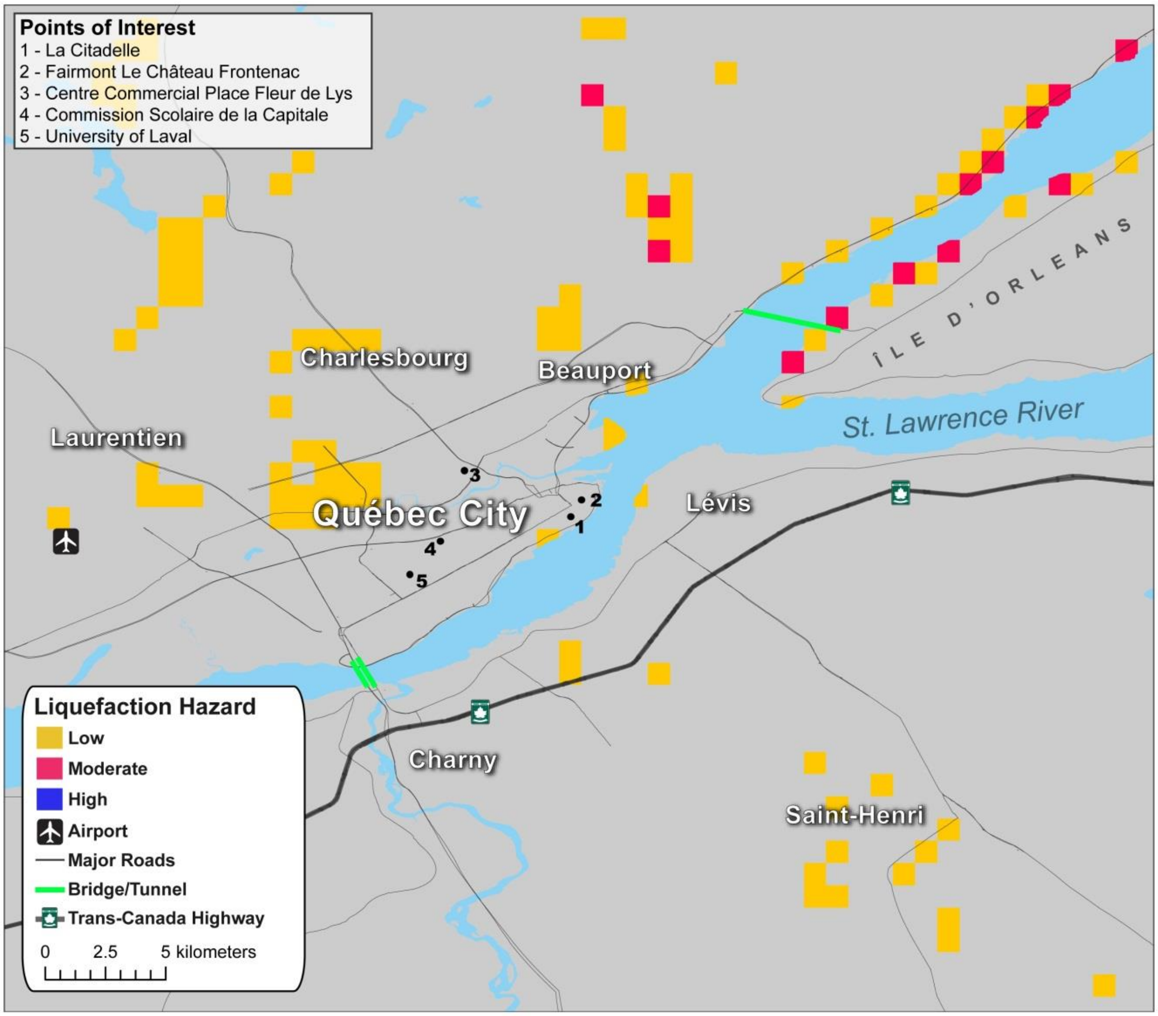


Figure 91: Liquefaction hazard map for Québec City area

Landslide

In the eastern scenario earthquake, slope failures are expected on the steep hills adjacent to the St. Lawrence River close to the epicentre. A landslide hazard map for the scenario event can be seen in Figure 92. Landslides come in several forms—rockfalls, deep failure of slopes and shallow debris flows for example—and have many causes. Earthquakes are one of them. Landslides can pose a significant threat to both human life and property, causing loss of life and destroying structures, roads, lifelines and pipelines. They can have a direct impact on the social and economic life of the hazard region.

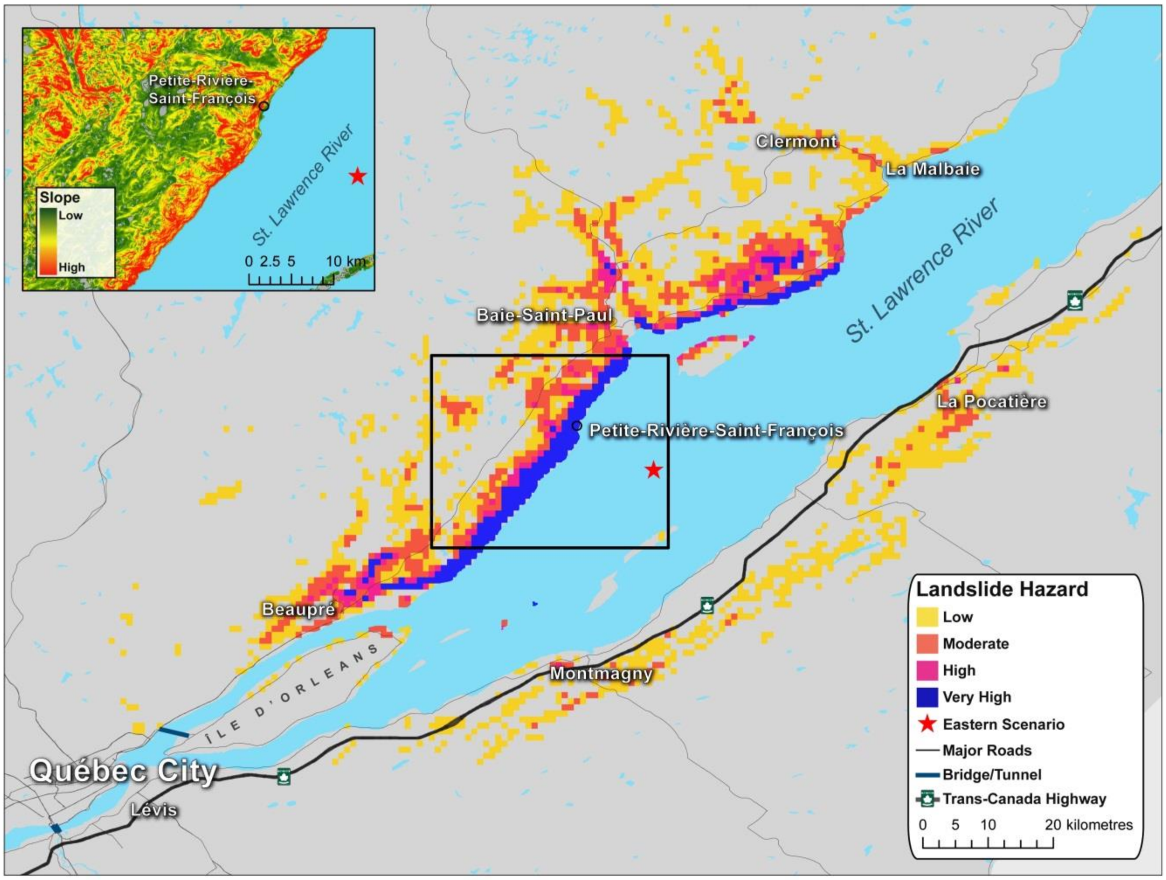


Figure 92: Landslide hazard map for the eastern scenario

Fire Following earthquake

Earthquakes which cause strong levels of ground shaking in and around large population centres are capable of causing significant fire following losses. The eastern scenario earthquake falls in this category as it generates strong levels of ground shaking very close to Québec City. The eastern scenario is accompanied by a wind speed of 28 km/h based on the historical wind speed distribution for the region. Below is the assessment of the risk of fires following this earthquake. The assessment suggests that locally intense fires, capable of spreading through multiple buildings and from city block to city block, will result from the scenario event.

Built environment

Nearly half of the single family homes in the Québec City area are constructed with non-combustible exteriors. When a fire ignites inside a building, the level of damage sustained in that building is unrelated to the combustibility of its exterior.

The combustibility of the exterior mainly impacts the spread of a fire from one structure to another, and the presence of non-combustible buildings can hamper fire spread. However, these non-combustible buildings are not fire proof, as fire can spread to them through vulnerable building components, such as vents, porches, and windows. Most of the buildings in the urban centre of Québec are within close proximity of other buildings, raising the risk of fire spreading from one building to another. Homes and other buildings in the suburban and rural regions have greater spacing between building faces which hampers fire spread.

Ground motion

Given the location of the epicentre of the eastern scenario earthquake, the densely built area of Québec City experiences some of the strongest ground shaking produced by the earthquake. The communities along the St. Lawrence River, such as Montmagny and Beaupré, experience even stronger ground motion and are threatened by fires following the ground shaking.

Ignitions

The strong ground motion from this earthquake could trigger several types of post-earthquake ignitions. In the minutes immediately following the ground shaking, ignitions are likely to come from overturned water heaters, electrical shorts, and broken gas mains. Depending on the timing of the event commercial buildings may be unoccupied, and many ignitions could go unnoticed for quite some time.

Ignitions should be expected to occur over several hours following the ground shaking (see below for the ignition timeline). The timeline of ignitions caused by the earthquake throughout the entire affected region does not include fires that were ignited by fire spread, and only include fires that started independently as a result of the earthquake. Ignitions which occur well after the earthquake shaking has stopped usually occur as a result of restoring power to earthquake damaged areas which have been without power since the shaking. In total, we expect 80–90 primary ignitions from the eastern scenario.

Table 31: Timeline of ignitions

Time since earthquake	Cumulative primary ignitions
20 minutes	17
1 hour	35
3 hours	70
10 hours	77

Spread

Wind plays an active role in fire spread during the eastern scenario. With a wind speed of 28 km/h, fire brands and sparks may travel farther, and a breach of firebreaks between city blocks is more easily achieved. From a fire following perspective, this wind speed is relatively high, but not an extreme case like the winds that fueled fires following the 1923 Kanto earthquake in Japan (where observed wind speeds surpass 50 km/h). The wind speed of 28 km/h used in the scenario is slightly higher than the average wind speed of 23 km/h for this region, but the difference between these wind speeds from the perspective of fire behavior is negligible.

The primary fires are able to spread and ignite subsequent fires due to both wind conditions and inadequate fire suppression. Though fires ignite on 80 – 90 city blocks following the earthquake, the fires resulting from those ignitions spread and encompass a total of 140 city blocks. The fires are expected to burn over 3 million square feet of building floor area (see Figure 95 for an image of a single fire simulation).

The high risk areas are highlighted in Figure 93 and Figure 94. The fire following risk footprint extends over most of the metro Québec City area. The loss footprint depicted in Figure 93 and Figure 94 is based on the average results of 50 fire simulations. This loss footprint is greater than that in Figure 95, which shows the results of a single fire simulation, because the average footprint accounts for variability of ignition location and other parameters.

The result is a map which highlights areas at risk for fire following damage from the earthquake scenario in this case study. (Note that in Figure 95 the diamonds represent loss for a single fire following scenario, while the squares represent average loss for fire following earthquake.)

Suppression

With no auxiliary suppression resources in the Québec City region, only standard, everyday suppression resources would be available to fight post-earthquake fires. Québec City and the surrounding communities possess enough resources to protect against fires during routine calls; however, in a post-earthquake environment, the simultaneous ignitions combined with damage to the water supply infrastructure will overwhelm the local fire fighters and their fire engine resources.

It is likely that in an event of this magnitude, the damage from the shaking alone will hinder suppression efforts. Some fire stations may sustain structural damage, such as in the 1906 San Francisco earthquake where 10 fire stations sustained serious damage (Scawthorn, 2005). Luckily, in 1906 San Francisco, no engines were disabled, but the possibility remains that fire station damage might cause the engines they house to be inaccessible.

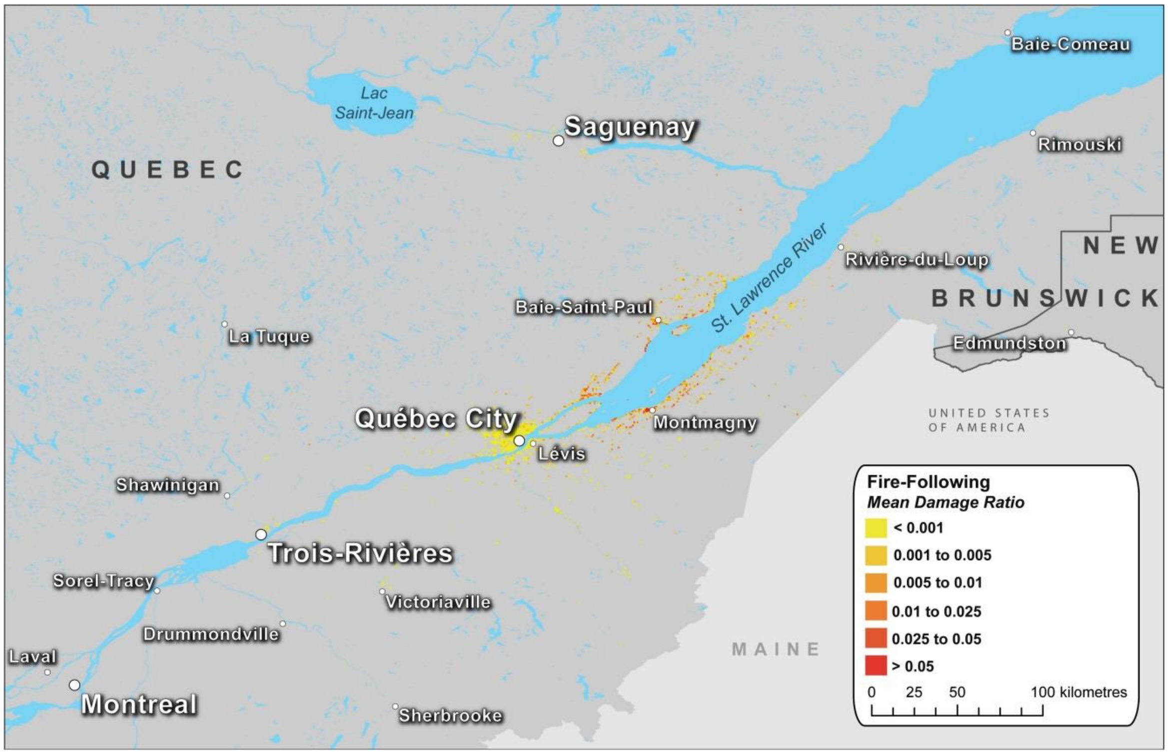


Figure 93: Average fire following damage ratio distribution for the full extent of the eastern scenario

Additionally, some streets may be impassable due to debris blocking the roads, like what was observed in the 1995 Kobe earthquake (Scawthorn, 2005), and this would force engines to find an alternative route. Communication systems may be out of service or flooded, hindering the ability of residents to report a fire, such as in the 1995 Kobe earthquake (Thomas, 2005) and 1989 Loma Prieta Earthquake (O'Rourke, 1992).

Inconveniences like these increase the time elapsed before fire engines arrive, and allow a fire to grow larger before suppression begins. The average duration of a fire is almost four hours in this scenario, suggesting that fires would typically involve several buildings and require more than one fire engine to be controlled.

In our analysis of fire risk from this earthquake through the 50 simulated outcomes that were modeled, an interaction of several of these situations was captured including damaged fire stations, crippled water systems, and delayed fire reporting resulting in scenarios with more widespread damage that cause losses that were more than twice the average loss presented for this scenario.

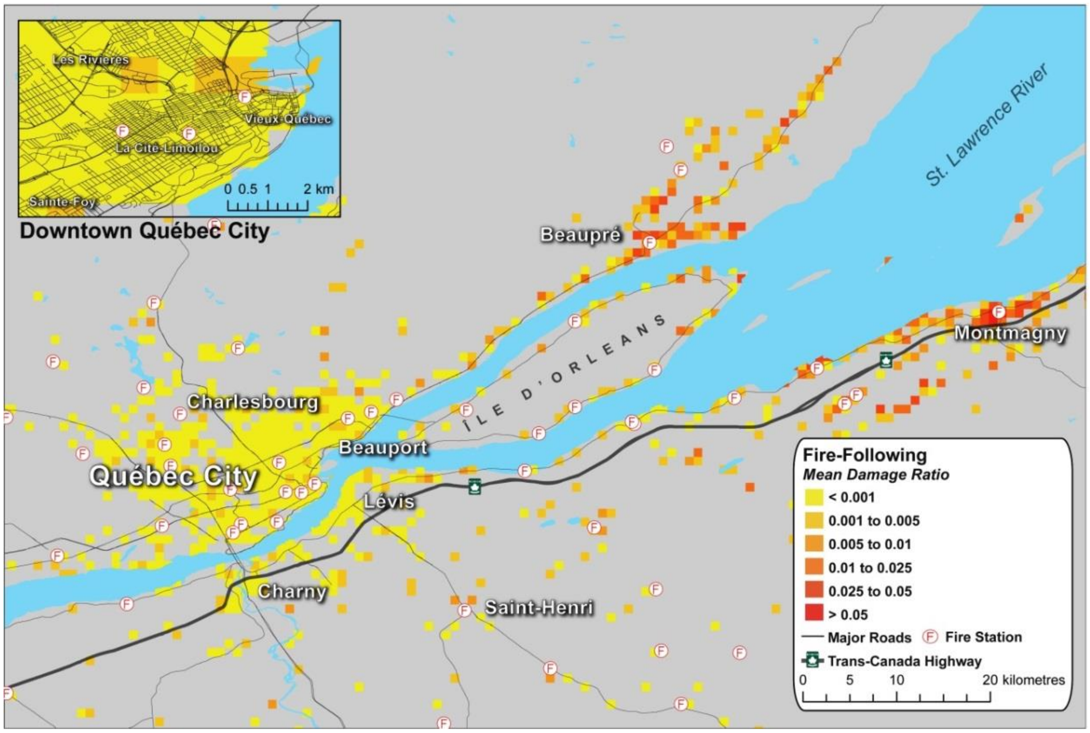


Figure 94: Average fire following damage ratio distribution in the Québec City metro area for the eastern scenario

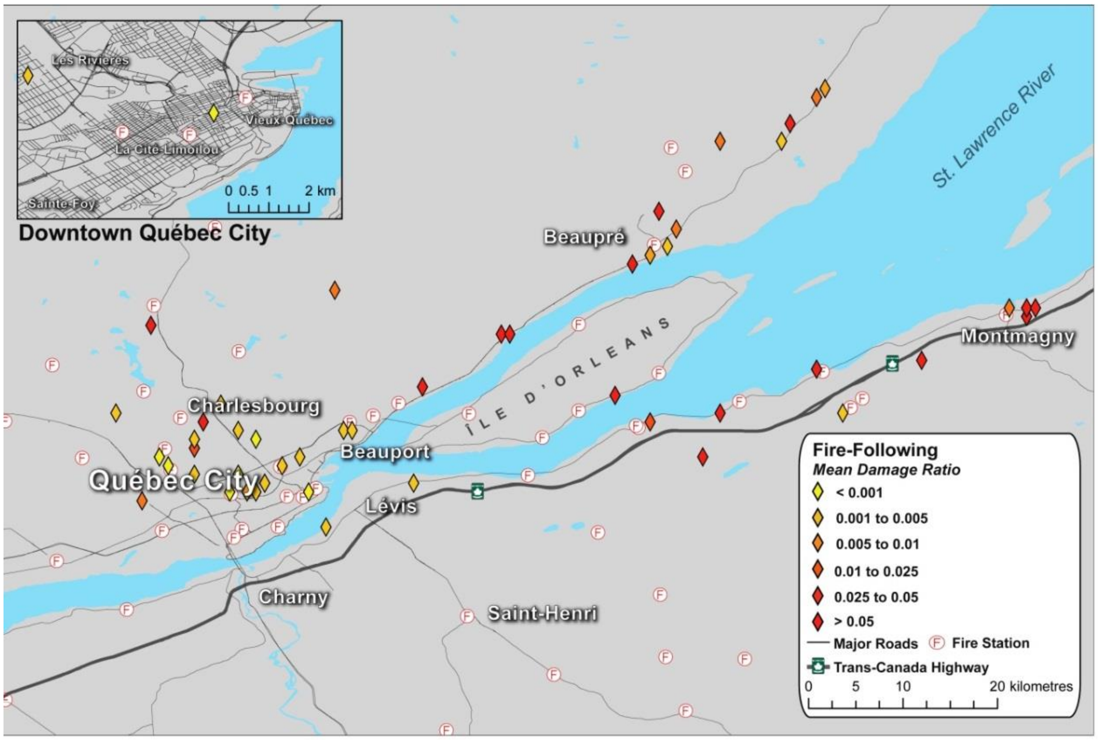


Figure 95: One possible distribution of fire following damages in the eastern scenario

Vulnerability to and damage from the eastern scenario

According to the data published by Statistics Canada from the 2011 census, the population of the province of Québec increased by about 4.7% between 2006 and 2011, reaching about 7.9 million in 2011. More than 80% of the population resides in urban areas. The total number of private dwellings in the 2011 census was 3,685,926, which are typically single family detached houses and apartment buildings.

Similar to British Columbia, wood construction is the most common construction type for residential buildings in Québec followed by masonry construction. In Québec City, which is the closest major city to the epicentre of the eastern scenario, residential buildings are dominated by wood construction. In the downtown area of Québec City, about 15% of the residential buildings are of masonry construction. The proportion of wood construction among commercial and industrial buildings in Québec City is notably smaller than in British Columbia.

Masonry construction is prevalent in commercial buildings followed by steel construction. In contrast, for industrial buildings, steel construction is the most common followed by masonry construction (AIR's IED, 2012; Nollet et al., 2012; Nollet et al., 2013). The expected seismic performance of different construction types has been previously described in the western scenario section (see Section 6).

Seismic design codes in Canada (whose evolution was outlined in the western Scenario section) explicitly identify the regions near Charlevoix seismic zone (e.g. Québec City) that exhibit high earthquake hazard. The level of seismic design requirements set by the NBCC codes for buildings in this region is generally comparable to that of buildings in western Canada (Figure 60).

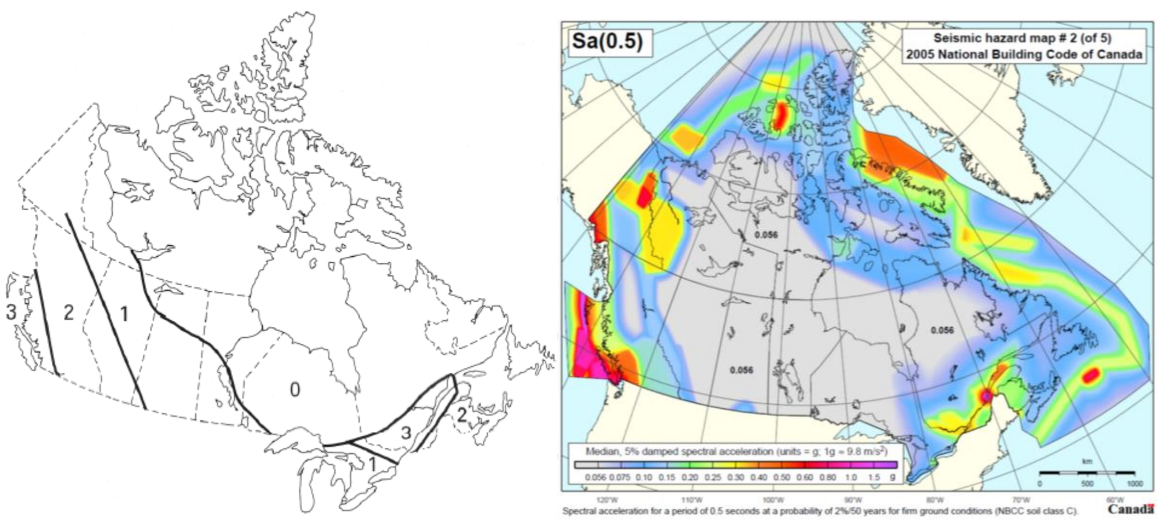


Figure 96: Seismic hazard maps in NBCC design codes (Left: NBCC 1953; Right: NBCC 2005)

Although seismic design provisions have been set by the NBCC codes, enforcement of these provisions in the Québec region has not been as rigorous as in western Canada. Specifically, the NBCC code had been adopted by Québec government before 2000; however, since November 2000 the government enacted the "Code de construction de Québec." For example, the seismic provisions in the 2000 version of the Québec code were taken from the NBCC 1995 and those of the 2008 version of the Québec code are taken from the NBCC 2005.

Moreover, cities in eastern Canada (e.g. Montreal and Québec City) are generally older than the cities in the western Canada (Vancouver and Victoria). A survey of household energy used in 2007 by Natural Resources Canada (NRC) showed that a large portion of the buildings in Québec were built before 1970 when the seismic design code was in its infancy and was not enforced in practice. The combination of construction type and age in the area affected by the eastern scenario indicates significant risk of economic and insured losses from this scenario.

7.2 Estimated Economic and Insured Losses

Economic losses

Economic losses include both direct and indirect losses due to damage to buildings and contents, as well as both direct and indirect losses resulting from damage to infrastructure.

Direct and indirect losses can contribute to the economic losses from the eastern scenario. These are described in detail below.

Direct losses

Modeled losses in total and by sub-category

Direct Losses: The event causes a total of CAD 49,259 million in direct economic losses to properties and infrastructure in British Columbia. Out of this total, CAD 47,300 million is inflicted on the properties and the remaining CAD 1,958 million on the infrastructure.

The losses shown above comprise the losses due to buildings, their contents and the direct business interruption due to the immediate reduction or cessation of production in the damaged property or the loss of service. Indirect losses due to interconnectivity between the economic sectors and the infrastructure are excluded from the above numbers and are presented separately in the following section.

More information about these losses is given in the following tables and figures. In Table 32 for example, we provide a summary of all-property losses by peril and by line of business, and the proportion of the total losses attributable to each line of business is shown in Figure 97.

Table 32: Summary of all direct property losses by coverage

	Building	Contents	Direct BI	Total	Contribution of Peril
Shake	24,392	15,066	6,811	**46,269**	97.8%
Tsunami	-	-	-	-	-
Fire Following	386	211	128	**725**	1.5%
Liquefaction and Landslide	201	65	40	**306**	0.6%
Total	**24,979**	**15,342**	**6,979**	**47,300**	
Contribution of coverage	52.8%	32.4%	14.8%		

All figures are in millions and include demand surge

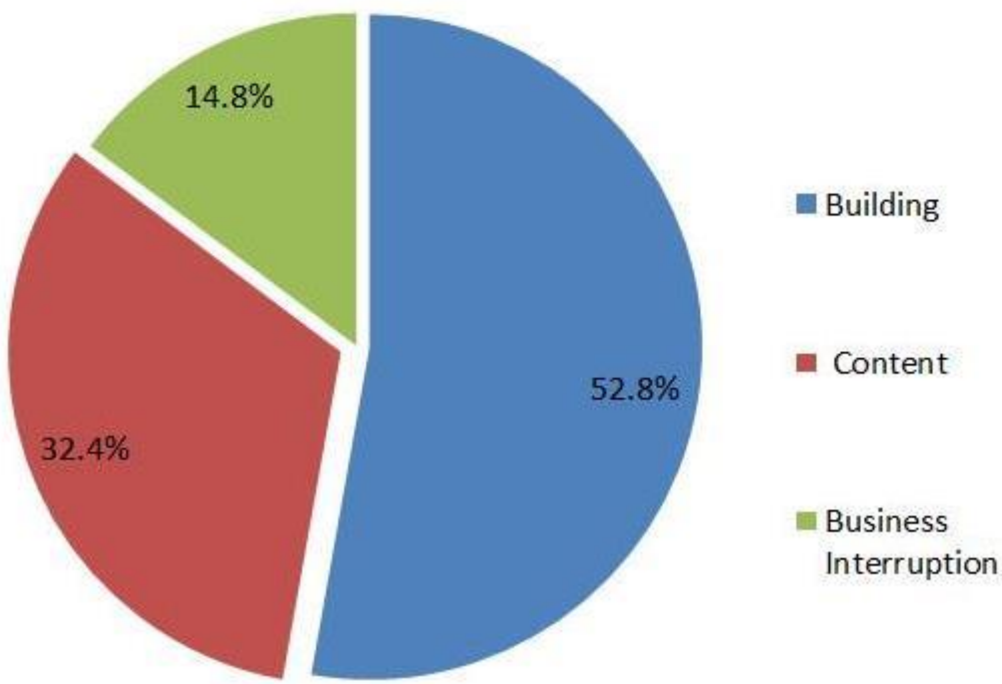


Figure 97: Contribution of each coverage to all direct property losses

Table 33: Summary of all direct property losses by line of business

	Residential	Commercial/ Industrial	Auto	Agricultural	Total	Contribution of Peril
Shake	19,159	26,448	282	380	**46,269**	97.8%
Tsunami	-	-	-	-	**-**	-
Fire Following	289	415	20	1	**725**	1.5%
Liquefaction and Landslide	206	87	9	4	**306**	0.6%
Total	**19,654**	**16, 951**	**311**	**384**	**47,300**	
Contribution of Line of Business	41.6%	57.0%	0.7%	0.8%		

All figures are in millions and include demand surge

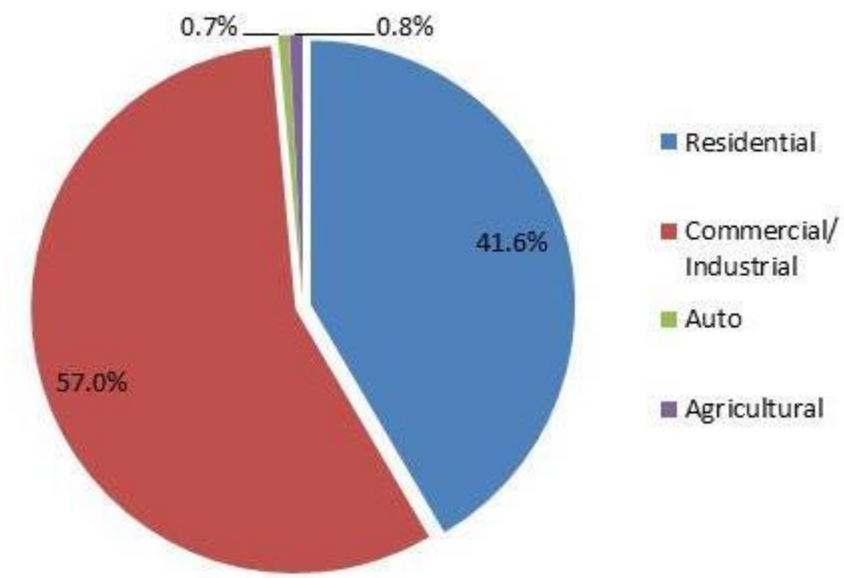


Figure 98: Contribution of each line of business to all direct property losses

Table 34 summarizes all infrastructure losses by peril and by category and the contribution of each coverage to total ground up loss is indicated in Figure 98. A summary of eastern scenario all infrastructure losses by category is provided in Table 34.

Table 34: Summary of all infrastructure losses by category

	Transportation		Airport	Port	Pipelines			Electric/ Telecom	Total	Contribution of Peril
	Road	Rail			Gas	Oil	Water			
Shake	469	137	39	175	11	0	101	961	**1,891**	96.5%
Tsunami	-	-	-	-	-	-	-	-	-	-
Fire Following	0	0	0	0	0	0	0	0	**0**	0.0%
Liquefaction & Landslide	36	4	0	3	0	0	15	8	**67**	3.5%
Total	**505**	**141**	**39**	**178**	**11**	**0**	**116**	**969**	**1,958**	
Contribution of Type	25.8%	7.2%	2.0%	9.1%	0.6%	0.0%	5.9%	49.5%		

All figures are in millions and include demand surge

Indirect losses

The direct losses to property and infrastructure from the earthquake have an indirect impact on the economy of the Québec region. In this section, those indirect impacts are explored in detail to gain an understanding of the total economic damage. Indirect losses presented in this section refer to losses due to interruption in supply chain, integrity of the infrastructure network and interconnectivity of economic sectors. Indirect losses are estimated by thoroughly analyzing the ripple effects associated with the supply chain or customer chain of the directly affected business.

As mentioned previously, resiliency of the network has a significant impact on the total indirect losses. (See Section 6.2 for a description of resiliency in general, and for a list of the specific types of resiliency included in this study.) Indirect losses are presented with a range that shows the upper bound (with no resiliency) and lower bound (considering all applicable resiliencies), and midpoint estimate (considering all applicable resiliencies, but these resiliencies are not necessarily implemented effectively, as might be expected in the aftermath of a major earthquake).

The total indirect losses in the eastern scenario are CAD 17,078 million without resilience (upper bound), CAD 5,594 million with all the sources of resilience (lower bound), and CAD 11,336 million with resilience measures implemented "realistically" (midpoint). Table 35 shows the indirect losses from various sources with and without resilience after the adjustments for potential double counting. The table also shows the midpoint indirect loss estimate.

Consistent with what was observed in the western scenario, the eastern scenario indirect losses associated with the loss of building property have the highest contribution to the total indirect losses, and all sources of resilience affect a reduction in indirect losses by about 70%. However, actual implementation of resilience is likely to fall short of this potential due to problems in management, unforeseen interdependencies in business operations, and supply-chain conditions that hinder a business from resuming operations even if its facilities have been completely repaired or reconstructed. Therefore the actual indirect loss falls somewhere between the upper bound and lower bound of the losses presented here with the midpoint estimate of CAD 11,336 million considered to be the most likely.

Table 35: Indirect losses to infrastructure from various sources

Source of Impact	Indirect Loss w/o Resilience	Indirect Loss with Resilience	Indirect Loss with Resilience – Midpoint
Building Damages	13,997	5,224	9,610
Oil Pipeline Disruption	50	5	28
Gas Pipeline Disruption	240	8	124
Water Supply Disruption	385	20	203
Power Supply Disruption	1315	156	735
Telecom System Disruption	738	36	387
Air Ports Disruption	32	16	24
Sea Ports Disruption	163	82	123
Roads Disruption	61	11	36
Railroads Disruption	97	36	67
Total	**17,078**	**5,594**	**11,336**

All figures are in millions

The total losses shown in Table 35 can be further broken down to the losses by each sector of economy. Table 36 and Table 37 show the indirect losses in each sector of economy from various sources of disruption respectively without and with resilience effects. The numbers in these tables are before the adjustment for potential double counting.

Table 36: Sectorial indirect losses by various impact sources without resilience

Sector	Building	Oil	Gas	Water	Power	Tele-com	Air Ports	Sea Ports	Roads	Rail-roads	Total Output Losses
Crop & Animal Production	179	1	7	11	37	21	1	14	1	5	277
Forestry & Logging	50	1	2	4	13	8	0	4	1	1	84
Fishing, Hunting & Trapping	3	0	0	0	1	0	0	0	0	0	5
Support Activities for Agriculture & forestry	14	0	1	1	4	3	0	1	0	0	25
Mining and Oil & Gas Extraction	191	1	4	6	19	11	0	5	1	3	240
Utilities	219	2	11	18	62	35	0	0	2	0	349
Construction	1,517	7	31	50	170	96	0	43	5	4	1,921
Manufacturing	2,819	19	92	148	505	283	19	176	34	66	4,160
Wholesale Trade	627	5	24	38	130	73	3	24	5	6	935
Retail Trade	1,061	6	30	49	166	93	4	0	5	9	1,423
Transportation & Warehousing and Transportation Margins	747	6	26	42	144	81	6	43	7	14	1,115
Information & Cultural Industries	564	4	18	29	98	55	2	17	4	6	796
Finance, Insurance, Real Estate & Rental & Leasing	1,602	14	66	105	360	202	9	0	9	11	2,379
Professional, Scientific & Technical Services	732	5	23	37	125	70	3	0	3	3	1,000
Administrative, Waste Management & Remediation Services	362	3	14	22	75	42	2	0	2	2	522
Educational Services	54	0	1	1	5	3	0	0	0	0	64
Health Care & Social Assistance	337	2	10	16	55	31	1	0	2	1	453
Arts, Entertainment & Recreation	167	1	5	8	26	15	1	0	1	0	223
Accommodation & Food Services	477	3	13	22	73	41	3	0	2	1	635
Other Services (Except Public Administration)	459	2	9	15	51	29	0	0	1	0	566
Operating, Office, Cafeteria & Laboratory Supplies	281	3	13	21	71	40	0	0	0	0	429
Travel, Entertainment, Advertising & Promotion	415	4	17	27	91	51	0	0	0	0	604
Non-Profit Institutions Serving Households	136	2	7	11	39	22	1	0	1	1	219

Sector	Building	Oil	Gas	Water	Power	Tele-com	Air Ports	Sea Ports	Roads	Rail-roads	Total Output Losses
Government Sector	985	12	57	91	310	174	10	0	7	12	1,657
Total	**13,997**	**100**	**480**	**770**	**2,630**	**1,477**	**64**	**327**	**91**	**145**	**20,080**

All figures are in millions

Table 37: Sectorial indirect losses by various impact sources with resilience

Sector	Building	Oil	Gas	Water	Power	Tele-com	Air Ports	Sea Ports	Roads	Rail-roads	Total Output Losses
Crop & Animal Production	81	0	0	1	7	1	0	7	0	2	100
Forestry & Logging	24	0	0	1	2	0	0	2	0	1	30
Fishing, Hunting & Trapping	1	0	0	0	0	0	0	0	0	0	2
Support Activities for Agriculture & forestry	6	0	0	0	1	0	0	1	0	0	8
Mining and Oil & Gas Extraction	75	0	0	0	0	0	0	2	0	1	79
Utilities	99	0	1	2	12	2	0	0	0	0	117
Construction	531	0	0	1	5	1	0	21	1	2	563
Manufacturing	997	0	1	1	9	1	9	88	9	33	1,148
Wholesale Trade	197	0	1	1	14	4	2	12	1	3	235
Retail Trade	310	1	1	2	17	4	2	0	1	5	342
Transportation & Warehousing and Transportation Margins	585	3	3	8	61	17	3	22	2	7	710
Information & Cultural Industries	114	0	0	0	2	0	1	8	1	3	129
Finance, Insurance, Real Estate & Rental & Leasing	480	1	1	3	29	8	5	0	2	6	534
Professional, Scientific & Technical Services	202	0	0	1	10	2	1	0	1	2	220
Administrative, Waste Management & Remediation Services	102	0	0	1	6	1	1	0	0	1	113
Educational Services	27	0	0	0	2	0	0	0	0	0	29
Health Care & Social Assistance	168	0	1	2	17	3	0	0	0	0	192
Arts, Entertainment & Recreation	84	0	1	1	8	2	1	0	0	0	98
Accommodation & Food Services	243	1	1	4	23	6	2	0	1	1	280
Other Services (Except Public	265	1	1	2	20	4	0	0	0	0	293

Sector	Building	Oil	Gas	Water	Power	Tele-com	Air Ports	Sea Ports	Roads	Rail-roads	Total Output Losses
Administration)											
Operating, Office, Cafeteria & Laboratory Supplies	91	0	0	1	6	1	0	0	0	0	99
Travel, Entertainment, Advertising & Promotion	119	0	0	1	7	2	0	0	0	0	130
Non-Profit Institutions Serving Households	73	0	1	1	11	2	0	0	0	1	89
Government Sector	353	1	2	5	44	9	5	0	2	6	426
Total	**5,224**	**9**	**15**	**40**	**312**	**73**	**32**	**163**	**23**	**73**	**5,964**

All figures are in millions

Direct losses to infrastructure constitute 4% of total direct losses in this scenario. This ratio for indirect losses rises to 15%. Considering both direct and indirect losses, infrastructure contribution of the total economic loss is 6%.

Insured losses

Insured losses, which are estimated from economic losses, reflect the level of earthquake insurance purchased in an area, as well as insurance policy conditions. For information about the insurance penetration and policy condition assumptions that affect the insured losses presented in this report, see Section 3.6.

Typically insurance policies having earthquake as a covered peril utilize two deductibles, one for the non-earthquake loss event (this is the standard policy deductible), and another for the earthquake loss event. In calculating the insured losses shown in this report, in the case where there is only an earthquake loss, we have used the earthquake deductible. When there is only a fire following earthquake loss, we have used the standard policy deductible. If there is both earthquake and fire following loss, then we have used the highest deductible, which is standard practice in the industry.

Insurance company reactions to recent changes in legislation in British Columbia have resulted in evolving policy conditions. For this reason, we ran a sensitivity test utilizing the policy deductible where there is both fire and earthquake loss, the resulting insured loss would be 12% higher.

Insured losses from the eastern scenario amount to a total of CAD 12,228 million. The losses are determined using the latest policy conditions and the best estimates of the take up rates in the areas as discussed in section 3.6.

It must be noted that the infrastructure losses have no contribution to the total insured losses presented here. Infrastructure can be privately, publicly, or self-insured, but the prevalence of each of these types of insurance was unable to be determined from available data. For this reason, market penetration rates, which are measures of the total value of insured property in relation to the value of all property, could not be determined. Table 38 below provides a summary of all insured property losses by peril and by coverage, and Figure 99 indicates the proportion of each coverage to the total losses shown and Figure 100 shows the proportion of losses attributable to each coverage.

It is interesting to note that the change in the proportions from ground up to insured losses is mainly due to different take-up rates in the commercial and residential lines. Insurance penetration in the residential lines in the province of Québec is notably less than that for other lines. Hence, thus the contribution of residential losses to the total insured loss is much smaller than its contribution to ground up losses.

A summary of insured losses by coverage is given in Table 38 below, and Figure 99 shows the contribution of each coverage to total losses.

Table 38: Summary of insured losses by peril and coverage

	Building	**Contents**	**Direct BI**	**Total**	**Contribution of Peril**
Shake	5,753	3,545	2,245	**11,543**	94.4%
Tsunami	-	-	-	-	-
Fire Following	341	189	98	**628**	5.1%
Liquefaction and Landslide	38	8	10	**56**	0.4%
Total	**6,133**	**3,742**	**2,353**	**12,228**	
Contribution of Coverage	50.2%	30.6%	19.2%		

All figures are in millions and include demand surge

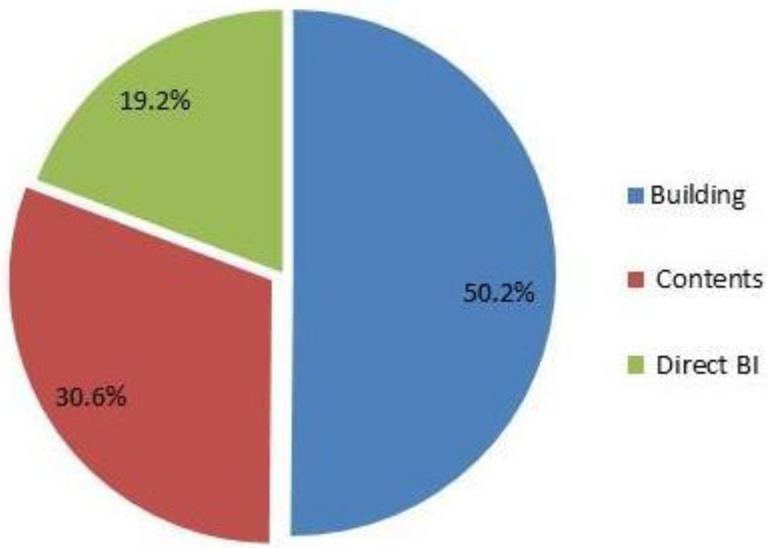


Figure 99: Contribution of each coverage to total insured property losses

Insured losses by line of business are summarized below in Table 39, and the contribution of each line of business to total insured loss is depicted in Figure 100.

Table 39: Summary of insured property losses by line of business

	Residential	Commercial/ Industrial	Auto	Agricultural	Total	Contribution of Peril
Shake	274	10,828	171	270	**11,543**	94.4%
Tsunami	-	-	-	-	-	-
Fire Following	279	332	16	1	**628**	5.1%
Liquefaction and Landslide	4	41	8	3	**56**	0.5%
Total	**557**	**11,202**	**194**	**274**	**12,228**	
Contribution of Line of Business	4.6%	91.6%	1.6%	2.2%		

All figures are in millions and include demand surge

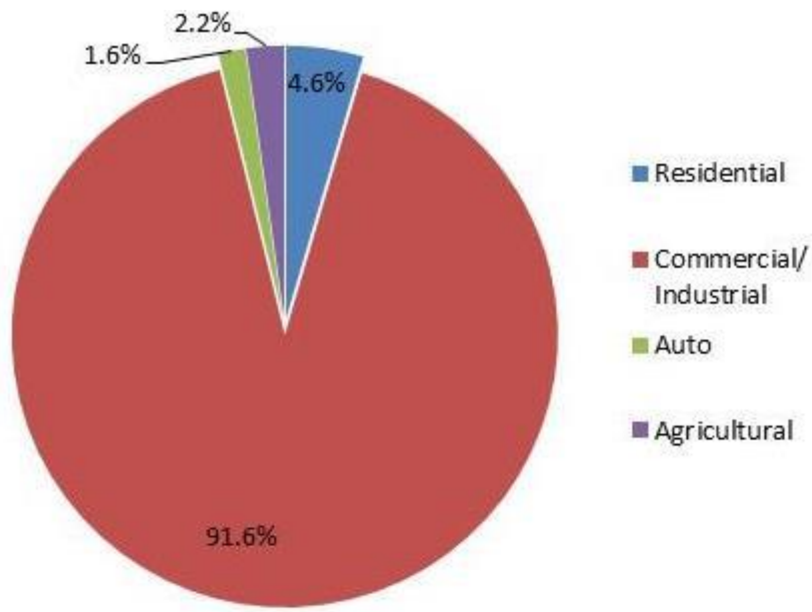


Figure 100: Contribution of each line of business to total insured property losses

The losses shown in Figure 100 are the amount of the scenario losses to be paid to policyholders of earthquake insurance. Insurance policies contain provisions that require the policyholder to retain some portion of the loss as a deductible.

The next figures illustrate the commercial, residential and infrastructure losses for the region in general, and for the Québec City area in detail. Figure 101 shows the commercial losses for the region as a whole, and Figure 102 shows commercial losses for the Québec City area.

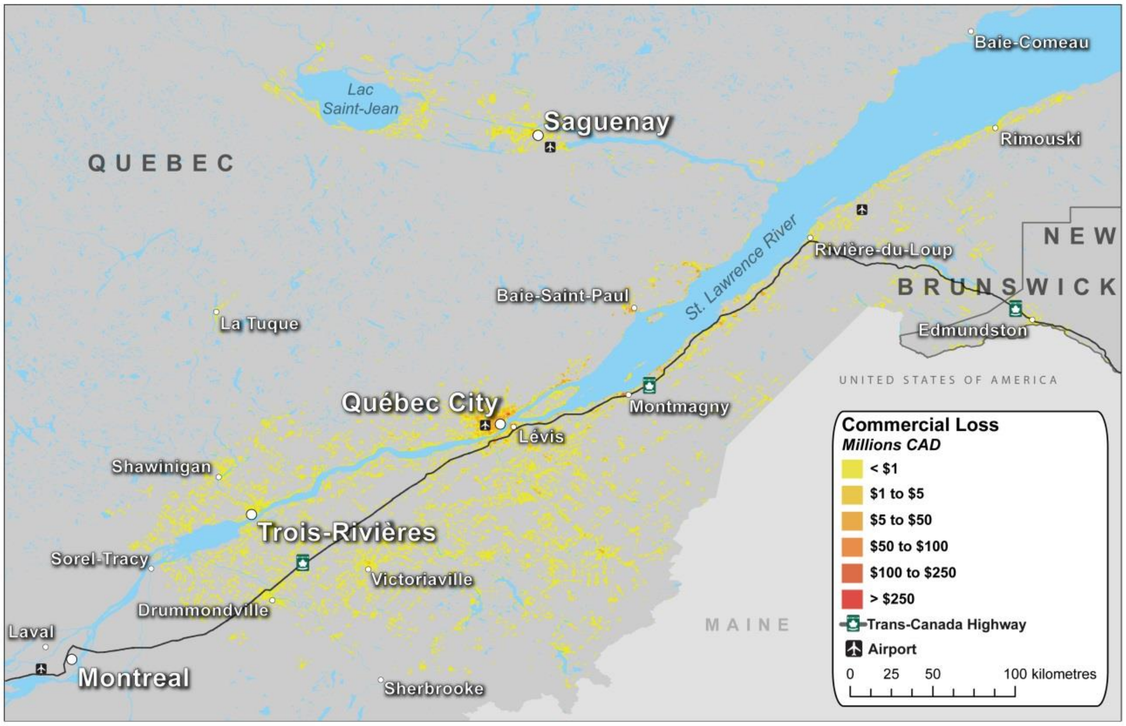


Figure 101: Eastern scenario region commercial losses

The distribution of commercial losses for the eastern scenario area follows the pattern of population density. Losses are concentrated in the communities around Québec City, Trois Rivieres, Saguenay and along the south bank of the St. Lawrence River. Elevated levels of loss can be seen in the centres of Baie-St-Paul on the north bank of the St. Lawrence, and Montmagny on the south bank—the municipalities closest to the epicentre of the event. A larger concentration of losses at the upper end of the range produced by the model can be seen in central Québec City. These are shown in greater detail in Figure 102 below.

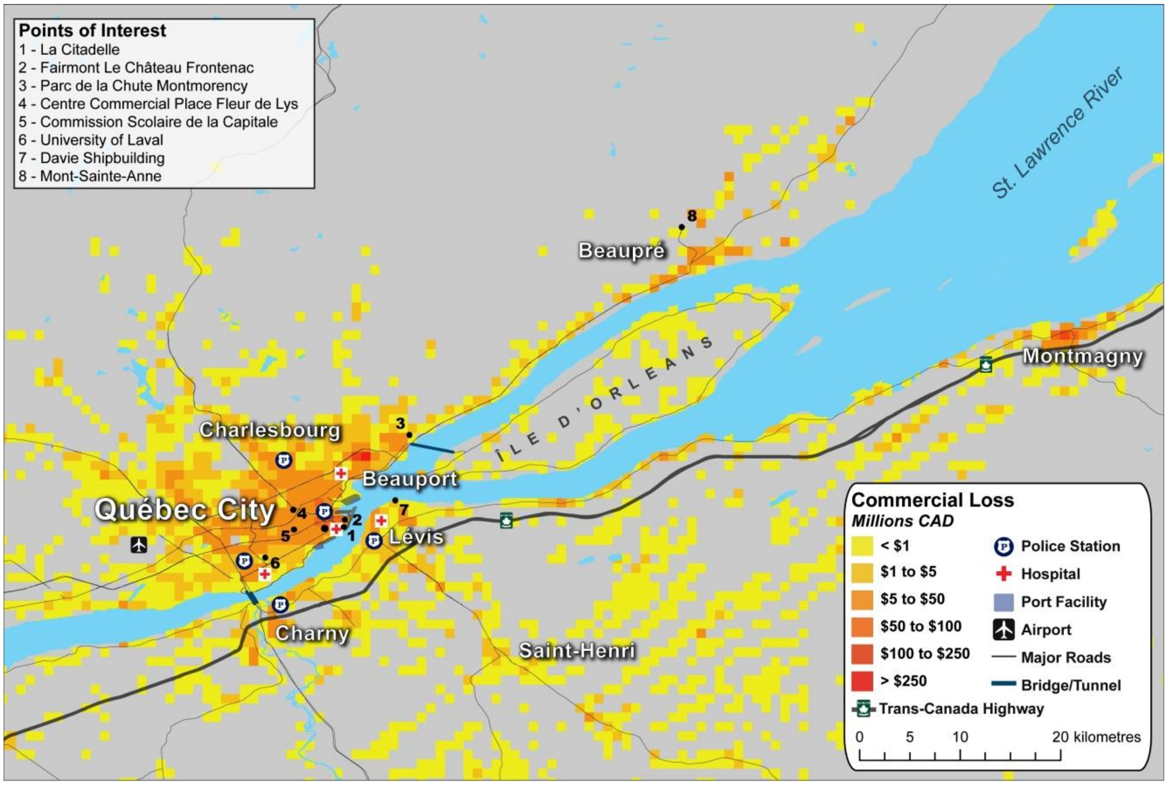


Figure 102: Québec City commercial losses

Commercial losses at an elevated level are noted throughout the greater Québec area, with a particular concentration of losses at the higher levels seen in the vicinity of Québec City and Beauport. Grid squares without loss generally represent areas with little or no development.

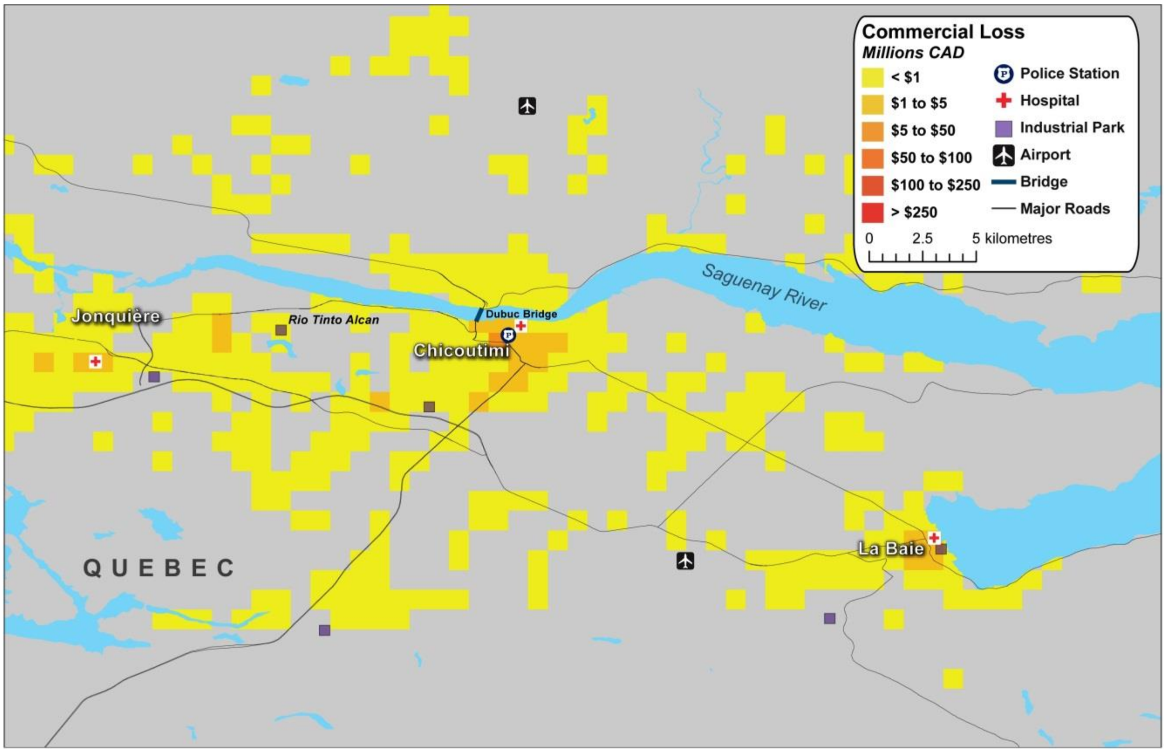


Figure 103: Saguenay commercial loss

The insured commercial losses incurred within communities in and around Saguenay can be seen in Figure 103. Losses are generally at the lower end of the range, but with higher levels in the more developed centres of population.

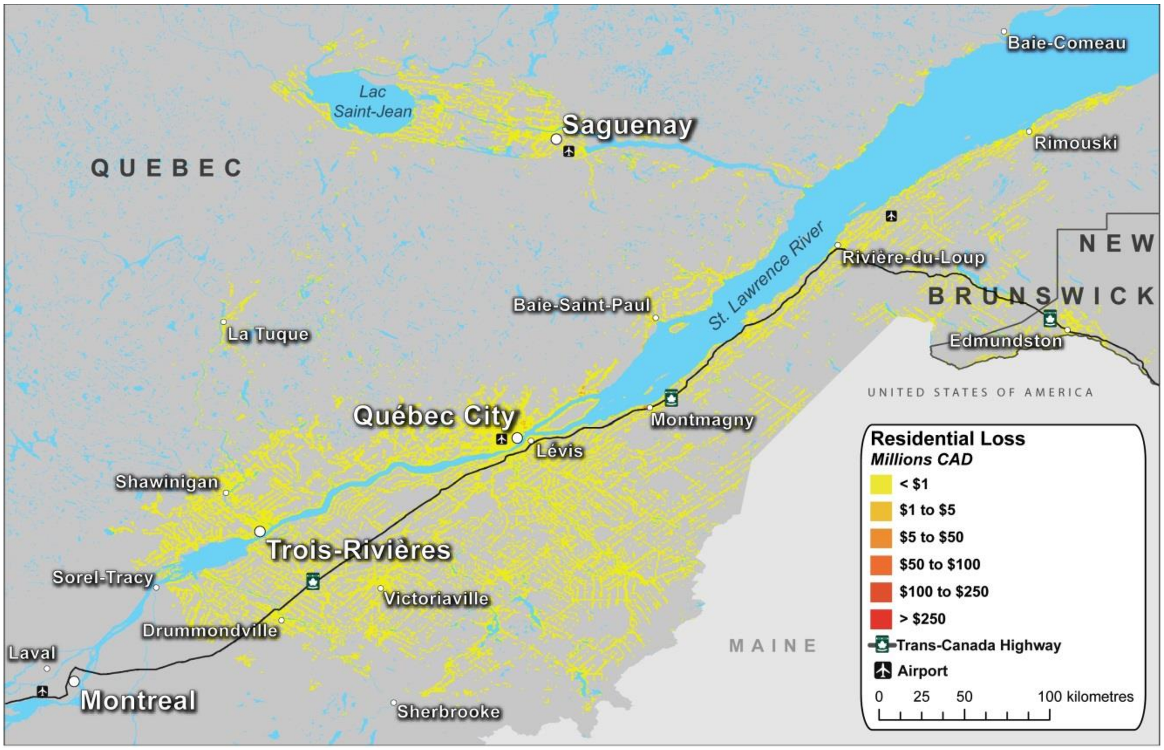


Figure 104: Eastern scenario region residential losses

Residential losses for the region as a whole are depicted above in Figure 104. Most communities, particularly those to the south and west of Québec City show damage on the lowest level on the scale give above. Those closest to the epicentre of the event however show an elevated level of loss. This is particularly evident in the centres of Baie-St-Paul on the north bank of the St. Lawrence and Montmagny on the south bank—the largest municipalities close to the centre of the event.

Another, much greater, concentration of enhanced losses can be seen in and around Québec City. This area is shown in greater detail below in Figure 105.

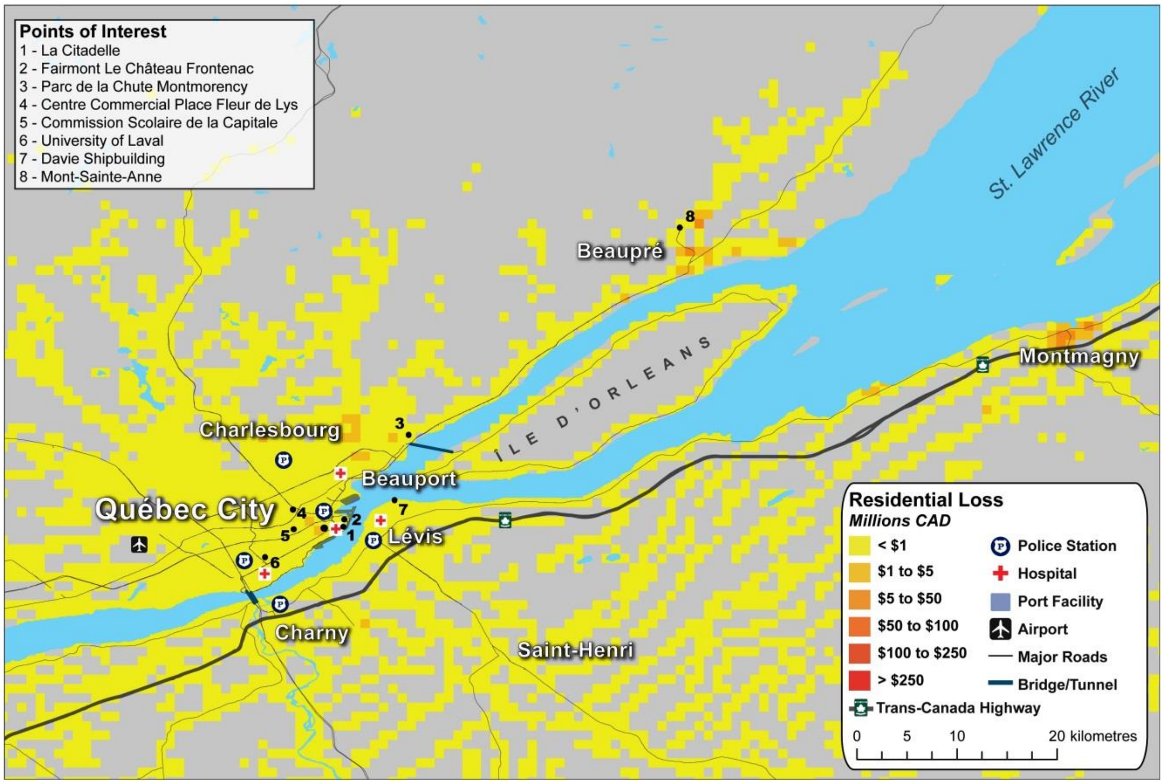


Figure 105: Residential losses in Québec City and its environs

The residential losses shown above in Figure 105 reflect extensive damage throughout the greater Québec City area, with the highest levels of loss mostly seen in pockets close to the centre of the city.

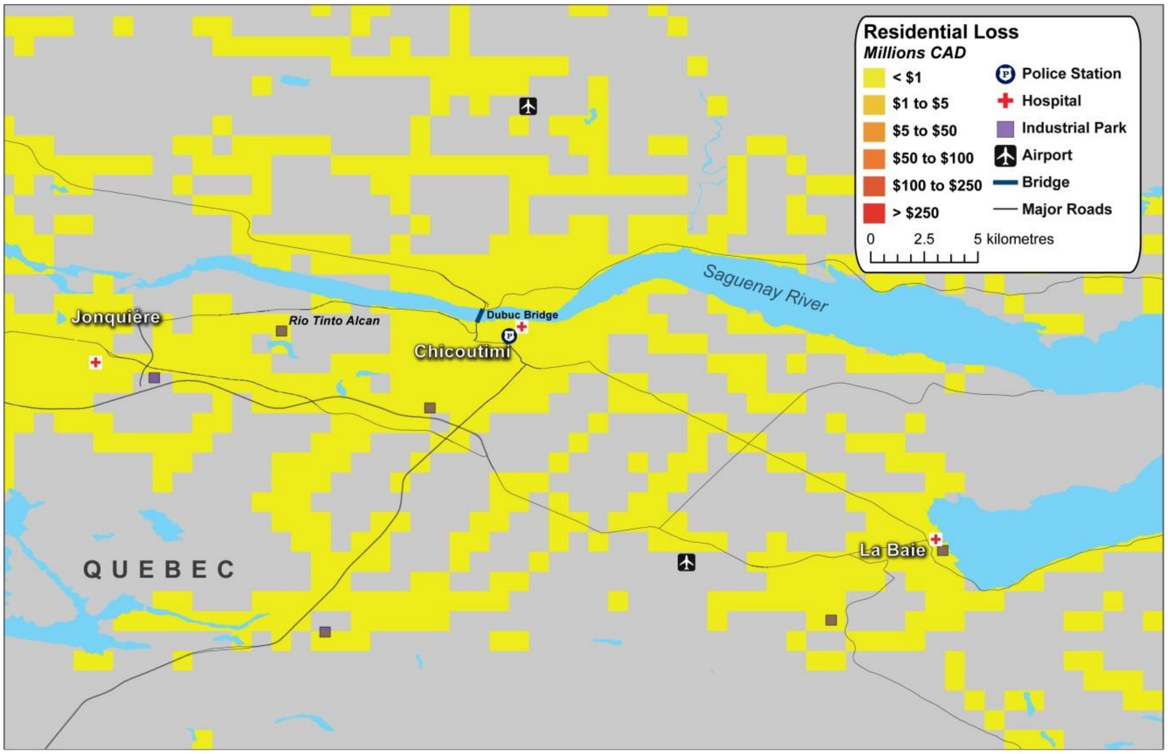


Figure 106: Saguenay residential losses

Infrastructure

Losses to infrastructure across the eastern scenario region are summarized in Figure 107 and those for the Québec City area can be seen in Figure 108.

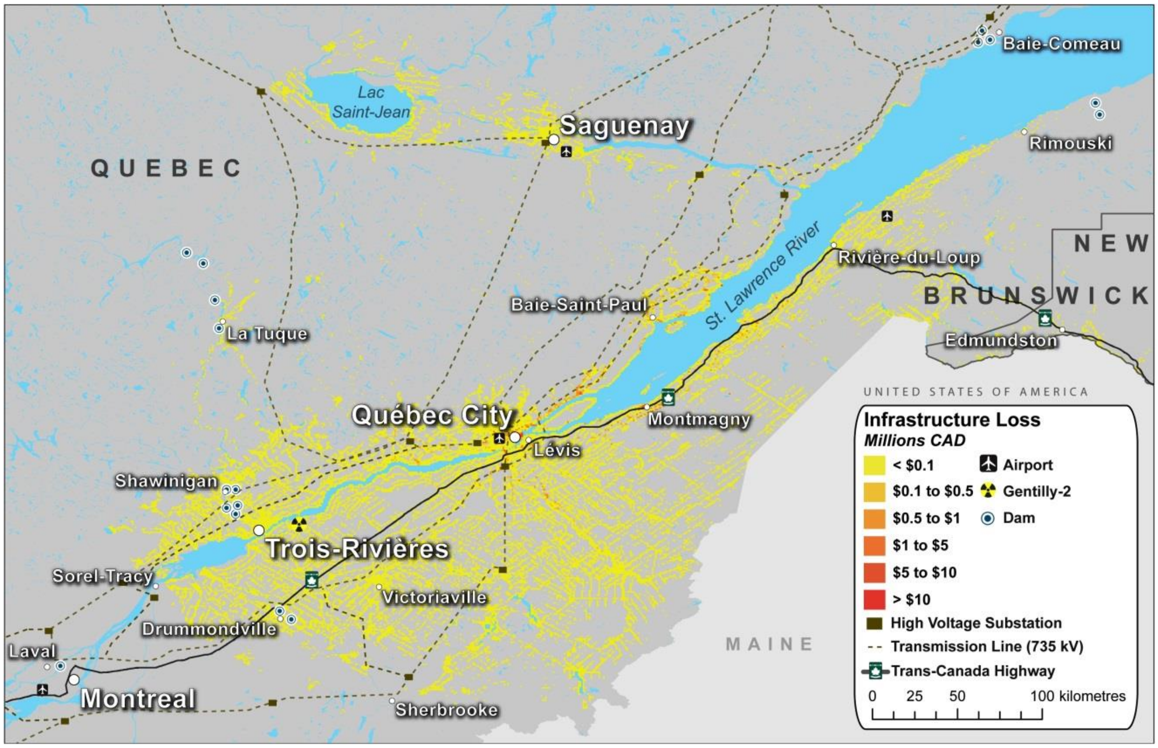


Figure 107: Eastern scenario region infrastructure losses

The infrastructure losses seen above in Figure 107 show a pattern of distribution that follow the development of the communities within the region. The greatest concentrations of losses are focused on the principal municipalities, but infrastructure is also the arteries that supply essential services such as power, water and communications and the roads, railroads and bridges that connect communities—it is the lifelines that enable them to function and their economies to prosper. Major power transmission lines for example extend along the north bank of the St. Lawrence bringing power to this densely populated valley. Damage to this network contributes almost half of the losses to infrastructure sustained in the region in this scenario.

Figure 108 shows low levels of loss throughout the greater Québec City area. Pockets of elevated loss levels can be seen, and some of these mark Jean Lesage International Airport, downtown Québec City, the three bridges across the St. Lawrence River and the Port de Québec's principal facilities.

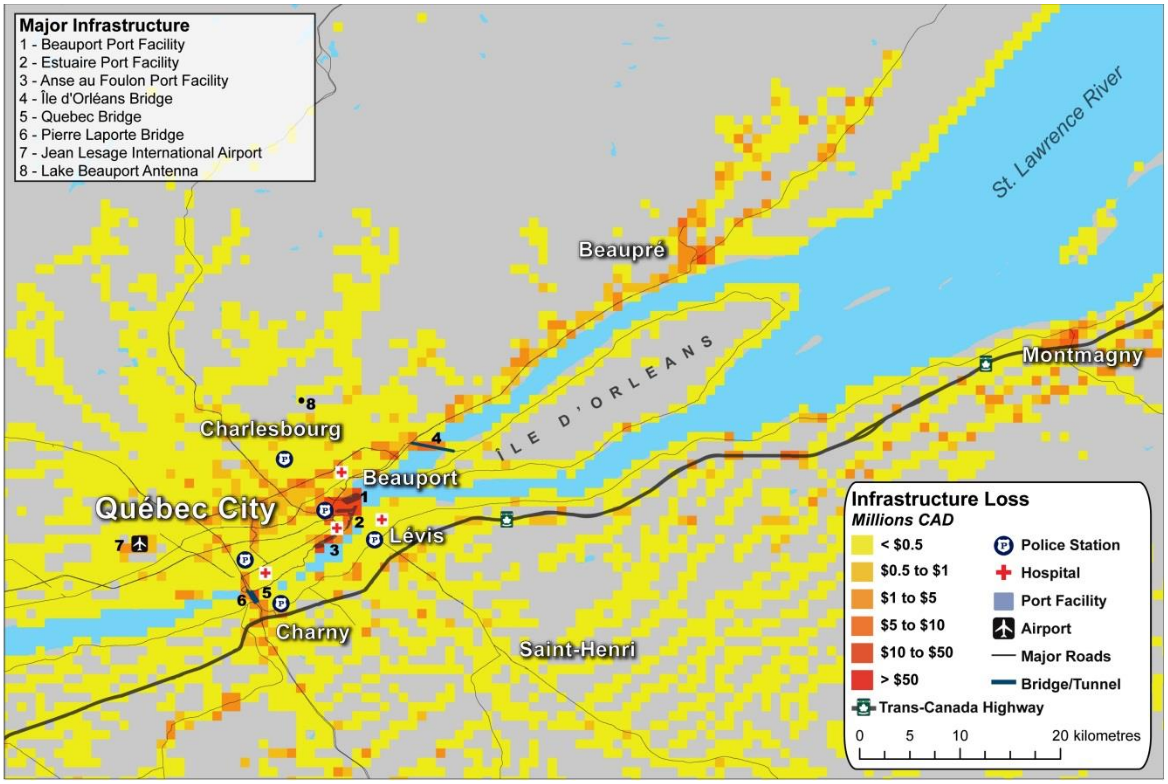


Figure 108: Québec City infrastructure losses

Infrastructure losses for the area around Saguenay are shown below in Figure 109. The losses anticipated in this area are generally at the lower end of the scale, with slightly elevated losses associated with the two airports in the region.

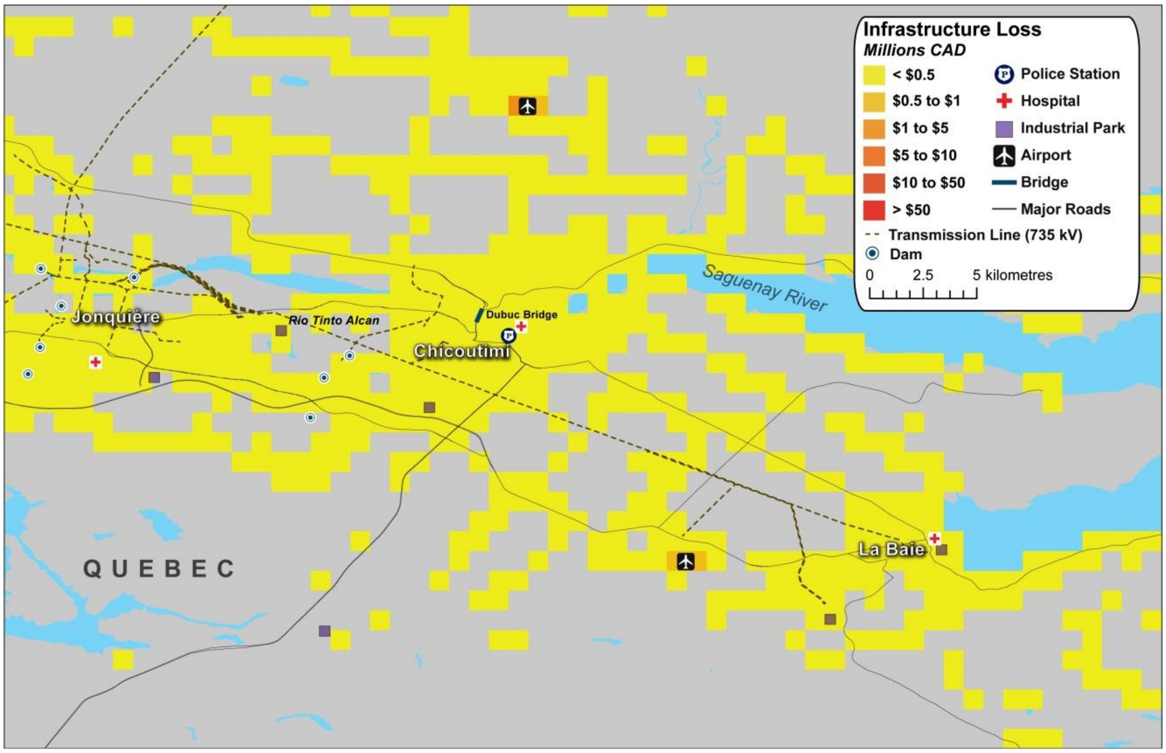


Figure 109: Saguenay infrastructure losses

The contribution of each infrastructure type to total losses is shown below in Table 40, and, in pie chart form, in Figure 110.

Table 40: Contribution of each infrastructure type to total losses

Type	Direct Loss	Contribution of Type
Transportation—Road	505	25.80%
Transportation—Rail	141	7.20%
Airport	39	2.00%
Port	178	9.10%
Pipeline—Gas	0	0.00%
Pipeline—Oil	116	5.90%
Pipeline—Water	11	0.60%
Electrical—Transmission System	966	49.30%
Telecommunication System	3	0.20%
Total	**1,958**	

All figures are in millions

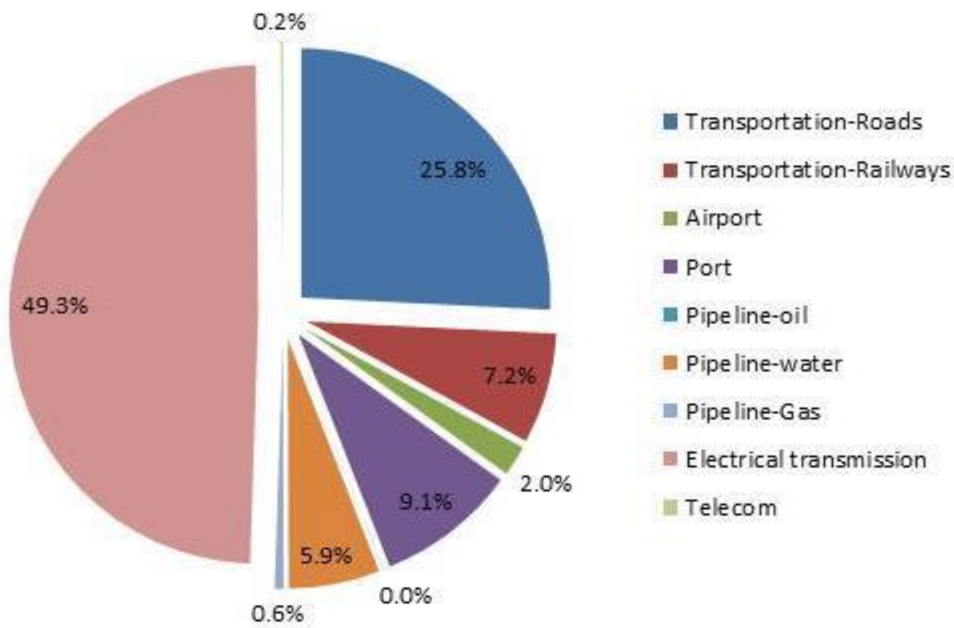


Figure 110: Contribution of each infrastructure type to total losses

Public buildings

Losses to public buildings are summarized in the following tables. Total ground up losses by coverage are given in Table 41.

Table 41: Total ground up loss to public buildings

LOB	Type	Building	Content	Direct BI	Total	Contribution of Peril
Commercial	Healthcare	276	160	92	**528**	38.3%
	Government	184	105	65	**354**	25.7%
	Education	190	106	61	**357**	25.9%
Industrial	Public Utility Facilities	41	67	30	**139**	10.1%
Total		**691**	**438**	**248**	**1,378**	
Contribution of Coverage		50.1%	31.8%	18.0%		

All figures are in millions

8 Methods for Estimating Indirect Economic Losses

8.1 Estimating Indirect Economic Losses from Damage to Property and Infrastructure[10]

For many years, disaster loss estimation focused on property damage to structures. All other types of impacts (economic, sociological, psychological, etc.) were thrown into a grab bag category termed "indirect" or "secondary" losses. Direct property damage relates to the effects of natural phenomena, such as fault rupture, ground shaking, ground failure, landslides, tsunami, etc., while collateral, or indirect, property damage is exemplified by ancillary fires caused by ruptured pipelines, frayed electrical wires, etc., and exacerbated by loss of water services.

Direct Business Interruption (BI) refers to the immediate reduction or cessation of economic production in a damaged factory or in a factory cut off from at least one of its utility lifelines. Indirect BI (referred to as contingent BI by the insurance industry) stems from the "ripple," or "multiplier," effects associated with the supply chain or customer chain of the directly affected business. The reader is referred to Rose (2004) for an exposition of these concepts, as well as related ones below, and to European Union (2003), MMC (2005), National Research Council (2005) and Rose et al. (2007) for examples of their application.

An important consideration is that nearly all direct property damage takes place at a given point in time (during the ground shaking), and that ancillary (or indirect) property damage takes place during a fairly short time span. BI, on the other hand, being a flow variable, is time-dependent. It begins when the ground shaking starts and continues until the built environment is repaired and reconstructed to some desired or feasible level (not necessarily pre-disaster status) and a healthy business environment is restored.

As such, BI is complicated because it is highly influenced by the choices of private and public decision makers about the pattern of recovery, including repair and

[10] This section has been summarized from Analysis of Indirect Impacts of the Earthquake Scenario in British Columbia, by Drs Dan Wei, Adam Rose and Michael Lahr. The report in its entirety has been included in Appendix 9.

reconstruction. Recent events, such as 9/11 and Hurricane Katrina, and hypothetical policy simulations, such as the ShakeOut Catastrophic Earthquake Scenario indicate the size of BI can rival that of property damage (Rose et al., 2009; Rose et al., 2012).

We present losses in terms of two types of flow variables relating to BI. The first is gross output, a concept akin to sales revenue, which equals the cost of all inputs plus a profit term for most industries (exceptions include wholesale and retail trade, where gross output is more closely aligned with the sales margin, and does not include the cost of goods sold). The second is value added, a net measure that corresponds only to the cost of primary factors of production (labor, capital, and natural resources, and excludes the cost of intermediate, or processed goods). At the regional level, it is the counterpart of Gross Domestic Product (GDP)—a measure of the annual change in overall wealth within a specific geographic area.

Indirect business interruption impacts were estimated in this study with an input-output (I-O) model. I-O analysis is a static, linear model of all purchases and sales between sectors of an economy based on the technological relationships of production (Rose and Miernyk, 1989). It was developed by Nobel laureate Wassily Leontief and is the most widely used tool of economic impact analysis, primarily because it is both well-established and straightforward. Moreover, its properties are well-known to hazard modelers since it has been used extensively to analyze the economic impacts of earthquakes and other natural hazards (see, e.g., ATC, 1991; Shinozuka et al., 1998; Rose and Lim, 2002; and Gordon et al., 2007; FEMA, 2008). Due to its extraordinary sectorial detail compared to other models, it is especially adept at articulating accurate ripple or multiplier, effects.

Essentially, input-output tables are a detailed, comprehensive, double-entry bookkeeping record of all production activity in an economy. They are actually used periodically to benchmark a nation’s or region’s GDP estimates. As a result, practically every country in the world has constructed an input-output table, usually through an exhaustive census or at least an extensive survey.

In terms of manageability, I-O models are relatively straightforward and can readily be manipulated for basic simulations. This is because they are simultaneously models and databases. More sophisticated analyses can be performed with the help of Excel spreadsheets. I-O models are also very transparent. The empirical basis for these models is contained in an I-O table, which model users and the general public can readily appreciate.

Effect of resilience on the indirect losses

In our analysis, we incorporate the loss reduction strategy of *resilience,* in both static and dynamic forms. We define static economic resilience as the ability of an entity or system to maintain function (e.g., continue producing) when shocked by the types of disruptions taken into account. It is thus aligned with the fundamental economic problem—the efficient allocation of resources, which are made even scarcer in the context of disasters.

This aspect is interpreted as static because it can be attained without repair and reconstruction activities, which affect not only the current level of economic activity but also its future time path. Another key feature of static economic resilience is that it is primarily a demand-side phenomenon involving users of inputs (customers) rather than producers (suppliers). This is in contrast to supply-side considerations, which definitely require the repair or reconstruction of critical inputs.

A more general definition of dynamic resilience is the speed at which an entity or system recovers from a severe shock to achieve a desired state. This also subsumes the concept of mathematical or system stability because it implies the system is able to bounce back. This version of resilience is relatively more complex because it involves a long-term investment problem associated with repair and reconstruction, and is thus omitted from our analysis.

The following are relevant resilience tactics:

1. Use of inventories. This pertains to the use of various types of stockpiles of the businesses that experience direct and indirect input disruptions due to the interruption of the supply chain under the disaster.

2. Conservation. This pertains to finding ways to use less of disrupted inputs in production processes that are potentially disrupted by the damages to critical utility supply systems, as well as conserving critical inputs whose production is curtailed indirectly.

3. Input Substitution. This refers to using in a production process goods that are similar to those whose production has been disrupted (again both directly and indirectly). An example would be using natural gas rather than coal in electric utility and industrial boilers.

4. Import substitution. This is basically the same as input substitution but more explicitly replacing an imported good with a domestic substitute.

5. Utility Unimportance. This refers to the portions of a production process that are insulated from lifeline service requirements, and hence are not affected by service disruptions (e.g., much of agricultural production does not require electricity).

6. Production Recapture (Rescheduling). This resilience strategy refers to the ability of businesses to recapture lost production by working overtime or extra shifts once their operational capability is restored and their critical inputs and employees are available. This is a viable option for short-run disruptions, where customers are less likely to have cancelled orders.

7. Transportation Re-routing. This refers to redirecting traffic (e.g., flights, ships, vehicles) to alternative routes to arrive at destinations when parts of the transportation systems are down due to the damages caused by the earthquake.

In this study, given the short time of the disruption, input and import substitution are not likely to come into play, and data are not available for inventories. Hence, we confine our attention to conservation, unimportance, production recapture and transportation re-routing. Also, according to the literature, the effects of most of the other resilience actions are very small in comparison to those that we actually model (Tierney, 1997; Rose and Lim, 2002).

Methodology

For this study, we obtain the Canadian provincial I-O tables for British Columbia from Statistics of Canada (StatsCan). The I-O table includes 24 sectors, which is largely based on the two-digit North American Industrial Classification System (NAICS) sectoring scheme.

I-O models have both demand- and supply-side versions. The demand-side I-O model is the standard version, where a change in final demand affects the economy by causing product supply to respond through a multiplier process. The supply-side I-O model is a variant of the standard model in which the impacts to the economy takes place through the production side of the economy. This can be a change in primary factors (e.g., labor) of individual sector economic activity that ripples throughout the economy through marketing patterns of sales of one sector to another (Rose and Wei, 2011). In this study, both demand-side and supply-side I-O models are applied to provide a more comprehensive evaluation of the potential economic losses stemming from building-related damages and utility lifeline disruptions of the earthquake scenarios.

For the analysis of indirect economic impacts stemming from the disruption to the transportation infrastructures, i.e., highways, railroads, airports, and sea ports, we use the approach illustrated in the report by Applied Technology Council (ATC, 1991). Appendix Tables B3-B6 present the ATC estimates on percentage losses in value-added of different economic sectors resulting from increasingly severe interruptions of major transportation infrastructure types.

9 Assumptions and Limitations of Scenario Selection and Analysis

9.1 General Assumptions and Sources of Uncertainty for All Models

Catastrophe models are developed based on assumptions about complex physical phenomena of which there is imperfect understanding, and the observed data for model calibration is limited, particularly in regions of very low frequency of catastrophic events. There are multiple sources of uncertainty in catastrophe models and these can typically be grouped into two main classes—aleatory and epistemic.

Aleatory uncertainty represents the intrinsic variability of a process and is a form of uncertainty which cannot be reduced as more information is gathered since the variability is inherent within the process. The second source of uncertainty is epistemic, which results from lack of knowledge. This is commonly manifested by uncertainty in the choice of the form of the model, known as model uncertainty, and in the estimation of parameters, known as parametric uncertainty.

Model uncertainty can be illustrated by the choice of whether the recurrence of earthquakes on faults is treated as time dependent or time independent, or by whether the current climate is considered to be stationary. Parametric uncertainty relates often to scarcity of data in the estimation of model parameters, particularly in non-active regions.

Additionally, there are uncertainties that are known but not accounted for in the model—for example, loss from levee or dam failures that are triggered by the occurrence of an earthquake. Finally, some uncertainties are unknown, such as the probability of occurrence of earthquakes on as yet undiscovered faults.

Stationarity

To estimate hazard, catastrophe models use historical data, pre-historical data, geo-physical data and a deep scientific understanding of the physical processes that cause these events. In the model development process, AIR is careful to examine the stationarity of the time series and completeness time so that biases are not inadvertently introduced into the models. However, there remains a significant reliance on historical data and therefore an implicit assumption that the past record can be used to predict the frequency and intensity of future events.

Thus all models rely to varying degrees on the assumption that past experience provides a reasonable representation of the physical parameters of events that can be expected to occur in the future. The uncertainty in this regard is especially magnified for the rare but extreme events for which there is limited—or even no—historical data.

For regions for which little data is available, there is an increasing trend towards physical modeling, as in the case of kinematic modeling for the earthquake hazard or numerical weather prediction modeling for complex wind hazards.

Damage estimation

Damage functions are developed based on assumptions derived from engineering studies, published research, post-disaster surveys, and actual claims data where available. There is uncertainty in the performance of newer structures that have not yet been tested by actual events.

Also, there is greater uncertainty for less studied regions or regions for which there is limited claims data whose damage functions may have been derived using first principles of engineering and have not been validated using actual observed data.

Part of the intra-event uncertainty of the ground motion is captured in vulnerability functions. Vulnerability functions which relate mean damage ratio with the median ground motion parameters are modified to account for the uncertainty of ground motion parameters around the median values. The intra-event uncertainty in the ground motion parameters are often quantified in the ground motion prediction equations (attenuation functions) by log normal distributions.

Secondary uncertainty

The probability distributions that characterize secondary uncertainty—that is, the uncertainty in damage ratio given a level of event intensity—are developed from loss experience data. The fitting of the secondary uncertainty distributions (which vary by peril and intensity), in some cases to a sparse set of claims data, is associated with parameter uncertainty.

Exposure (input) data

Exposure data quality remains a key issue in catastrophe risk management.

AIR's scenario loss estimates contained in this report rely on accurate replacement values, risk counts and take-up rates, about which there is uncertainty to the extent the underlying exposure data does not accurately reflect the true industry exposures, policy conditions and insurance penetration in Canada.

Although the combination of CanVec data and additional infrastructure maps provided coverage for most geographic areas and types of infrastructure, there were still some cases where data was not available. This happened for the local distribution lines for natural gas, water systems, and electrical transmission lines in some areas of Canada. In these cases, the local distribution lines were modeled based on road networks.

Demand surge

An additional source of uncertainty in modeled losses is demand surge. Market forces generally ensure that the availability of materials and labor in any particular geographical area is sufficient to accommodate a normal level of demand without affecting price. However, demand can increase sharply and unexpectedly after a catastrophe such as a significant hurricane or earthquake.

The resulting widespread property damage can cause a sharp increase in the need for—and prices of—building materials and labor. Scarce resources can also result in an increase in the time required to repair and rebuild damaged property, which may cause greater business interruption losses and additional living expenses. Infrastructure damage, delayed building-permit processes and a shortage of available building inspectors also increase BI loss. These factors can lead to insured losses exceeding expectations for a particular event and portfolio, a phenomenon known as demand surge.

The current default AIR demand surge function was developed using economic principles and validated based on U.S. loss levels and component cost analyses. Because demand surge is a phenomenon seen only with especially large catastrophes, there are relatively few events with which to validate demand surge functions outside of the U.S. There are resulting uncertainties in the demand surge function because of the relative scarcity of detailed data.

The use of expert judgment

AIR's large and diverse team of experts continually strives to improve the accuracy and realism of catastrophe models. However, catastrophe modeling will always remain an inexact science and there are inherent uncertainties and assumptions throughout the model development process. AIR is committed to explaining all known sources of uncertainty and how they are treated within the models in our detailed technical documentation.

For particular areas of inquiry or less well-studied regions of the world that lack ample historical data, model development requires the use of expert scientific judgment. In some situations, AIR supplements in-house knowledge with external expertise using consultants or peer reviewers.

9.2 Assumptions and Limitations Specific to the AIR Earthquake Model for Canada

Ground motion and seismicity

The AIR Earthquake Model for Canada uses geological, seismic and geodetic data collected from the literature, as well as information obtained from unpublished reports. Expert judgment is applied as needed, to ensure that the latest information is used in model development. However, it should be noted that AIR did not collect or compile the original data; therefore, the model relies on the accuracy of these published data or results.

In particular, AIR used a recently released historical earthquake catalog compiled by seismologists in the Geological Survey of Canada (GSC). The modeled seismicity rate and location largely depends on the accuracy of the historical catalog. The magnitudes of historical events in this new catalog are significantly different from the events in the previous release from the GSC, which was used by the GSC to develop the existing national hazard map of Canada. AIR assumes that the new earthquake catalog from the GSC represents the latest understanding of historical earthquake magnitudes and seismic characteristics of Canada.

Each selected scenario represents just one outcome of many possible rupture scenarios in the source zone in which it occurred. It is important to recognize that the selected scenario does not represent AIR's prediction of the most likely output of a future rupture in the source. For example, there are many ways the seismic energy currently accumulated in the Cascadia subduction zone may be released by the next major earthquake or earthquakes. For example, it might be released in a single megathrust earthquake rupturing the entire fault, along with a series of smaller aftershocks, similar to the 2011 Tōhoku earthquake sequence. Alternatively, several great earthquakes involving the individual rupture of smaller fault segments over the course of a few years or decades might occur. The impact of these possible rupture scenarios would be very different.

The rupture geometry of Cascadia subduction zone events is based on the USGS 2008 rupture model for the Cascadia subduction zone. The USGS employs three alternative models for the Cascadia subduction zone and these different rupture models are combined using a logic tree in hazard calculation. The western scenario selected in this study represents one of these alternative models. Other rupture scenarios might have a significantly different loss impact on Canada even if the magnitude, rupture length and depth are the same as this event.

Except for the Cascadia subduction zone, the AIR Earthquake Model for Canada is a time independent model. That is, the probability of earthquake occurrence at any location or along any segment of a fault follows a Poissonian model, and is thus independent of past earthquake occurrences.

It is assumed that expected ground motion is appropriately modeled with the use of empirical ground motion prediction equations (GMPEs), or attenuation equations. These GMPEs use site conditions, the average shear wave velocity of shallow soil, and formulation of the site amplification factor, about which there is uncertainty.

Additionally, in developing GMPEs, ground motion recordings at different sites generated by different earthquakes are pooled. Empirical data has shown that this approach produces higher variation in ground motion than has been recorded from repeated earthquakes of a similar magnitude at distance R from a particular fault. This inflated variability can cause an inflated seismic hazard at some sites. Engineering seismology data and research are used to remove this potential source of bias.

Liquefaction

The AIR regional liquefaction model relies on surficial geological maps and a limited number of soil profile data to evaluate liquefaction hazard. This approach provides reasonable estimates of liquefaction damage; however, predicting site-specific liquefaction damage requires detailed geotechnical data and information regarding the foundation and type of the structure, which may not be available. The model also does not consider countermeasures taken against liquefaction at specific sites.

The AIR Earthquake Model for Canada supports liquefaction only at six urban areas where high-quality surficial geological maps are available. These six regions are the Lower Mainland, Metro Victoria Area, Greater Toronto Area, National Capital Region, Greater Montreal Area, and Québec City.

Landslide

The AIR regional landslide model follows a generalized method based on bedrock/surficial geological maps and digital elevation data. This method provides reasonable estimates of landslide damage at a regional scale, but does not provide site-specific slope stability analysis. Site-specific evaluations require more detailed slope profile and geotechnical information; therefore, it is not practical to perform site-specific evaluations at the regional level. The landslide model also does not consider countermeasures taken against slope failure at specific sites.

Areas that are underlain by sensitive marine sediments (e.g., the Leda clay) in the Ottawa and St. Lawrence River valleys are highly vulnerable to earth flows. However, AIR does not model this type of landslide because the identification of areas where sensitive sediments may be present requires extensive site-specific surveys, and there are not sufficient data to fully resolve the location and extent of these sensitive sediments.

Fire following earthquake

The fire following model accounts for a variety of conditions and circumstances that could impact the behavior of fires following an earthquake. However, there are certain limits to what the model can incorporate.

For example, AIR was unable to explicitly account for arson in the wake of the earthquake. Some building owners without earthquake insurance look to fire as a financial scapegoat. Additionally, the fire following model is limited in its ability to predict explosions and resulting fires caused by an earthquake. These rare cases are simply treated as normal fire ignitions. When a tsunami inundates a populated area, it can ignite chemical fires as cars full of gasoline smash into buildings or other dangerous ignitions sources are disturbed, the model is unable to predict this highly localized ignition behavior, and AIR implicitly accounts for these ignitions in normal ignition rate function. Sometimes, a fire may ignite that is suppressed before it can do any serious damage, often by civilians, and thus a fire department response is not necessary. AIR does not model the damage caused by fires unless the fire department is required to successfully suppress them.

Tsunami

Modeling tsunami for a large subduction zone earthquake requires detailed information on the geometry of the subduction zone and the slip distribution of the design earthquakes over its rupture area. The details of the slip distribution, the slip direction (rake), and the dipping angle control the vertical uplift of the ocean floor and thus scale the tsunami waves in open ocean. The relative location of the subduction zone with respect to the coast, the geometry of the subduction zone, and the slip distribution on the rupture plane also control the scale and spatial distribution of the subsidence or uplift at different coastal areas which could result in a more or less severe tsunami impact.

It is practically impossible to predict the slip distribution of future earthquakes. However, the information on the slip distribution of past earthquakes could provide guidance for constructing realistic scenarios. Additionally, during the last decade a number of studies have successfully used GPS data to explore the state of coupling of subduction zones. The observation on the slip distribution for some of the recent large subduction interface earthquakes have demonstrated that there is a very good correlation between the observed slip distribution and the predicted pattern from the GPS-based studies, e.g. 2010 Maule M8.8 earthquake of central Chile.

Accordingly, AIR seismologists constructed a physical model for the Cascadia subduction zone and used regional GPS data, as is described in the report, to estimate the state of coupling for the subduction zone state. Following the results from Maule earthquake, the results of our study were interpreted that regions with the highest coupling coefficients will have the highest likelihood for experiencing large displacements. AIR seismologists also compiled information on the maximum displacement for some past subduction zone earthquakes. This information in conjunction with the magnitude and the rupture area were used to put further constraints on the slip distribution for the Cascadia type earthquake. Using this data and allowing for some randomness in parameters, scenarios for slip distribution on Cascadia were simulated.

10 Appendix—Glossary

Acceleration: A measure of the level of ground shaking that results from an earthquake.

Actuary: A Fellow of the Canadian Institute of Actuaries and professional who is skilled in the application of mathematics to financial and insurance problems.

Attenuation: The decrease in size of waves as they radiate from their source. Seismic waves become attenuated as they move away from the source of an earthquake.

Bathymetry: The underwater equivalent of topography, describing the measurement of depth along ocean or lake floors.

Commercial lines: Category of insurance protecting the real and personal property of businesses and non-profit organizations.

Crust: The outermost major layer of the earth, between 10 and 65 km in thickness worldwide. The uppermost 15-35 km of crust is brittle enough to produce earthquakes.

Damage ratio: Ratio of the cost to repair a building to the cost of replacing it.

Deductible: The share of loss that the policyholder agrees to pay out-of-pocket before the insurance company pays the remainder of a claim. A deductible may either be a flat amount or a percentage of the total value, depending on the policy. A deductible of 10% applied to a $150,000 claim on a $300,000 policy indicates that the policyholder will pay $30,000 and the insurer $120,000.

Demand surge: The temporary inflation of prices and labor costs, and the resultant increases in the time and cost required to repair and rebuild damaged property after a catastrophic event.

Displacement (for earthquake and liquefaction): The amount a point on the ground has moved from where it was before an earthquake.

Displacement (Tsunami): The amount of vertical movement of a large volume of water due to the motion of the seafloor during earthquake. For example a 5 m displacement would refer to the surface of the water being lifted or dropped 5 m in the area above a fault.

EP curve: An exceedance probability (EP) curve is a graph that describes the probability that various levels of loss will be exceeded in a one year period.

Exposure: Insured property that is exposed to a risk.

Exceedance probability: A way of expressing the probability that a given loss will occur or be exceeded in a given period of time. A 1.0% annual exceedance probability is a 1.0% chance that the loss will occur or be exceeded in any given year; a loss with this annual exceedance probability is a 100 year return period loss. See also EP Curve.

Fire following: Fires that break out following an earthquake as fuel comes into contact with a source of ignition, such as an overturned stove or shorted electrical line.

Ground motion: Ground shaking caused by an earthquake.

Intensity: The severity of an earthquake in terms of its effects on the earth's surface and on humans and their structures. Though it can have only one magnitude, an earthquake's intensity will be experienced differently in different locations. Several scales exist to describe intensity.

Kinematic: Refers to the general movement patterns and directions of the earth's crust that produce crustal deformation.

Limit: The maximum amount that an insurer will pay over a given period of time or over the life of the policy. A limit can either be a flat amount or a percentage of the total value, depending on the policy. A limit of 100% indicates that the insurer will cover 100% of eligible losses after deductibles are applied.

Liquefaction: A phenomenon in which earthquake shaking temporarily reduces the strength and stiffness of a soil that is both composed of unconsolidated sediments and saturated with water.

Loss: The dollar amount associated with a claim.

Loss return period: A statistical measurement typically based on historical data denoting the average recurrence interval for a loss of a given size, and is usually used for risk analysis.

Magnitude: A number characterizing the relative size of an earthquake, based on measurement of the maximum motion recorded by a seismograph.

Moment: Seismic moment is a measure of the size of an earthquake based on the area of fault rupture, the average amount of slip, and the force that was required to overcome the friction sticking the rocks together that were offset by faulting.

Moment magnitude: This, the latest concept in magnitude determination, is based on the seismic moment of an earthquake and is a measure of the energy released from the entire rupture.

Natural frequency: The frequency at which a particular object vibrates when pushed by a single force, unhindered by external forces or damping.

Peak acceleration: The largest rate of change in ground velocity recorded by a particular station during an earthquake.

Peril: The cause of a possible loss. Earthquake, flood, hurricane, and tsunami are examples.

Personal property lines: Category of insurance protecting residences, possessions, and personal automobiles of private individuals or families from unexpected losses.

Probabilistic: A statistical term applied to processes that have probability-based characteristics.

Recurrence interval: The average time span between earthquake occurrences on a fault or in a source zone.

Replacement value: The value of an asset as determined by the estimated cost of replacing it.

Residential lines: Category of insurance protecting private property such as homes and their contents.

Return period: (1) A way of expressing the probability of a given annual loss occurring in a given period of time. A 100-year return period for example, which can also be expressed as a 1.0% exceedance probability—means a 1.0% chance that the loss will occur in any given year. (2) The average time span between earthquake occurrences on a fault or in a source zone.

Seismic: Of, subject to, or caused by an earthquake.

Seismicity: The geographic and historical distribution of earthquakes.

Seismic wave: Waves of energy that travel through the earth's layers and are a result of an earthquake.

Spectral acceleration: What is experienced by a building, as modeled by a particle on a massless vertical rod having the same natural frequency as the building. This is the component of acceleration at a particular period of oscillation.

Standard deviation: A statistical measure of spread or variability—how much a set of data is different from the best-fit curve when plotted on a graph. Or, the square root of the average of the squares of deviations about the mean of a set of data.

Stochastic: A statistical term applied to processes that have random characteristics.

Subduction: Geologic process in which one edge of one crustal plate is forced below the edge of another.

Tectonic: Refers to rock-deforming processes and resulting structures that occur over large sections of the earth's crust and uppermost mantle. Tectonic plates are the large and relatively rigid plates that form the outer surface of the earth, whose movement relative to one another causes earthquakes.

Tsunami: A series of waves caused by the displacement of a large volume of ocean or lake water. The name is Japanese and means "harbor wave"; it has been generally adopted to replace the misleading term "tidal wave."

Workers' compensation: A form of commercial insurance that covers workers' wages and medical expenses.

11 Appendix—Collaboration

11.1 Biographies of Partners:

AIR would like to express our appreciation to the following individuals for their invaluable collaboration efforts in this study. The reports provided by our partners to summarize the work completed have been provided as a separate addendum.

Robert McCaffrey, Ph.D.

A research professor in the Department of Geology at Portland State University, Dr. McCaffrey applies his expertise to the study of crustal deformation processes. Specifically, Dr. McCaffrey utilizes the Global Positioning System (GPS), earthquake statistics, and active faults to probe the deformational characteristics of Earth's major tectonic plates, subduction zones, and plate margins.

Dr. McCaffrey is a leader in understanding the crustal deformation in the Pacific Northwest, Cascadia subduction zones, the Sumatra island of Indonesia. Dr. McCaffrey has been studying the deformation kinematics of western North America plate margin since 1996.

His work on the deformation of the Cascadia subduction zone and shallow crustal in the western U.S. and Canada will be incorporated into the earthquake hazard model of the upcoming national hazard map update of the U.S.. As a partner in this study, Dr. McCaffrey provides AIR various types of GPS, active fault data along with the model setup for crustal blocks and constraints. In addition, Dr. McCaffrey assists in the formulation of a logic tree that helps AIR capture the main sources of uncertainty in interpreting GPS data for western Canada.

Through his participation in this study, Dr. McCaffrey helps AIR ensure that spatial variation of the coupling coefficients for the Cascadia subduction zone, as well as for other seismic sources in western Canada, are correctly incorporated into the model. Dr. McCaffrey has authored or coauthored 85 peer-reviewed, scientific manuscripts including 10 on the crustal deformation process germane to the Pacific Northwest region.

Oh-Sung Kwon, Ph.D.

A professor in the Department of Civil Engineering at the University of Toronto, Dr. Kwon has been carrying out research in the field of earthquake engineering for the past twelve years. His major research interest is on seismic performance and fragility assessment of civil structures through reliable numerical and experimental methods.

He developed seismic fragility curves of a typical non-seismically designed reinforced concrete structure and a typical bridge structure of Midwest America. He also carried out an in-depth investigation of hybrid (numerical-experimental) simulation methods in which a part of a structure can be represented experimentally and the rest are modeled numerically. In this method, the substructures are analyzed or tested concurrently interacting with each other through a network.

The simulation method can take advantage of strengths of both experimental and numerical simulations which allow more accurate assessment of seismic performance of structures. Using the simulation method, he is currently investigating the seismic fragility of steel structures with self-centering energy dissipating brace system.

He participated in field reconnaissance missions after 2005 Hurricane Katrina, 2007 Peru Earthquake, and 2010 Chile Earthquake and co-authored reports and journal papers on the fragility of civil structures due to the natural disasters.

Professor Kwon is a secretary of ASCE Performance Based Design of Structures Committee, a member of ACI 341 Performance Based Design of Bridges Committee, and an associate member of ACI 374 Performance Based Seismic Design of Concrete Buildings. He also served as a member in the Requirement Analysis and Assessment Subcommittee in Network for Earthquake Engineering Simulation (NEES).

Dan Wei, Ph.D., Research Assistant Professor, University of Southern California

Dr. Wei is a Research Assistant Professor in the Price School of Public Policy at the University of Southern California (USC). She received her Ph.D. in Geography from Penn State University and has been active in research in environmental policy, economic impact analysis, and the economics of natural hazards and terrorism.

She performed the macroeconomic impact analysis of state climate action plans for several state and conducted the analysis of cap and trade and/or carbon tax policies for several states and regions in the U.S. She is the co-author of a study for the U.S. Coast Guard on the impacts from and resilience to a shutdown of a major U.S. port, developing a capability to perform rapid impact analyses for disasters for Cal EMA, and studying the economic impacts of the USGS ShakeOut Earthquake Scenario and SAFRR Tsunami Scenario.

Her research has been published in journals such as *The Energy Journal*, *Environment and Planning A*, *Earthquake Spectra, International Regional Science Review*, *Climate Policy*, *Energy Policy*, *Regional Science Policy and Practice, Contemporary Economic Policy, and Economic Systems Research*.

Adam Rose, Ph.D.

Adam Rose is a Research Professor in the USC Sol Price School of Public Policy, and Coordinator for Economics at USC's Center for Risk and Economic Analysis of Terrorism Events (CREATE).

Much of Professor Rose's research is on the economics of natural and man-made hazards. He recently served on a National Research Council panel on Earthquake Resilience and as co-PI of a DHS-sponsored study examining tradeoffs and synergies between urban security and commerce.

Previously, he was the lead researcher on the Multi-Hazard Mitigation Council report to the U.S. Congress on the net benefits of FEMA hazard mitigation grants, and he coordinated 8 studies to arrive at a definitive estimate of the economic consequences of 9/11.

A major focus of his research has been on resilience to natural disasters and terrorism at the levels of the individual business, market, and regional economy.

Michael L. Lahr, Ph.D., Associate Research Professor, Rutgers University

Dr. Lahr is Associate Director of Rutgers Economic Advisory Service (R/ECON™). As Associate Research Professor of Planning and Public Policy at Rutgers University, he teaches urban economics and the application of advanced econometric techniques.

Dr. Lahr has supervised R/ECON™ research on a broad array of public policy issues in the fields of housing, economic development, program evaluation, and fiscal and economic impact analysis.

He has published over 30 articles in journals and edited volumes on economic modeling techniques; development economics; the economics of various planning and fiscal issues; the economic impacts of catastrophes; and the mobility of poor families.

In addition to being co-editor of The Review of Regional Studies, Lahr sits on the editorial boards of the Journal of Regional Science, Economic Systems Research, and Papers in Regional Science. He has co-edited three books and two journal special issues.

He is presently is President of the Southern Regional Science Association, Vice President of the International Input-Output Association, Treasurer of the Benjamin H. Stevens Graduate Fellowship of the North American Regional Science Council, and a member of both Bordentown City Environmental Commission and Bordentown City Planning Board.

12 Appendix—Peer Review Reports

12.1 Biographies of Peer Reviewers:

AIR would like to thank the following individuals for their outstanding assistance in providing professional peer review of various components of AIR's model.

Keisuke Himoto, Ph.D.

Dr. Keisuke Himoto is on the faculty of Kyoto University. He received his Ph.D. in Architectural Engineering from Kyoto University and is an expert in the field of disaster management and prevention.

Dr. Himoto developed a physics-based fire spread model to estimate potential damage from fires following earthquakes. He was the co-organizer of "Urban and Wildland-Urban Interface (WUI) Fires: A Workshop to Explore Future Japan/USA Research Collaborations" (2011) sponsored by the National Institute of Standards and Technology (NIST) and has surveyed damage following many natural catastrophes, including the Niigataken Chuetsu-oki earthquake (2007) and the Tohoku earthquake (2011).

Dr. Himoto's research interests include physics-based modeling of large outdoor fires, and disaster mitigation city planning.

Stephane Mazzotti, Ph.D.

Dr. Stephane Mazzotti, a professor in the Geosciences Department of the University of Montpellier, France, specializes in the geodynamics, earthquake hazards, and tectonic processes in active margins and continental intraplate regions using GPS, seismicity, and other geophysical data.

Dr. Mazzotti's past work has contributed to improved seismic hazard analysis in regions such as the Cascadia subduction zone, the Queen Charlotte transform fault margin, and the Yakutat-Northern Canada Cordillera collision system. Prior to joining the faculty at the University of Montpellier, Dr. Mazzotti worked for eight years as a seismologist for the Geological Survey of Canada.

Marie-José Nollet, Ing. Ph.D.

Dr. Nollet is professor of structures at the Construction Engineering Department at École de Technologie Supérieure of Montreal, Québec, Canada.

She has conducted research on the seismic vulnerability of structures and on the development of seismic vulnerability evaluation tools for the City of Québec, the Ministry of Transportation, and the Ministry of Education of Québec. Her work also includes the development of fragility curves for buildings with a focus on masonry buildings for risk assessment studies.

She is presently collaborating with the Geological Survey Canada on a risk assessment project. She is an active member of the research team DRSR at ETS (Development and Research in Structure and Rehabilitation), the "Centre d'étude Interuniversitaire des structures sous charges extrêmes (CEISCE)" and the strategic project on "Post-earthquake Functionality of Schools and Hospitals in Eastern Canada."

She is the author of more than 40 papers and 15 expert reports. She received her civil engineering degree from Université Laval (Québec, Canada) and her Ph.D. in structural engineering from McGill University (Montreal, Canada).

Geoff Thomas, Ph.D.

Dr. Geoff Thomas is a faculty member of the School of Architecture at Victoria University of Wellington, New Zealand.

He is an active researcher in several aspects of the fire following earthquake field, including the study of post-earthquake fires, the assessment of the fire resistance of timber structures, and modeling the behavior of building components subject to fire.

Dr. Thomas has authored and co-authored numerous papers related to fire safety, fire behavior of buildings and fires following earthquakes and presented at numerous international conferences on the topic.

Dr. Thomas, working in collaboration with researchers at the Institute of Geological and Nuclear Sciences, developed a cellular automata based fire following model that provides the framework of AIR's new approach to modeling fires following earthquake.

Peer Review Report of the AIR Fire Following Earthquake Model for Canada

Keisuke HIMOTO, Dr.Eng.

This is a peer review report of the new "AIR Fire Following Earthquake Model for Canada", a risk assessment and management tool for insurers, reinsurers and others which will be released in 2013. This review report is based on the peer review workshop held on August 27th 2012 and a report on the following model update issued on December 19th 2012.

1. Brief Summary of the Model

The model divides city area into a number of city blocks which represent variability of burning characteristics. Burn area functions for respective characteristic city blocks are obtained by conducting the cellular automata based fire spread simulation. The resulting city block burning patterns are then extended to larger areas to estimate fire spread between city blocks. The goal of the model is to estimate potential fire following losses for earthquakes in 10,000-100,000 scenario years of simulated earthquake activity, making use of the industry exposure database, to estimate annual probabilities of fire following losses exceeding certain levels.

a. Data Sources

The model uses variety of country-wide data sources on land use, building configuration and distribution data, wind speed and direction data, fire suppression data including the location and number of fire engines, and ground motion data. The requirement on the data is strict that they must cover the entire county to conduct risk assessment using a single risk scale. From this viewpoint, the data sources used in this model are ones of the few data sources which meets the requirement at this time.

b. Characteristic City Block

The model introduces the concept of "characteristic city block" representing the variability of burning characteristics. Burn area functions obtained for respective characteristic city blocks are used for estimating fire spread between city blocks.

By using data on building separation, size, height, combustibility and occupancy type, actual city blocks are classified into 20 characteristic city blocks for Canada. The characteristic city blocks include pure residential, commercial, apartment buildings types, as well as those of mixed usage.

c. Ignitions

Ignition rate should be carefully modeled because it is a critical parameter for the risk assessment, i.e., the risk is very sensitive to the ignition rate. The ignition model by Scawthorn (2009) is used. The model predicts the number of ignitions as a function of peak ground acceleration, which is calculated using a ground motion equation plus local site amplification.

d. City Block Scale Fire Spread

Burn area functions for respective characteristic city blocks are obtained by conducting the cellular automata based fire spread simulation. Cellular automata modeling is a common approach for the fire spread simulation in city area. In this cellular automata model, a city block is divided into 3m by 3m grid cells which are assigned uniform burn properties based on the structures they represent. Progress of burn state of a cell and successive fire spread between cells are modeled based mostly on the work done by Thomas, Heron and Cousins. As a matter of course, the result of fire spread simulation should change due to the assumptions of the model, e.g., those on fire growth rate inside a building or fire spread probability between buildings. The model parameters are determined empirically, but with consideration to fire safety characteristics of cities of Canada. As for the validation of the new model, rate of fire spread in a hypothetical urban area is simulated. The result is compared with that of the existing fire spread models and reasonable agreement is obtained.

e. Regional Fire Spread

Characteristic city blocks are randomly distributed within a 1km by 1km grid cell according to the land use and occupancy data of the grid cell. Each grid cell contains 25 blocks for Canada. The probability of fire spread between blocks is estimated by using a probability curve originally developed by Scawthorn with an adjustment to the "calm wind no suppression" crossing probability based on branding research. With this probability curve, whether or not a fire will spread depends on wind speed, wind direction, suppression, and firebreak width. It is reasonable to divide target city area into a number of city blocks to involve variability of burn characteristics into fire risk estimation.

f. Suppression

The model uses data on location and number of fire engines for the entire country. Following a certain period of discovery and reporting time, fire engines at the nearby fire station moves to the ignition point. The effectiveness of suppression is determined based on two factors, i.e., number of fire engines and amount of water flow available. Damage functions of buried pipelines based on peak ground velocity and permanent ground displacement are used to estimate the amount of available water flow at the fire site. The effectiveness of suppression is also dependent on the size of a fire at the arrival time of fire engines. The schematic of the suppression model is well organized. The effectiveness of suppression is logically modeled by comparing the fire phase and water availability which both change with time.

2. Strengths of the Model

Strength of the model is that it can estimate the risk of post-earthquake fire spread for the entire country of Canada using a sole risk scale. Ones of the major tasks to accomplish this were: (1) maintaining the model reliability while minimizing the computational load to conduct the country-wide computation; and (2) acquiring standardized country-wide data for unbiased evaluation. As for (1), the model took an approach of representing city block scale burning characteristics of target city area by that of manageable number of "characteristic city blocks". Instead of estimating risks of individual buildings and converting them into a real risk, the model uses burn-area functions of "characteristic city blocks" to model the burning of blocks that experience primary ignitions caused directly by the earthquake, and other blocks to which fire spreads, thus estimating the post-earthquake fire risk to the entire region affected by the earthquake. As for (2), the model uses the country-wide data sources on land use data, building configuration and distribution data, wind speed and direction data, and fire suppression data including the location and number of fire engines. They are integrated and converted to important prerequisites of the risk assessment.

In addition, the model can conduct integrated risk assessment of fire following earthquake by using the full advantage of the AIR's accumulated knowledge and skills on earthquake hazard and vulnerability modeling. This includes the use of the 10,000-100,000 years stochastic catalogue for the evaluation of seismic motion, modeling damage of water supply pipelines due to ground motion and deformation, etc. They are the critical prerequisite for reliable estimation of ignition and structural damage of target city area, but are generally not considered in fire risk assessments in the past.

3. Applicability of the Model to the Cities of Canada

The model is intended to estimate the risk of fire following earthquake for the entire country of Canada. The new model introduces the "characteristic city block" concept to maintain the computational load at the manageable level, and at the same time, to make full use of the standardized country-wide data sources. Because earthquake itself is a rare event in Canada, the new model was validated by the data of the past fire following earthquake events in countries other than Canada. However, the model parameters were adjusted to correctly represent fire safety characteristics of cities in Canada. Thus, the new model is considered to be one of the most appropriate models to evaluate the fire following earthquake risk of cities of Canada.

Keisuke HIMOTO, Dr.Eng.

Review of "AIR Earthquake Hazard Model for Canada"

Dr. Stephane Mazzotti, Prof. of geodesy and geophysics

Univ. Montpellier 2, France

This review consists of comments, questions and notes about the document "Overview of the AIR Earthquake Hazard Model for Canada" provided by the AIR Worldwide hazard group. The various comments and questions are presented in the order of appearance in the report, with appropriate page numbers. Some of the points are only minor and relate to the form of the documents, a few points are more significant and relate to the core of the hazard model.

Overall, the documents provided (Overview and Appendix) give a very clear, well explained, and well documented report of the AIR earthquake hazard model. A significant effort is made to integrate the most recent scientific knowledge and information in the model. These recent developments are well referenced, and are discussed in terms of their impact and significance (e.g., integration of geodetic data). The earthquake hazard model is built on the most recent science and knowledge for the region considered, including some unpublished data.

Dr. Stephane Mazzotti, Prof. of geodesy and geophysics

Univ. Montpellier 2, France

In Montpellier, Sunday Feb. 10th, 2013

Review of "AIR Earthquake Vulnerability Model for Canada"

Dr. Marie-José Nollet, Professeure, Département de génie de la construction

École de technologie supérieure, Montréal (QC) Canada

This review consists of comments, questions and notes about the document "Overview of the Vulnerability Component of the AIR Earthquake Model for Canada" provided by the AIR Worldwide earthquake vulnerability group.

This document summarizes the assumptions and approach taken in the AIR vulnerability module for calculating shake damage in buildings. It outlines the vulnerability assessment framework in the model and elaborates on how the model captures the temporal and spatial variation of vulnerability. The document also discusses the generation of vulnerability (damage) functions and presents the validation process, including preliminary results for historical events.

The document was sent to the reviewer in January 2013 and a 2 hour workshop was held on February 8th, 2013 during which AIR presented and discussed the model and reviewer made the initial feedback and comments on the methodology and approach.

Upon receiving the written feedback and comments, AIR responded to the questions and implemented the feedbacks in the model. Majority of the feedbacks concerned the definition of building classes used in the model (compared to the Canadian building inventory) and on the "age bands" used in the model to distinguish the vulnerability of buildings built in different era. In particular, the peer reviewer pointed out that the province of Québec uses a different construction code than the National Building Code of Canada (NBCC). Moreover, some comments were made on validating the damage estimation module in which we compare AIR damage functions with some expert-opinion based damage functions from the USA and Canada.

A revised document to address the peer reviewer comments was submitted and the final peer review report was received in April 2013. In general the peer reviewer approved the modeling approach and assumptions and agreed with the responses AIR provided. Further recommendations were made regarding the building classifications and construction split in certain regions in British Columbia and Québec provinces. The full report is presented separately.

Peer Review of The AIR Fire Following Earthquake Model for Canada

by

Geoff Thomas, B.E. (Hons), M.E., PhD, MSFPE, C.P.Eng, Int.PE (NZ)

School of Architecture

Victoria, University of Wellington

Wellington, New Zealand

Version C, 31st January 2013.

Model Summary

This model is designed to provide an estimation of potential country wide losses arising from fire following earthquake. It uses a cellular automation approach and is mostly based on the work by Cousins et al (2002), Thomas et al (2012), Himoto and Tanaka (2010) and Zhao et al (2006 & 2011) with input data from HAZUS and Scawthorn (2009). Geospatial and other data are taken from what appears to be the best reasonably available data sources in Canada.

Fire spread parameters are based on fire physics and the work referenced above. As it is a total loss model, timing of fire spread is not significant apart from consideration of the timing of commencement of fire suppression.

The model is based on typical blocks of different types that model a range of building configuration and layouts. These are combined according to data on land use to form cells that represent an area in the model. Fire spread is calculated within the block using cellular automata and fire spread to other blocks is assessed based on wind speed and direction, and firebreak width.

Suppression is modeled based on notification times, travel speed to fire, firefighting resource availability and water availability.

Review of the Model

This review is based on the report "Overview of the AIR Fire Following Models for Japan and Canada" (Air Worldwide 2012a), a PowerPoint presentation on 28th August 2012 by Erik Olson, Ken Lum and Anna Morgante of AIR worldwide, and the report "Updates to the Air Fire Following Model for Japan and Canada" (AIR Worldwide 2012b)

Overall model concept

A more comprehensive model is highly desirable. The previous models were based on Hamada's equations, which include few variables and are based on historic Japanese data, so are less likely to be appropriate for other countries and to a lesser extent modern Japan.

A higher resolution model is also more desirable. The rapid speed of the model is highly advantageous as it allows for multiple simulations and sensitivity analysis.

The model predicts a damage ratio for fire, which is expected to be modified when considering losses from multiple hazards in an overall risk model.

Data sources

Land use data

As I am not familiar with the availability of land use data in Canada it is difficult to comment other than to say that one can only use what is available and what is being used appears to be the best reasonably available data.

Building configuration and distribution data

Again as I am not familiar with the availability of building data in Canada it is difficult to comment other than to say that one can only use what is available and what is being used appears to be the best reasonably available data.

Characteristic City Blocks

This approach is a good way of characterising the built environment without having to identify and describe all the buildings in a country, something which is obviously not feasible and is a more realistic approach than assuming buildings of regular size and spacing.

Block Distribution

Again given the impossibility of surveying all the buildings in a country and inputting them individually into a model this is a good way of characterising the buildings in an area.

The correlation between observed and calculated floor area when the block distribution is applied is not perfect, but I do not believe that a significantly better comparison could be achieved without surveying many of the buildings in the country.

Wind speed and direction data

The model incorporates an adjustment to the wind speed distribution at the higher end compared with the best-fit Weibull distribution for recorded data which allows for the fact that wind speeds can exceed well over 35 km/h, but such high wind speeds may not have been adequately included in the wind data (1991-2010) used for the model.

The model ignores topographical and local wind effects. Obviously on a model of this scale it is not possible to characterise all of these, however higher localized wind speeds and variation in direction and dynamic changes in wind speed and direction are likely to increase fire spread as the wind gusts and directions change to a greater extent than any potential reduction in fire spread due to localized areas where topographical shielding and lower local wind speeds occur.

Fire suppression data including the location and number of fire engines

Our modelling (Cousins et al. 2002, Thomas et al. 2012) ignored suppression due to the low population density and distance between main centres in New Zealand and because, Wellington where our case study was centred is not expected to be accessible by road after a major earthquake, suppression is not something we have studied in depth. However in terms of water supply, informal sources such as surface water have been accounted for.

Fire station locations in Canada have been assumed based on population in areas where data is incomplete.

Earthquake ground motion.

Not an area of expertise.

Ignition rate calculation and ignition timing

This is the best data available and limiting the derivation of the equation to data accumulated since 1974 has to some extent limited the effect of the trend of decrease in rates of ignition over time. In earlier earthquakes such as San Francisco 1906 and Kanto 1923, potential ignition sources, such as open fires, wood and coal fuel stoves, and gas lighting were more common.

Also as societies become more affluent quality of appliances, electrical systems and so on have also improved. The more widespread provision of items such as gas shut-off valves and heightened awareness of utility operators in regard to delaying timing of re-establishing service supply will also reduce the rate of ignitions since 1974. It is likely that the expected ignition rate in a future earthquake will be less than in past earthquakes, but there is insufficient data to establish the magnitude of any such trend, and if we only rely on very recent earthquakes then the data set for establishing an ignition rate equation becomes very limited.

This reducing trend is expected to follow, but not to the same extent as the reduction in fires that has occurred in normal conditions over time.

The Scawthorn equation is based on California data. Ignition rates are strongly affected by the presence or absence of gas reticulation, with 29% of fires with known causes after the Kobe earthquake being caused by gas (Hokugo 2002). Reducing the ignition rate by say 30% may be appropriate in areas without gas reticulation, but this reduction may be less in areas where portable and non-reticulated gas appliances are common.

The model assumes that the ignition rate increases at a rate approaching peak ground acceleration (PGA) squared compared with PGA, above a PGA of about 0.7g. There is little data from higher PGAs and although only one event, the Tōhoku earthquake, with very high PGAs recorded had relatively fewer ignitions. At high PGAs it is likely that most buildings have been damaged to some extent, causing ignitions from damaged wiring, piping and appliances.

As the PGA increases it may be that there is little difference in ignition rate as most of the ignitions that could occur could already have occurred at a lower PGA. To extrapolate the ignition rate beyond a PGA of 0.8, based on data for PGAs below 0.8 is difficult to justify and a high degree of variation in ignition rates above a PGA of 0.7g should be assumed.

Temporal distribution

This seems reasonable and is based on the best available data, but with increased awareness by utilities of the perils of turning on energy supplies early, in the future it is likely the tail will lengthen as the fires that are initiated when energy supplies are restored occur at a later point in time.

Fire Spread

The use of characteristic blocks is much more realistic than using uniformly sized and spaced buildings.

The cell numbers for spread in Thomas et al. (2012) were based on a radiator height of 4.5m, based on a single storey building with some flame projection. If a building has two or more floors on fire, spread becomes more likely, but the increase in view factor is less than linear, particularly for wide emitters.

Branding is extremely difficult to predict and the definition we used is different from the one that appears to be used in North America. We treated sparked and piloted ignitions separately and defined brands as items that were large enough to sustain combustion and ignite other material without incident radiation. There is a continuum in size between sparks with little energy and requiring at least 12.5 kW/m2 of incident radiation to ignite and those that can ignite other material without incident radiation. There is also the potential for showers of sparks, as

described by Manzello et al (2006, 2008a, &2008b) which cannot ignite a substrate individually but may do so as a group. Manzello describes such sparks as "brands".

The values used for branding are reasonable, but larger spread distances are possible.

The distance and probability of ignition from a neighbouring roof is not well justified, but there is no data available to support any values.

Conditional Probabilities for Fire Spread via Windows

The conditional probabilities used for window sizes in Thomas et al (2012) were based on a survey of buildings in Wellington, New Zealand's, Central Business District. The degree of consistency is apparent because these buildings were built, for the most part, to the current or previous New Zealand code requirements for building separations. There is a large degree of continuity in these requirements over time in New Zealand and they were originally based on United Kingdom practice with some North American and Australian influence. They were

traditionally based on experience of fire spread and more recently on calculations of radiation.

Canadian codes in this respect have some similarity with New Zealand, but I would expect some differences in code requirements and building practice, hence the size and proportion of windows in buildings in Canada in relation to boundary distance is likely to be different and hence the conditional probabilities of fire spread as a function of building separation would differ. These

probabilities have been altered to better reflect Canadian building stock. The values given appear reasonable, but I cannot comment on their accuracy as I have not seen the raw data.

Adjoining roofs

There is little information on the probability of fire spread from adjacent lower roofs and the value of 6m from Thomas et al.2012, was based on the New Zealand Building Code Acceptable Solutions value of 5m, increased to 6m to allow for the 3m cell size. This value seems to be gaining a lot of use but is not well justified.

Implementation of the cellular automata model

The cell counting method was used in our work (Cousins et al. 2002, Thomas et al. 2012) because it suited the data we had and allowed for very rapid simulations. A direct calculation for radiation based on actual emitter dimensions and target distance will always give a more accurate result for each individual radiation calculation. On the other hand such calculations require detailed knowledge of individual buildings, with height in particular being difficult to ascertain from available data. If direct calculations were to be used, then the number of simulations that can be carried out on each block may be reduced, with the potential to reduce the overall model reliability to a greater extent than the enhanced accuracy by calculating radiation directly would improve it. The model has been compared with Himoto and Tanaka's (2009) model with good results.

Time step

Cellular automata is a valid method for determine fire spread. The time step is critical in trying to model the timing of historical fires, but has little influence on total losses, except where it interacts with a suppression model. The time step used in Cousins et al (2002) of 2.5 minutes was increased to 10 minutes to model the timing of spread in the Napier and Kobe fires and a time step of 5 minutes may have been more appropriate (Thomas et al. 2012). It may be more appropriate to increase the number of time steps taken for fire to spread by modes other than direct contact. Reducing the probability of spread at each time step will have the same effect of slowing the extent of fire spread. As this model is to estimate total loss, this has little effect, other than when the timing of the commencement of fire suppression model is significant.

The timing of fire spread has been compared with Himoto and Tanaka's (2009) model with reasonable results but further validation against urban fires and other models is recommended.

Firebreak crossing

This is based on crossing probability as a function of wind speed and direction, effective suppression and firebreak width from Scawthorn et al. (2005) with reduced probabilities for the "calm wind no suppression case". These values seem reasonable and are the best set available.

The model assumes that there is a 25% probability of spread by branding over 25m, which is less than the 50% probability suggested by Scawthorn et al. (2005). Anthenien, Tse, and Fernandez-Pello (2006), found that spread by branding over more than 25m in calm winds was unlikely, a finding I concur with. This model has assumed an intermediate value of 25%.

The work on determining average firebreak widths between blocks is good; the rule that fire cannot spread to an already ignited block may limit spread to a small extent in some limited circumstances, but is unlikely to be significant and will affect the rate of fire spread more than the extent.

The assumptions that the time to spread across a firebreak is related to the fire spread within the block and the reduction in ignition probability of 50% for blocks which contain only noncombustible buildings is a reasonable assumption given the lack of available data.

The model assumes vegetation is not combustible. This may not be the case, depending on vegetation types and recent weather conditions.

The firebreak width may be reduced, or the firebreak completely filled with fallen debris, which can increase the likelihood of fire spread across a street. Similarly earthquake damage to claddings may facilitate fire spread between buildings that otherwise have non-combustible claddings.

Suppression

Discovery and reporting of Fires

The times from HAZUS for discovery and reporting of fires are really the only ones available and seem reasonable, however the tail will be extremely long and some fires may never get reported until they become obvious by their large size if they spread.

As well as a reduction in speed of travel for firefighting appliances there is also potential for appliances to not be able to reach a site. This possibility has been allowed for in the Japan model but not in the Canada model. Although it is less likely to be an issue in Canada than Japan it still may occur. This may be due to debris on the street near to a site, or debris blocking roads on the way. This problem will be more likely and more severe in cities where the street pattern is based on a limited number of routes between areas. In cities with a highly gridded street pattern and multiple routes to different areas, it will be less of an issue, but time will be taken up with vehicles having to back track and find alternative routes.

It is assumed a small fire can be extinguished using water carried on fire appliances, but for larger fires effectiveness of suppression is partly based on water availability, based on probability of pipe breakages which is a reasonable approach. Effectiveness is also based on fire appliance availability compared to the size of the fire. This approach is straightforward and the variation in likelihood of suppression for specific fires will be averaged out in the prediction of overall losses over multiple areas and multiple simulations.

Model Strengths and Weaknesses

Given the current state of knowledge, and the limited data due to the limited number of events to gather data from, the model is as good as can reasonably be expected. It is a substantial improvement from the previous model that used Hamada's equations. There are a number of assumptions for different inputs as discussed in the previous sections, but these have to be made because of the lack of available data.

The use of typical blocks is a good approach to modeling a country without having to go into a level of detail that is obviously impractical.

The use of cellular automata and cell counting to determine spread within blocks is cruder than direct calculations of radiation, but is computationally much less expensive and in my opinion the ability to run more simulations with randomized variables and carry out broader sensitivity studies with a faster model more than compensates for the less accurate calculations of fire spread.

The model is also a framework for future development. Different parts of it could be revised in the future, for example the cell-counting technique changed to direct calculations and different firebreak spread models used.

There is the uncertainty around timing. This does not directly affect the extent of losses; however the timing of spread, especially between blocks is critical along with timing of suppression, which is also highly uncertain, when determining the extent of fire spread.

Localized wind effects may increase the extent of fire spread, however the degree of data collection and modeling effort required to address this issue is difficult to justify.

The model does not allow for fire spread through debris in firebreaks that may negate or reduce the effect of firebreaks in slowing or preventing fire spread. Nor does it allow for damage to non-combustible claddings leading to increased possibility of fire spread. Ignoring local wind effects, flammable vegetation, debris in firebreaks and damage to noncombustible claddings will reduce the expected loss, but the likelihood in the future that ignition rates after earthquakes will be lower will compensate for this.

Fitness for Purpose

As a model to predict the extent of losses in an estimation of fire following losses on a countrywide basis for 10,000-100,000 years of stochastically generated events this model, given the limitations of current knowledge and poor data available, is as good as can be reasonably expected.

Any user of the output from this model must be aware that there is a significant possible variation in results, particularly when looking at smaller areas and/or single events.

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14 Appendix—Exposures

14.1 Developing the Industry Exposure Database for Canada

The inventory of property and infrastructure exposures for Canada is referred to as the industry exposure database (IED). The IED contains counts of properties and infrastructure and their respective replacement values, along with information about the occupancy and physical characteristics of these exposure counts, such as construction types and height classifications for buildings. This database provides a foundation for loss estimates in Canada due to earthquake and associated perils.

An overview of the process used to create the IED is seen in Figure 111 below. Exposure counts are counts of properties or infrastructure, such as buildings or kilometres of road.

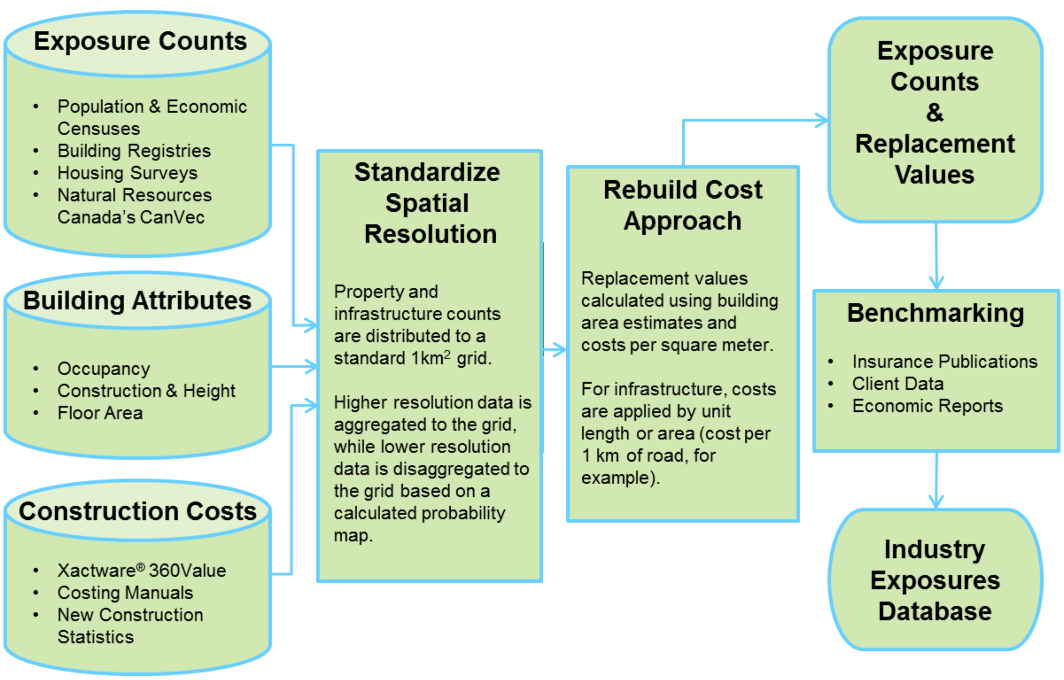

Figure 111: IED development process

This section provides additional details regarding the development of the IED for Canada that were not discussed in the main body of the report.

14.2 Developing Structural Type and Height for Buildings in the IED

Building attributes such as construction type and height are key components of the IED. The classification of buildings by structural type plays an important role in catastrophe modeling because differences in construction materials, quality and design all have a significant impact on building vulnerability and hence modeled loss estimates. Consequently, AIR has invested significant time and effort in creating a construction distribution for the Canada IED, which captures the proportion of buildings represented by various structural types—such as wood frame, masonry, concrete frame and steel frame.

AIR's methodology, however, did not simply identify the number of wood, concrete, or steel buildings; rather, the focus was on obtaining an understanding of how changes in engineering and construction practices, as well as variations in the built environment due to influences from urbanization, economic development, and planning laws, impact the construction distributions for Canada.

The starting point in developing the construction distribution was gathering information about the characteristics of the building stock. AIR construction engineers also collected and analyzed data as they relate to construction codes and practices from sources such as censuses, published surveys and engineering journals. These data sets were used to derive structural type, occupancy, and height relationships.

In classifying the building stock, buildings were grouped according to their main structural characteristics, namely construction material, the load resisting mechanism and height. This categorized the building stock into a sufficient number of distinct classes so that each is unique in terms of its structural response to the dynamic loads imposed by different hazards.

Leveraging additional sources such as land use plans (GIS layers) and building code requirements enabled a more realistic characterization of each structure, such as its location relative to other buildings and a particular hazard. Thus the correlation between structural type, hazard, construction practices and location was captured.

Figure 112 shows the steps used in developing the structural type and height attributes of the buildings in the IED. Infrastructure and automobiles are excluded from this process.

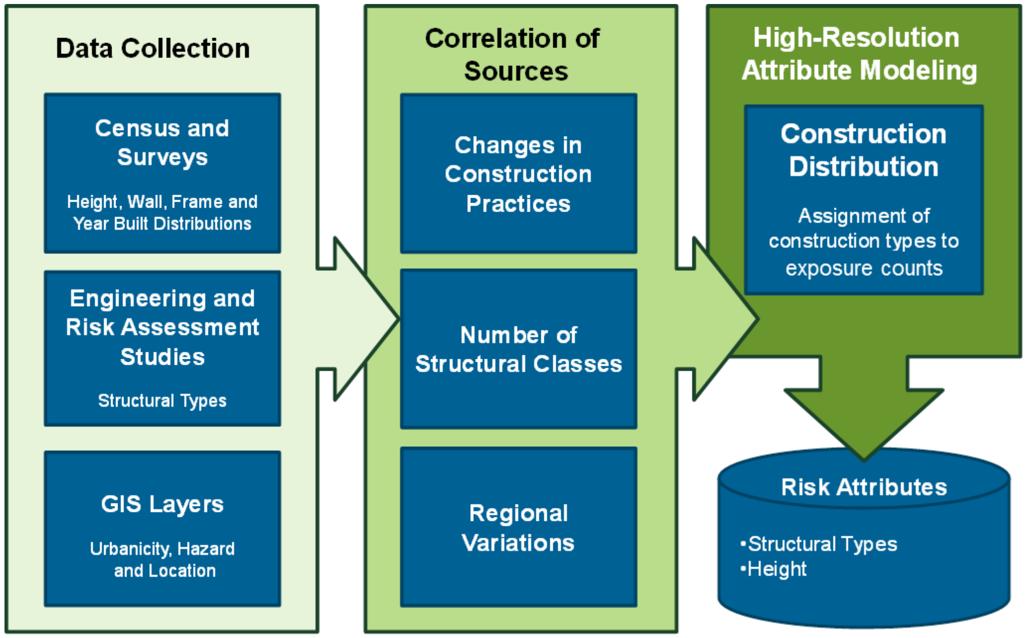

Figure 112: Developing structural type and height for buildings in the IED

14.3 Data Validation

AIR corroborated its raw data sets against alternative regional and global data sets containing reported building and economic attributes. When anomalies were discovered, additional research was conducted to verify any questionable data. The list of statistics validated includes, but is not limited to:

- Population per dwelling
- Dwellings per apartment building
- Share of dwellings represented by single-family homes and apartments
- Average dwelling sizes for single-family homes and apartments
- Ratios of dwelling sizes between single-family homes and apartments
- Population per commercial establishment
- Population per industrial establishment
- Ratio of commercial establishments per industrial establishment

- Total commercial employees
- Total industrial employees
- Total commercial employees as a share of population
- Total industrial employees as a share of population
- Average employees per commercial establishment
- Average employees per industrial establishment
- Automobiles per person
- Residential and commercial vehicles per person
- Residential vehicles per commercial vehicle

All of the data sets used, or created, in the IED development process were also validated spatially within each region. The list of statistics spatially validated includes, but is not limited to:

- Exposure counts per km^2 by occupancy type
- Unemployment rate
- Per capita income
- Average rebuild costs per building by occupancy type
- Average rebuild costs per dwelling by occupancy type
- Average rebuild costs per m^2 by occupancy type
- Total value per km^2 by occupancy type

Aggregate benchmarking

In addition to checking the input data sets, AIR benchmarked its national total values against various independent sources, such as gross capital stock and client data aggregates. The benchmark was compared to the total values from the all property database, which includes all properties or infrastructure eligible for insurance.

Gross capital stock

Independent valuations of building stock, called gross capital stock, are available for Canada from the National Accounts. Gross capital stock (GCS) is made up of several components, including commercial and residential buildings, roads and bridges, and transportation like ships and trains. For each of these components, it contains estimates of the replacement cost. The values for residential and commercial building stock are directly comparable to the aggregate residential and commercial building values in the all-property database.

In addition to the GCS reported in Canada's National Accounts, AIR estimated the GCS using its own methodology. This modeled GCS starts with annual changes in capital stock, called gross fixed capital investment, or GFCI. The GFCI contains new additions to the capital stock as well as subtractions when something is taken out of service or demolished. After modeling a starting value for each component of GCS for a fixed point in time, for example 1970, the annual GFCI up to the current year was summed and added to the initial capital stock, resulting in the estimated GCS. Then this estimated GCS was inflated to get current value in today's currency and compared to the GCS reported in Canada's National Accounts.

Client data

Because AIR had access to a large amount of client data covering much of the insured industry in Canada, client data was a valuable validation tool for the IED. A key validation analysis performed with client data was a market share analysis. In this analysis, the estimated market share for the client data was calculated by dividing the all-perils client aggregate data by the estimated industry insured aggregate. This market share was then compared with published insurance market reports from various insurance industry sources, including the latest AXCO Insurance Market Reports.

Client estimates of the insured market were divided by the industry all-property estimate to derive a market penetration rate, or the percentage of all properties that are actually insured for a given peril. This information was then used to validate the estimated industry all-property aggregates and the AIR-estimated market penetration rates.

When client data contained detailed information, such as data on both exposure counts and values, several additional validation analyses were possible. For example, the average value per exposure count was calculated and compared with industry average values. Client coverage splits (percent of building, appurtenant structures, contents, and ALE/BI coverage) was also compared to estimated industry coverage splits. Attribute data such as construction and year-built distributions, and policy conditions, such as deductibles and limits, were also compared between client data and industry estimates.

While client data was a valuable tool for validation, there were also challenges to analyzing this data. For instance, because many comparisons were performed according to occupancy type, any differences in mapping the occupancy type between clients and the industry created the potential to skew analysis results. In addition, because AIR received client data from several sources, such as insurers, reinsurers, brokers, and insurance associations, instances of data duplication had to be taken into account. Furthermore, there was inherent uncertainty in the reported market shares and it was not always clear what measure was used to calculate a reported market share.

15 Appendix—Data Sources

The primary data sources used in the development of each component of the AIR Earthquake Model for Canada are as follows:

Earthquake Shake
Historical earthquake catalog data from Geological Survey of Canada (J. Adams, personal communication, 2012)
U.S. Geological Survey - PDE and significant earthquake database. Available online: http://earthquake.usgs.gov/earthquakes/eqarchives/epic/
U.S. Geological Survey (Wesson et al., 2007 and Peterson et al., 2008)
Division of Geological and Geophysical Surveys of Alaska (Koehler et al., 2012)
Canadian Base Network (Craymer et al., 2011)
Elliott et al. (2010)
Leonard et al. (2007, 2008), Campaign and Continuous
Mazzotti at al. (2011)
McCaffrey et al. (2012)
GSC (Adams and Halchuck, 2003)
2011 paper by Dr. John Adams of the GSC
Atkinson and Goda (2011)
Abrahamson and Sliva (2008)
Boore and Atkinson (2008)
Campbell and Bozorgnia (2008)
Chiou and Youngs (2008)
Chouinard and Rosset (2007, 2011)
Motazedian et al. (2011)
Hunter et al. (2010)
Ventura et al. (2004)
Monahan et al. (2000)
Fulton, R.J., Compiler, 1996, Surficial materials of Canada, Geological Survey of Canada, Map 1880A
Klassen, R.A., Paradis, S. Bolduc, A.M., and Thomas, R.D., 1992: Glacial landforms and deposits, Labrador, Newfoundland and eastern Québec, Geological Survey of Canada, Map 1814A
Surficial Geological Map, Urban and Environmental Geology of St. Lawrence Valley, Natural Resources Canada, Government of Canada, 2004 - 2010
Prest, V.K., and J. Hode-Keyser, Surficial Geology, Montreal Island, 1975
Chouinard Luc and Rosset Philippe, Microzonation of Montreal, variability in soil classification, 4th IASPEI/IAEE International Symposium, August 2011
Urban and Environmental geology of the St. Lawrence Valley, Surficial Geology, Government of Canada, Earth Sciences Sector of Natural Resources Canada, 2010

Earthquake Shake
Utting, D.J., B.E. Fisher, A.L. Ehler, Digital geological data generated as part of the surficial mapping project of the Halifax metropolitan and surrounding areas, Halifax and Hants countries, Nova Scotia, 2011
Ontario Geological Survey and Geological Survey of Canada, 2003, Surficial geology of Southern Ontario.
Ontario Geological Survey, 1997, Quaternary geology of Ontario-seamless coverage of the province of Ontario: Ontario Geological Survey, ERLIS Data Set 14.
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Quaternary geological map of Metro Victoria, Patrick A. Monahan and Victor M. Levson, 2000.
Geological Survey of Canada, 1980, Surficial geology, New Westminster, British Columbia
Geological Survey of Canada, 1979, Surficial geology, Vancouver, British Columbia
Geological Survey of Canada, 1980, Surficial geology, Mission, British Columbia
Geological Survey of Canada, 1980, Surficial geology, Chilliwack, British Columbia
Massey, N.W.D., MacIntyre, D.G. Desjardins, P.J. and Conet, R.T., 2005, Digital Geology Map of British Columbia, B.C. Ministry of Energy and Mines, Open File 2005-2
Liquefaction & Soil Maps
Groundwater Information Network (GIN) water well data base. Geological Survey of Canada / Natural Resources Canada. Available online: http://analysis.gw-info.net/gin/public.aspx
British Columbia Groundwater Observation Well Network. Available online: http://www.env.gov.bc.ca/wsd/data_searches/obswell/map/obsWells.html
The Canadian Digital Elevation Data (CDED). Available online: http://www.geobase.ca/geobase/en/data/cded/description.html
Geological Survey of Canada, 1980, Surficial geology, New Westminster, British Columbia, scale 1:50,000.
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Relative Liquefaction Hazard Map of Metro Victoria, Patrick A. Monahan, Victor M. Levson, Paul Henderson, and Alax Sy, scale 1:25,000, 2000.
Liquefaction Hazard Map of Richmond, British Columbia, Patrick A. Monahan, Victor M. Levson, Ben Kerr, scale 1:20,000, 2010.
Preliminary Liquefaction Potential Map of Chilliwack Area, Victor M. Levson, Patrick A. Monahan, Daniel G. Meldrum, (B.C. Geological Survey) scale 1:20,000, 2010.
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National Climate Data and Information Archive. Available online: http://climate.weatheroffice.gc.ca/prods_servs/index_e.html
Fire Following Earthquake
Land use data from Agriculture and Agri-Food Canada (2005)
Impervious surface data from the National Geophysical Data Centre (2012)
LandScan population data from Oak Ridge National Laboratory (2007)
Building densities data from Natural Resources Canada CanVec Data (2011) and Geografx Digital Mapping Services (2011).
Wind speed and direction data obtained from Integrated Surface Hourly data from National Climatic Data Centre (2010).
Fire station location data obtained from Natural Resources Canada CanVec data set (2011) and municipal fire departments public information (2012)
Tsunami
Bathymetry and elevation: NOAA ETOPO Relief Model (2009)
Bathymetry: National Geophysical Data Centre – South Alaska (2011)
Bathymetry: National Geophysical Data Centre – Strait of Juan de Fuca (2003)
Bathymetry: National Geophysical Data Centre – Northern California (2006)
Elevation: United States Geological Survey 30m National Elevation Data (NED)

Tsunami
Elevation: Geobase Canada 23m Digital Elevation Data
Levee data: developed internally
Land Use Land Cover (LULC): 150m Resolution: Commission for Environmental Cooperation North America LULC (2005)
WWW Tide and Current Predictor, http://tbone.biol.sc.edu/tide/
Shake Vulnerability
National Building Code of Canada (1953-2010)
Internation Building Code (IBC) 2000-2009
Claims data from the 1994 Northridge earthquake, obtained from the California Department of Insurance (DOI) and private insurers.
Damage reports from 1989 Loma Prieta earthquake, the 2003 San Simeon earthquake and the 2008 Chino Hills earthquake, obtained from the Office of Emergency Services (OES) in California.
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17 About AIR Worldwide

AIR Worldwide (AIR) is the scientific leader and most respected provider of risk modeling software and consulting services. AIR founded the catastrophe modeling industry in 1987 and today models the risk from natural catastrophes and terrorism in more than 90 countries. More than 400 insurance, reinsurance, financial, corporate, and government clients rely on AIR software and services for catastrophe risk management, insurance-linked securities, detailed site-specific wind and seismic engineering analyses, and agricultural risk management. AIR is a member of the Verisk Insurance Solutions group at Verisk Analytics (Nasdaq:VRSK) and is headquartered in Boston with additional offices in North America, Europe, and Asia. For more information, visit www.air-worldwide.com.