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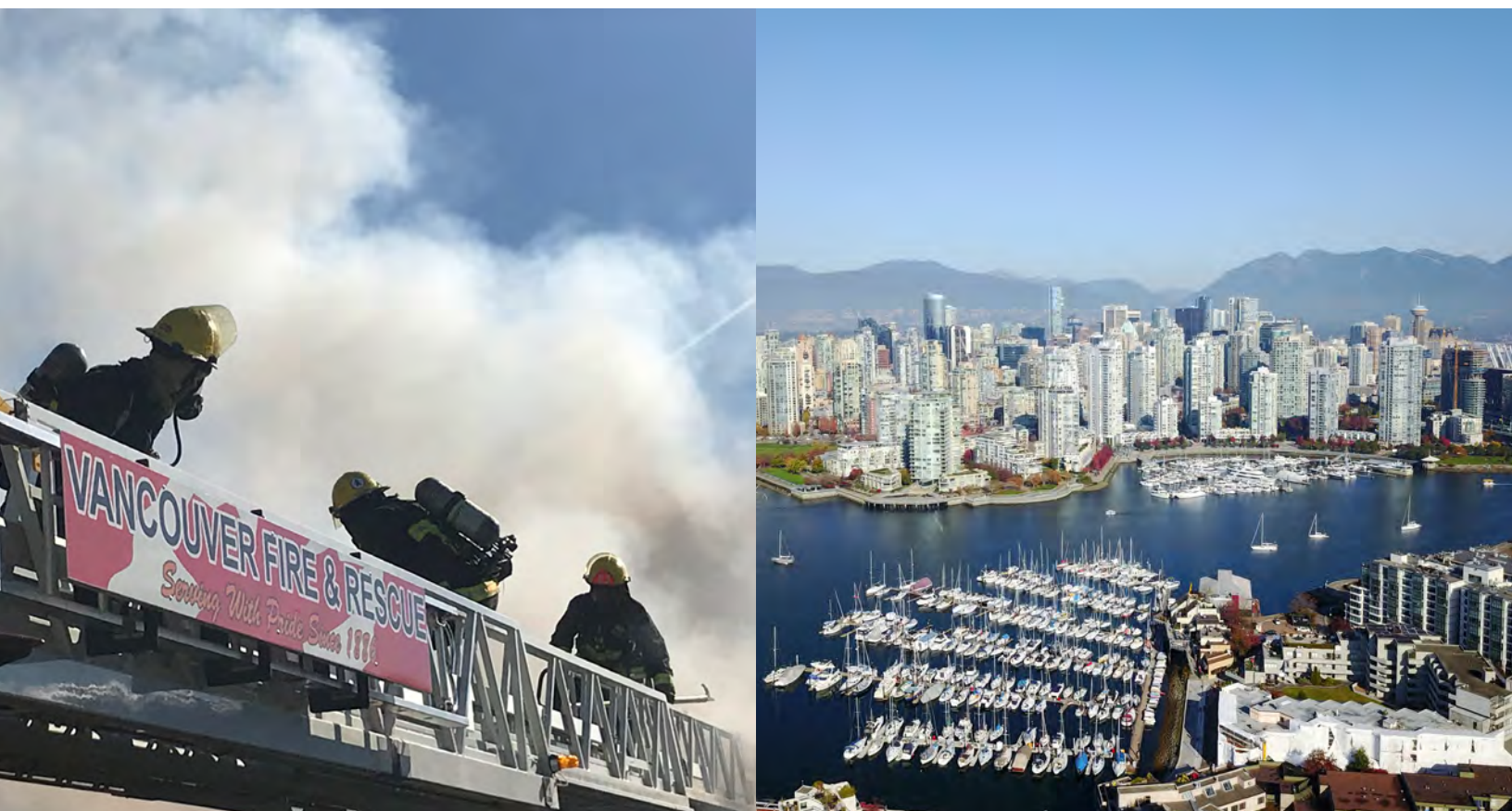
SPA Risk LLC

## Fire following earthquake in the Vancouver region

Prepared for the Institute for Catastrophic Loss Reduction

By Charles Scawthorn, S.E.

November 2020





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SPA Risk LLC

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# Abstract

The Lower Mainland of British Columbia has significant earthquake hazard and potential for ground motions that will cause significant damage to ordinary buildings and infrastructure. Earthquakes are sometimes followed by major fires, whose damage can greatly exceed the shaking damage.

To assess the risk of fire following earthquake and identify opportunities to reduce the risk, five scenario events are examined for the number of fires and amount of firespread they would cause: two distant events: a Mw 9.0 Cascadia Subduction Zone event and a relatively distant Mw 7.3 event on Vancouver Island; and three relatively nearby events: a deep in-slab Mw 6.8 event on the subducting Juan de Fuca Plate, a Mw 7.3 event in the Georgia Strait just to the west of the city of Vancouver, and a Mw 6.5 shallow crustal event centred on the city of New Westminster.

Accounting for fire department response, water system damage, weather and other conditions, the growth and ultimate final burnt area of fires are estimated to result in losses from nil to \$10 billion.\* These are median estimates – there are significant probabilities of greater or less damage, and the range is a function of the specific earthquake scenario (i.e., location and magnitude), time of day, weather and other factors.

This loss would be almost entirely insured and would have a very significant impact on the Canadian insurance industry. Fire losses would come on top of shaking and other losses, which would be insured to a lesser extent. A leading global reinsurer has stated that losses of this magnitude would likely result in failure of some insurers, would entail secondary and contingent losses, and could conceivably lead to financial contagion.

This risk need not be tolerated and indeed the Province of British Columbia, City of Vancouver, and regional agencies such as Metro Vancouver and BC Hydro have implemented excellent programs to reduce this risk. Further actions, however, can still be taken to reduce the risk of fire damage and include creation of a regional portable water supply system and providing secondary water supplies for high-rise buildings.

Lastly, two things should be noted about this study: (1) it has focused solely on fire following earthquake – there are many other ways in which a major earthquake will cause damage, which haven't been treated here; (2) this report has not assessed the seismic vulnerability of the gas distribution or other energy industry assets, many of which are concentrated in the highly liquefiable Fraser River Delta. In this respect, two actions have been de rigueur in other regions and should be considered in the Lower Mainland: (a) a review of the overall seismic vulnerability and reliability of major energy facilities; (b) a review of the gas distribution operator's ability to control and isolate its transmission and distribution networks in the event of a major earthquake, and consideration by the gas distribution operator of incorporating an automatic gas shutoff device in gas meters.

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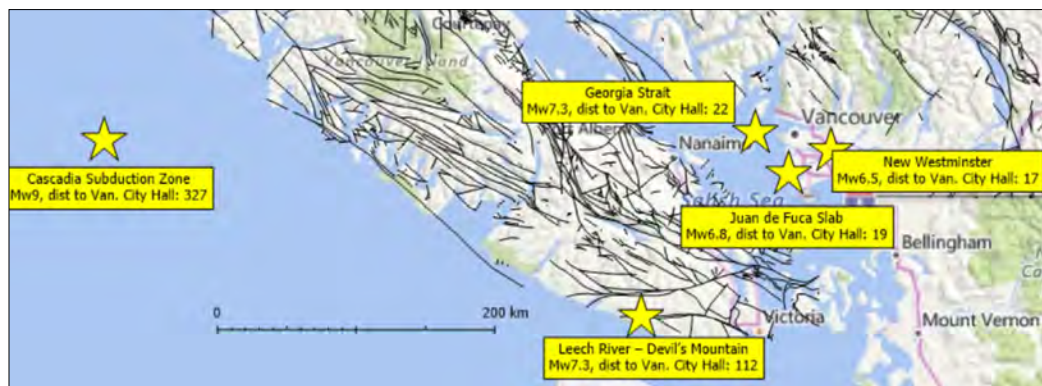
\* All dollar amounts are in Canadian dollars, unless otherwise indicated.

## Executive summary

The Geological Survey of Canada assesses the Vancouver region as having significant earthquake hazard and potential for ground motions that will cause significant damage to ordinary buildings and infrastructure. The region suffered a magnitude 9.0 earthquake in 1700 on the Cascadia Subduction Zone, which is considered likely to re-occur in the near future.

Earthquakes are sometimes followed by major fires, whose damage can greatly exceed the shaking damage. To assess the risk of fire following earthquake and identify opportunities to reduce the risk, five scenario events are examined for the number of fires and amount of firespread they would cause: two distant events: a Mw 9.0 Cascadia Subduction Zone (CSZ) event and a relatively distant Mw 7.3 event on Vancouver Island (Leech River–Devil’s Mountain, or LRDM); and three relatively nearby events: a deep in-slab Mw 6.8 event on the subducting Juan de Fuca Plate (JDF), a Mw 7.3 event in the Georgia Strait (GS) just to the west of the city of Vancouver, and a Mw 6.5 shallow crustal event centred on the city of New Westminster (NWM), as shown in Figure ES-1.

**Figure ES-1: Scenario events, this study. Black lines are mapped surface faults.**



Accounting for fire department response, water system damage, weather and other conditions, the growth and ultimate final burnt area of fires are estimated to result in losses from nil to \$10 billion, as shown in Table ES-1.

These are median estimates – there are significant probabilities of greater or less damage, and the range is a function of the specific earthquake scenario (i.e., location and magnitude), time of day, weather and other factors (see section 4 for details).

This loss would be virtually fully insured and would have a very significant impact on the Canadian insurance industry. Fire losses would come on top of shaking and other losses, which would be insured to a lesser extent. A leading global reinsurer has stated that losses of this magnitude would likely result in failure of some insurers, would entail secondary and contingent losses, and could conceivably lead to financial contagion.

**Table ES-1: Median number of fires, large fires and losses (in billions \$).**

Scenario	EQ1 Mw 9.0 CSZ	EQ2 Mw 6.8 JDF	EQ3 Mw 7.3 LRDM	EQ4 Mw 7.3 GS	EQ5 Mw 6.5 NWM
Median ignitions	16	106	4	216	93
Median no. large fires	0.6	31	0.02	47	29
Median losses in billions \$	\$0.16	\$7.4	\$0.01	\$10.7	\$7.2

This risk need not be tolerated and indeed the Province of British Columbia, City of Vancouver, and regional agencies such as Metro Vancouver and BC Hydro in recent decades have implemented excellent programs to reduce this risk. Further actions, however, can still be taken to reduce the risk of fire damage. For example, the fire service in the Lower Mainland is modern, advanced, well-equipped and of a high caliber in its organization, methods and tactics. The earthquake risk is understood and appears to be a focus for fire departments and, as a result, Vancouver has built a specialized high-pressure dedicated fire protection system and a defence in depth, with fireboats, hose tenders and hose reels, as well as training citizen volunteer Neighbourhood Emergency Assistance Teams (N.E.A.T.s). Other departments need to follow this model, tailored to their needs. We recommend development of an integrated regional Portable Water Supply System (PWSS) of hose tenders / hose reels, with compatible fittings, that can be used to access alternative water supply sources and relay water to the fireground. Such a regional system would also benefit from a number of HydroSubs®\* among the various larger departments and would have wider applicability than just earthquake – it can be used for wildfires, dewatering flooded areas and other emergency needs.

A significant number of, but not all, high-rise buildings in Vancouver are sprinklered, to the region's credit, as is the City's requirement that all new construction – low- as well as high-rise – be sprinklered. However, sprinklers rely on underground water mains for supply, which are likely to fail in a major earthquake. This was recognized decades ago in the California Building Code, which requires a secondary on-site water supply in high seismicity zones for firefighting purposes – typically about 60,000 litres. Vancouver and the Provincial Building By-laws lack a similar provision, which we recommend should be seriously considered. Retrofitting existing high-rise buildings with 60,000-litre water tanks may seem a large and expensive task, but actually it isn't. Such a tank would take up the equivalent of perhaps two parking spaces in a basement parking garage, for example, and the cost would be significantly less than 1 % of the value of the building – perhaps on the order of the cost to renovate the building lobby.

Lastly, two things should be noted about this study: (1) it has focused solely on fire following earthquake – there are many other ways in which a major earthquake will cause damage, which haven't been treated here; (2) this report has not assessed the seismic vulnerability of the gas distribution or other energy industry assets, many of which are concentrated in the highly liquefiable Fraser River Delta. There is a long history of major energy facilities being damaged in earthquakes,

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\* We use the eponym HydroSub® to refer to hydraulic driven portable submersible floating pump(s) linked to a prime mover (e.g., diesel powered hydraulic powerpack) that permit quick access to and pumping from water sources such as rivers and lakes. It should be noted that while HydroSub® is a commercial trade name of Hytrans Systems, similar systems are manufactured by other companies (e.g., US Pump), and that the term HydroSub® is used here as an eponym. ICLR does not endorse commercial products.



including by fire, so this aspect should not be ignored. Additionally, particularly in winter, millions of people are dependent on energy services. While we didn't address energy industry aspects, in this respect two actions have been de rigueur in other regions and should be considered in the Lower Mainland: (a) a review of the overall seismic vulnerability and reliability of major energy facilities; (b) a review of the gas distribution operator's ability to control and isolate its transmission and distribution networks in the event of a major earthquake, and consideration by the gas distribution operator of incorporating an automatic gas shutoff device in gas meters. Following the 1995 Kobe earthquake, Japan replaced every gas meter in the country with meters incorporating an automatic gas shutoff device, so the technology is well-established and the cost quite nominal if meters are being replaced for other reasons. The opportunity afforded by the operator's plan to replace these meters for more efficient operation permits inclusion of the seismic shutoff device at a very modest marginal cost.

This study was aided by many persons in the region – we met with a number of fire, water, city and emergency planning and other officials, whose assistance was generously provided and is gratefully appreciated. Natural Resources Canada (NRCan) generously provided assistance and data, which contributed to this study and which is also gratefully acknowledged.

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## Short forms

AWS	Alternative water supplies
AWSF	Alternative Water Supply Factor
CatIQ	Catastrophe Indices and Quantification Inc., a catastrophe data provider, see <a href="http://www.catiq.com">www.catiq.com</a>
CSZ	EQ1 Mw 9.0 Cascadia Subduction Zone event
DFPS	Dedicated Fire Protection System
FRA	Fire Response Area
GMPE	Ground motion prediction equation
gpm	Gallons per minute
GS	EQ4 Mw 7.3 Georgia Strait shallow crustal event
Igpm	Imperial gallons per minute
JDF	EQ2 Mw 6.8 Juan de Fuca Plate in-slab event
LDH	Large Diameter Hose (typically, 5" [125mm] or larger diameter)
LRDM	EQ3 Mw 7.3 Leech River–Devil's Mountain shallow crustal event
MMI	Modified Mercalli Intensity
NRCan	Natural Resources Canada
NWM	EQ5 Mw 6.5 New Westminster shallow crustal event
PGA	Peak ground acceleration
PGD	Permanent ground displacement
PGV	Peak ground velocity
PWSS	Portable Water Supply System
TFA	Total floor area
TIV	Total Insured Value
VFRS	Vancouver Fire Rescue Services
Vs30	Shear wave velocity of the upper 30 m of soil
WSF	Water Supply Factor
WUI	Wildland-urban interface





# 1. Introduction

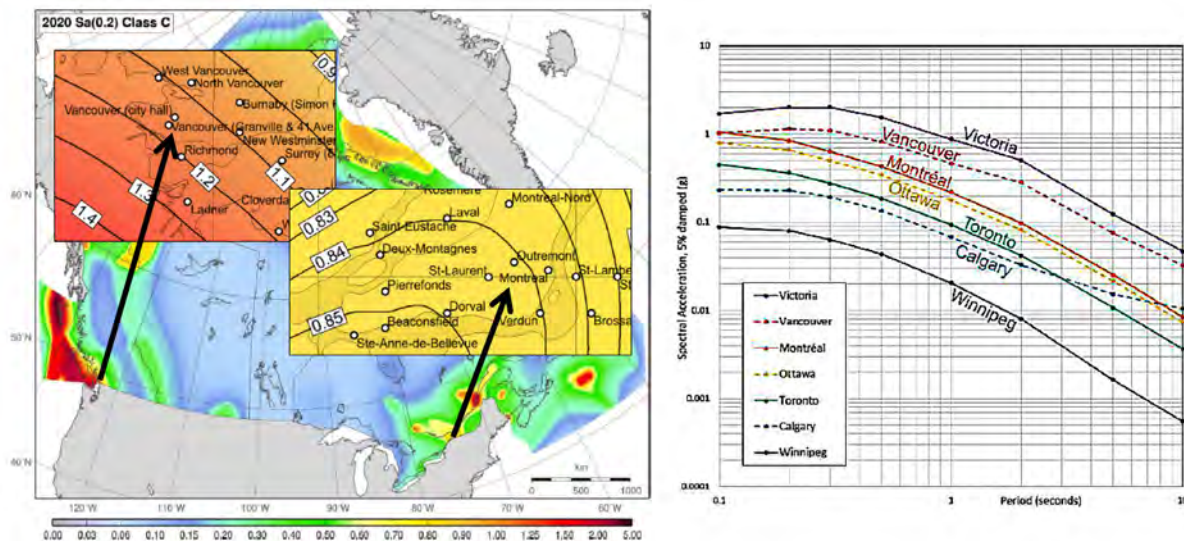
## 1.1 Purpose

*Fire following earthquake* refers to a series of events or a *stochastic process* initiated by a large earthquake. Fires occur following all earthquakes that significantly shake a human settlement but are generally only a very significant problem in a large metropolitan area predominantly comprised of densely spaced wood buildings. In such circumstances, the multiple simultaneous ignitions can lead to catastrophic conflagrations that may be the dominant agent of damage for that event. Such regions – high seismicity, densely spaced wood buildings – are the regions at highest risk of post-earthquake fire, and include Japan, New Zealand, parts of Southeast Asia and North America including the Lower Mainland of British Columbia.

## 1.2 Background

The Lower Mainland of British Columbia has a significant risk of earthquake shaking. Geologic and seismologic studies have led the Geological Survey of Canada and the National Building Code of Canada to rate the likelihood of peak ground acceleration at Vancouver as among the highest for a major city in Canada (Adams et al. 2019), Figure 1.

**Figure 1: Seismic hazard for major Canadian cities (Adams et al. 2019). Note that 2%/50-year peak ground acceleration (PGA) for Vancouver is 0.49g.**



$S_a(0.2)$  for Canada (mean values of 5% damped spectral acceleration for Site Class C and a probability of 2%/50 years, units = g).

Uniform Hazard Spectra for mean 2%/50-year ground motions on Site Class C for key cities.

Large earthquakes are sometimes followed by large fires. Large fires, for example measured in terms of square miles of burnt area, have not been unique to fires following earthquakes – indeed, the great fires of London (1666) and Chicago (1871) are only the most noteworthy of a long succession of non-earthquake related urban conflagrations. Among these was the Great Vancouver Fire of 1886, which killed 21 and destroyed 600~1,000 buildings (Matthews 1960), Figure 2.

**Figure 2: Sketch showing 1886 Great Vancouver fire extent (drawing made in 1932 based on interviews with survivors)**

(Source: <https://www.vancouverheritagefoundation.org/place-that-matters/crab-park-the-great-fire/75-54-the-great-vancouver-fire-major-matthews-sketch-1930/>).



Large urban conflagrations were actually the norm in 19<sup>th</sup> Century North America, so that long experience allowed the National Board of Fire Underwriters to state with some confidence when considering another North American city (NBFU 1905):

“...In fact, San Francisco has violated all underwriting traditions and precedent by not burning up. That it has not done so is largely due to the vigilance of the fire department, which cannot be relied upon indefinitely to stave off the inevitable.”

While the 1906 San Francisco earthquake had major geological effects and damaged many buildings, it was the fire that resulted in 80% of the total damage – a fire foreseen and expected, irrespective of an earthquake.

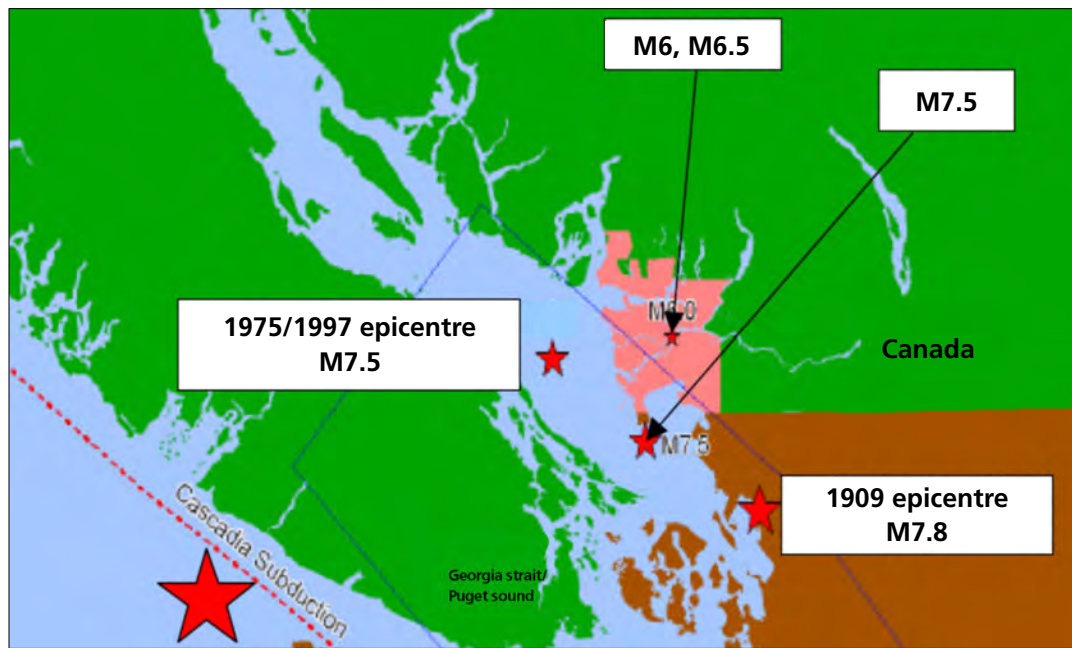
As the fire service was professionalized in the 20<sup>th</sup> Century, however, with improvements in equipment, communications, training and organization, large urban conflagrations tended to become largely a thing of the past (National Commission on Fire Prevention and Control 1973). Largely, but not entirely, however, as witnessed in the 1991 East Bay Hills Fire where 3,500 buildings were destroyed in a matter of hours, in Fort McMurray Canada in 2016 where more than 2,500 dwellings were destroyed, in 2017 in Northern California where 10,000 buildings were destroyed, in 2018 in Northern California where 20,000 buildings were destroyed, or in 2019 and 2020 when large wildland-urban interface (WUI) fires spread throughout western North America. While these losses were WUI fires, they show that even a single ignition can lead to the overwhelming of regional fire agencies. After an earthquake, there will be many ignitions, as well as many other demands on fire agencies. It is worth noting that the two largest peace-time urban conflagrations in history have been fires following earthquakes: 1906 San Francisco and 1923 Tokyo, the latter resulting in the great majority of the 140,000 fatalities.

Although a combination of a professionalized fire service, improved water supply and better building practices have been thought to have largely eliminated large urban conflagrations in the U.S., there is still a gap – an Achilles Heel – which is fire following earthquake. This is due to the correlated effects of a large earthquake, simultaneously causing numerous ignitions, degrading building fire resistive features, dropping pressure in water supply mains, saturating communications and transportation routes, and thus allowing some fires to quickly grow into conflagrations that outstrip local resources. It is not sufficiently appreciated that the key to modern fire protection is a well-drilled rapid response by professional firefighters during the early stages of structural fires, who arrive in time to suppress the fire while it is still manageable. A typical response goal for urban fire departments, for example, is about four minutes from time of report to arrival. If suppression is delayed, due either to delayed response or lack of water, a single structural fire can quickly spread to neighbouring buildings and grow to the point where an entire municipality's fire resources are required, and perhaps even assistance from neighbouring communities. This is for a *single* ignition. Simply put, most fire departments are not sized or equipped to cope with the multiple simultaneous fires following a major earthquake. A major earthquake and its associated fires is a low-probability event for which, although having very high potential consequences, it may not be feasible to adequately prepare. There are exceptions to this – San Francisco Fire Department, Los Angeles City Fire Department and Vancouver Fire Rescue Services have all undertaken special measures.

### **1.3 Previous studies**

Several previous studies of how the Lower Mainland would be affected by an earthquake are relevant. An aspect of the fire-following-earthquake problem in the Lower Mainland has been the concern for reliable firefighting water supply in the region. Water supply for the City of Vancouver is discussed below, but in summary is mainly from north of Burrard Inlet, and in the late 1980s was identified as significantly vulnerable to an earthquake. This concern heightened in the late 1980s when the City sold its only fireboat. A 1990 study (EQE Engineering 1990) found "... the City has inadequate in-city water storage, such that...less than a day's supply...and little or no emergency water supply...." finding that "... emergency water demand is estimated to be 20,000 to 30,000 lpgm... [or] ...approximately 12 million gallons...[and]... Vancouver emergency water capabilities are virtually non-existent..." This situation has to be, to some extent, offset by the construction and deployment of the Dedicated Fire Protection System (DFPS), which is discussed below.

**Figure 3: Scenario events studied in EQE (2001).**



A qualitative examination of the situation in the city of Vancouver concluded that conditions were such that "...likely to result in the vulnerability of Vancouver to post-earthquake fires exceeding that of San Francisco or Los Angeles and approaching more closely to that prevailing in Japanese Cities" (Robertson and Mehaffey 1998).

Losses due to fire following earthquake in the Lower Mainland were first studied in detail in 2001 (EQE 2001). Based on the seismotectonics of the region, several scenario earthquakes were analyzed and are shown in Figure 3. The study area was basically the Metro Vancouver area, with building exposure and values as shown in Table 1.

**Table 1: EQE (2001) Building square footage and values (Loss in 2001 millions \$).**

City	Total bldg. area (millions sq. ft.)	Total bldg. value (2001 \$ M)	Total content value (2001 \$ M)	Total value (2001 \$ M)
Burnaby	222.4	20,512	9,447	30,181
City of North Vancouver	17.6	1,341	693	2,052
Coquitlam	96.5	7,990	4,335	12,422
Delta	70.4	5,810	3,224	9,104
District of North Vancouver	102.3	8,625	4,459	13,186
New Westminister	82.6	7,076	3,909	11,068
Port Coquitlam	32.9	2,695	1,515	4,243
Port Moody	16	1,357	769	2,142
Richmond	214.1	16,901	8,783	25,898
Surrey	197.4	16,768	8,900	25,865
Vancouver	713.7	63,937	27,774	92,425
West Vancouver	32.6	2,703	1,395	4,131
<b>Total</b>	<b>1,798</b>	<b>155,715</b>	<b>75,203</b>	<b>232,717</b>

Estimated median losses for the scenario events are shown in Table 2. The current study is essentially an update of the 2001 EQE study.

**Table 2: EQE (2001) scenario events, fires and losses (Loss in 2001 millions \$, % of total value at risk).**

Georgia Strait Mw=7.5		1909 Epicentre Mw=7.8		1975/1997 Epicentre, Mw=7.5		New Westminster Mw=6.5		Subduction Zone Mw=9.0	
113 fires		31 fires		101 fires		157 fires		155 fires	
Loss	%	Loss	%	Loss	%	Loss	%	Loss	%
\$2,795	1.04%	\$1,172	0.43%	\$2,685	1.00%	\$8,529	3.12%	\$4,700	1.74%

More recently, the Insurance Bureau of Canada sponsored a study of earthquake risk (AIR Worldwide 2013), which examined a magnitude 9.0 earthquake occurring in the Cascadia Subduction Zone at the shallow depth of 11 km at epicentre location (Lat. 44.706, Lon. -124.569) to the west of Vancouver Island in the Pacific Ocean, some 300 km from downtown Vancouver. The study employed a single scenario windspeed of 19 km/h and found ground shaking responsible for most ground-up losses, but landslides, the tsunami, and fires following the rupture also contribute to the damage inflicted, Table 3 and Table 4. In summary, the study found:

“that 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... Some of the 55-65 primary fires that were ignited by the earthquake subsequently ignite fires on neighbouring 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.”

**Table 3: IBC/AIR (2013) Worldwide study – all property values in British Columbia Buildings only – (2013) millions \$.**

Property type	Building or structural value	Contents value	Total
Residential	465,184	327,007	792,191
Commercial/industrial	420,400	223,843	644,347

**Table 4: IBC/AIR (2013) Worldwide study – modelled losses Mw 9.0 Cascadia Subduction Zone Buildings only – (2013) millions \$.**

<b>Peril</b>	<b>Property</b>	<b>%</b>
Shake	48,639	3.4%
Tsunami	4,208	0.3%
Fire following	519	0.04%
Liquefaction and landslide	5,250	0.4%
<b>Total direct loss</b>	<b>58,617</b>	<b>4.1%</b>

It should be noted that the IBC/AIR study is for the entirety of British Columbia and does not break out losses for the Metro Vancouver area, so comparison with other studies focused on the Metro Vancouver area is difficult.

#### **1.4 Outline of this report**

The next section presents a summary of the study region and the data covering the natural, built and social environments that were employed in this analysis. Section 3 then outlines the analysis methods, section 4 the findings, and section 5 opportunities for mitigation. References conclude the report.



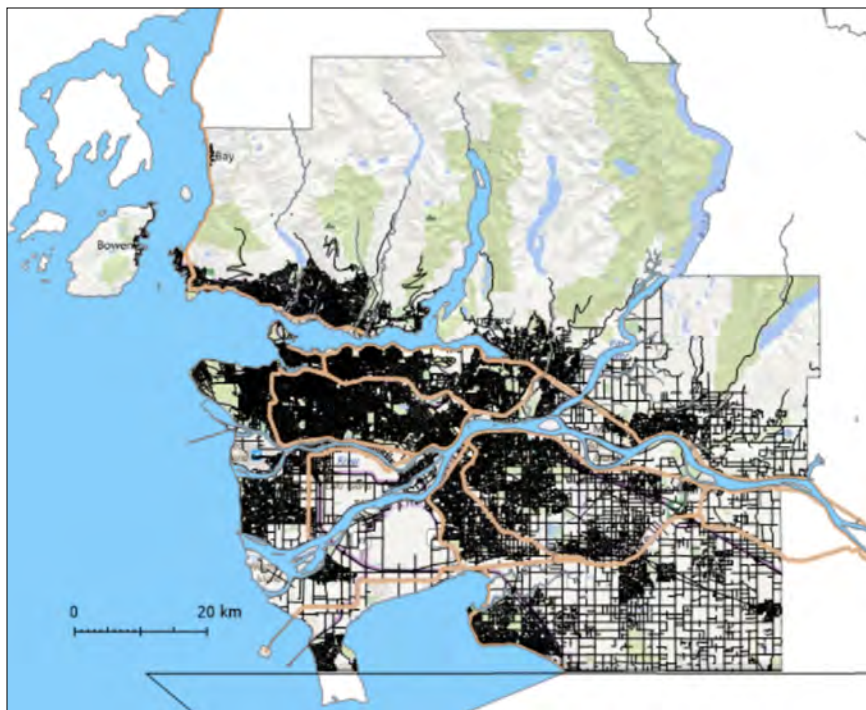
## 2. Study region

### 2.1 The study region

The study region is the Vancouver metropolitan region, consisting of 12 municipalities on the shores of Burrard Inlet and the Fraser River Delta in the southwestern portion of the Lower Mainland of the province of British Columbia as shown in Figure 4 to Figure 6.

Table 5 indicates a study area population of about 2.5 million<sup>1</sup>, making the region the most populous metropolitan area in western Canada, and the third most in Canada, and comprising more than 7% of Canada's population. Population growth is shown in Figure 7 and population density is shown in Figure 8 per SAUID (Settled Area Unit ID) and within the study region varies from 10 to over 16,000 per sq. km. About a quarter of the study area's population is within the City of Vancouver, which is the eighth largest city in Canada, a major cultural centre with leading universities, major rail hub and port.

**Figure 4: Study region road map.**

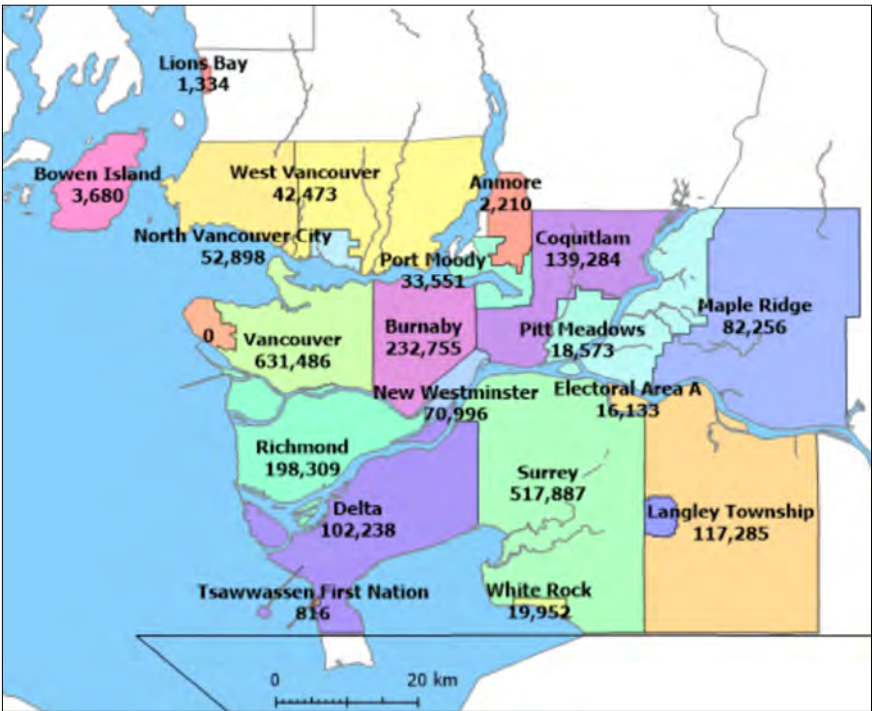


<sup>1</sup> 2016 Vancouver Census metropolitan area.

Figure 5: Study region aerial photograph.



Figure 6: Study region municipalities.



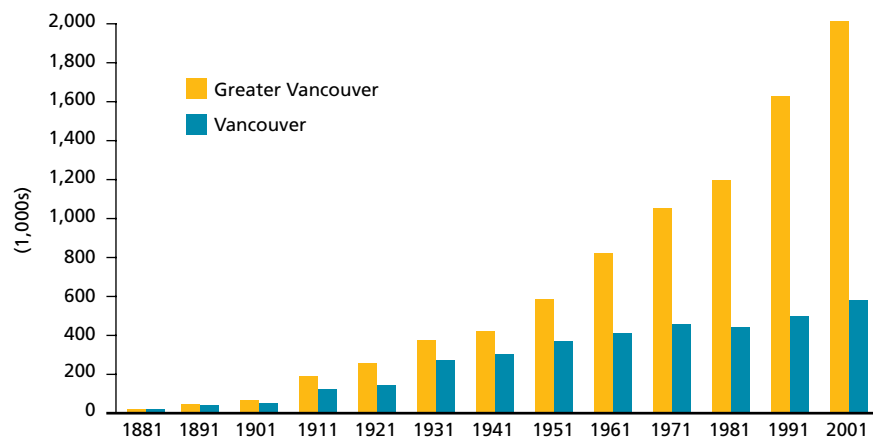


**Table 5: Study region municipalities and population.**

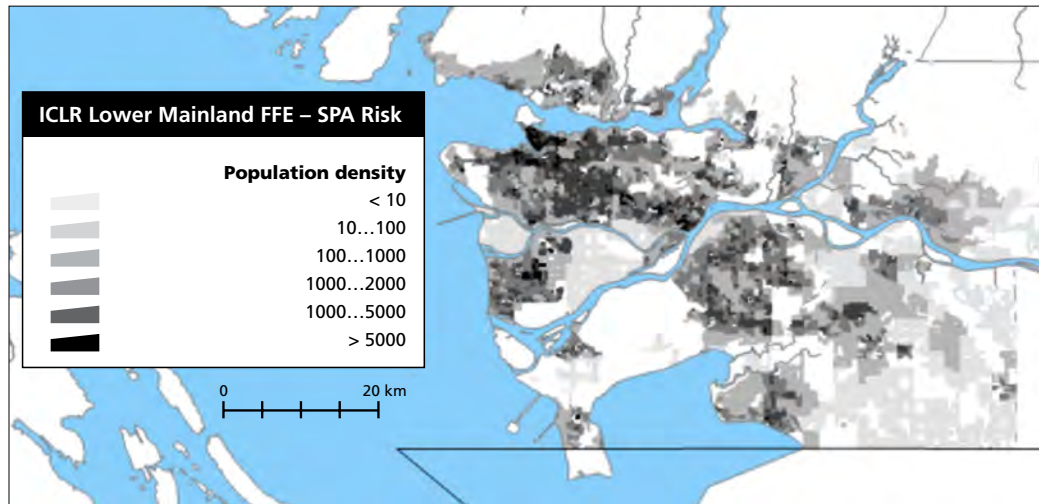
Jurisdiction	Population (2016)
City of Burnaby	232,755
City of Coquitlam	139,284
City of Delta	102,238
Electoral Area A	16,133
Township of Langley	117,285
City of Langley	25,888
City of Maple Ridge	82,256
City of New Westminster	70,996
City of North Vancouver	52,898
District of North Vancouver	85,935
City of Pitt Meadows	18,573
City of Port Coquitlam	58,612
City of Port Moody	33,551
City of Richmond	198,309
City of Surrey	517,887
Tsawwassen First Nation	816
City of Vancouver	631,486
City of White Rock	19,952
District of West Vancouver	42,473
<b>Total population</b>	<b>2,447,327</b>

**Figure 7: Population growth for Vancouver and region**

(Source: [https://en.wikipedia.org/wiki/Demographics\\_of\\_Metro\\_Vancouver#Population\\_growth](https://en.wikipedia.org/wiki/Demographics_of_Metro_Vancouver#Population_growth)).



**Figure 8: Study region population density per SAUID (Settled Area Unit ID).**



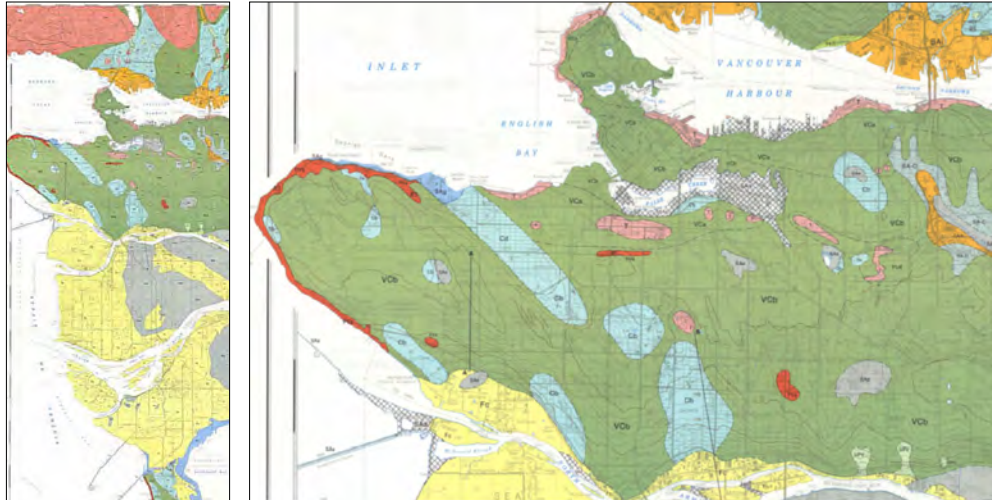
## 2.2 Earth science aspects

### 2.2.1 Geology

The geology of the Vancouver region is well studied (Armstrong 1990) and is relevant to the estimation of fire following earthquake in two aspects: the sources of seismicity, and the local site conditions that affect shaking intensity and permanent ground deformation.

In summary, “the Vancouver area is composed of two distinct geographical areas: the Coast Mountains along the North Shore and the Fraser Lowland encompassing the city and extending south to the Canada-U.S.A. border. These are flanked on the south and east by the Olympic and Cascade Mountains and to the west by the Georgia Strait and the Insular Mountains on Vancouver Island. The Fraser Lowland is a triangular plain, not a true valley that resulted from erosion by rivers. It is a depression between the Coast Plutonic Complex, Vancouver Island and the Cascade Mountains that has been filled with sediments during the last 70 million years... Most of the landforms in the Fraser Lowland were produced during or since the last major glaciation. The most important agent for the deposition and sculpturing of these sediments has been the Fraser River, which developed after ice left the Lowland some 8,000 to 10,000 years ago. Currently, it discharges approximately 18 million tonnes of sand, silt and mud each year, mostly during May, June and July. In order to keep the river channel open for navigation, about 2.4 million tonnes of sediment, mostly sand, has to be dredged annually. The nearly flat delta top is nowhere more than a few metres above high tide level. Between it and the open water, tidal flats are swept by currents and waves. A three-metre-high dyke or berm has been constructed around the seaward edge of the municipality of Richmond. The dyked area is largely underlain by fine sediments, laid down when the Fraser River overflowed its banks and when the sea flooded over the land during storms and at extremely high tides. On Lulu Island, and south of the present course of the river, these sediments are overlain by peat that accumulated in large swamps and bogs. Sand underlies most of the tidal flats and mud occurs in a fringe of marsh around the edge of the delta.” (Armstrong 1990 ), see Figure 9.

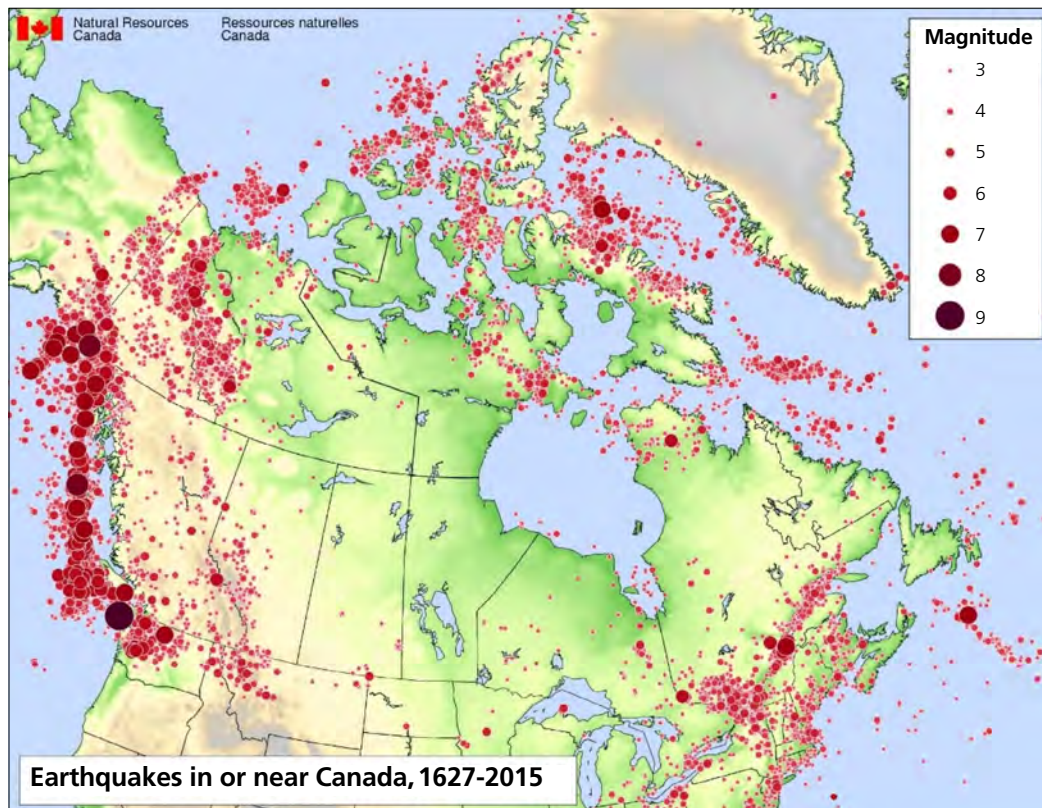
**Figure 9: Surficial geology Vancouver area (Armstrong 1979).**



### **2.2.2 Historic seismicity and seismic hazard**

The Lower Mainland of British Columbia is one of the highest earthquake risk regions in Canada, Figure 10. The fundamental source of seismicity is the subduction of the Juan de Fuca tectonic plate beneath the North American plate, Figure 11, termed the Cascadia Subduction Zone (CSZ). West of

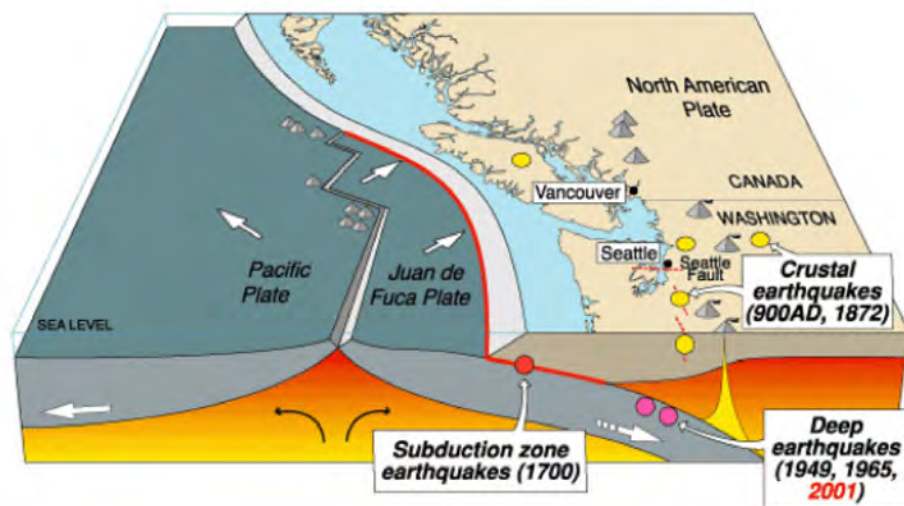
**Figure 10: Historical seismicity of Canada (Source: Geological Survey of Canada).**



Vancouver Island, and extending from the north tip of the Island to northern California, the oceanic Juan de Fuca Plate is moving towards North America at about 2-5 cm/year. This region is called the Cascadia Subduction Zone. Here, the much smaller Juan de Fuca Plate is sliding (subducting) beneath the continent (it is about 45 km beneath Victoria, and about 70 km beneath Vancouver). The ocean plate is not always moving, though. There is good evidence that the Juan de Fuca and North America plates are currently locked together, causing strain to build up in the earth's crust. It is this squeezing of the crust that causes the 300 or so small earthquakes that are located in southwestern British Columbia each year, and the less-frequent (once per decade, on average, damaging crustal earthquakes (e.g., a magnitude 7.3 earthquake on central Vancouver Island in 1946). At some time in the future, these plates will snap loose, generating a huge offshore "subduction" earthquake similar to the 1964 Mw=9.2 Alaska earthquake, or the 1960 Mw=9.5 Chile earthquake. Current crustal deformation measurements in this area provide evidence for this model. Geological evidence also indicates that huge subduction earthquakes have struck this coast about every 240 years and that there currently is a greater than one in three probability of such an event in the next 50 years (Goldfinger et al. 2012; Lovett 2010).

**Figure 11: Subduction of Juan de Fuca Plate beneath North American plate (Source: USGS).**

### Cascadia earthquake sources



Source	Affected area	Max. size	Recurrence
● Subduction zone	W.WA, OR, CA	Mw 9	500-600 year
● Deep Juan de Fuca Plate	W.WA, OR	Mw 7+	30-50 year
● Crustal faults	WA, OR, CA	Mw 7+	Hundreds of years?

As indicated below, the largest number of fires in the Lower Mainland is not likely to be caused by a large CSZ event, but rather by closer shallower crustal events that occur during the build-up of crustal stresses prior to the main subduction zone event.

Selected significant historical earthquakes are listed in Table 6. Current seismological research indicates that there are several active seismic sources in the region that have caused destructive earthquakes in the past and are potential sources of future destructive shocks. The region is most affected by earthquakes originating (1) in the shallow crust, (2) on the Cascadia Subduction Zone, and (3) at depth under Vancouver Island and the Strait of Georgia.

**Table 6: Historical earthquakes in the study area.**

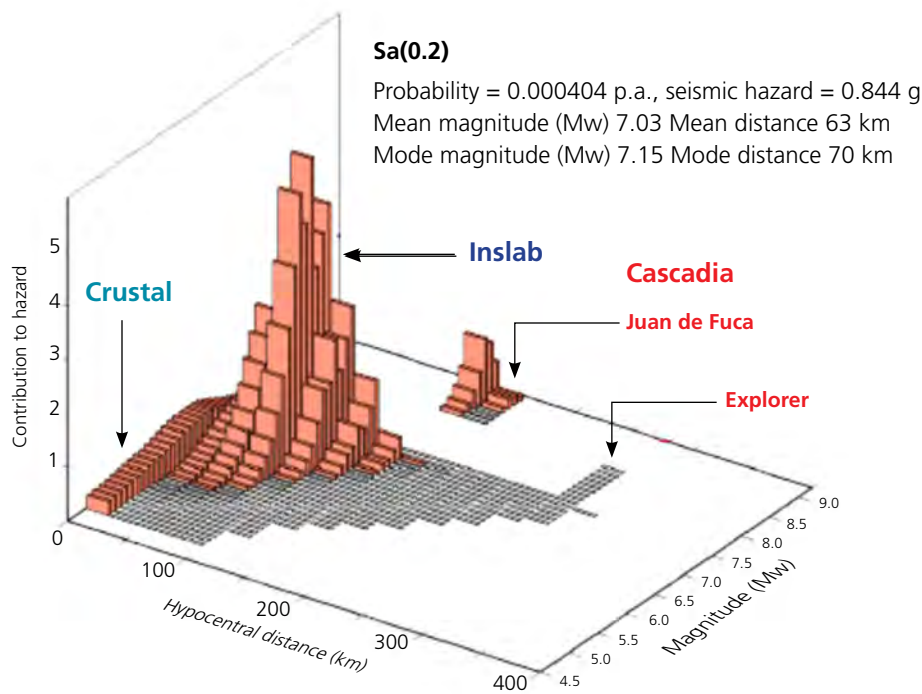
Date	Mw	Comments
~900	7+	Crustal event in Puget Sound near the present city of Seattle. Surface rupture and tsunami deposits in Puget Sound.
26 Jan 1700	~9	Subduction earthquake off the west coast of Vancouver Island with major tsunami. Coastal native village destroyed and native houses on Vancouver Island may have been damaged.
29 Oct 1864	~5.5	Gulf Island region. Probably deep, no reported aftershocks. Felt strongly in the Lower Mainland and the Victoria area.
15 Dec 1872	~7.4	Washington state, south of Hope. Crustal earthquake, followed by many aftershocks. Location uncertain. Felt strongly in the Lower Mainland and the Victoria area.
11 Jan 1909	~6.0	Gulf Island region. Probably deep, no reported aftershocks. Felt strongly in the Lower Mainland and on southern Vancouver Island.
6 Dec 1918	~7.0	West coast of Vancouver Island. Crustal earthquake, many aftershocks. Felt by most in the Lower Mainland and on Vancouver Island. Damage on the west coast of Vancouver Island.
24 Jan 1920	~5.5	Gulf Island region. Probably deep, no reported aftershocks. Felt strongly in the Lower Mainland and on southern Vancouver Island.
23 Jun 1946	7.3	Central Vancouver Island. Crustal earthquake, very few aftershocks. Much damage in central Vancouver Island, and slight damage in the Lower Mainland. Felt strongly all over Vancouver Island, throughout the Lower Mainland.
13 Apr 1949	~7.0	Puget Sound area – at a depth of 54 km. Much damage in Seattle. Felt by most in the Lower Mainland and on southern Vancouver Island.
29 Apr 1965	6.5	Beneath downtown Seattle – depth of 63 km. Much damage in Seattle. Felt by most in the Lower Mainland and on southern Vancouver Island.
30 Nov 1975	4.9	Beneath the Strait of Georgia. Shallow, many aftershocks. Felt by many in the Lower Mainland and on Vancouver Island.
16 May 1976	5.3	Beneath Pender Island at a depth of 60 km. No aftershocks. Felt by most, and some damage (broken windows) in the Lower Mainland and on southern Vancouver Island.
14 Apr 1990	4.9	Northern Washington. Shallow, many aftershocks. Felt by many in the Lower Mainland.
3 May 1996	5.0	East of Seattle. Shallow, many aftershocks. Felt by many in the Lower Mainland and on southern Vancouver Island.
24 Jun 1997	4.6	Beneath the Strait of Georgia. Shallow, many aftershocks. Felt by many in the Lower Mainland and on Vancouver Island.
8 Feb 2001	6.8	Nisqually earthquake, lower Puget Sound, caused some damage in Seattle.



2.2.3 Scenario events

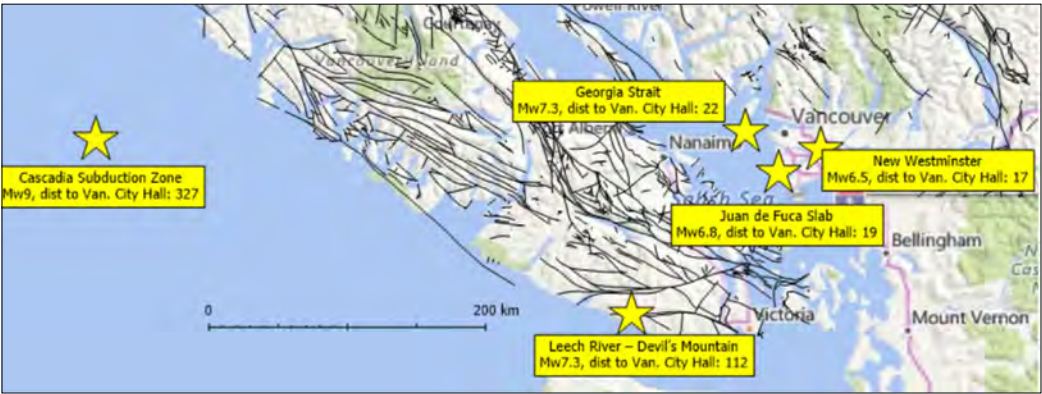
Studies of deaggregation of Vancouver’s seismic hazard (Halchuk et al. 2019) show that the earthquake events contributing most to the hazard are in-slab events of about magnitude 7 at about 20 to 60 km distance followed by close-in shallow crustal events, Figure 12.

Figure 12: Seismic hazard deaggregation for Vancouver (Halchuk et al. 2019).

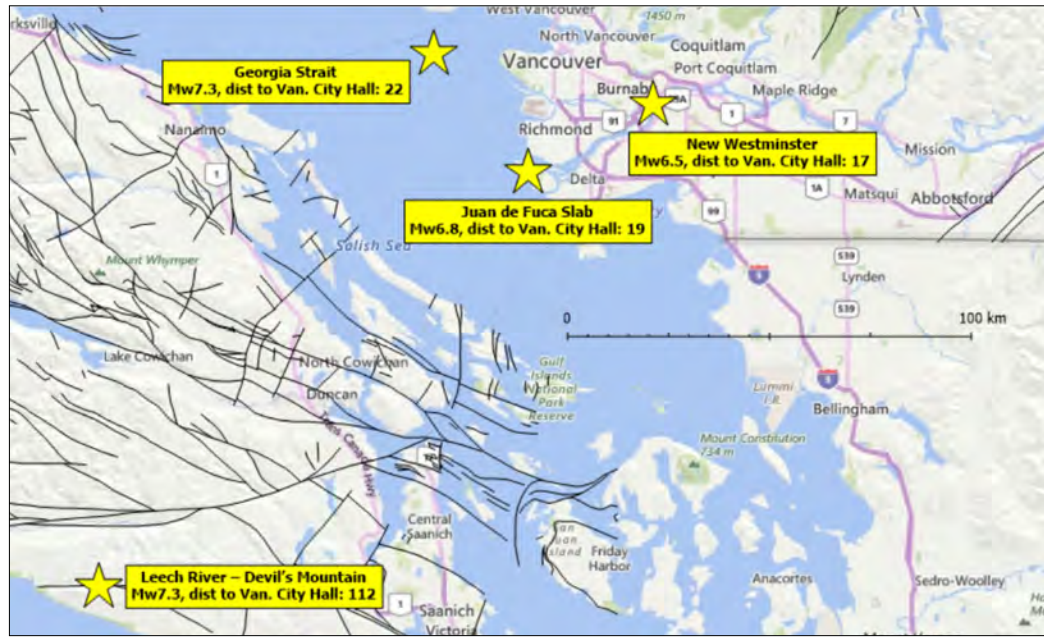


Based on similar analyses and the historic earthquake record, NRCan has recently selected five scenario events for damage and loss studies (Journey 2020), which are shown in Figure 13, Figure 14 and Table 7.

Figure 13: Scenario events, this study. Black lines are mapped surface faults.



**Figure 14: Scenario events detail, this study. Black lines are mapped surface faults.**



This study employs these same five earthquake scenarios as they affect the Metro Vancouver area. Table 7 summarizes relevant characteristics of the five scenarios. The location and orientation of each rupture model is given in Table 8. The first scenario (on the CSZ) assumes a total rupture of the CSZ. The length of each other rupture is determined according to Wells and Coppersmith (1994).

**Table 7: Characteristics of the five earthquake scenarios considered in this study.**

ID	Moment magnitude (Mw)	Fault	Tectonic environment	Faulting mechanism
EQ1	9.0	Cascadia Subduction Zone	Subduction	Interface
EQ2	6.8	Juan de Fuca Plate	Subduction	In-slab
EQ3	7.3	Leech River – Devil's Mountain	Shallow crustal	Strike Slip
EQ4	7.3	Georgia Strait	Shallow crustal	Strike Slip
EQ5	6.5	New Westminster	Shallow crustal	Strike Slip

**Table 8: Locations of the earthquake rupture models used in this study.**

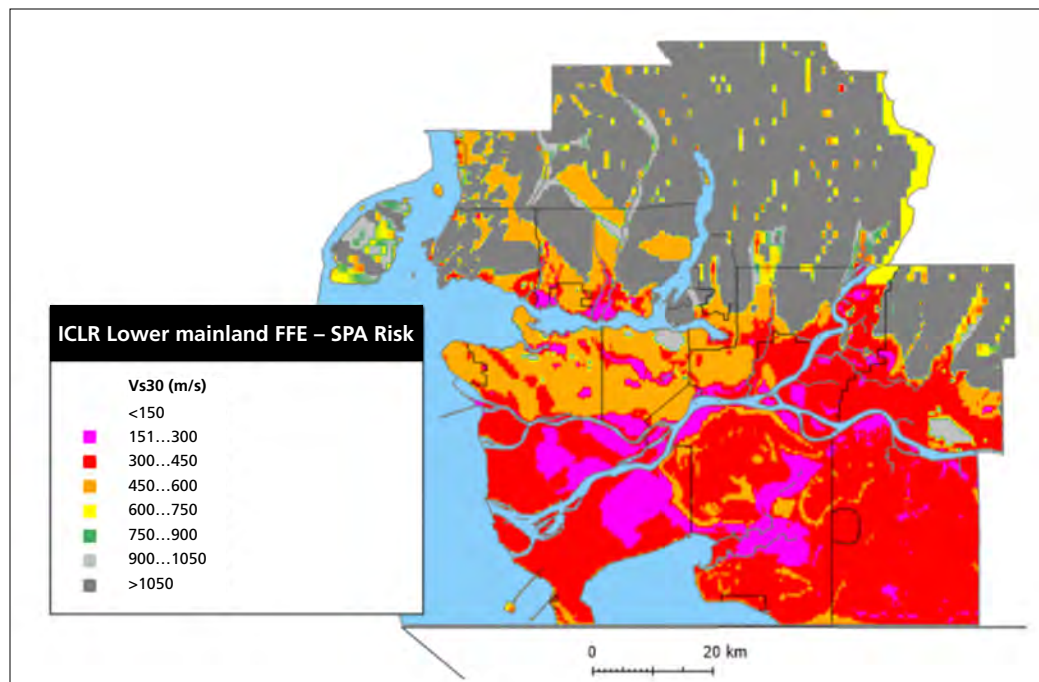
ID	Hypocentre Latitude (deg.)	Hypocentre Longitude (deg.)	Depth to top of rupture (km)	Strike (deg.)
EQ1	49.24	-127.63	5	312
EQ2	49.10	-123.20	63 (hypocentre)	312
EQ3	49.49	-124.15	5	100
EQ4	49.27	-123.41	5	82
EQ5	49.20	-122.92	5	90

A motive for selecting these events is that authorities would then have estimates of fire following earthquake losses on the same basis as those for the NRCAN studies of building damage. Source mechanisms, style of faulting and other parameters for this study's scenario events are based on the above review of seismicity. Length of faulting was calculated using accepted relations (Wells and Coppersmith 1994). It should be noted, however, that the NRCAN estimates of ground motion were not available for this study; therefore, this study performed its own estimates of ground motion, with the intent to replicate as closely as possible the scenarios being employed by NRCAN.

#### 2.2.4 Local site conditions

Surficial or local soil conditions are a key factor affecting ground motions and thus fire following earthquake. A key measure of soil conditions for seismic ground motions is  $V_{s30}$ , the shear wave velocity of the upper 30 m of soil (Borcherdt and Gibbs 1976). NRCAN provided detailed  $V_{s30}$  data for use in this study, consistent with their own studies, Figure 15.

**Figure 15: Regional  $V_{s30}$  mapping (Source: NRCAN).**



#### 2.2.5 Ground motion estimation

Estimates of ground motion are needed as an input for the estimation of post-earthquake ignitions (Lee et al. 2008; Scawthorn 2018b; TCLEE 2005). This study applies four of the NGA-West2 ground motion prediction equations (GMPEs) to predict ground motion in the shallow crustal earthquake scenarios (EQ3 and EQ4), specifically (Abrahamson, Silva and Kamai 2014; Boore et al. 2014; Campbell and Bozorgnia 2014; Chiou and Youngs 2014). Each of the GMPEs is assigned equal weight for predicting both the peak ground acceleration ( $PGA$ ) and peak ground velocity ( $PGV$ ).



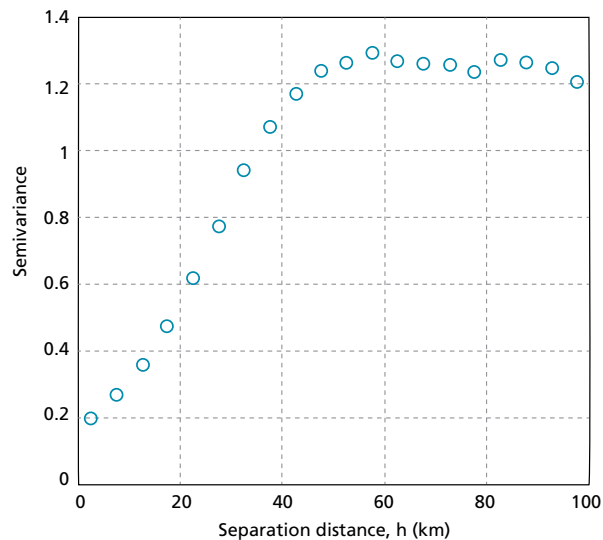
For the subduction earthquake scenarios (EQ1 and EQ2), the (Abrahamson, Gregor and Addo 2016) (“BC Hydro”) GMPE is used to predict *PGA*. This GMPE does not provide coefficients for the prediction of *PGV*, nor do other subduction models in the literature (Atkinson and Boore 2003; Zhao et al. 2006). We therefore apply the suite of NGA-West2 GMPEs for predicting *PGV* in EQ1 and EQ2, acknowledging that these models are not directly applicable to these scenarios.

For all scenarios, the Jayaram and Baker (Jayaram and Baker 2009) model for spatial correlation of ground motion was applied. This model gives the correlation coefficient ( $\rho$ ) for the within-event residuals of ground motion at two locations as a function of their separation distance. This model is not strictly applicable to subduction events or to earthquakes in British Columbia, but no more specific model is available in the literature, so we apply it despite this limitation. Further, Jayaram and Baker (2009) did not study *PGV* directly. However, it is generally accepted that the spatial correlation of *PGV* is similar to that of spectral acceleration at a period of one second, and we apply this general rule to obtain correlation coefficients for *PGV*. This use of spatially correlated ground motions for infrastructure performance and loss estimation is still rather innovative, and a novel contribution of this study.

To generate a spatially correlated field of ground motion for a given scenario, we take the sum of (i) the logarithmic median predicted by the GMPE(s) on a per-location, per-realization basis, (ii) a random sample of the between-event residual, which is normally distributed with zero mean and variance  $\tau^2$  given by the GMPE(s), on a per-realization basis, and (iii) spatially correlated samples of the within-event residual, which is normally distributed with zero mean and variance  $\phi^2$  given by the GMPE(s), on a per-location, per-realization basis. We generate 100 realizations of each scenario for both *PGA* and *PGV*.

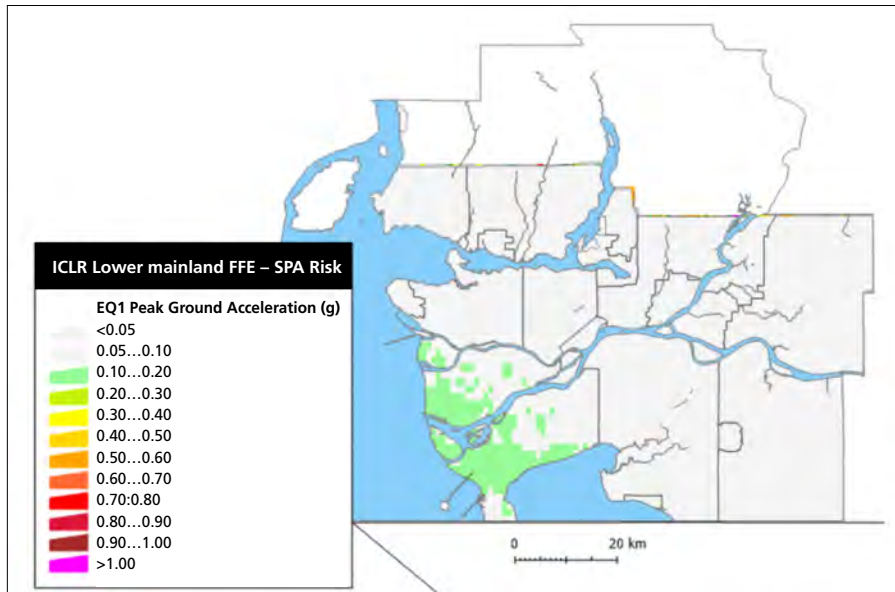
The Jayaram and Baker (2009) model for the spatial correlation of ground motion depends on whether site conditions in the region of interest are clustered. We assume that the site conditions in the Metro Vancouver area are clustered based on Figure 16, which shows a semivariogram of the  $V_{S,30}$  data used in this study, which shows a clear relationship. See Jayaram and Baker (2009) for examples of the clustered and unclustered cases.

**Figure 16: Empirical semivariogram of the site conditions in the Metro Vancouver area.**

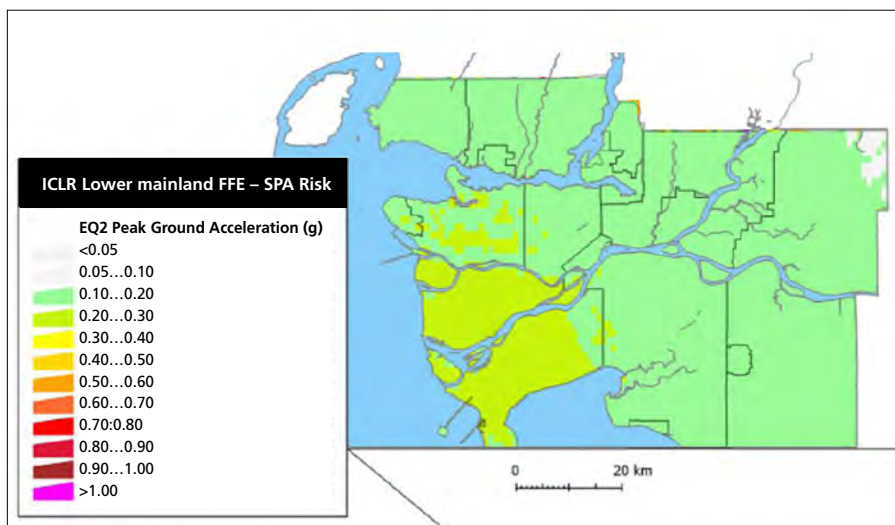


Median *PGA* for each of the five scenarios are shown in Figure 17 to Figure 21. As discussed above, there is considerable variation in actual ground motion – for example, Figure 22 shows mean *PGA* for EQ4, which can be seen to be considerably greater than median values, as expected, and Figure 23 shows three of the 100 realizations of spatially correlated ground motion, for EQ4.

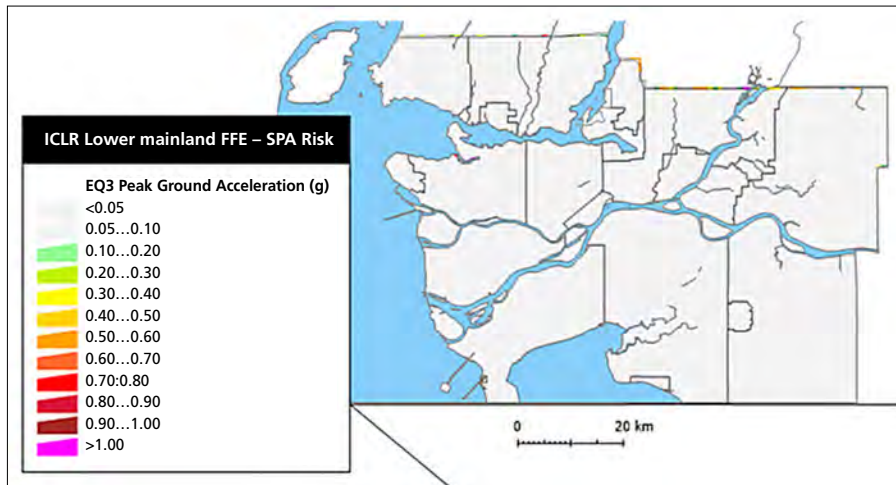
**Figure 17: Median peak ground acceleration (g), EQ1 Mw 9.0 Cascadia Subduction Zone event.**



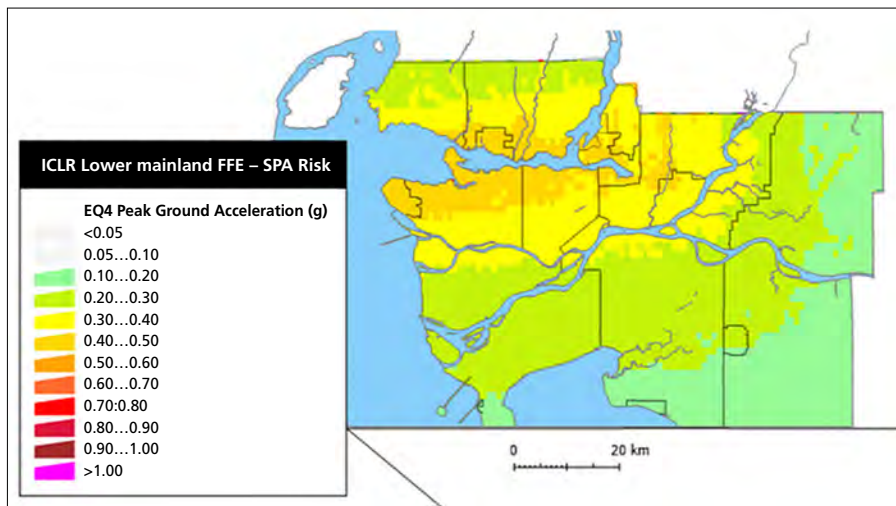
**Figure 18: Median peak ground acceleration (g), EQ2 Mw 6.8 Juan de Fuca Plate (JDF) in-slab event.**



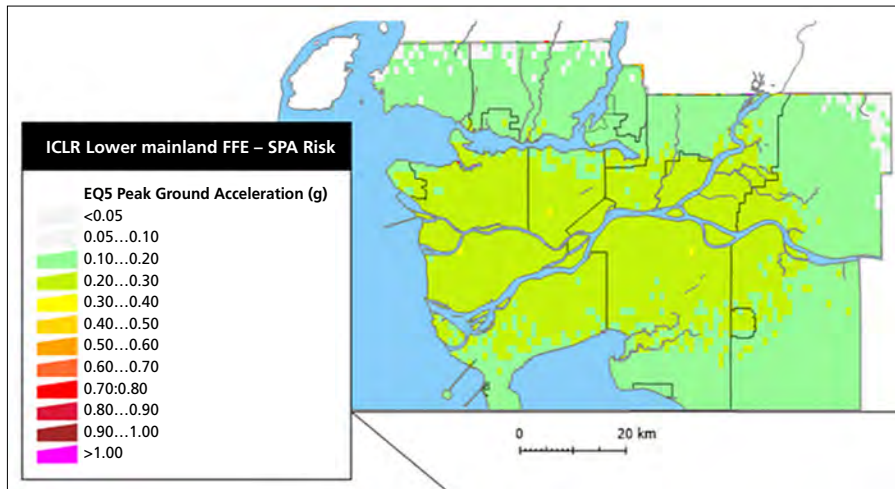
**Figure 19: Median peak ground acceleration (g), EQ3 Mw 7.3 Leech River–Devil’s Mountain (LRDM) shallow crustal event.**



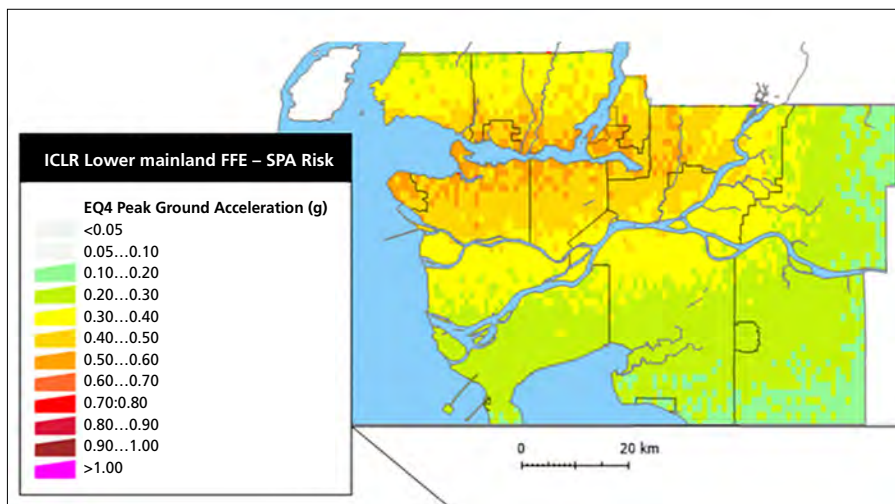
**Figure 20: Median peak ground acceleration (g), EQ4 Mw 7.3 Georgia Strait (GS) shallow crustal event.**



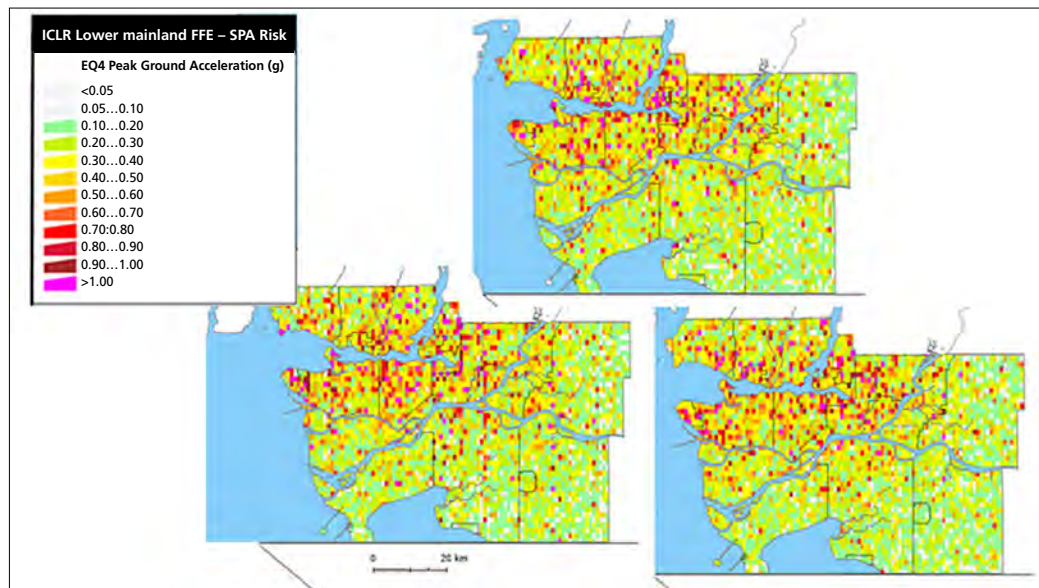
**Figure 21: Median peak ground acceleration (g), EQ5 Mw 6.5 New Westminster (NWM) shallow crustal event.**



**Figure 22: Mean peak ground acceleration (g), EQ4 Mw 7.3 Georgia Strait (GS) shallow crustal event.**



**Figure 23: Three of 100 realizations considering spatial correlation: mean peak ground acceleration (g), EQ4 Mw 7.3 Georgia Strait (GS) shallow crustal event.**



### 2.2.6 Permanent ground displacement

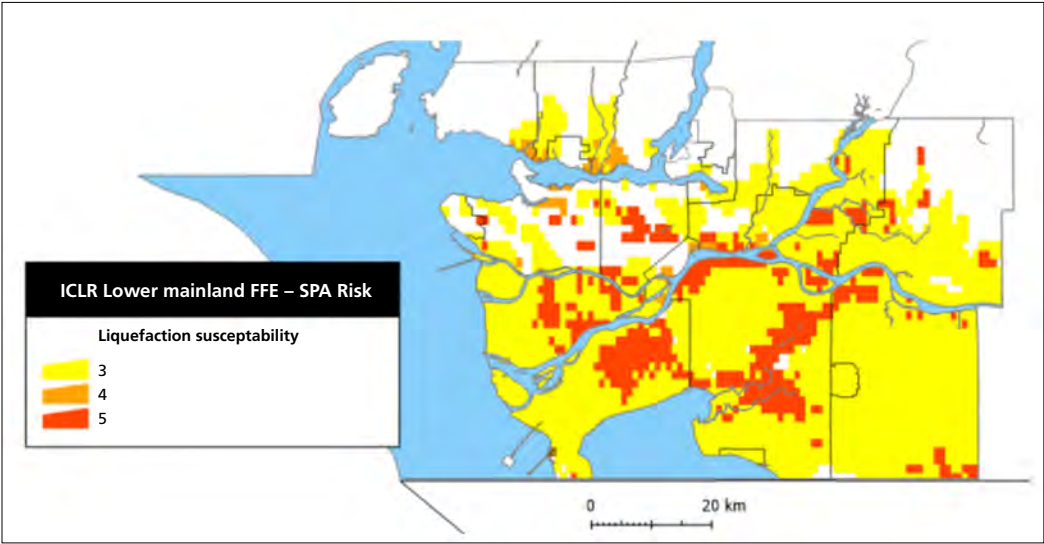
Permanent ground displacement (PGD) is relevant to fire following earthquake due to the damage and loss of service it will cause to buried water and gas pipelines, thus reducing availability of firefighting water while simultaneously increasing the presence of flammable gas and potential for fire and explosion. Permanent ground displacements can occur due to a number of mechanisms: abrupt relative displacement such as at the surface expression of a fault or at the margins of a landslide, or in spatially distributed PGD, which can result, for example, from liquefaction-induced lateral spreads or ground settlement due to soil consolidation. In this study, we only consider soil liquefaction, as it is anticipated to be a major influence on buried water pipe in the urbanized portions of the study area, particularly in the Fraser River Delta.

Liquefaction is generally associated with saturated, cohesionless, uniformly graded soils that contain few fines, and results from seismic shaking that is of a sufficient intensity and duration to cause soils to undergo volume reduction upon shaking. Under these conditions, cohesionless soils will tend to densify when subjected to cyclic shear stresses from ground vibrations but will be temporarily prevented from doing so at depth due to restricted drainage. As a result, excess pore pressures accumulate, effective stresses decrease, and soils lose strength and may become liquefied (Seed and Idriss 1982). Because the capacity of soils to withstand loads (including their own self-weight) is directly related to their strength, liquefied soils may undergo permanent displacements both vertically and horizontally, so that liquefaction poses a serious hazard to constructed structures whether above ground or buried. The first step in quantifying the potential for liquefaction and PGD is mapping surficial soils and their relative vulnerability.



Estimation of the probability of liquefaction follows established procedures (DHS 2003) and is based on a mapping of liquefaction susceptibility, data for which was provided by NRCan (Journey 2020), Figure 24.

**Figure 24: Areas of moderate, high and very high (3 to 5, resp.) liquefaction potential (Source: Journey 2020).**



**2.3 Assets at risk**

This section describes the assets at risk due to fire following earthquake, primary of which is the building inventory. In fact, this study focuses solely on the loss of buildings of all occupancies, including structural, non-structural and contents values, as the primary asset at risk. Not considered are human casualties, vehicles, art and other high-value assets, or time element losses (e.g., business interruption). Moreover, certain high-value structures, such as Vancouver International Airport, the Port of Vancouver, rail depots and/or energy complexes are not considered, due to their specialized nature.

Nevertheless, there is a lot to lose. Data on assets distribution and attributes were acquired from a number of sources, particularly the Open GIS portals of the Province of British Columbia and various cities in the study region, especially the City of Vancouver, as well as NRCan and CatIQ, an insurance database. The fundamental exposure database used for this study is consistent with that employed by NRCan in recent studies (Journey 2020).

In summary, including all residential, commercial, industrial, institutional and government buildings within the study area, there are approximately 400,000 buildings with a total floor area of about 180 million square metres. For the study area, this equates to an aggregate of 72 sq. m. of building floor area per capita.<sup>2</sup>

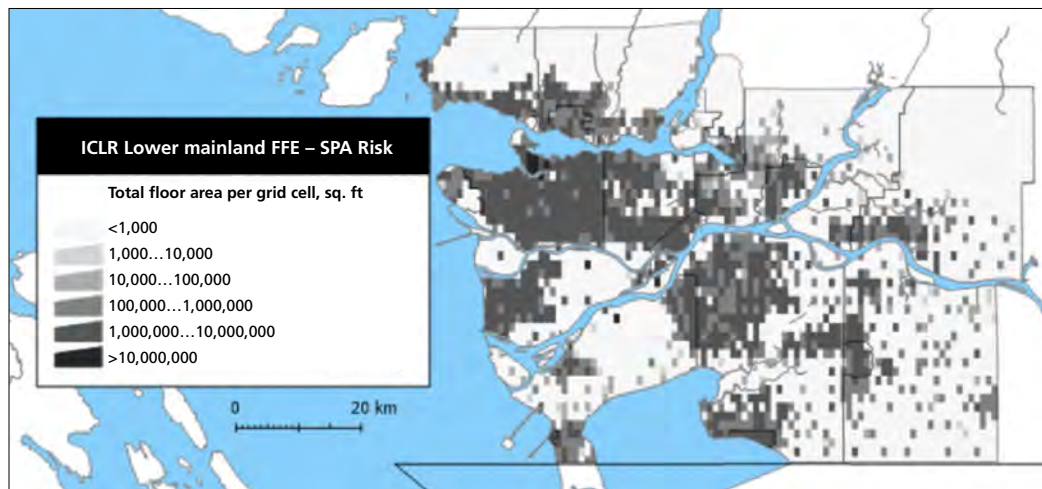
<sup>2</sup> Note that this value is significantly less than was found for the Montreal region in a recent study (SPA, 2019), where the value was 120 sq. m. per capita. This may be due to various factors such as climate or real estate prices.

The monetary value of this real property can be gauged in various ways. For this study, we employ the data of and same approach as NRCan (Journey 2020) and consider the value at risk to be the replacement value of the physical building (structural and non-structural components) and ordinary contents. We do not include the value of land or infrastructure. The result is a total building and contents value of about \$642 billion at risk (2018).

Fire insurance would cover a large portion of this value, although the entire Personal and Commercial Lines Total Insured Value (TIV<sup>3</sup>) is not available. Insurance data that is available shows a TIV of \$651 billion for the study area, consisting of 800,000 Personal Lines and 217,000 Commercial Lines policies in force.<sup>4</sup> These policies cover fire-related perils, also including fire following earthquake.<sup>5</sup> Examples of the assets at risk and data collected are shown in Figure 25 to Figure 28.

In order to understand the potential for fire spread in various parts of the study region, windshield surveys were conducted in the cities of Vancouver, Burnaby and Surrey. A somewhat unique aspect of construction in the Central Business District (CBD) of Vancouver is the presence of overhead electric distribution poles (Figure 29), which had been noted in the (EQE 2001) report. It appears significant progress has been made in reducing overhead electric lines since 2001, but some still remain and may have a significant effect on post-earthquake ignitions.

**Figure 25: Building total floor area (TFA) per analysis grid cell (sq. ft.).**



<sup>3</sup> TIV, also termed loss limit, is the sum of limits for all coverages. Minus deductibles, it is the maximum amount the insurer is responsible to pay. For Commercial Lines, TIV breaks down as having an average deductible of about 1.5%, with building value being about 83% of TIV. For Personal Lines, deductibles are negligible and building value is about 57% and contents 24% of TIV.

<sup>4</sup> That there are more insurance policies than buildings is not surprising – one building may have 100 apartments, which might each have a fire, tenant, condominium or homeowner policy. Note that the TIV exceeds the NRCan estimate of building value, which probably indicates the NRCan values used in this study are on the low side.

<sup>5</sup> This statement neglects certain insurance policy terms, present in some Personal Lines policies, which provide for “guaranteed replacement,” “code upgrades” and other such covers, which may act to increase the actual claim paid.

Figure 26: Detail of building density distribution, central Vancouver.

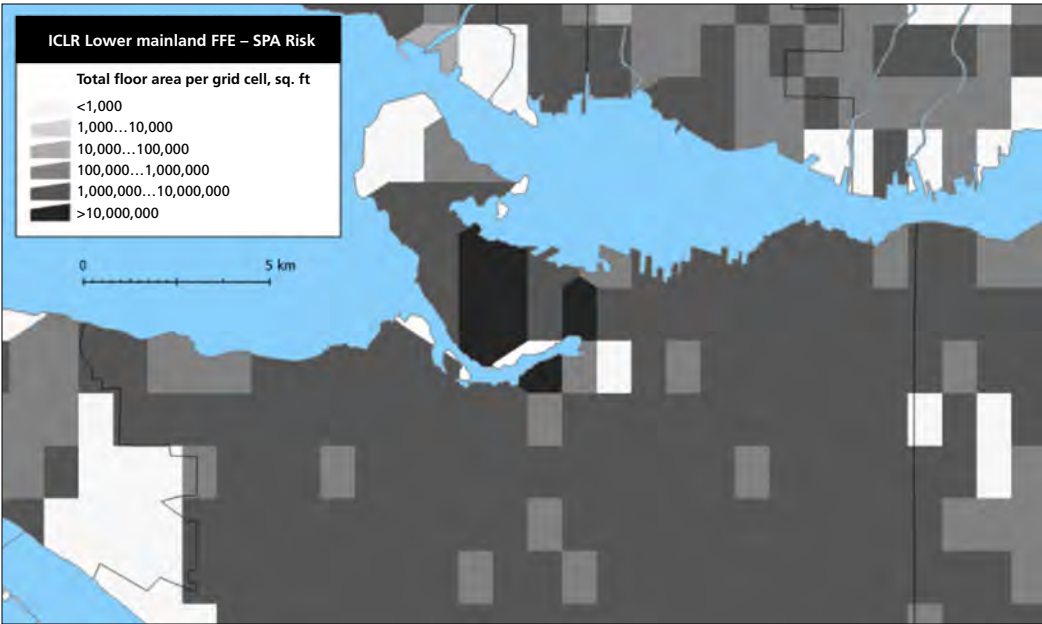


Figure 27: Detail of building footprint data, downtown Vancouver. Building footprint data is especially useful for estimation of fire spread.

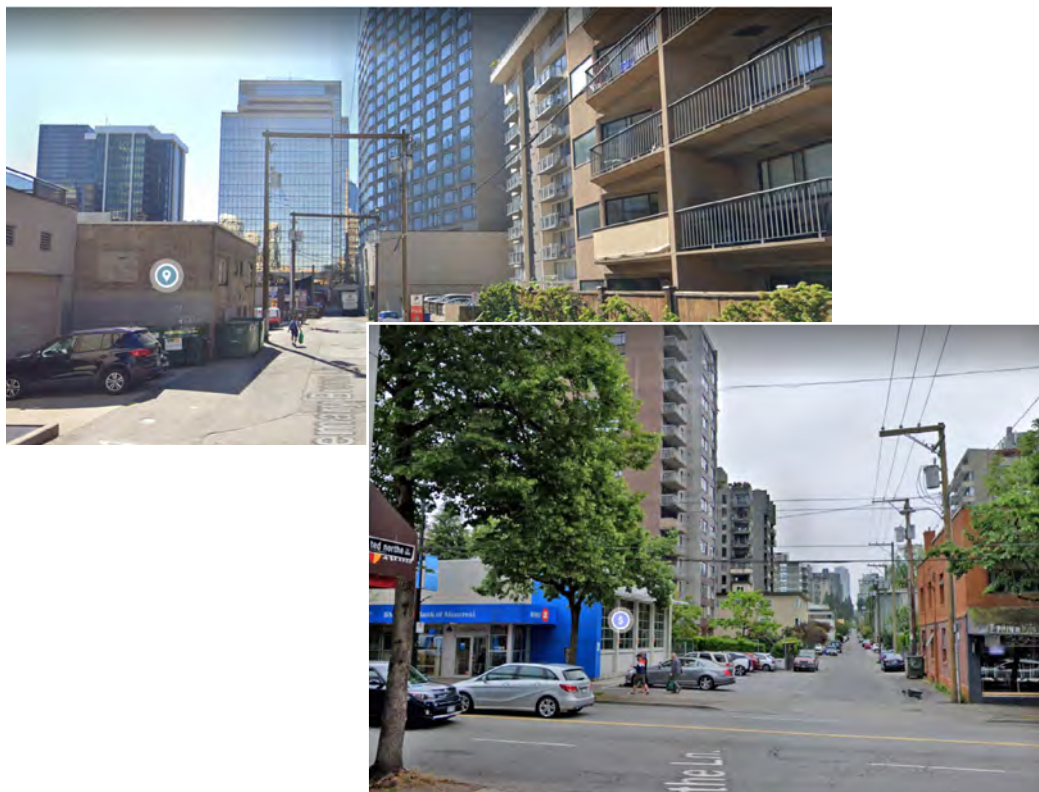




**Figure 28: Detail of building footprint data, central Vancouver.**



**Figure 29: Examples of overhead electric distribution lines in densely built areas of downtown and central Vancouver.**



## 2.4 Fire aspects

This section discusses aspects related to fire spread and firefighting, particularly the fire service and water supply.

### 2.4.1 Fire service

The fire service in the Lower Mainland in general is very advanced, well-equipped, and modern in its organization, methods and tactics. There is a total of 98 fire halls within the study area, as shown in Figure 30 and Table 9, among which are distributed approximately 200 fire engines available for immediate firefighting,<sup>6</sup> which is consistent with normal practice in North American urban regions of a comparable size.<sup>7</sup> Each fire hall has a “first-due” area, termed a Fire Response Area (FRA), within which the fire apparatus are expected to normally be the first to arrive. Detailed mapping data for each fire hall’s FRA was not available, so Voronoi areas were generated for each fire hall and are used in lieu of the actual FRA mapping,<sup>8</sup> as shown in the figure by lines between fire halls.

**Table 9: Number of fire halls by jurisdiction.**

Jurisdiction	Fire halls	Jurisdiction	Fire halls
Village of Anmore	1	City of North Vancouver	1
City of Burnaby	7	District of North Vancouver	6
Bowen Island Municipality	1	City of Pitt Meadows	1
City of Coquitlam	4	City of Port Coquitlam	2
City of Delta	7	City of Port Moody	2
Electoral Area A	0	City of Richmond	8
Township of Langley	7	City of Surrey	17
City of Langley	1	Tsawwassen First Nation	0
Village of Lions Bay	1	City of Vancouver	20
City of Maple Ridge	4	City of White Rock	1
City of New Westminster	3	District of West Vancouver	4
<b>Total</b>		<b>98</b>	

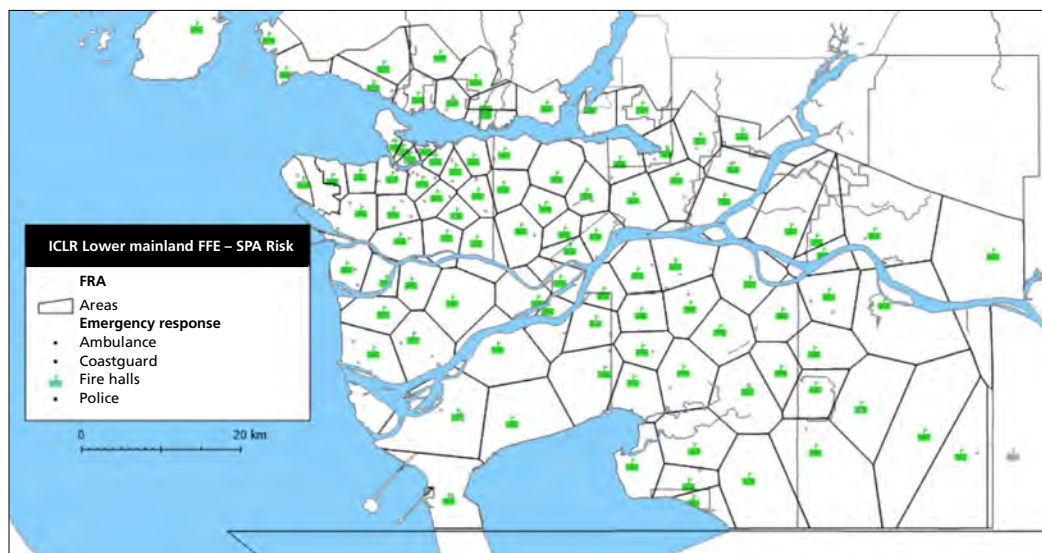
<sup>6</sup> Quantifying the number of engines available for immediate firefighting is a matter of judgment. In addition to fire engines in fire stations staffed and ready to go, fire departments routinely keep a number of “spares,” which replace engines when they are out for maintenance, and which can be put in service if extraordinary need arises. Not all spares are likely to be available at any given time, nor is there likely to be adequate on-duty staffing for all spares. For this study, the number of spares was taken into account along with other factors, to arrive at an estimate of the total immediately available for firefighting. Other apparatus, such as ladder trucks, are important but don’t pump water, which is the *sine qua non* for fire suppression, and therefore don’t enter into the analysis.

<sup>7</sup> Particularly Canadian practice, which tends to be closer to the European model for fire halls, where there are fewer but larger fire halls, as opposed to typical U.S. practice.

<sup>8</sup> Voronoi areas, named for the Russian mathematician Georgy Voronoy (1868-1908) partition a region according to specified rules, in this case, lines are drawn equidistant between stations, so that points within the resulting FRAs are always closest to that station (measured in a linear distance – traffic patterns, barriers and other factors are not considered). In other studies, the author has found use of Voronoi diagrams to be a good approximation of actual FRAs.

Fire agencies in the study region are generally organized by municipality and have mutual aid agreements with neighbouring departments. Discussions with several departments indicated they looked to Vancouver Fire Rescue Services (VFRS) for specialized equipment and expertise. In order to understand VFRS and other departments' capabilities and earthquake planning and preparedness, meetings were held with the fire departments of Vancouver, Surrey and Burnaby, whose cooperation is gratefully acknowledged. It should be noted there are a large number of fire halls beyond the area likely to be affected to varying degrees by the scenario earthquakes, indicating mutual aid should arrive in a timely manner (i.e., several hours).

**Figure 30: Fire stations and corresponding Voronoi areas.**



#### 2.4.1.1 Vancouver Fire Department

Primary sources of information on Vancouver Fire Rescue Services (VFRS) were Deputy Chief Rob Renning and Assistant Chiefs Rick Cheung and Ray Bryant. VFRS is the largest fire department in the study area and is highly regarded. The city has not suffered a major fire loss in a number of years, and fire hall density is less than in comparable cities (TriData 2009). Interspersed among its 20 fire halls are 37 first line fire engines with a total pumping capacity of 262,000 litres per minute (lpm) or 69,000 U.S. gallons per minute (gpm), or an average of 1.85 engines per fire hall (13,000 lpm or 3,456 gpm). VFRS engines typically carry 5" Large Diameter Hose (LDH). VFRS maintains an additional 10 reserve engines in various states of readiness, which typically have a pumping capacity of 8,000 lpm (2,100 gpm). VFRS has a number of other apparatus, notable of which and relevant to fire following earthquake are:

- **Fireboat:** VFRS operates three fireboats:
  - Fireboat 1 (B9001) – 2016 MetalCraft Marine 43' FireStorm 40 (7500 IGPM) (Docked at Burrard Civic Marina), see Figure 31.
  - Fireboat 2 (B9002) – 2016/18 MetalCraft Marine 43' FireStorm 40 (7500 IGPM) (Docked at Main Street Dock) [1].
  - Fireboat 5 (A9005) – 1992 Celtic Shipyards (2x1250 GPM, 1250 & 2000 Monitors) (Docked at False Creek).



Figure 31: VFRS fireboat 1.



Fireboats are particularly valuable with regard to fire following earthquake as they are floating pump stations that can supply hose lines independent of the buried water distribution network, from an inexhaustible water source.

- **HydroSub®:** VFRS operates a diesel powered hydraulically actuated pump (trade name HydroSub®), Figure 32. HydroSubs® are operated by other fire departments concerned about fire following earthquake (San Francisco FD, Oakland FD, Berkeley FD) and are essentially an onshore fireboat, in the sense that they can draft water beyond the reach of fire engines and supply hose lines from large alternative water sources.
- **Hose tender:** VFRS operates one hose tender carrying 5,000 ft. of 5" hose, Figure 33, which essentially permits creation of an emergency above-ground water distribution network.

Figure 32: VFRS HydroSub.®



Figure 33: VFRS hose tender.

- **Hose reels:** In lieu of additional hose tenders, VFRS recently acquired three towed hose reels each carrying 6000 ft. of 6" hose, Figure 34, which provide a capacity essentially equivalent to a hose tender (lacking important appurtenances, however, as discussed later).

Figure 34: VFRS hose reels.

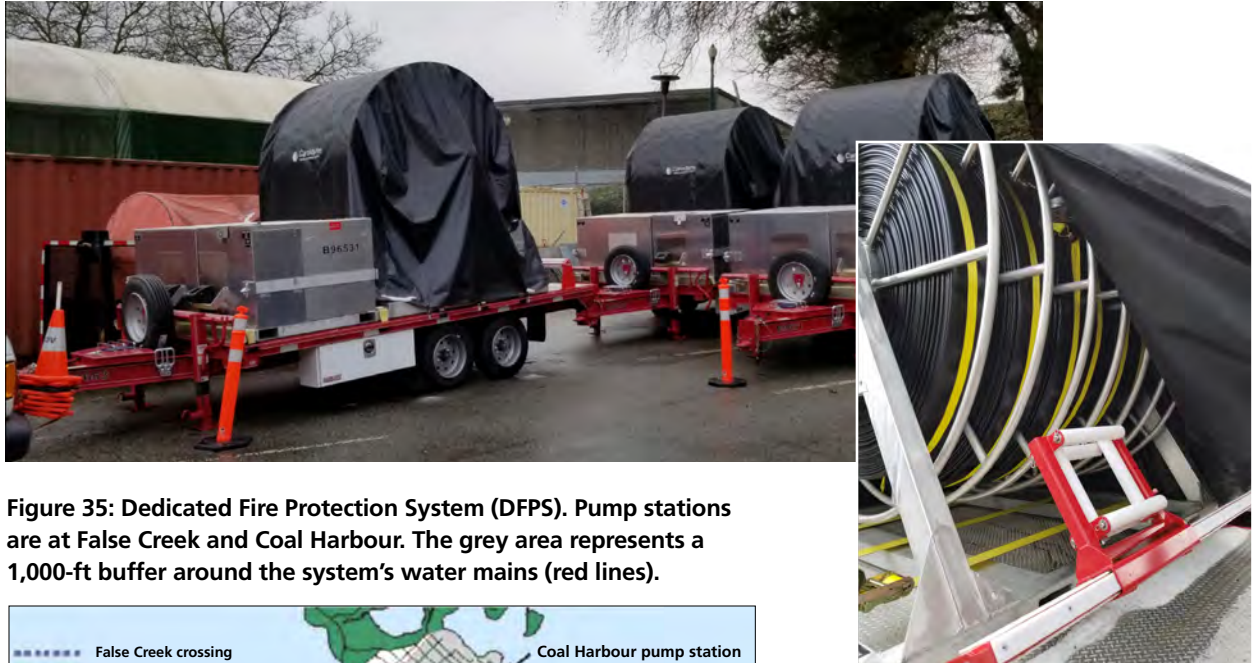


Figure 35: Dedicated Fire Protection System (DFPS). Pump stations are at False Creek and Coal Harbour. The grey area represents a 1,000-ft buffer around the system's water mains (red lines).



- **DFPS:** The City of Vancouver operates a Dedicated Fire Protection System (DFPS) to protect the downtown and selected other high-density areas, Figure 35. The DFPS was constructed in the late 1990s and is a high-pressure water distribution network specially designed against earthquake. It is relatively unique, the only comparable such system being San Francisco's EFWS (Emergency Firefighting Water System). The DFPS provides a seismically reliable redundant water supply independent of the buried potable water distribution network. It is supplied from two pump stations and can also be supplied by the fireboats.



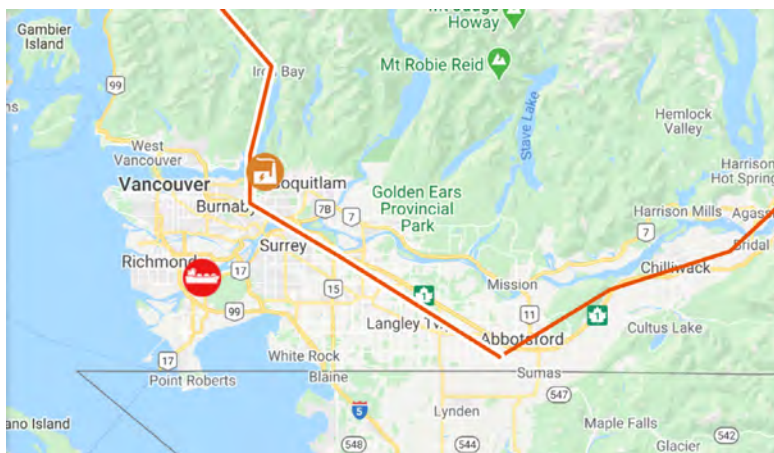
#### 2.4.1.2 Burnaby Fire Department

The primary source of information on the Burnaby FD (BFD) was Chief Joe Robertson. BFD protects about 248,000 population within a 98.6 sq. km service area and has 283 uniformed firefighters housed in seven fire halls. BFD operates eight engines with three in reserve and has two fireboats (for rescue, however, with no pumping capacity). BFD's engines are typical of most engines in the study area in that they carry 4" rather than 5" LDH (as opposed to VFRS), and lack adapters, which is an obstacle to effective mutual aid.

Information on other fire departments was retrieved from department websites and other sources.

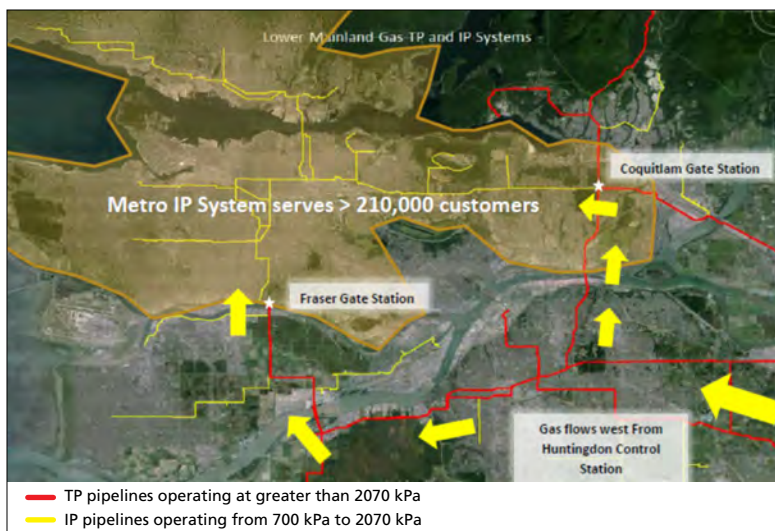
#### 2.4.2 Gas and liquid fuel pipelines

Crossing and serving the study area are several major gas and liquid fuel transmission lines and facilities as shown in Figure 36, serving over 200,000 customers as shown in Figure 37.



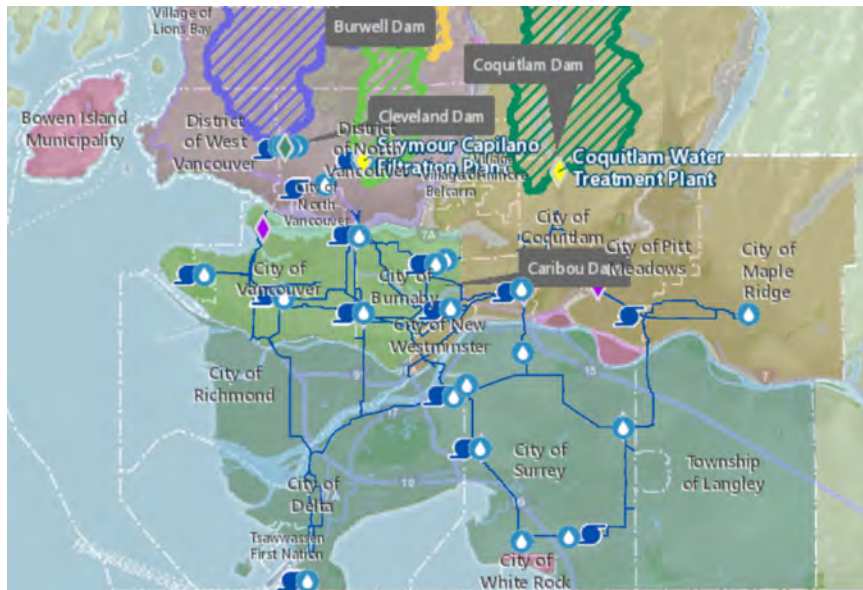
**Figure 36: Major gas infrastructure in the study area includes the high pressure Fortis BC transmission pipeline shown in red, and the 3 million ton per year capacity WestPac LNG terminal (red icon) on the Fraser River**

Source: <http://www.energybc.ca/gasmap.html>.



**Figure 37: There are over 200,000 natural gas customers within the study area (Source: Fortis BC, 2015, Lower Mainland Natural Gas Intermediate Pressure System Upgrade Projects, BCUC Workshop – CPCN Overview).**

**Figure 38: The study area is supplied by Metro Vancouver from primary sources on the Capilano, Seymour and Coquitlam river watersheds north of Burrard Inlet via large transmission lines (Source: <https://gis.metrovancouver.org/mvmaps/Water>).**

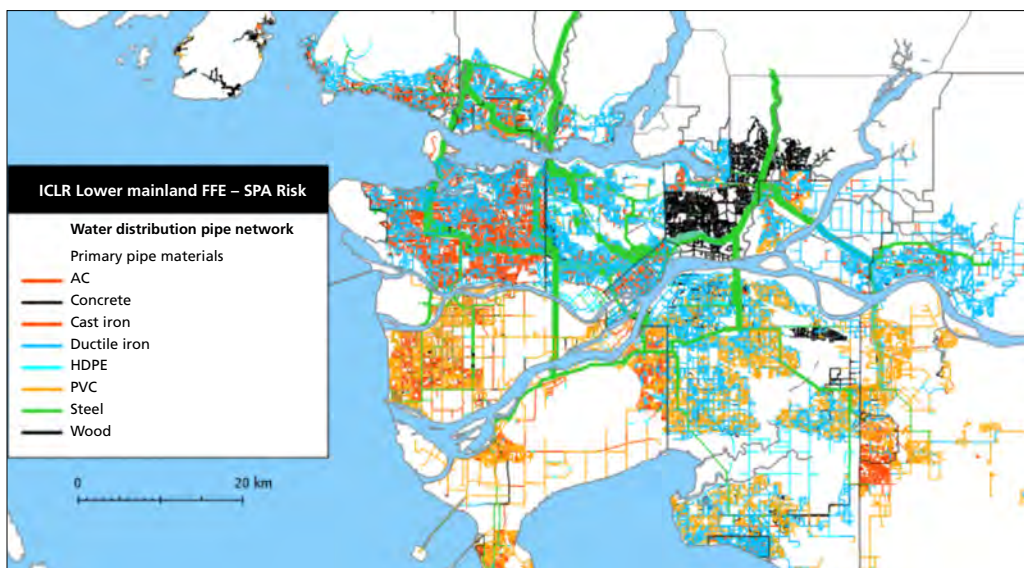


### 2.4.3 Water supply

Adequate firefighting water supply is essential to prevent ignitions from growing into conflagrations following an earthquake. If water supply is severely impacted by the scenario event, firefighters will not be able to access water from fire hydrants, and valuable time will be lost accessing alternative water sources, during which fires may grow out of control.

The study area is supplied by Metro Vancouver from primary sources on the Capilano, Seymour and Coquitlam river watersheds north of Burrard Inlet via large transmission lines, Figure 38. The performance of these transmission lines is important following an earthquake, although fire hydrants are supplied from the smaller distribution network, whose performance is most crucial and depends on their materials of construction, diameter, joints and the types of ground they are buried in. These aspects are discussed in Section 3, while pipe data is shown in Figure 39 (pipe data was provided by NRCan).

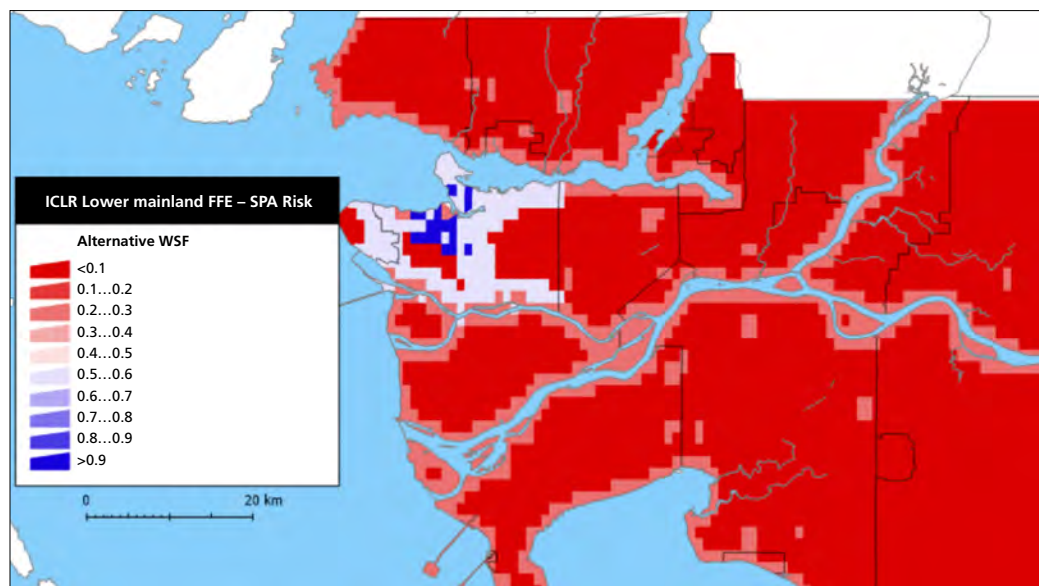
**Figure 39: Water distribution network, differentiated by material (Sources: NRCan, Journey 2020).**



#### 2.4.3.1 Alternative water supplies

Because water supply systems may sometimes fail, such as due to buried water pipe breaks in an earthquake, it is good practice for fire departments to identify and practise accessing alternative water supplies (AWS). Discussions with the study region's fire departments indicated they follow this practice, and VFRS provided an excellent compilation of their AWS. Based on a review of alternative water sources, and the capability of fire departments to relay water from those sources to various locations, an Alternative Water Supply Factor (AWSF) was determined and is shown in Figure 40, where AWSF is the probability of receiving water from an alternative water source.

**Figure 40: Study area Alternative Water Supply Factor, AWSF.**



#### 2.4.4 Weather

An important factor in large conflagrations is weather (NFPA 1951; TCLEE 2005), where hot, dry, windy weather ("red flag" days) are especially critical for the occurrence of large fires. The climate of Vancouver may be summarized as:

"The climate of Vancouver, British Columbia, Canada, is a moderate oceanic climate (Köppen climate classification *Cfb*) that borders on a warm-summer Mediterranean climate (*Csb*). Its summer months are typically dry, often resulting in moderate drought conditions, usually in July and August. In contrast, the rest of the year is rainy, especially between October and March. Like the rest of the British Columbia Coast, the city is tempered by the North Pacific Current, which has its origins in the milder Kuroshio Current and is also, to an extent, sheltered by the mountains of Vancouver Island to the west."<sup>9</sup>

<sup>9</sup> [https://en.wikipedia.org/wiki/Climate\\_of\\_Vancouver](https://en.wikipedia.org/wiki/Climate_of_Vancouver)

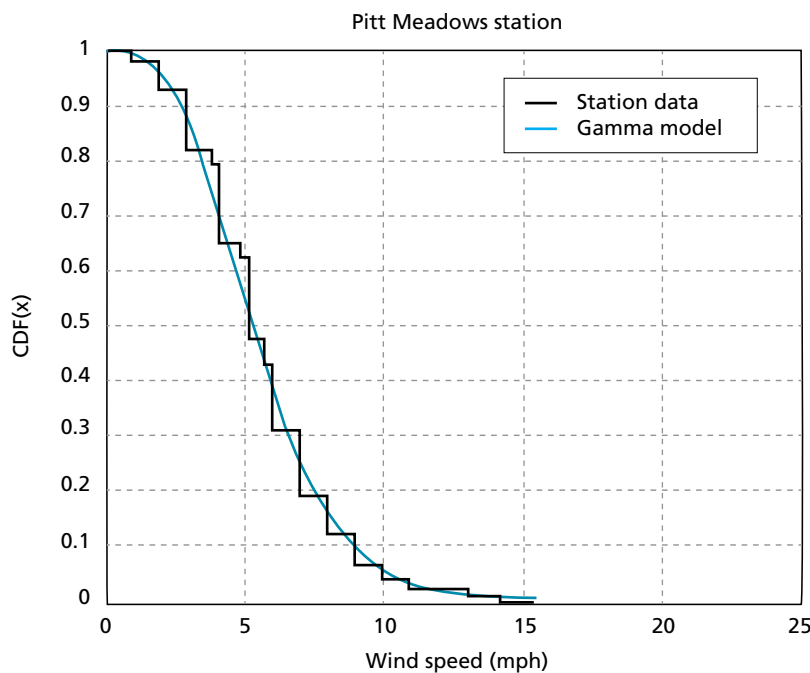


These patterns are shown in Figure 41, while windspeed complementary cumulative distribution is shown in Figure 42.

**Figure 41: Vancouver weather pattern** (Source: [https://en.wikipedia.org/wiki/Climate\\_of\\_Vancouver](https://en.wikipedia.org/wiki/Climate_of_Vancouver)).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Record high °C (°F)	15.6 (60.1)	16.4 (61.5)	19.1 (66.4)	23.9 (75.0)	32.7 (90.9)	30.0 (86.0)	31.7 (89.1)	31.7 (89.1)	28.5 (83.3)	24.2 (75.6)	17.0 (62.6)	15.0 (59.0)	32.7 (90.9)
Average high °C (°F)	6.8 (44.2)	8.4 (47.1)	10.6 (51.1)	13.5 (56.3)	16.8 (62.2)	19.6 (67.3)	22.0 (71.6)	22.3 (72.1)	19.0 (66.2)	13.9 (57.0)	9.3 (48.7)	6.8 (44.2)	14.1 (57.4)
Daily mean °C (°F)	4.8 (40.6)	5.9 (42.6)	7.6 (45.7)	10.0 (50.0)	13.2 (55.8)	15.9 (60.6)	18.1 (64.6)	18.3 (64.9)	15.4 (59.7)	11.1 (52.0)	7.1 (44.8)	4.8 (40.6)	11.0 (51.8)
Average low °C (°F)	2.7 (36.9)	3.4 (38.1)	4.6 (40.3)	6.5 (43.7)	9.5 (49.1)	12.2 (54.0)	14.1 (57.4)	14.4 (57.9)	11.6 (52.9)	8.2 (46.8)	4.8 (40.6)	2.8 (37.0)	7.9 (46.2)
Record low °C (°F)	-13.3 (8.1)	-6.7 (19.9)	-5 (23)	-1.1 (30.0)	1.1 (34.0)	2.8 (37.0)	2.8 (37.0)	5.0 (41.0)	1.7 (35.1)	-3.2 (26.2)	-9.9 (14.2)	-15.6 (3.9)	-15.6 (3.9)
Average precipitation mm (inches)	178.8 (7.04)	183.8 (7.24)	155.8 (6.13)	117.9 (4.64)	86.7 (3.41)	69.9 (2.75)	53.4 (2.10)	50.8 (2.00)	73.3 (2.89)	147.8 (5.82)	239.2 (9.42)	231.3 (9.11)	1,588.6 (62.54)
Average rainfall mm (inches)	143.6 (5.65)	173.5 (6.83)	153.1 (6.03)	117.0 (4.61)	86.7 (3.41)	69.9 (2.75)	49.1 (1.93)	48.3 (1.90)	71.0 (2.80)	131.9 (5.19)	219.5 (8.64)	211.5 (8.33)	1,474.9 (58.07)
Average snowfall cm (inches)	15.3 (6.0)	10.2 (4.0)	2.7 (1.1)	0.9 (0.4)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	2.7 (1.1)	11.8 (4.6)	43.6 (17.2)
Average precipitation days (≥ 0.2 mm)	18.3	16.4	16.6	14.9	12.9	11.6	7.6	7.7	9.4	14.9	19.8	19.1	169.1
Average rainy days (≥ 0.2 mm)	14.8	16.3	15.9	14.2	13.2	10.7	7.6	7.7	9.8	12.0	16.8	16.2	154.5
Average snowy days (≥ 0.2 cm)	2.8	1.9	0.89	0.24	0.0	0.0	0.0	0.0	0.0	0.05	0.88	2.9	9.6
Mean monthly sunshine hours	51.1	79.6	124.7	161.3	222.8	223.5	276.8	256.6	178.3	127.3	66.9	49.6	1,818.4

**Figure 42: Study area windspeed complementary cumulative distribution** (for example, a windspeed of 5 mph has about 55% probability of being exceeded, and 10 mph about 7% probability of exceedance).



### 3. Analysis

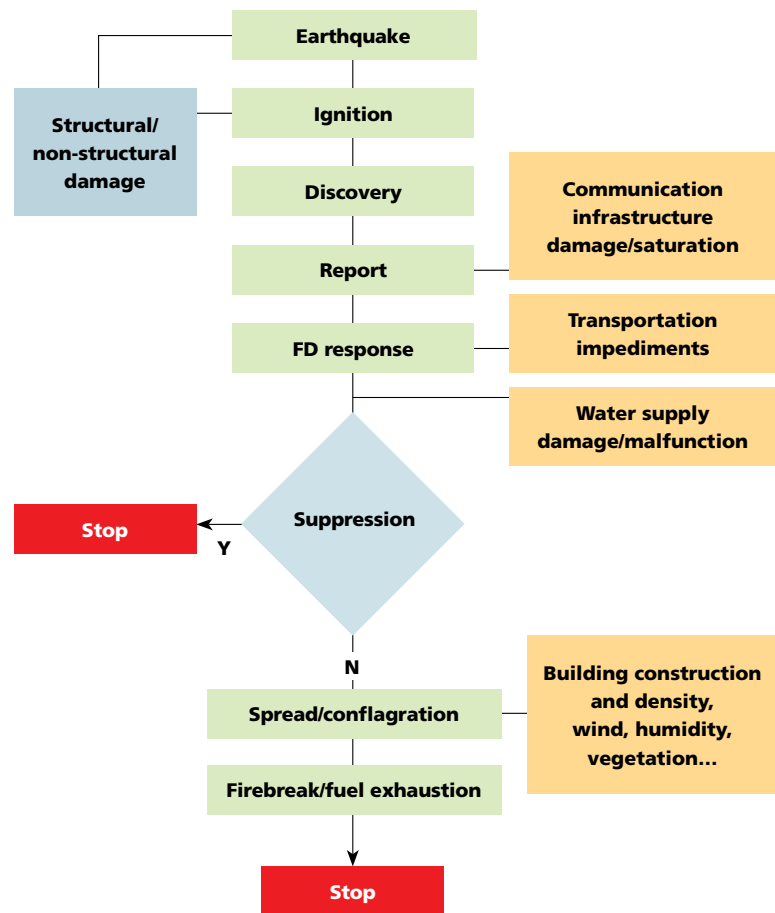
#### 3.1 Modelling of fire following earthquake

The first step towards solving any problem is analyzing the problem and quantifying its effects.

A full probabilistic methodology for analysis of fire following earthquake was developed in the late 1970s (Scawthorn, Yamada and Iemura 1981) and has been applied to major cities in western North America (Scawthorn 1992). An American Society of Civil Engineers' monograph (Scawthorn, Eidinger and Schiff 2005) details the state of the art in modelling fire following earthquake, so that only a brief review is presented here. In summary, the steps in the process are shown in Figure 43.

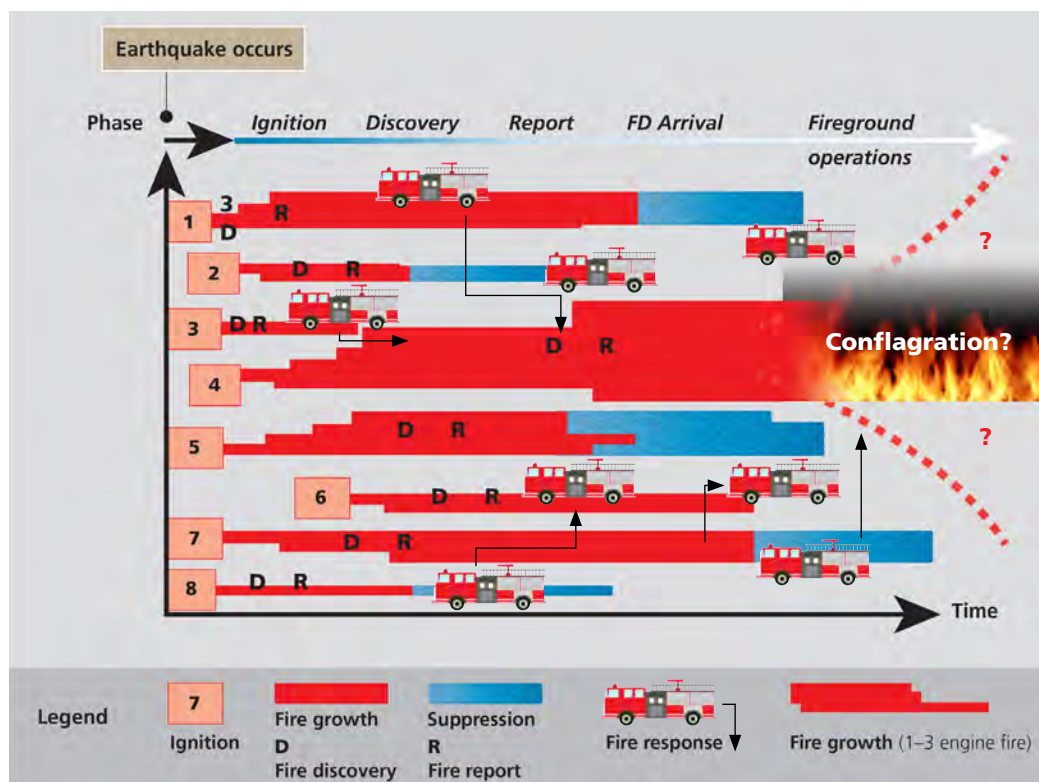
- *Occurrence of the earthquake* – causing damage to buildings and contents, even if the damage is as simple as knocking things (such as candles or lamps) over.
- *Ignition* – whether a structure has been damaged or not, ignitions will occur due to earthquakes. The sources of ignitions are numerous, ranging from overturned heat sources, to abraded and shorted electrical wiring, to spilled chemicals having exothermic reactions, to friction of things rubbing together.
- *Discovery* – at some point, the fire resulting from the ignition will be discovered, if it has not self-extinguished (this aspect is discussed further, below). In the confusion following an earthquake, the discovery may take longer than it might otherwise.
- *Report* – if it is not possible for the person or persons discovering the fire to immediately extinguish it, fire department response will be required. For the fire department to respond, a report to the fire department has to be made. Communications system dysfunction and saturation will delay many reports.
- *Response* – the fire department then has to respond but is impeded by non-fire damage emergencies they may have to respond to (e.g., building collapse) as well as transportation disruptions.
- *Suppression* – the fire department then has to suppress the fire. If the fire department is successful, they move on to the next incident. If the fire department is not successful, they continue to attempt to control the fire, but it spreads, and becomes a conflagration. Success or failure hinges on numerous factors including water supply functionality, building construction and density, wind and humidity conditions, etc. If unable to contain the fire, the process ends when the fuel is exhausted or when the fire comes to a firebreak.

Figure 43: Flow chart of fire-following-earthquake process (TCLEE 2005).



This process is also shown in Figure 44, which is a fire department operations time line. Time is of the essence for the fire following earthquake problem. In this figure, the horizontal axis is Time, beginning at the time of the earthquake, while the vertical axis presents a series of horizontal bars of varying width. Each of these bars depicts the development of one fire, from ignition through growth or increasing size (size is indicated by the width or number of bars). Fire following earthquake is a highly non-linear process, modelling of which does not have great precision and is such that in many cases the only clear result is differentiation between situations of a few small fires, versus major conflagration.

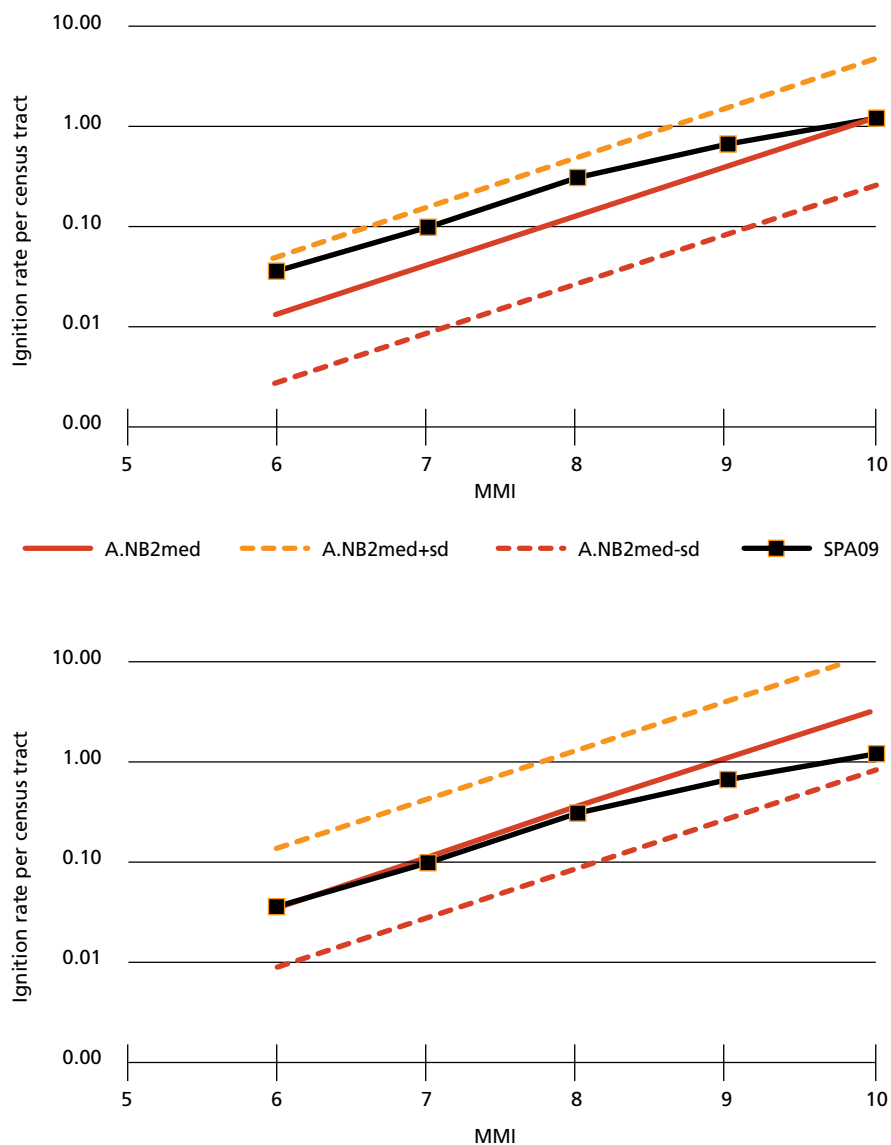
**Figure 44: Chart of fire department operations time line. Horizontal axis is time, beginning at time of earthquake. Horizontal bars depict development of fires, from ignition through growth or increasing size (size is indicated by width or number of horizontal bars) (Scawthorn 1987).**



### 3.2 Ignitions

The number and pattern of ignitions are based on methods in (SPA Risk 2009), which are further discussed in (Scawthorn 2018a) and are shown in Figure 45. The cause of these ignitions will likely be similar to causes in the 1994 Northridge earthquake, which is the best U.S. data set for recent fires following an earthquake – about half of all ignitions would be electrical-related, a quarter gas-related, and the other due to a variety of causes, including chemical reaction. Also based on the Northridge experience, about half of all ignitions would typically occur in single-family residential dwellings, with another 26% in multi-family residential occupancies – that is, about 70% of all ignitions occur in residential occupancies. Educational facilities would be a small percentage of all ignitions (3% in Northridge), and most of these are due to exothermic reactions of spilled chemicals in chemistry laboratories.

Figure 45: Ignition models, taken from (Scawthorn 2018a): comparison of ignition regression models (1) [Davidson 2009] and (3) [SPA 2009] using median values per census tract. Dotted lines are equation (1) plus and minus one standard deviation. Abscissas in the figure are Modified Mercalli Intensity (MMI), but analysis for this study employed peak ground acceleration (PGA) as the hazard measure.



### **3.3 Initial response**

#### **3.3.1 Citizen response**

Ignitions requiring fire department response will initially be responded to by citizens – as noted, they will be able to suppress some fires, which are not included in the estimates in section 4. When citizens realize the fire is beyond their capabilities, they will endeavour to call the fire department, by telephone since fire alarm street pull boxes have largely disappeared from the North American urban landscape. Attempts to report via 911 will almost universally be unsuccessful, not so much due to damage to the telephone system as much as simple saturation of the system and 911 call centres. Citizens will then go by auto to the nearest fire station, but such “still alarms” will be largely unneeded, since the fire companies will have already responded to the nearest fire (“self-dispatched”), if not dispatched by 911.

Experience shows that citizens on scene will respond rationally (Van anne et al. 1994) rescuing as many people as possible and protecting exposures. Water supply from mains (discussed below) will often be unavailable.

#### **3.3.2 Reporting**

As noted above, 911 centres will be overwhelmed, and doing as much as possible to triage events and dispatch resources. Reports of fires during the initial period will be haphazard. Most fire departments do not have their own helicopters, and TV helicopter news reporting will be a valuable resource for a few major incidents, but not most. An anecdote demonstrates this – the first knowledge the San Francisco Fire Department EOC had of the Marina fire in the 1989 Loma Prieta earthquake was from television news reports (despite several companies having responded). Quickly gaining an accurate complete situational awareness is still a challenge.

#### **3.3.3 Fire service initial response**

The initial response of fire companies and personnel in the study area will be to protect themselves during violent shaking, and as soon as possible open the doors and remove apparatus (e.g., pumpers and ladder trucks) from the fire stations. Different departments have somewhat varying earthquake procedures but, in general, companies will remove apparatus to a pre-designated location, often simply in front of the fire station, check the station for damage and perform a radio check. By this time, typically within five minutes, they will either have self-dispatched to an observed smoke column, responded to a citizen still alarm, or been instructed to mobilize with other companies into a strike team.

Debris and bridge damage may block some roads and impede access to fire sites, although most cities are sufficiently redundant in street layout such that added travel time is limited to a few minutes, typically less than time lost due to delayed reporting. This has been specifically studied for a portion of Vancouver Island (Tamima and Chouinard 2017), finding that debris typically added about four minutes to travel time, with another four minutes added by bridge closures (i.e., a total of about eight minutes when both debris and bridge closures were considered).

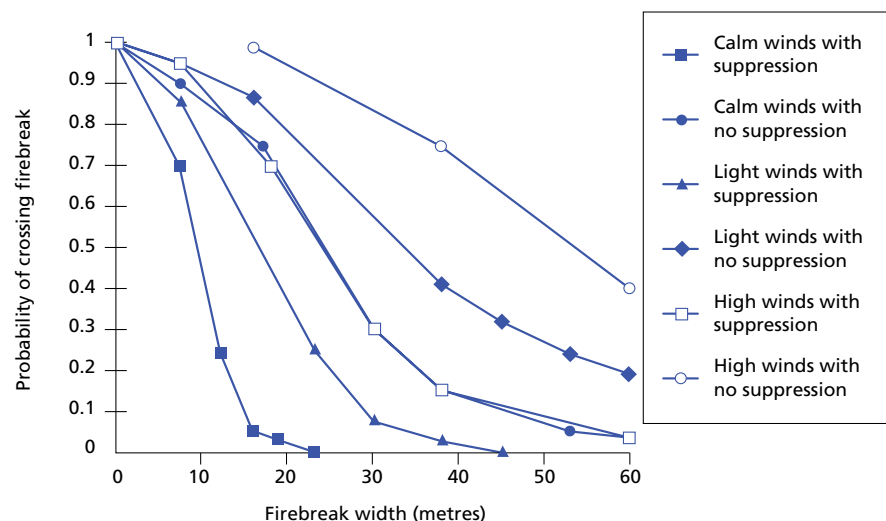
Local fire service resources will be completely committed, and in need of assistance from outside the study area. The primary needs will be personnel, additional hose, hard suction hose (that is, hose that does not collapse when used to draft water from a source that is not already under pressure), foam, light equipment (gloves, hand tools, self-contained breathing apparatus [SCBA]) and heavy equipment (cranes, bulldozers, backhoes). Additional fire apparatus (pumpers and ladder trucks) will not be the primary need initially, but will still prove useful as extra-regional strike teams arrive.

In the initial stage, personnel needs may be significantly supplemented by Community Emergency Response Teams (CERT) but will be more significantly strengthened by the recall of off-duty trained firefighters. Off-duty personnel can be expected to have doubled staffing within 3-6 hours and tripled it within 12-24 hours. While responding, an issue will be how these personnel marry up with their companies, and there will be some inefficiencies as personnel join first available companies. Nevertheless, arrival of off-duty personnel will be very important, to spell on-duty personnel nearing their physical limits.

### 3.4 Fire spread

The analysis assumes all fire service resources will initially focus on firefighting, leaving search and rescue, hazmat response and other emergencies until fires are brought under control. The initial ignitions will not all develop into large fires. Nevertheless, the normal structural fire response time will hardly be met. Delayed response, due primarily to failure of the 911 system, will result in many of the fires on arrival having grown such that a multi-engine capacity is needed. That is, an unfought ignition will grow into a room-sized fire within several minutes, and a fully-involved single family structural fire within several more. To protect neighbouring buildings (“exposures”) typically two or more companies are needed. If only one company is available, it is possible that it might be able to protect two exposures (using monitor and a hand line, with civilian assistance), but sometimes unlikely. In fire following earthquake modelling, such fires, where the fire has grown exceeding one engine company’s capabilities, are termed “large fires.” The spread of these fires is a function of building materials and density, windspeed and firefighting efforts. Within city blocks, unfought fires can spread rapidly – experience of urban fire spread in the absence of firefighting in modern urban regions is limited, although some data is available from wildland-urban interface (WUI) fires and other events. Spread from block to block – that is, across streets and other fuel breaks – can easily occur in the absence of firefighting, Figure 46.

**Figure 46: Probability of crossing firebreak (Scawthorn 1987; TCLEE 2005).**





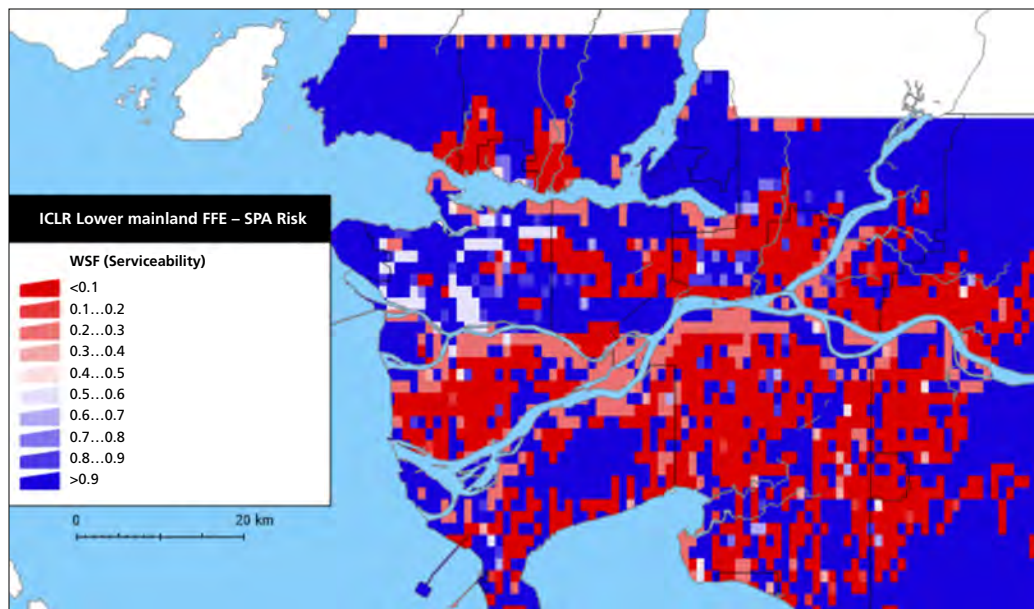
### 3.5 Lifelines

The performance of infrastructure or “lifelines,” such as water supply, gas integrity, electric power, communications and transportation, is integral to the fire-following-earthquake process and is briefly discussed here.

#### 3.5.1 Water supply

Water supply systems have been discussed above and will be severely impacted by the scenario events. Water supply is the sum of at minimum two sources: fire hydrants typically supplied by the buried potable water distribution network and, if this source should fail, then from alternative water sources (defined via AWSF, discussed above). Using methods in (Porter 2018), median estimates of the number of buried pipe repairs in the study area were found to be as high as 15,000, the precise number and location depending on the scenario event. Repairs in this case means leaks as well as breaks – the general rule is about 20% of repairs are full breaks. Based on this data, the scenario events severely impact the normal water supply in the study area, causing a lack of normal water supply (“serviceability”), where serviceability is the probability of required flow actually being delivered after the earthquake (Markov, Grigoriu and O’Rourke 1994; Porter 2018). Without normal water, firefighters will have to resort to AWS as discussed above. Combining the effects of degraded serviceability and the accessibility of AWS, this study characterizes the resulting availability of water in each grid cell by a factor termed the Water Supply Factor (WSF) where a WSF of 1.0 means an adequate (i.e., good) supply of water, and a WSF of zero means no water. The pattern of WSF for one realization of EQ4, Mw 7.3 Georgia Strait is shown in Figure 47.

**Figure 47: Water Supply Factor (WSF) for one realization of EQ4, Mw 7.3 Georgia Strait (effectively, likelihood of water at a fire considering buried pipe network and accessibility of AWS).**





### **3.5.2 Gas and liquid fuels**

As discussed earlier, Vancouver and portions of the neighbouring communities are served by a buried gas distribution network. Gas distribution-related ignitions typically account for about 25% of the total number of fire-following-earthquake ignitions (Scawthorn, Cowell and Borden 1997) and are accounted for in this study. Breaks and ignitions of gas and liquid fuel transmission lines are not accounted for in this study.

### **3.5.3 Communications**

Communications systems, particularly telephone, will sustain some damage but not enough to reduce functionality following the scenario event. However, saturation, especially of the 911 system, will reduce functionality to a great degree, for several hours or more. This lack of telephone reporting will result in delayed reports of fires, with consequences as discussed above.

### **3.5.4 Transportation**

The transportation system most relevant to fire following earthquake is the road network, which is most vulnerable at bridge crossings. Local and highway networks are typically sufficiently dense that redundant pathways exist within the region such that emergency services will probably not be greatly impeded. Mutual aid arriving from outside the study area, however, may be delayed due to traffic disruption, particularly at water crossings. Another issue is winter conditions – Vancouver suffers occasional severe snowstorms – the effect of these on response is complex and has not been considered.

## **3.6 Regional response**

There is a large number of fire agencies within a few hours of Vancouver that can be assumed to be sending fire companies within 12 hours or less. However, in our analysis and in the immediate post-earthquake period, mutual aid will be largely ineffective, due to the following factors:

- Delayed time to fire scene
  - Fire departments in the study area will husband resources and not be able to respond quickly.
  - Mutual aid will have to come from further afield in the Lower Mainland, requiring at least several hours. If arriving at night in blackout conditions (due to wide scale failure of electric power), response will be further retarded.
- Water shortages
  - Water tanker truck refills will be at some distance from fires, resulting in delays. However, VFRS in particular is well-equipped with fireboats, hose tenders, hose reels, a HydroSub® and, above all else, the DFPS, so at least the city of Vancouver will be better served.
  - Aerial attack – effectiveness of aerial attack in urban areas is currently unclear.
  - Foam is a “force-multiplier,” greatly increasing the effectiveness of a hose stream. However, current local fire-department supplies of foam are limited.
- Access
  - The Fraser and other rivers are all barriers if bridges are impassable, which they will be at least initially due to the need to inspect for damage.

## 4. Findings

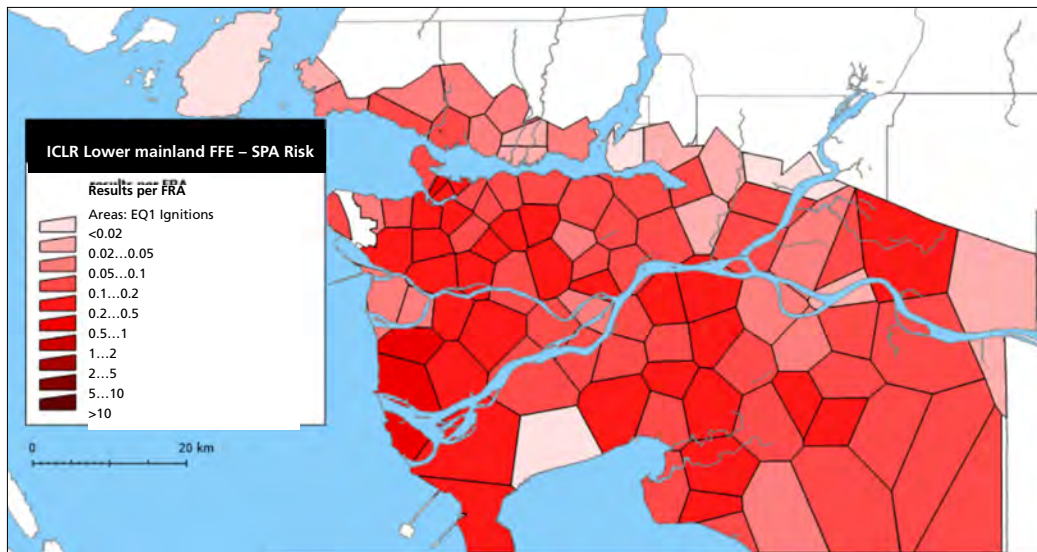
### 4.1 Final burnt area and loss

The above methods and data have been employed to estimate ignitions, fire agency response, fire spread and final burnt area and losses for the five scenario events. To account for uncertainty, 100 trials were run for each scenario, with results presented below.

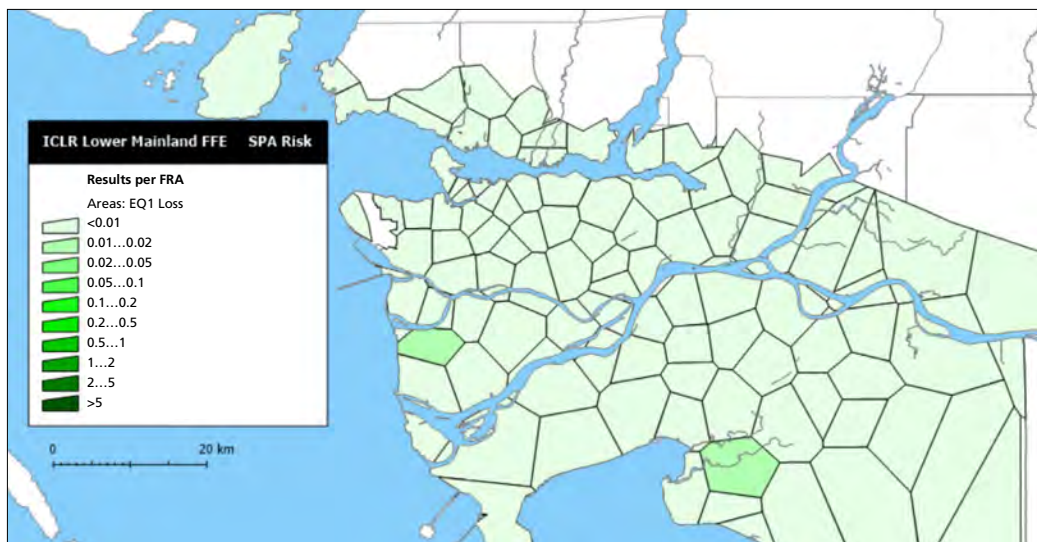
#### 4.1.1 EQ1 Mw 9.0 CSZ

As seen above, the ground motions for the Cascadia Subduction Zone event are relatively modest and result in, on average for the 1,000 realizations, about 15 ignitions with a distribution as shown in Figure 48, with typically one or less of these becoming large fires – if so, primarily due to lack of water for firefighting. The mean loss for this event is \$162 million, with a distribution as shown in Figure 49 and Figure 50.

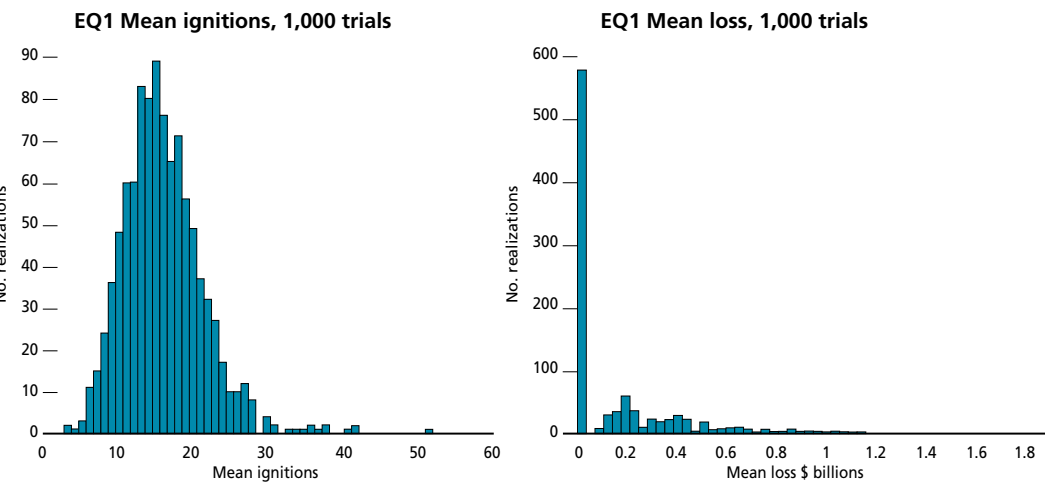
**Figure 48: EQ1 distribution of mean ignitions per FRA, entire study area.**



**Figure 49: EQ1 distribution of mean losses (in billions \$) per FRA, entire study area.**



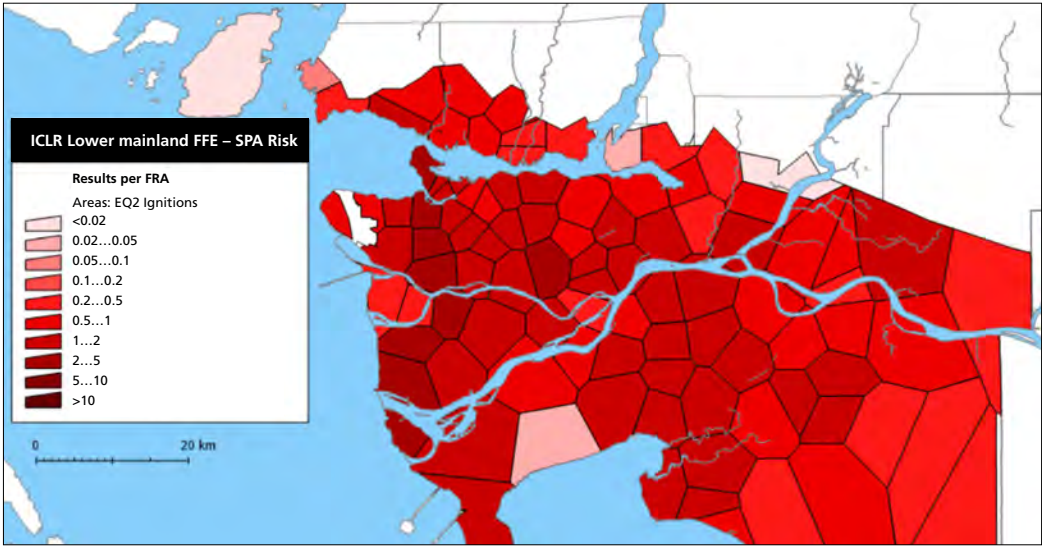
**Figure 50: EQ1 histogram of (left) ignitions per FRA, and (right) losses (in billions \$) per FRA, given 1,000 realizations.**



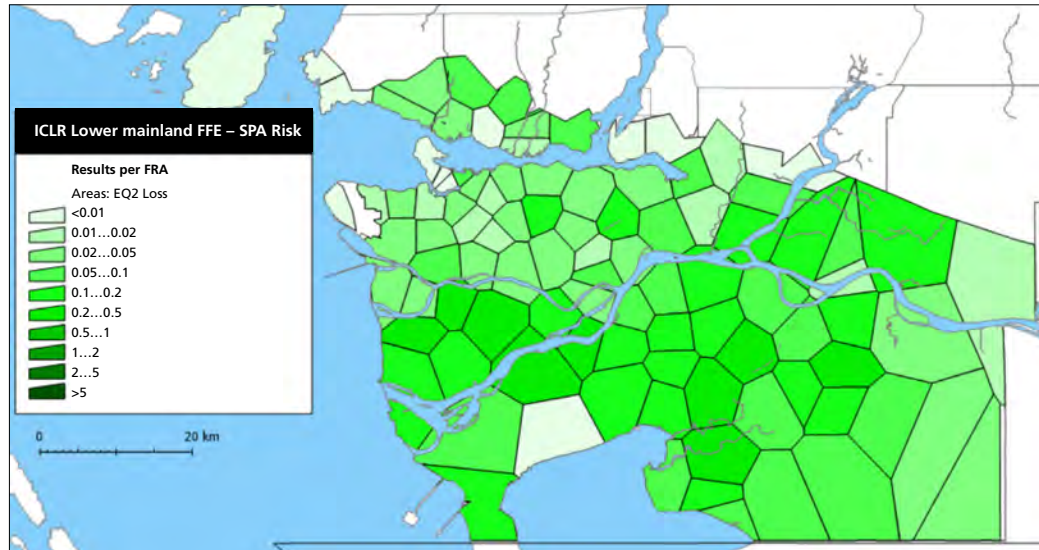
**4.1.2 EQ2 Mw 6.8 JDF**

As seen above, the ground motions for the Juan de Fuca event are considerably strong and result in, on average for the 1,000 realizations, about 106 ignitions with a distribution as shown in Figure 51, with 31 on average of these becoming large fires, primarily due to lack of water for firefighting. The mean loss for this event is \$7.4 billion, with a distribution as shown in Figure 52 and Figure 53.

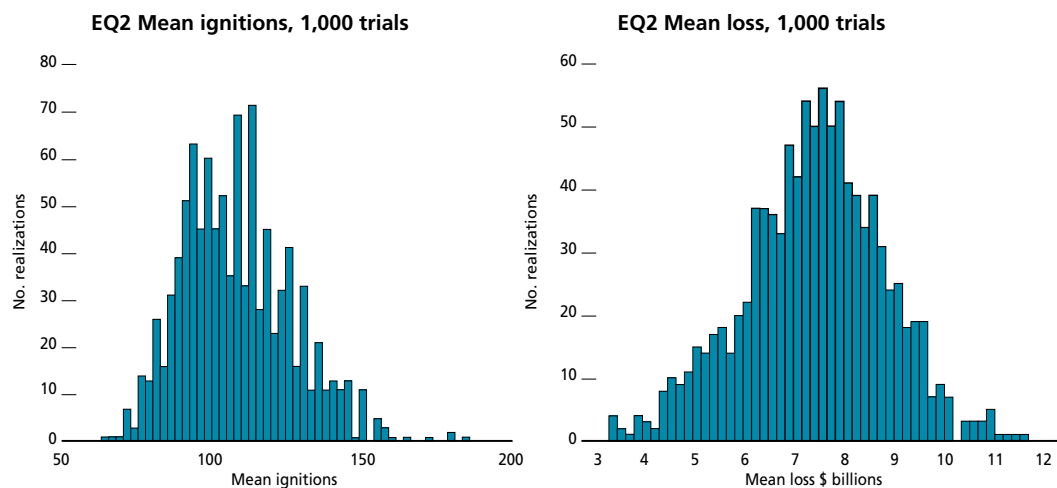
**Figure 51: EQ2 distribution of mean ignitions per FRA, entire study area.**



**Figure 52: EQ2 distribution of mean losses (in billions \$) per FRA, entire study area.**



**Figure 53: EQ2 histogram of (left) ignitions per FRA, and (right) losses (in billions \$) per FRA, given 1,000 realizations.**



#### **4.1.3 EQ3 Mw 7.3 LRDM**

As seen above, the ground motions for the LRDM event are almost nil and result in, on average for the 1,000 realizations, only a few ignitions typically being dealt with and resulting in no large fires. The mean loss for this event is negligible. Given the low level of these losses, no figures are provided.

4.1.4 EQ4 Mw 7.3 GS

As seen above, the ground motions for the Georgia Strait event are very strong, it having an epicentre very close to downtown Vancouver, and result in, on average for the 1,000 realizations, over 200 ignitions with a distribution as shown in Figure 54, with about 50 of these becoming large fires, primarily due to lack of water for firefighting, as well as there being simply too few firefighters and apparatus. The mean loss for this event is \$10.7 billion, with a distribution as shown in Figure 55 and Figure 56.

Figure 54: EQ4 distribution of mean ignitions per FRA, entire study area.

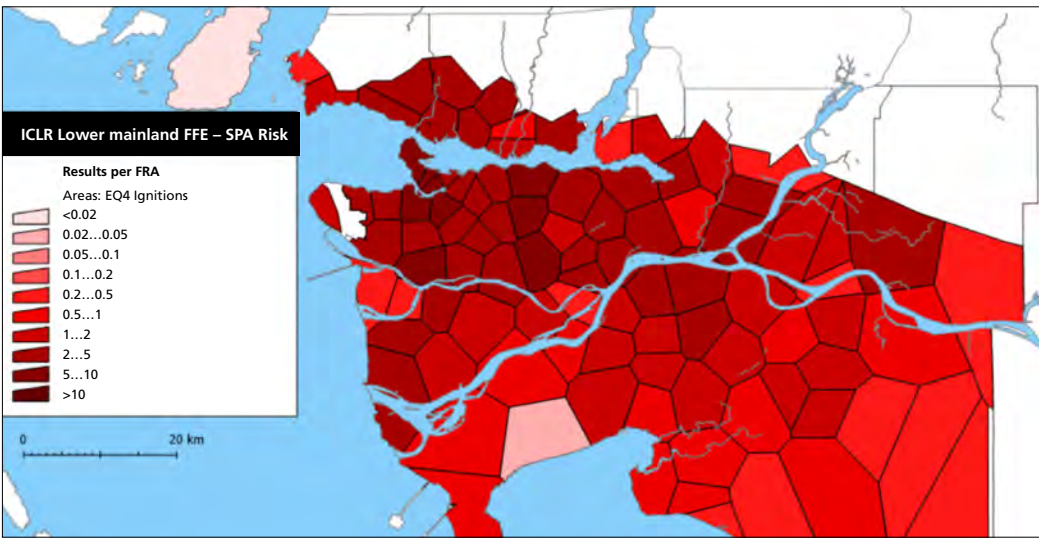
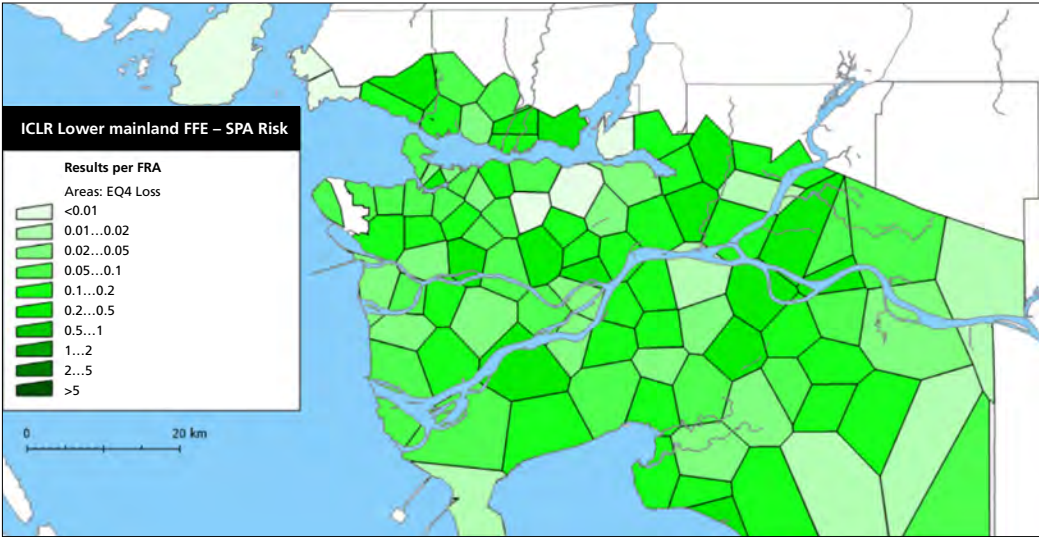
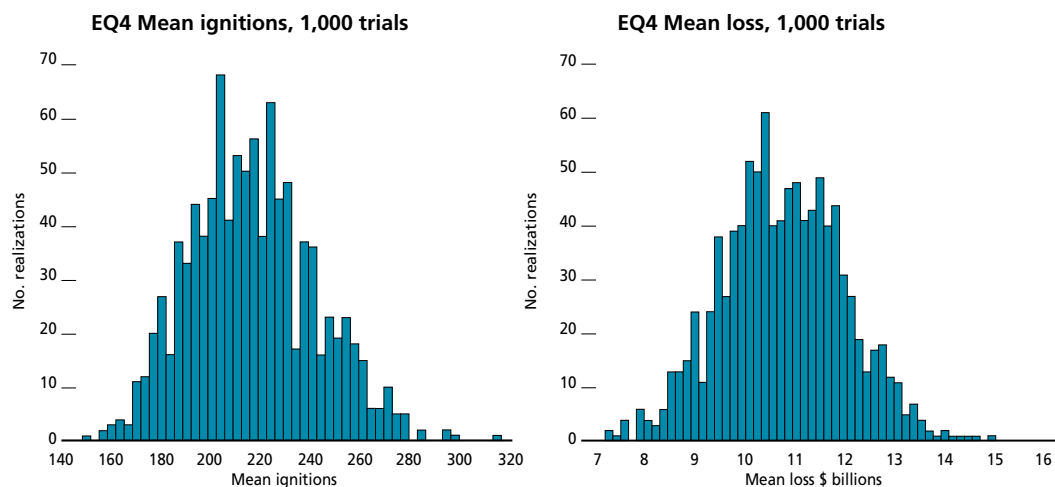


Figure 55: EQ4 distribution of mean losses (in billions \$) per FRA, entire study area.





**Figure 56: EQ4 histogram of (left) ignitions per FRA, and (right) losses (in billions \$) per FRA, given 1,000 realizations.**



#### 4.1.5 EQ5 Mw 6.5 NWM

Ground motions for the New Westminster event are intermediate to the other events and result in, on average for the 1,000 realizations, about 100 ignitions with a distribution as shown in Figure 57, with about half of these becoming large fires, primarily due to lack of water for firefighting. The mean loss for this event is \$10.9 billion, with a distribution as shown in Figure 58 and Figure 59.

**Figure 57: EQ5 distribution of mean ignitions per FRA, entire study area.**

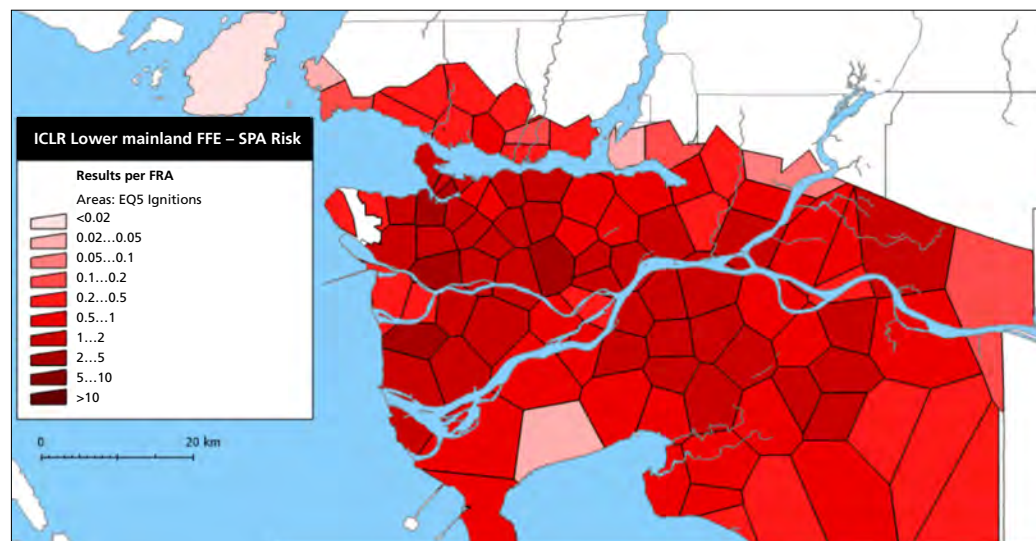




Figure 58: EQ5 distribution of mean losses (in billions \$) per FRA, entire study area.

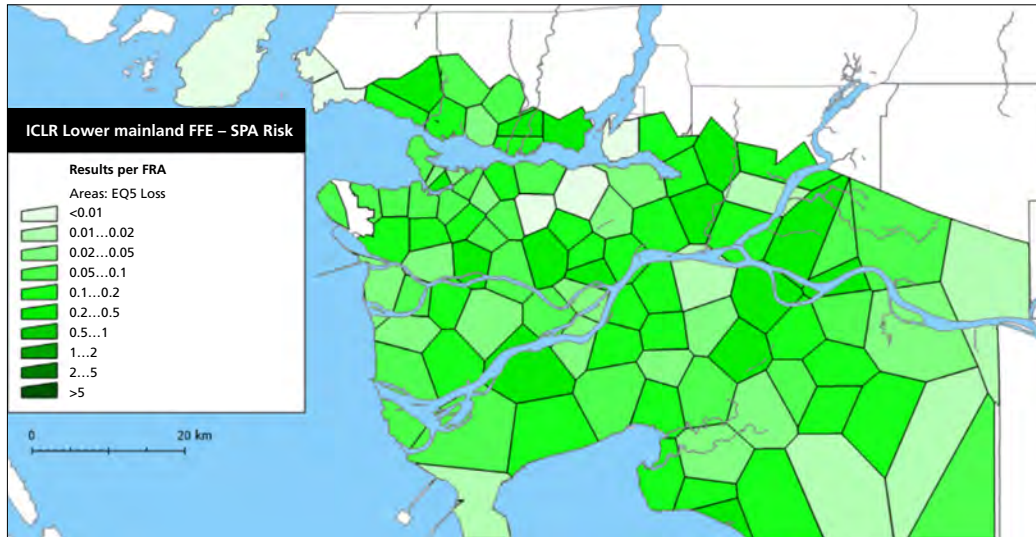
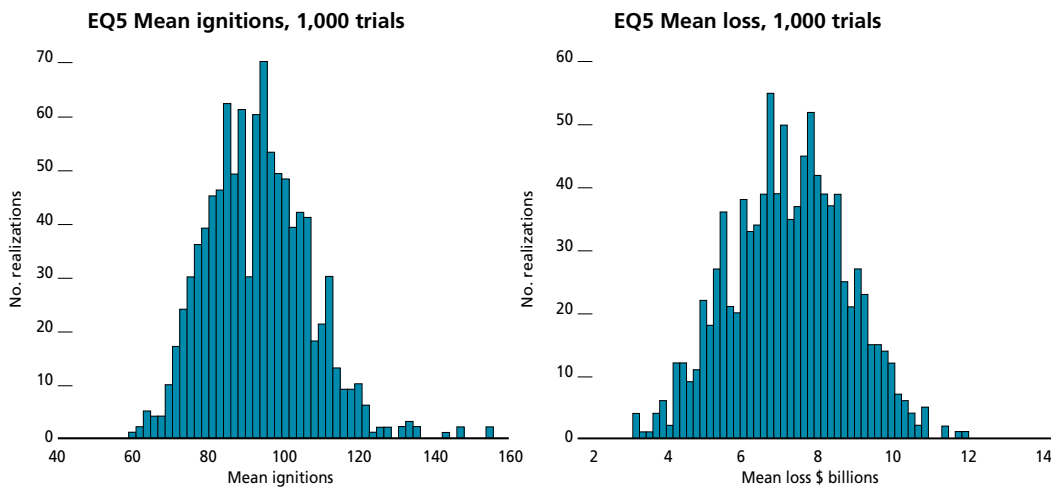


Figure 59: EQ5 histogram of (left) ignitions per FRA, and (right) losses (in billions \$) per FRA, given 1,000 realizations.



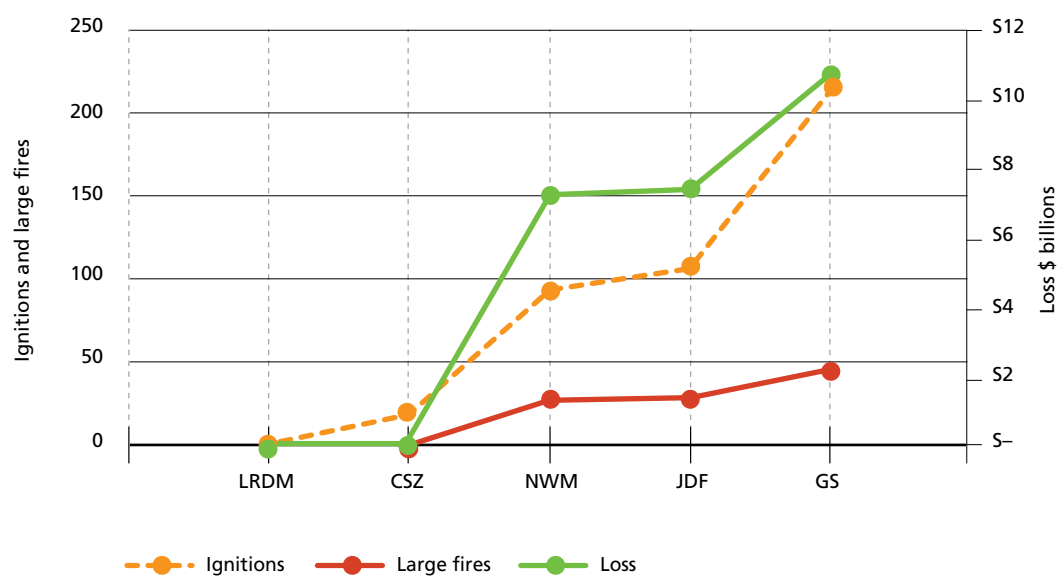
## 4.2 Summary of all scenario events

Median loss results for all scenarios are presented in Table 10 and Figure 60. Financial loss (total value of structural, non-structural components and contents) varies from nil to \$10 billion, depending on the scenario.

**Table 10: Median results by scenario.**

Scenario	EQ1 Mw 9.0 CSZ	EQ2 Mw 6.8 JDF	EQ3 Mw 7.3 LRDM	EQ4 Mw 7.3 GS	EQ5 Mw 6.5 NWM
Mean ignitions	16	106	4	216	93
Mean no. large fires	0.6	31	0.02	47	29
Mean losses in billions \$	\$0.16	\$7.4	\$0.01	\$10.7	\$7.2

**Figure 60: Lower Mainland fire following earthquake scenario losses, plotted in ascending order.**



## 5. Mitigation of fire following earthquake

Mitigation of fire following earthquake has been extensively discussed elsewhere (TCLEE 2005), so that only some limited recommendations are provided here, structured according to opportunities for improving fire department response and water service reliability and reducing building post-earthquake fire vulnerability.

### 5.1 Fire service opportunities

The fire service in the Lower Mainland is modern, advanced, well-equipped and of a high caliber in its organization, methods and tactics. The earthquake risk is understood and appears to be a focus for fire departments.

The city of Vancouver is bordered on several sides by water as was San Francisco in 1906 – indeed, San Francisco had direct access to the largest body of water on earth yet burned for three days due to lack of firefighting water. As a result, San Francisco and Vancouver have both built specialized high-pressure dedicated fire protection systems, for which they are to be commended. In addition to the DFPS, Vancouver has built a defence in depth, with fireboats, hose tenders and hose reels, as well as training citizen volunteer Neighbourhood Emergency Assistance Teams (N.E.A.T.s).

Other departments need to follow this model, tailored to their needs. We recommend development of an integrated regional Portable Water Supply System (PWSS) of hose tenders / hose reels, with compatible fittings, that can be used to access alternative water supply sources and relay water to the fireground. Such a regional system would also benefit from a number of HydroSubs® among the various larger departments. Such a system exists to some extent in the San Francisco Bay Area (although they could be doing more), Figure 61. Note that a PWSS has wider applicability than just earthquake – it can be used for wildfires, dewatering flooded areas and other emergency needs.

**Figure 61: Example of LDH system (Vallejo FD):** unit on left is a hose tender with monitor, carrying 5,000 ft. (1,538 m) of 5" (125 mm) hose; unit on right is HydroSub®, a hydraulically driven detachable pump. The pump head can pump 1,500 gpm (6,000 lpm) up to 20 m vertically from a bridge or other point. Here it is shown pumping from San Francisco Bay. See (Scawthorn 2018a) for more details.



## 5.2 Building standards opportunities

A significant number of, but not all, high-rise buildings in Vancouver are sprinklered, to the region's credit. To the City's credit, all new construction, low- as well as high-rise buildings, are required to be sprinklered, but at least some older high-rise and many older low-rise buildings are not sprinklered (the precise number is not known). However, sprinklers rely on the buried water mains for supply. In an earthquake, water mains may lose pressure, so that the sprinklers will have no supply, Figure 62. This was recognized decades ago in the California Building Code, which requires:

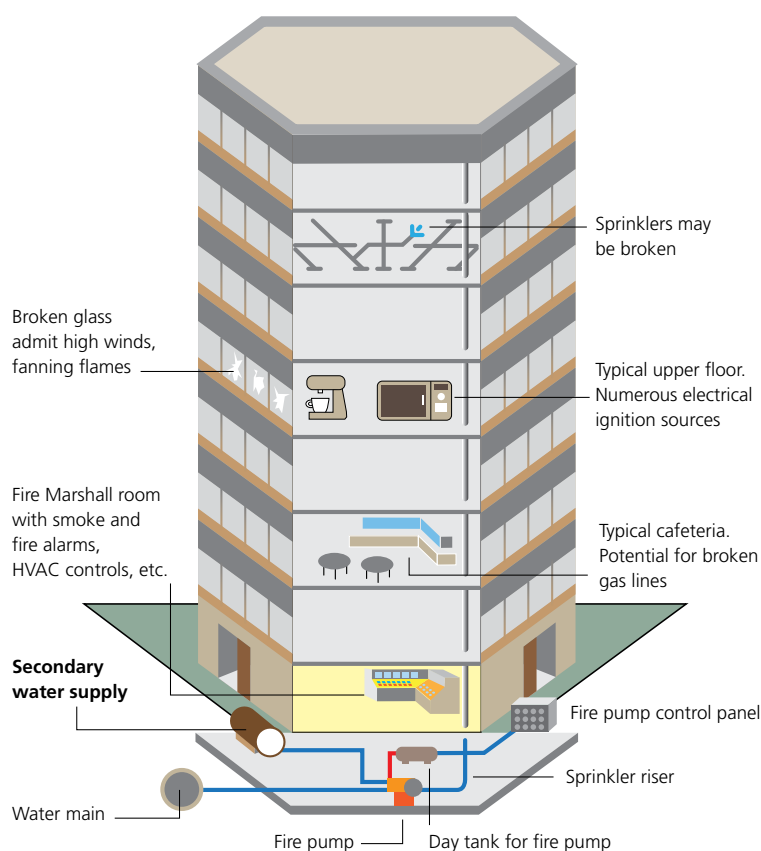
### "403.3.3 Secondary water supply

An automatic secondary on-site water supply having a *useable* capacity of not less than the hydraulically calculated sprinkler demand, including the hose stream requirement, shall be provided for high-rise buildings and Group I-2 occupancies having occupied floors located more than 75 ft above the lowest level of fire department vehicle access assigned to Seismic Design Category C, D, E or F as determined by Section 1613. An additional fire pump shall not be required for the secondary water supply unless needed to provide the minimum design intake pressure at the suction side of the fire pump supplying the automatic sprinkler system.

The secondary water supply shall have a *useable capacity of not less than the hydraulically calculated sprinkler demand plus 100 GPM for the inside hose stream, allowance, for a duration of not less than 30 minutes or as determined by the occupancy hazard classification in accordance with NFPA 13, whichever is greater. The Class I standpipe system demand shall not be required to be included in the secondary on-site water supply calculations. In no case shall the secondary on-site water supply be less than 15,000 gallons.*" <https://up.codes/viewer/california/ca-building-code-2016-v1/chapter/4/special-detailed-requirements-based-on-use-and-occupancy#403>

Vancouver and the Provincial Building by-laws lack a similar provision, which we recommend should be seriously considered throughout the Lower Mainland. Retrofitting existing high-rise buildings with 60,000-litre water tanks may seem a large and expensive task, but actually it isn't. Such a tank would take up the equivalent of perhaps two parking spaces in a basement parking garage, for example, and the cost would be significantly less than 1% of the building value and less than might be spent on renovating a building lobby.

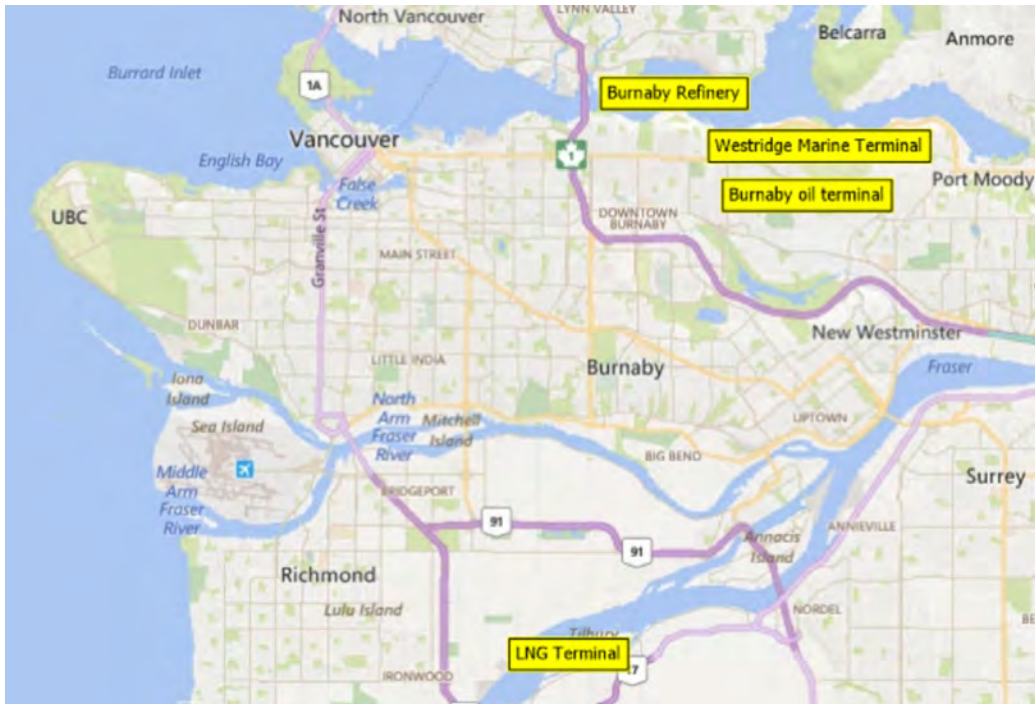
**Figure 62: High-rise building and post-earthquake fire aspects. Secondary water supply is required in seismic zones in U.S. because it is anticipated water mains may fail. If mains fail, sprinklers have no supply (Scawthorn 1989).**



### 5.3 Energy industry

This study did not assess the seismic vulnerability of the gas distribution or other energy industry assets, many of which are concentrated in the highly liquefiable Fraser River Delta. There is a long history of major energy facilities being damaged in earthquakes, including by fire, so this aspect should not be ignored. Additionally, particularly in winter, millions of people are dependent on energy services. While we didn't address energy industry aspects, in this respect two actions have been de rigueur in other regions, and should be considered in the Lower Mainland: (1) a review of the overall seismic vulnerability and reliability of major energy facilities, Figure 63; (2) a review of the ability to control and isolate the gas transmission and distribution networks in the event of a major earthquake and consideration by the gas distribution operator of incorporating an automatic gas shutoff device in gas meters.

**Figure 63: Selected Lower Mainland large energy facilities.**



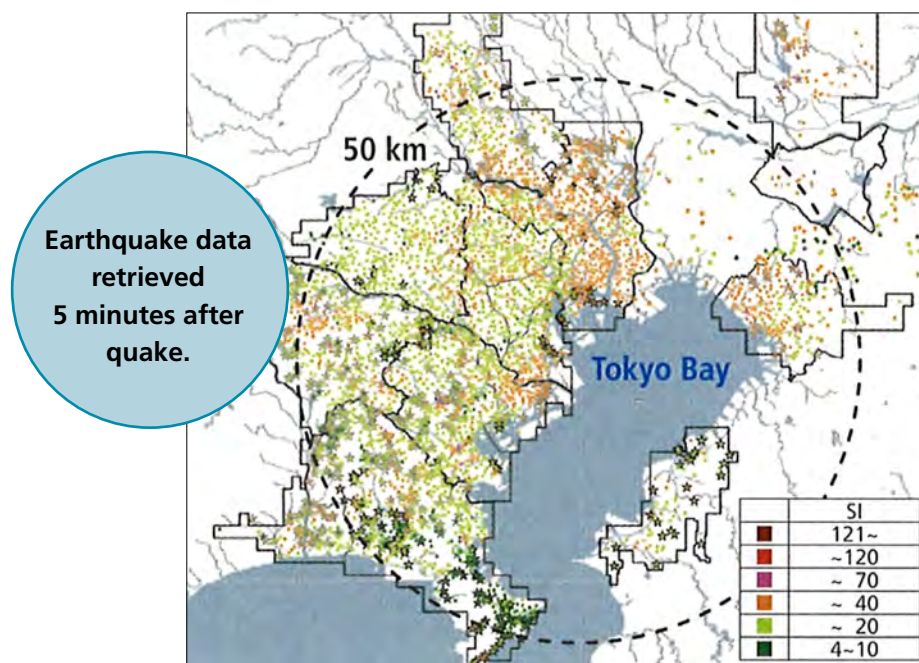
Regarding the gas transmission and distribution networks, there are two levels of control that might be considered: (a) "block" control, and (b) individual meter shutoff devices.

Block control consists of sub-dividing the network into a number of blocks, each of which can be monitored for seismic intensity and automatically or remotely isolated if the intensity exceeds a threshold. Such systems have been employed by Tokyo Gas and other utilities in Japan for decades and function well (Katayama, Sato and Saito 1988), Figure 64.



Following the 1995 Kobe earthquake and resulting fires, the government of Japan mandated that all gas meters be replaced with meters having an automatic gas shutoff device. Every gas meter in Japan was thus replaced within several years, with a standardized gas meter that differed little from the pre-earthquake meter excepting a simple seismic intensity monitoring circuit board and spring-activated gas shutoff device. In the more than two decades since, these meters have functioned well, with very few false triggers (Japan Gas Assn. personal communication). In the event of a false trigger, the device can be easily reset by the customer, Figure 65.

**Figure 64: Seismic intensities measured in Tokyo Gas service area within five minutes following 2011 Tohoku earthquake.**



**Figure 65: Seismic gas shutoff device built into gas meter (Source: Tokyo Gas).**

### Intelligent gas meter recovery

If a gas leak or an earthquake measuring intensity 5 or greater on the Japanese seismic intensity scale (JMA) is detected, or if a gas device was accidentally left on or there is a high flow of gas, the gas meter automatically shuts off the gas supply. The customer can restore the gas supply by following a simply recovery operation procedure.

\* Refer to the instruction manual provided with the meter for further details.

**1**

Turn off **all** gas devices. Do not forget to turn off outside devices. (Meter gas tap is left open).

**2**

Remove the reset button cap. (There are also types without caps.)

**3**

Press the reset button all the way in, and then slowly release it. (After the red lamp lights up, it starts to flash.)

**4**

**Do not use the gas and wait approximately 3 minutes.**

(Gas meter checks the safety during this time.)  
When it stops flashing, the gas can be used. If it does not stop flashing, start over from step 1.  
(Contact Tokyo Gas if this procedure does not restore the gas.)

Scan the QR code or use the following URL to view the Tokyo Gas website in English.

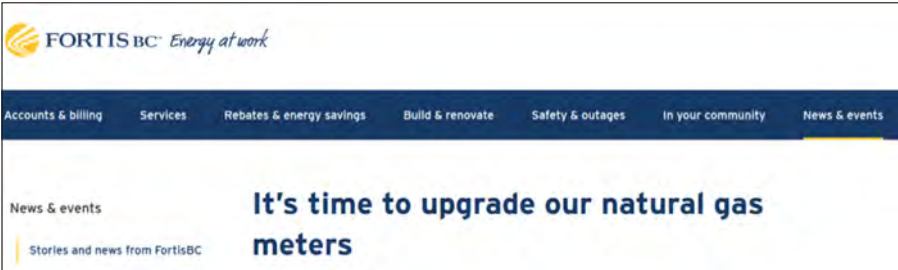
[Tokyo Gas website]  
[http://www.tokyo-gas.co.jp/index\\_e.html](http://www.tokyo-gas.co.jp/index_e.html)



The main gas utility for the Lower Mainland is now “exploring a number of ways to modernize our natural gas system for our more than one million customers across BC. One of the ways we’re proposing to do this is by **upgrading our existing gas meters with new advanced meters** [emphasis added]... send the information to FortisBC... meaning FortisBC would no longer need to enter customers’ properties regularly to read meters.”<sup>10</sup>

We recommend inclusion of a seismic gas shutoff device in these new meters, similar to meters installed in Japan following the 1995 Kobe earthquake. The opportunity afforded by the utilities’ plan to replace these meters for more efficient operation permits inclusion of the seismic shutoff device at a very modest marginal cost. Figure 66.

**Figure 66: Lower Mainland gas utility meter upgrade announcement.**<sup>10</sup>



<sup>10</sup> <https://www.fortisbc.com/news-events/stories-and-news-from-fortisbc/it-s-time-to-upgrade-our-natural-gas-meters>

## 6. Concluding remarks

The Geological Survey of Canada assesses the Vancouver region as having significant earthquake hazard and potential for ground motions that will cause significant damage to ordinary buildings and infrastructure. The region suffered a magnitude 9.0 earthquake in 1700 on the Cascadia Subduction Zone, which is considered likely to re-occur in the near future.

Earthquakes are sometimes followed by major fires, whose damage can greatly exceed the shaking damage. To assess the risk of fire following earthquake and identify opportunities to reduce the risk, ground motions for five scenario events – two distant events: a Mw 9.0 CSZ event and a relatively distant Mw 7.3 event on the island of Vancouver; and three relatively nearby events: a deep in-slab event on the subducting Juan de Fuca Plate, a Mw 7.3 event in the Georgia Strait just to the west of the city of Vancouver, and a Mw 6.5 shallow crustal event centred on the city of New Westminster.

Accounting for fire department response, water system damage, weather and other conditions, the growth and ultimate final burnt area of fires are estimated to result in median losses from nil to \$10 billion. These are median estimates – there are significant probabilities of greater or less damage, and the range is a function of the specific earthquake scenario (i.e., location and magnitude), time of day, weather and other factors.

This loss would be virtually fully insured and would have a very significant impact on the Canadian insurance industry. Fire losses would come on top of shaking and other losses, which would be insured to a lesser extent. A leading global reinsurer has stated that losses of this magnitude would likely result in failure of some insurers, would entail secondary and contingent losses, and could conceivably lead to financial contagion.

This risk need not be tolerated and indeed the Province of British Columbia, City of Vancouver, and regional agencies such as Metro Vancouver and BC Hydro have implemented excellent programs to reduce this risk. Further actions, however, can still be taken to reduce the risk of fire damage. The potential loss involved represents a local, provincial and national threat that all involved in have worked to reduce, but more still needs to be done.

This study was aided by many persons in the region – we met with a number of fire, water, city and emergency planning and other officials, whose assistance was generously provided and is gratefully appreciated.

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