Fire following earthquake in the Montreal region

Prepared for the Institute for Catastrophic Loss Reduction

By Charles Scawthorn, S.E.
August 2019
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SPA Risk LLC

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Abstract

The Montreal region comprises more than 10% of Canada's entire population and is a major economic driver and cultural centre of Canada.

The Geological Survey of Canada assesses the Montreal region as having significant earthquake hazard and potential for ground motions that will cause significant damage to ordinary buildings and infrastructure.

Three scenario earthquakes – a magnitude 6.5 event centred in downtown Montreal and magnitude 7 events to the Northwest and Southwest of Montreal – were found to cause very strong ground motions in the study area, resulting in hundreds of breaks in the water distribution systems and hundreds of fires.

Accounting for fire department response, water system damage, weather and other conditions, the growth and ultimate final burnt area of fires were estimated and in summary found to result in median losses of between $10 billion and $30 billion.*

These are median estimates – there are smaller 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 largely 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.

This risk need not be tolerated and can be significantly reduced. Making earthquake risk reduction a high priority by all concerned parties would be a necessary and salutary advance. Specific initial steps would include assessing the seismic vulnerability of emergency facilities and the water system including providing secondary water supply for high-rise buildings. Lastly, there is a large concentration of energy facilities in Montreal East, whose seismic vulnerability should be assessed.

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

The Montreal region with a population of about 3.5 million is the most populous metropolitan area in Quebec and the second most in Canada and comprises more than 10% of Canada’s entire population. It is a major economic driver and cultural centre with leading universities, a major rail hub and port as well as being the entrance to the St. Lawrence Seaway.

The Geological Survey of Canada assesses the Montreal 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 5.8 in a 1732 earthquake which shook Montreal strongly and caused significant damage. In 1852 the City lost half its housing in a Great Fire.

While the fire service in Quebec is very advanced, well-equipped and modern in its organization, methods and tactics, earthquakes are sometimes followed by major fires whose damage can greatly exceed the shaking damage, despite the best efforts of the fire service.

To assess the risk of fire following earthquake (FFE) and identify opportunities to reduce the risk, ground motions for three scenario earthquakes – a magnitude 6.5 event centred in downtown Montreal and magnitude 7 events to the Northwest and Southwest of Montreal – were determined and found to cause very strong ground motions in the study area, resulting in hundreds of breaks in the water distribution systems and hundreds of fires.

Accounting for fire department response, water system damage, weather and other conditions, the growth and ultimate final burnt area of fires were estimated and in summary found to result in losses of between $10 billion and $30 billion. These are median estimates – there are smaller 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 largely 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 can be significantly reduced. Making earthquake risk reduction a high priority by all concerned parties would be a necessary and salutary advance. Specific initial steps would include:

- **Assess emergency facilities’ seismic vulnerability**: Many fire stations in the region, especially in older neighbourhoods, are many decades old (the oldest station in Montreal was built in 1891), seismically vulnerable and probably in need of strengthening or replacement. Damage to fire stations in an earthquake can cause injuries to firefighters and degrade the capacity of the fire department when it is most needed. A regional seismic vulnerability assessment of fire stations and emergency facilities would be the first step towards a seismic upgrading program.

- **Assess water system seismic vulnerability**: Water is necessary for fire suppression. This study could not adequately assess the several water distribution systems in the region, but it is likely they will sustain hundreds of breaks and widespread loss of pressure in an earthquake such that firefighters will be forced to seek alternative water sources. A seismic vulnerability assessment of the water distribution systems in the region would be a solid basis for a seismic upgrading program.
• **Enhance access to alternative water supplies:** Prudence and normal fire service practice dictates having an alternative to the water distribution system, in case of water system failure. This is common practice for the fire service in general, and for Montreal and other fire departments in the region. Montreal has excellent access to the St. Lawrence and other alternative water supplies yet lacks adequate capacity to move this water from the source to the fireground. Development of a regional Portable Water Supply System (PWSS) would greatly improve this situation. In the regional context, a PWSS is not expensive and could be used for emergencies other than earthquakes, such as wildland fires, water main breaks and dewatering flooded areas.

• **Secondary water supply for high-rise buildings:** High-rise buildings are particularly vulnerable to fires at all times and fire departments depend to a great extent on sprinkler systems slowing or extinguishing fires in these buildings. For this reason, almost all high-rise buildings in Montreal are sprinklered, which is very good. However, sprinklers depend on the buried water distribution system for supply and, if that system fails in an earthquake, sprinklers may be left without water and fires can grow unimpeded. For this reason, building codes in the United States for decades have required high-rise buildings in high seismic zones to have a secondary water supply, typically a 60,000-litre tank located in the basement or mechanical room near the backup fire pump. Montreal has no such requirement (it appears the National Building Code of Canada does not have this requirement). Consideration should be given to installing secondary water supply tanks in high-rise buildings. The cost and space requirements are not very great, and pale when compared with the value of a high-rise building, not to speak of the potential consequences.

• **Energy facilities** were largely not treated in this study, even though there is a large concentration of energy facilities in the region and a long history of similar facilities being damaged in earthquakes, including by fire. For these reasons as well as that millions of people are dependent on energy services, particularly in winter, two actions suggest themselves and should be considered in the Province of Quebec: (1) a review of the overall seismic vulnerability and reliability of major energy facilities; (2) review by Énergir of its ability to control and isolate its transmission and distribution networks in the event of a major earthquake.

An innovative aspect of this report has been the inclusion of spatial correlation for the analysis of fire following earthquake. To our knowledge, this is the first time this has been considered for fire following earthquake, and one of the very few times it has been considered for assessing seismic performance of infrastructure or emergency response.

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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<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>AWS</td>
<td>Alternative water supplies</td>
</tr>
<tr>
<td>CatIQ</td>
<td>Catastrophe Indices and Quantification Inc., a catastrophe data provider, see <a href="http://www.catiq.com">www.catiq.com</a></td>
</tr>
<tr>
<td>CI</td>
<td>Cast iron (pipe)</td>
</tr>
<tr>
<td>DI</td>
<td>Ductile iron (pipe)</td>
</tr>
<tr>
<td>FBA</td>
<td>Final Burnt Area</td>
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<tr>
<td>FRA</td>
<td>Fire Response Area</td>
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<tr>
<td>FSA</td>
<td>Forward Sortation Area</td>
</tr>
<tr>
<td>GMM</td>
<td>Ground Motion Models</td>
</tr>
<tr>
<td>gpm</td>
<td>Gallons per minute</td>
</tr>
<tr>
<td>GSC</td>
<td>Geological Survey of Canada</td>
</tr>
<tr>
<td>LDH</td>
<td>Large Diameter Hose (typically, 5” [125mm] or larger diameter)</td>
</tr>
<tr>
<td>Ma</td>
<td>Million years</td>
</tr>
<tr>
<td>MFD</td>
<td>Montreal Fire Department (Service de sécurité incendie de Montréal)</td>
</tr>
<tr>
<td>MMI</td>
<td>Modified Mercalli Intensity</td>
</tr>
<tr>
<td>MWS</td>
<td>Montreal water system (Service de l’eau)</td>
</tr>
<tr>
<td>NEHRP</td>
<td>National Earthquake Hazards Reduction Program</td>
</tr>
<tr>
<td>NRCan</td>
<td>Natural Resources Canada</td>
</tr>
<tr>
<td>PGA</td>
<td>Peak ground acceleration</td>
</tr>
<tr>
<td>PGD</td>
<td>Permanent ground displacement</td>
</tr>
<tr>
<td>PGV</td>
<td>Peak ground velocity</td>
</tr>
<tr>
<td>TFA</td>
<td>Total Floor Area, sq. m</td>
</tr>
<tr>
<td>TIV</td>
<td>Total Insured Value</td>
</tr>
<tr>
<td>UMB</td>
<td>Unreinforced Masonry Building</td>
</tr>
<tr>
<td>Vs30</td>
<td>Shear wave velocity of the upper 30 m of soil</td>
</tr>
<tr>
<td>WSF</td>
<td>Water Supply Factor</td>
</tr>
<tr>
<td>WUI</td>
<td>Wildland-urban interface</td>
</tr>
<tr>
<td>ybp</td>
<td>Years before present</td>
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1. Introduction

1.1 Purpose

Fire following earthquake refers to a series of events or 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. Regions of high seismicity with large metropolitan areas predominantly comprised of 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. However, any area with a large inventory of densely spaced wood buildings struck by an earthquake has the potential for large post-earthquake conflagrations. Such a situation prevails in Eastern Canada particularly in portions of Quebec which, while less active seismically than some other parts of Canada, still has sufficient seismicity to be a concern.

1.2 Background

The Montreal region has a significant risk of earthquake shaking. Geologic and seismologic studies confirm this, as well as actual events such as the 1732 earthquake. The Geological Survey of Canada and the National Building Code of Canada rate the likelihood of peak ground acceleration at Montreal City Hall almost the same as at Vancouver, B.C. City Hall (Adams et al. 2019), albeit the response spectral accelerations\(^1\) are significantly higher for Vancouver, Figure 1.

Figure 1: Comparison of Montreal and Vancouver, B.C., seismic hazard results (Adams et al. 2019). Note that 2%/50 year peak ground acceleration (PGA) for Montreal (0.43g) and Vancouver (0.49g) are almost the same.

\[ Sa(0.2) \text{ for Canada (mean values of 5\% damped spectral acceleration for Site Class C and a probability of 2\%/50 years, units = g).} \]

\[ \text{Uniform Hazard Spectra for mean 2\%/50 year ground motions on Site Class C for key cities.} \]

\(^1\) Response spectral accelerations are the maximum accelerations experienced by structures of a specific fundamental period, given ground motions.
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 Montreal Fire of 1852, which occurred on a “red flag day”\(^2\) (i.e., 30 degr. C and a stiff southwesterly wind) and destroyed about half the city’s housing.

Figure 2: Map showing the extent of the damage in the Great Fire of 1852. The ravages of the first fire are shown in red and the second fire, in blue.
Source: http://ville.montreal.qc.ca/sim/en/file/489

Large urban conflagrations were actually the norm in 19\(^{th}\) Century 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.

\(^2\) This refers not to Canada’s flag at the time but rather to a term used in the fire service denoting hot dry windy conditions, conducive to conflagrations.
As the fire service was professionalized in the 20th Century 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 Ft. McMurray in 2016 where more than 2,500 dwellings were destroyed, in 2017 in Northern California where 10,000 buildings were destroyed, or in 2018 in Northern California, where 20,000 buildings were destroyed. While these losses were wildland-urban interface (WUI) fires, they show that even a single ignition can overwhelm regional fire agencies. Following 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 non-earthquake related large urban conflagrations in the US, 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 resistant 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 in the early stages of structural fires, arriving in time to suppress the fires while they are still relatively manageable. A typical response goal for urban fire departments for example is about 4 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 municipalities’ 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 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 (B.C.) Fire and Rescue Services have all undertaken special measures, which will be discussed below.
1.3 Previous studies

Eastern Canada has been the subject of several previous studies of how it would be affected by an earthquake.

Probably the first data point is historical – the September 16, 1732, earthquake which occurred at 11 am and had a body wave magnitude in the range of 5.6 to 6.0, an ascribed epicentre (45.5N 73.6W) beneath Mount Royal in Montreal, and an epicentral intensity of Modified Mercalli Intensity (MMI) VIII-IX (Leblanc 1981; NRC 2019). More than 300 buildings were destroyed. Given the sparseness of seismological knowledge at the time and the attenuation with time of the facts of this event, the epicentral location and other attributes of this event should be assumed to have some uncertainty. Other studies of historical eastern Canada events include (Bruneau and Lamontagne 1994; Cassidy et al. 2010; Lamontagne et al. 2008; Lamontagne 2002; Stevens 1995).

Potential damage in Montreal due to shaking has been examined by (Yu 2011a; Yu, Chouinard and Rosset 2016), who found for a “2% in 50 years seismic threat, which corresponds to the design level earthquake in the National Building Code of Canada… roughly 5% of the building stock would be damaged with direct economic losses evaluated at 1.4 billion dollars … maximum number of casualties would result in approximately 500 people being injured or dead at a calculated time of occurrence of 2 pm.” Neither damage to infrastructure nor losses due to fire following earthquake were considered.

The same group very recently re-examined shaking damage to residential buildings in Montreal (Rosset et al. 2019). Based on six scenario events including a repeat of the 1732 earthquake, they found shaking damage to residential buildings varied from 1 to 12% of exposure value, with losses of as much as $10 billion.

One of the leading global reinsurers, Swiss Re, examined earthquake risk in eastern Canada, finding (Swiss Re Institute 2017):

“...In the past, earthquakes have occurred close to the centres of Quebec City (magnitude 5.2 in 1997), Ottawa (magnitude 5.6 in 1944 in Cornwall, West of Ottawa) and Montreal (magnitude 5.8 in 1732). The modelled probability of such occurrences is very low. However, knowledge of earthquake frequency in Canada remains an active field of research and it cannot be precluded that another quake of similar magnitude to the historically recorded values will strike again. And in big cities, even events of lesser magnitude can cause extensive damage and trigger significant losses, as the 2010 and 2011 earthquakes in Christchurch demonstrated. In the case of Montreal, which is much bigger than Christchurch with a population of 3.6 million, according to the Swiss Re model, a repeat of the 1732 magnitude 5.8 earthquake could produce total losses of more than $45 billion from damage to residential buildings alone. If also counting damages to commercial and public assets, infrastructure and cascading economic effects, the losses would be much higher still.”

This estimate was based on proprietary Swiss Re models and focused on shake damage, which is the bulk of the estimate of $45 billion. The study discusses the low earthquake insurance penetration and given the magnitude of the losses the potential for insurance defaults and even financial contagion.
A 1995 study that explicitly examined fire following earthquake was sponsored by the Insurance Bureau of Canada (RMS 1995) and found that "The Quebec industry portfolio has approximately $179 billion of value exposed to potential fire following earthquake, over six times as much value as exposed to potential earthquake losses. Inclusion of fire following earthquake loss estimates increases ground up and gross losses for the worst-case Western Quebec 7.5R event [i.e., Montreal event] from $2.0 billion to $6.5 billion and $1.1 billion to $5.7 billion, respectively." That is, fire following earthquake insurance exposure was much greater than for shaking, and fire following earthquake losses were on the order of $5 billion and almost entirely insured. These estimates are point estimates (i.e., uncertainty is not discussed, and it is unclear if it was considered). As discussed below, fire policy insurance exposure has increased from $179 billion in 1995 to $809 billion today (450% increase).

More recently, the Insurance Bureau of Canada sponsored another study of earthquake risk (AIR Worldwide 2013) which examined a magnitude 7.1 event occurring at the shallow depth of 10 km beneath the St. Lawrence River, about 100 km north east of Québec City (epicentre Lat. 47.245, Lon. -70.470). Given its location the event doesn’t affect Montreal very strongly (MMI V) and is only relevant to this study in that it examines fire following earthquake, albeit in the vicinity of Quebec City where the ca. 1 million regional population is subjected to MMI VI to VII. Regarding fire following earthquake, the event is modelled as a daytime event early in December with average high temperature of -5 degrees Celsius, 73% probability of light or moderate snow and typical wind speed of 28 km/h. Uncertainty is considered for ignition location and number, wind speed, success of fire suppression, and fire severity, via 50 simulations. The study finds 80-90 primary ignitions that “spread and ignite subsequent fires due to both wind conditions and inadequate fire suppression… and encompass a total of 140 city blocks…burning over 3 million square feet [ca. 300,000 sq. m] of building floor area.” The total direct loss in the event, shaking, fire, liquefaction and landslide is about $49 billion, of which fire following earthquake direct losses are 1.5% or about $725 million. Indirect losses are in the range of $5- to $17 billion additional to the $49 billion. Almost all the fire following earthquake losses are considered insured.

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 was employed in this analysis. Section 3 then outlines the analysis methods, section 4 the findings, and section 5 opportunities for mitigation. References and an Appendix on Montreal building construction conclude the report.
2. Study region

2.1 The study region

The study region is the Montreal metropolitan region consisting of twelve municipalities centred on
the Hochelaga Archipelago at the confluence of the Saint Lawrence and Ottawa rivers in the
southwestern part of the province of Quebec as shown in Figure 4 to Figure 6. The Island of Montreal
at 50 kilometres long and an area of 465 square kilometres is the largest island of the archipelago
and has a maximum elevation at the top of Mount Royal of 229 m above sea level (Boyer et al. 1985).

As shown in Table 1, with a population of about 3.5 million3 the region is the most populous
metropolitan area in Quebec, and the second most in Canada, comprising more than 10% of
Canada’s population. Population growth for the City of Montreal reached its current level in the
1960s, with later growth in more outlying communities such as Laval and Longueuil, Figure 7.
Population density is shown in Figure 8 by postal Forward Sortation Area (FSA) and within the study
region varies from 10 to over 16,000 per sq. km. Half the study area’s population is within the
City of Montreal, a major cultural centre with leading universities, major rail hub and port as well as
the entrance to the St. Lawrence Seaway.

Table 1: Study region municipalities and population.

<table>
<thead>
<tr>
<th>Municipalities</th>
<th>Population (2019 est.)</th>
<th>% region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beauharnois-Salaberry</td>
<td>62,000</td>
<td>2%</td>
</tr>
<tr>
<td>Deux-Montagnes</td>
<td>96,000</td>
<td>3%</td>
</tr>
<tr>
<td>L’Assomption</td>
<td>120,000</td>
<td>3%</td>
</tr>
<tr>
<td>Laval</td>
<td>423,000</td>
<td>12%</td>
</tr>
<tr>
<td>Les Moulins</td>
<td>149,000</td>
<td>4%</td>
</tr>
<tr>
<td>Longueuil</td>
<td>400,000</td>
<td>11%</td>
</tr>
<tr>
<td>Marguerite-D’Youville</td>
<td>75,000</td>
<td>2%</td>
</tr>
<tr>
<td>Mirabel</td>
<td>50,000</td>
<td>1%</td>
</tr>
<tr>
<td>Montréal</td>
<td>1,705,000</td>
<td>48%</td>
</tr>
<tr>
<td>Roussillon</td>
<td>162,000</td>
<td>5%</td>
</tr>
<tr>
<td>Thérèse-De Blainville</td>
<td>154,000</td>
<td>4%</td>
</tr>
<tr>
<td>Vaudreuil-Soulanges</td>
<td>149,000</td>
<td>4%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>3,545,000</strong></td>
<td><strong>100%</strong></td>
</tr>
</tbody>
</table>

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3 The 2016 Montreal Census metropolitan area population was 4.1 million, but the study area does not comprise the entire Census metropolitan area population.
Figure 4: Study region road map.

Figure 5: Study region aerial photograph.
Figure 6: Study region municipalities.

![Map of study region municipalities](image)

Figure 7: Population growth for Montreal, Laval and Longueuil cities (Montreal population scale on left, Laval and Longueuil on right).

![Graph of population growth](image)

2.2 Earth science aspects

2.2.1 Geology

The geology of the Montreal region is well studied (Boyer et al. 1985) and is relevant to 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 study area “lies within the St. Lawrence Lowlands, between the Precambrian Shield 4 to the northwest and the Appalachians to the east, and is underlain by slightly deformed and faulted sandstone, carbonate rocks and shales of Cambro-Ordovician age. Mount Royal is one of a series of Mesozoic plutons that intruded the sedimentary rocks” (Boyer et al. 1985). The end of the Wisconsin age marked the close of the last glacial period during which the mass of ice had depressed the rock so that the study region, Saint Lawrence and Ottawa River valleys and surrounding areas, were below sea level and flooded with rising sea levels, forming the Champlain Sea from about 13,000 to 10,000 ybp. At that time, the sea overtopped Mount Royal by about 170 m (Prest and Hode-Keyser 1975). With the retreat of the glaciers, the land isostatically rebounded and the sea coast gradually retreated to its current location. Erosional features at high elevations on Mount Royal are marine-littoral, and lower ones estuarine-fluvial. Thus, surficial deposits in the study region are “of Wisconsin age or younger and include tills, interstadial silts and sands, marine clay, marine and estuarine beach materials and recent peat deposits.” (Boyer et al. 1985).

4 Precambrian (prior to 541 million years before present or Ma ybp) and other terms refer to geologic epochs and eras: Cambro-Ordovician is the period from 541 to about 444 Ma ybp, Mesozoic 250-66 Ma ybp, Pleistocene 2.6 Ma to about 12,000 ybp, Wisconsin is within the Pleistocene and is about 75,000 ybp to the end of the Pleistocene, and Holocene or Recent is from the end of the Pleistocene to today.
Surficial geology for the Island of Montreal was mapped in 1975 (Prest and Hode-Keyser 1975) and for Laval more recently (Bolduc and Ross 2001), Figure 9. Much of the region is glacial till with pockets of more recent softer material.

Figure 9: Surficial geology (Bolduc and Ross 2001; Prest and Hode-Keyser 1975).
2.2.2 Historic seismicity and seismic hazard


Recent seismicity relevant to the study region is shown in Figure 10 and historic seismicity in Figure 11, and appears to be associated with the Saint Lawrence rift system, which is a seismically active zone extending from the Ottawa – Montreal area in a northeast trend paralleling the Saint Lawrence River, and northwest trending intersecting graben structures (Adams and Basham 1991), Figure 11. Seismic studies indicate a crustal convergence across the Saint Lawrence valley of about .5 mm (0.020 in) per year (Mazzotti, Henton and Adams 2004). Focal mechanisms for selected events are shown in Figure 12, where the ‘beachballs’ are seismological symbology indicating the relative motion across the causative fault mechanism (see Figure 13 for how to interpret these).

Figure 10: The pattern of historical seismic activity recorded by the Canadian seismograph network since the beginning of the century shows the earthquakes concentrating in two sub-zones: one along the Ottawa River and the second along a more active Montreal-Maniwaki axis. (Natural Resources Canada, Earthquake Zones in Eastern Canada).
Figure 11: Historic seismicity showing two apparent source bands: the Western Quebec band trending northwest, and the Charlevoix-Lower St. Lawrence trending northeast.

Figure 12: Focal mechanisms for Eastern Canada (Bent, Drysdale and Perry 2003). See Figure 13 for example.
Historically, the most relevant earthquake for this study is the 1732 Montreal earthquake. The information on this event has been collated and reviewed by (Leblanc 1981) who ascribes an approximate body wave magnitude of 5.8 and allows an epicentre directly beneath Mont Royal (+/- 50 km). Simply put, there is not much known about this event but at a minimum it can be said that a relatively strong earthquake of about this magnitude did occur somewhere near Montreal at about 11 am September 16, 1732 and caused significant damage.

Other significant regional events include the 1870 Charlevoix earthquake (estimated magnitude of 6.5) and the 1925 Charlevoix region earthquake (magnitude of 7.0) whose epicentre was in the St. Lawrence River between the mouths of rivers La Malbaie and Ouelle, see Figure 11. This latter earthquake was felt over a region of about 2.5 million sq. km (from the Mississippi River on the west to the Atlantic seaboard on the east, and as far south as Virginia).
The most recent earthquake relevant to this study and largest to occur in the region in the last 80 years (Ma, Motazedian and Lamontagne 2018) was the 1988 Mw 5.9 Saguenay earthquake – data from Natural Resources Canada for this event are:

- Local Date and Time: November 25, 1988 at 6:46:04 pm Eastern time
- Magnitude: MW 5.9; mb 5.9; m\text{Lg} 6.5; M_s 5.8
- Maximum Intensity: Modified Mercalli VIII
- Latitude: 48.12° N
- Longitude: 71.18° W
- Depth: 28 km
- Preceded by a magnitude 4.7 foreshock on November 23, 1988, 4:11 am Eastern time
- Aftershock zone 35 km N-S by 35 km E-W

The epicentre was about 34 kilometres south of Saguenay, 145 kilometres north of Quebec City and 345 northeast of Montreal. The event was felt as far away as New York City, Washington D.C., Buffalo, and Detroit, illustrating the lower attenuation typical of eastern North American earthquakes.

While the damage that occurred in Saguenay and nearby communities, and even in Quebec, was substantial and not unexpected, the damage that occurred in Montreal was surprising. The Montreal-East City Hall, which was a 1937 two-story reinforced concrete frame structure with stone masonry cladding (and had experienced excessive settlements before the earthquake) suffered severe damage to the masonry cladding (Mitchell, Tinawi and Law 1990), Figure 14.

Two instances of earthquake-initiated fire were reported (EQE 1990). At a church in Chicoutimi, a fuel oil line to the furnace broke, spraying oil, which ignited on the pilot light. The fire was quickly contained. One serious residential fire was an indirect cause of the earthquake. When power was lost, the residents of one home happened to drop a match on flammable material while trying to light candles. The resulting fire caused an estimated $60,000 in damage.

Figure 14: Loss of Montreal East City Hall masonry cladding in 1988 Saguenay earthquake.
Source: Mitchell, Tinawi and Law (1990)
Based on historic seismicity as well as other geologic and geophysical data, Natural Resources Canada regularly performs probabilistic seismic hazard analyses of Canada, which are incorporated in the National Building Code, with the latest such results just now emerging (Adams et al. 2019; Halchuk et al. 2019).

2.2.3 Scenario events

Studies of deaggregation of Montreal’s seismic hazard (Halchuk et al. 2019) show that the mean and mode earthquake events contributing to the hazard are respectively magnitude 6.4 and 6.75 at about 30 km distance, Figure 15.

Figure 15: Montreal seismic hazard deaggregation (Halchuk et al. 2019).

2%/50 year probability, PGA
Probability = 0.000404 p.a., seismic hazard = 0.374 g
Mean magnitude (Mw) 6.42 Mean distance 29 km
Mode magnitude (Mw) 6.75 Mode distance 30 km

Based on similar analyses and the historic earthquake record, (Yu, Chouinard and Rosset 2016) selected the four scenario earthquake events shown in Figure 16 for the examination of potential damage to Montreal buildings. After a review of historic seismicity and sources, this study opted to employ two of the events considered by Yu et al for an examination of post-earthquake fire risk together with a third event. The three events considered in this study are a Mw6.5 event centred on downtown Montreal, and two Mw7.0 events, one centred to the Northwest and the other to the Southwest, as shown in Figure 17 and Table 2. The two magnitude 7 events approximately correspond to events identified by deaggregation as major contributors to the study region’s seismic hazard. The selection of a magnitude 6.5 event centred in central Montreal was rather arbitrary and is significantly less likely. Its choice was based on an assessment of an unlikely but still possible event directly impacting the island.
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 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).

Figure 16: Four scenario events shown as yellow squares employed by (Yu, Chouinard and Rosset 2016) for examination of building damage.

Figure 17: Three scenario events selected for this study. Black line is rupture length and yellow dot the epicentre.
Table 2: Scenario event parameters.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MC M6.5</td>
<td>NW M7</td>
<td>SW M7</td>
</tr>
<tr>
<td>Hypo long</td>
<td>-73.5944</td>
<td>-74.08</td>
<td>-74.1454</td>
</tr>
<tr>
<td>Hypo lat</td>
<td>45.5026</td>
<td>45.79</td>
<td>45.2762</td>
</tr>
<tr>
<td>Hypocentre depth (km)</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Magnitude, Mw</td>
<td>6.5</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Faulting mechanism</td>
<td>55</td>
<td>55</td>
<td>55</td>
</tr>
<tr>
<td>Strike angle (CW from North, deg.)</td>
<td>45</td>
<td>315</td>
<td>45</td>
</tr>
<tr>
<td>Length rupture (km) Wells &amp; C</td>
<td>18.2</td>
<td>42.66</td>
<td>42.66</td>
</tr>
<tr>
<td>Fault N end lat</td>
<td>45.5610</td>
<td>45.9359</td>
<td>45.4235</td>
</tr>
<tr>
<td>Fault N end lon</td>
<td>-73.5100</td>
<td>-73.2887</td>
<td>-73.9342</td>
</tr>
<tr>
<td>Fault S end lat</td>
<td>45.4438</td>
<td>45.6427</td>
<td>45.1275</td>
</tr>
<tr>
<td>Fault S end lon</td>
<td>-73.6773</td>
<td>-73.8778</td>
<td>-74.3571</td>
</tr>
</tbody>
</table>

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 Vs30, the shear wave velocity of the upper 30 m of soil (Borcherdt and Gibbs 1976). Several studies of Vs30 have been conducted for the island of Montreal (Ghofrani et al. 2015; Rosset, Bour-Belvaux and Chouinard 2015; Rosset and Chouinard 2009; Talukder 2017; Yu, Chouinard and Rosset 2016), Figure 18.

Figure 18: Regional Vs30 mappings for Montreal.
However, only one recent study by the Geological Survey of Canada (GSC) includes the surrounding region as well as the island (Nastev et al. 2016), and provides quantitative Vs30 results rather than NEHRP class results, Figure 19.

**Figure 19: Regional Vs30 mapping (Nastev et al. 2016).**

Data from the (Nastev et al. 2016) study was generously made available for this study and is shown in Figure 20. The data was available on an approximately 250 m grid, which was used as the primary unit of analysis for the study, resulting in 19,804 grid cells or a study area of almost 5,000 sq. km.

**Figure 20: Vs30 for the study area, after (Nastev et al. 2016).**
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). Ground motions for the Montreal region have been determined using one or more of several ground motion models (GMMs), as exemplified in (Yu, Chouinard and Rosset 2016). In a study of seismic hazard for the region, (Ghofrani et al. 2015) developed a series of ShakeMaps, referring to (Atkinson and Adams 2013) for ground motions, who in turn employ the geometric mean and standard deviation of five GMMs. In the magnitude and distance range of interest for this study, (Atkinson and Adams 2013) mean (geometric) ground motions agree well with (Atkinson and Boore 2006), one of the three GMMs in the study. In a study of Montreal building vulnerability, (Yu, Chouinard and Rosset 2016) employed three GMMs with approximately equal weighting: (1) (Atkinson and Boore 1995) (AB95), (2) (Atkinson and Boore 2006) (AB06) and (3) (Atkinson 2008) (A08). AB06 was also used for the 2010 edition of the National Building Code of Canada (NBCC 2010). None of these studies consider spatial correlation, which is not relevant for an individual site such as for a building, but is very important when considering spatially distributed assets such as water systems, or regional effects such as fire following earthquake.

A bit of background may be useful. Empirical relationships such as AB06, which are based on regression with databases of recordings from strong motion stations, are used to estimate shaking intensity for scenario earthquakes. Modern ground motion prediction equations yield median estimates of intensity, as well as a description of the uncertainty around those estimates. The latter typically consists of a log standard deviation ($\sigma$) for use in a lognormal distribution, which may be further broken down into between- and within-event standard deviations ($\tau$ and $\phi$, respectively, where $\sigma^2 = \tau^2 + \phi^2$). $\tau$ and $\phi$ reflect the standard deviations of the between-event error terms and the within-event error terms.

This study uses the AB06 ground motion prediction equations, which was developed for use in the central and eastern regions of the United States and Canada. The AB06 equations take moment magnitude ($M_w$), stress drop ($\Delta\sigma$), the closest distance to rupture ($R_{cd}$), the time-averaged shear wave velocity of the top 30 m of the site ($V_{S,30}$), and a vibration period ($T$), and returns a median estimate of peak ground acceleration ($PGA$), peak ground velocity ($PGV$), or peak spectral acceleration at the specified period ($Sa$) and a log standard deviation ($\sigma$). AB06 does not provide decomposed between- and within-event standard deviations. This study splits the AB06 value of $\sigma$ into $\tau$ and $\phi$ by setting $\tau^2 = 0.25\sigma^2$ and $\phi^2 = 0.75\sigma^2$. These proportions are typical of the NGA-West2 ground motion prediction equations (Abrahamson, Silva and Kamai 2014; Boore et al. 2014; Campbell and Bozorgnia 2014; Chiou and Youngs 2014). Additional guidance is provided by (Atkinson and Boore 2011) regarding setting the value of $\Delta\sigma$ as a function of $M_w$.

2.2.5.1 Spatially correlated ground motion prediction

When assessing seismic hazard in a study area (as opposed to at a single study site), spatial correlation can have a significant influence on the results. Spatial correlation means that certain areas within the study area will have higher than anticipated ground motion, while others will have lower than anticipated ground motion. Sites that are close together in space are more likely to experience similar shaking intensities. Without spatial correlation, the intensity at each considered site would be estimated independently from the neighbouring locations. Analysis of infrastructure such as water mains should therefore include spatial correlation, since the impacts may be amplified if damage is concentrated in particular areas.
Consideration of spatial correlation is a relatively recent development, with the relationship between correlation and the separation distance between a pair of locations being first quantified by (Jayaram and Baker 2009) (JB09) for PGA and $S_a$ for crustal earthquakes around the world. Application of spatial correlation for distributed infrastructure and interacting phenomena is important – ignoring it can significantly underestimate the risk. It is sort of as Mr. Micawber’s recipe for happiness:

"Annual income twenty pounds, annual expenditure nineteen [pounds] nineteen [shillings] and six [pence], result happiness. Annual income twenty pounds, annual expenditure twenty pounds ought and six, result misery." – Charles Dickens, David Copperfield

For example, if there are 50 fire engines and 49 ignitions, all else being equal all the ignitions may be quickly suppressed. However, if ground motions, and therefore ignitions and pipe breaks, are spatially correlated with a number concentrated in one district, then some fire engines will be confronted with multiple ignitions while other fire engines have no ignition nearby and will have to travel some distance to the area of concentrated ignitions. Thus, there will be a delayed response for some ignitions, which will grow into conflagrations. Moreover, pipe breaks rather than being uniformly randomly distributed will also be spatially correlated and therefore form concentrations of loss of pressure, in the same areas of concentrated ignitions. Lack of water will only impede firefighting and add to conflagration growth. For this reason, spatial correlations of ground motions and their effects on infrastructure have been a recent focus of research (Adachi and Ellingwood 2009; Han and Davidson 2012; Wu and Baker 2014).

The correlation coefficients from JB09 depend on whether the site conditions (i.e., $V_{S,30}$) in the area of interest are clustered. Further, JB09 does not explicitly provide correlation coefficients for $PGV$, although it is noted that $PGV$ appears similar to $S_a$ at $T = 1s$. This study therefore uses the JB09 coefficients for $S_a$ at $T = 1s$ in order to analyze $PGV$.

No such research has been performed specifically for the central and eastern United States and Canada, so this study applies the methods of JB09 to formulate spatial correlation. We describe the application of the JB09 methods for this study area, and the reader is referred to JB09 for further details. First, a between-event term is sampled from a normal distribution with zero mean and standard deviation equal to $\tau$. Then, a random field of normally distributed variables with zero mean, standard deviation equal to $\phi$, and correlation calculated according to JB09 is generated for each grid of sites.

2.2.5.2 Clustering of site conditions in Montreal

Geostatistical analysis of the $V_{S,30}$ data in the Montreal study area was performed to determine whether the site conditions in the study area should be considered clustered or unclustered. Figure 21 shows the empirical semi-variogram with a fitted model.

The $V_{S,30}$ data in Montreal has a correlation length of 11.5 km, meaning that a pair of sites closer than 11.5 km apart show a measurable degree of correlation. Two sites 5 km apart would have a correlation coefficient of 0.27. Additionally, the model regressed on the empirical semi-variogram fits the data well ($R^2 = 0.88$). These results suggest that the site conditions in the study area should be considered clustered per JB09. The resulting correlation lengths are 40.7 km for $PGA$ and 25.7 km for $PGV$. Spatial correlation of ground motions is more significant when the site conditions are clustered, amplifying the need to incorporate it into seismic hazard analysis.
2.2.5.3 Results

Median ground motions and 100 realizations of spatially correlated ground motions were calculated for each scenario in the study area. Median ground motions are used for the “deterministic analysis” presented later and are shown in Figure 22 for one of the scenarios.

Figure 23 shows several of the 100 realizations of PGA for Scenario 1 – comparable realizations were generated for all scenario PGA and PGV. Figure 24 shows a comparison of the Scenario 1 Mw6.5 median PGA vs. the median of 100 realizations, for 10,000 analysis grid cells. Good alignment as shown confirms the ground motion computations. Figure 25 below shows convergence of Scenario 1 PGA mean, median, standard deviation and coefficient of variation (COV) with increasing number of realizations. Convergence to mean within 200 realizations is demonstrated for all parameters, confirming that 500 realizations is an adequate number of realizations sufficient to capture considered uncertainty. Scenario 2 Mw7 median PGA and PGV are shown in Figure 26 and Scenario 3 Mw 7 median PGA and PGV in Figure 27. Variation in ground motions considering spatial correlation for these scenarios is comparable to that shown above for Scenario 1 and is omitted simply for space.
Figure 22: Scenario 1 Mw6.5 median PGA and PGV.
Figure 23: Several of 100 realizations of Scenario 1 Mw6.5 PGA.

Figure 24: Scenario 1 Mw6.5 median PGA vs. median of 100 realizations, for 10,000 analysis grid cells – good alignment is a computational check.
Figure 25: Convergence of Scenario 1 PGA mean, median, standard deviation and coefficient of variation (COV) with number of realizations. Convergence to mean within 200 realizations is demonstrated for all parameters, confirming that 500 realizations is sufficient to capture considered uncertainty.

Asymptotes
Montreal MC1 Monte Carlo 500n

Cum COV
Montreal MC1 Monte Carlo 500n
Figure 26: Scenario 2 Mw7 median PGA and PGV.
Figure 27: Scenario 3 Mw7 median PGA and PGV.
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.

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.

Surficial geology of the study area is discussed above and its potential for liquefaction has been studied by several investigators. Based on one-dimensional dynamic shear wave analysis as well as simplified methods (Pushpam 2005) demonstrated that Montreal is subject to moderate liquefaction risk for earthquake events of magnitude 5 to 7. Building on (Pushpam 2005), (Yu 2011b) employed methods recommended in (DHS 2003) to estimate areas of liquefaction potential, which can be closely correlated with soil mapping by (Prest and Hode-Keyser 1975). Observing these results and using soil mapping for Laval (Bolduc and Ross 2001) and Vs30 mapping for other portions of the study region, areas of high and very high liquefaction potential were estimated and are shown in Figure 28. The accuracy of this approach is considered highest for the island of Montreal, then the Laval area, and only moderate for other areas. In those latter areas, however, it can be seen in Figure 29 that most of the liquefiable areas are rural, so that the mapping in those areas is less important for our purposes.

It should be noted that, for the same seismic excitation level, (Goda et al. 2011) found that liquefaction hazard for western Canada is generally higher than that for eastern Canada, because of the greater seismic hazard contributions due to large earthquakes. Additionally, “Eastern Canada, including the Montreal region, is characterized with occasional presence of so-called sensitive clays (finer sediments with particle size of clayey silts in general) as well. The ratio between undisturbed and re-molded strengths of these soils attains values of 1 (over-consolidated sediments) to over 100 (quick clays). This feature becomes particularly apparent during dynamic loading and can further aggravate potential losses due to liquefaction… sensitive clays are found in the north-eastern part of the Island of Montreal and west of Montreal (Rigaud area)” (M. Nastev, personal communication).
Figure 28: Areas of high and very high liquefaction potential.

Figure 29: Areas of high and very high liquefaction potential outlined in red, overlaid on road network.
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 Montreal International Airport (YUL), the Port of Montreal, rail depots and the energy complex in Montreal East 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 Quebec and various cities in the study region especially the City of Montreal as well as NRCan and CatIQ, an insurance database.

In summary, including all residential, commercial, industrial, institutional and government buildings within the study area, there are over 1 million buildings with a total floor area of about 421 million square meters. Within the City of Montreal, there are about 520,000 parcels of land that are occupied by about 721,000 buildings (including outbuildings such as garages) with an aggregate floor area of about 196 million square meters. For the study area, there is an aggregate of 120 sq. m of building floor area per capita.

The monetary value of this real property can be gauged in various ways. For this study, we consider the value at risk to be the replacement value of the physical building (structure and non-structural components) and ordinary contents. We do not include the value of land or infrastructure. Review of various cost databases and guidelines showed a considerable range of construction costs for the study area, depending on the occupancy and other factors. In summary for valuation purposes we employed a single value of $4,200 per square meter of building floor area, which represents replacement cost for the building and contents.

This equates to a total building and contents TIV of about $1.8 trillion at risk, corresponding to a combined value of buildings (structural, non-structural and contents) for the study region estimated at $1.8 trillion (2019 $) by Natural Resources Canada (NRCan). Approximately two-thirds of this, or about $2,800 per sq. m, can be considered building replacement value.

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7 In insurance parlance, “new for old” – that is, no consideration is given to depreciation, “book value” or other methods of accounting value.
Fire insurance would cover a large portion of this value, although the entire Personal and Commercial Lines Total Insured Value (TIV) is not available. Insurance data that is available shows a TIV of $809 billion for the study area, consisting of 1.9 million Personal Lines and 225,000 Commercial Lines policies in force. These policies cover fire-related perils, generally including fire following earthquake. Examples of the assets at risk and data collected are shown in Figure 30 to Figure 35 (as noted earlier, the various asset, geotechnical and other datasets were mapped to a 250 m grid for consistent analysis).

In order to understand the potential for fire spread in various parts of the study region, windshield surveys were conducted in the cities of Montreal, Laval and Longueuil. Examples of different building types are shown in Appendix A.

Figure 31: Detail of building density distribution, central Montreal.
Figure 32: Distribution of number of stories of each building, City of Montreal.

Figure 33: Distribution of buildings by date of construction, City of Montreal.

Figure 34: Detail of building footprint data, east part of City of Laval. Building footprint data is especially useful for estimation of fire spread.
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 Quebec in general is very advanced, well-equipped and modern in its organization, methods and tactics. There is a total of 163 fire stations within the study area, as shown in Figure 36, among which are distributed about 238 fire engines available for immediate firefighting\(^1\), which is consistent with normal practice, Figure 38. Each fire station has a “first-due” area, termed a Fire Response Area (FRA), within which the station’s apparatus are expected to normally be the first to arrive. Detailed mapping data for each station’s FRA was not available, so Voronoi areas were generated for each station and are used in lieu of the actual FRA mapping\(^2\), and are shown in the figure by green lines between stations.

\(^{1}\) 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.

\(^{2}\) 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 the Montreal Fire Department (MFD, Service de sécurité incendie de Montréal), the seventh largest urban fire department in North America, for specialized equipment and expertise. In order to understand MFD and other departments’ capabilities and earthquake planning and preparedness, meetings were held with the fire departments of Montreal, Laval and Longueuil, whose cooperation is gratefully acknowledged. Figure 37 shows that there are a large number of fire stations beyond the area likely to be affected by the scenario earthquakes, indicating mutual aid should arrive in a timely manner (i.e., several hours).

Figure 37: Fire stations in Quebec, beyond the study area, showing a large number of stations beyond the area likely to be affected by the scenario earthquakes, indicating mutual aid should arrive in a timely manner (i.e., several hours).
Figure 38: Relation of number of fire engines (“pumpers”) per thousand population, based on general U.S. data. Montreal, Laval and Longueuil fire departments are consistent with general fire service practice.

2.4.1.1 Montreal Fire Department

The primary source of information on MFD was Division Chief (Fire Services) J. Gordon Routley, a distinguished person in the international fire service. Chief Routley has extensive experience — a native of Montreal he was educated as a civil engineer at McGill University and served as Assistant to the Fire Chief in Phoenix, Arizona; Fire Chief in Shreveport, Louisiana; Safety Officer in Prince George’s County, Maryland and as a team investigator for Tridata surveys of major fires and explosions for FEMA. He provided MFD annual reports and other reference material. In summary MFD protects a population of 2 million on the island, has 67 stations with a total of 2,317 uniformed firefighters (approximately 500 per shift). Including reserves MFD has 100 fire pumpers (70 in service and 30 reserves), all of which carry two lengths of hard suction and typically 2000 feet each of 3 inch supply and 1.75 inch hose. Currently eight engines carry foam and this will be increased. Regarding special equipment, MFD has heavy rescue apparatus and USAR teams, has four tanker trucks, no hose tenders, no special pumps and no fireboats although two or three harbor tugboats have monitors and are capable of pumping 10,000 gpm (discussed further below). Old Montreal was identified as an area of special concern for conflagration. There is an energy complex in Montreal East and it has several miles of 7.5 inch and 5 inch LDH hose and special pump equipment. Virtually all commercial high-rises are sprinkled and all but a few residential high-rises. Many homes are heated with oil furnaces, which are not anchored. Montreal has not had a recent history of conflagrations or major fires, the last notable fire being in 2012 (see Figure 39 – the same figure is on the cover of the 2017 MFD annual report). Other major fires in recent decades include:

- 1974: firefighters were on strike, several fires spread, one jumped Amherst and Ontario Sts.
- 1987: Alexis Nihon 16-story building, $100 million loss, started on 8-9 floor, spread to 2 floors, stand pipes had problems, wrong connections.
- 2012: 31 St. Jacques St, 50 x 150 ft 6 story 19th C building, under renovation.
One area of concern noted was the seismic capacity of MFD’s fire stations – for example, the headquarters building is in a 1932 Unreinforced Masonry Building (UMB) which also houses the Emergency Operations Centre. Of MFD’s 67 stations, the oldest dates from 1891, Figure 41, about 11 were built before WW1 and about 43 or almost two-thirds were built before 1980, which is generally considered the beginning of modern seismic design.

Another area of concern was the lack of ability to readily move water a significant distance – as discussed, MFD lacks Large Diameter Hose (LDH) and is limited by having only 3-inch hose.
2.4.1.2 Longueuil Fire Department

The primary sources of information on Longueuil FD were Jean Melançon, Director of Fire Services, Éric Bellerose, Deputy Director of Fire Services and Donald Fortin, Section Chief, Civil Security – City of Longueuil. Longueuil FD protects about 425,000 population within the Agglomeration of Longueuil and has 165 uniformed firefighters as well as about 100 other employees. The department goal is to place 10 firefighters on scene within 10 minutes. It has 22 engines with each engine carrying 1,000 feet of four inch diameter hose, four tanker trucks, no fireboat.

2.4.1.3 City of Laval Fire Department

The primary sources of information on Laval FD were Messrs. Pascal Lessard of Civil Security and René Daigneault, Director, City of Laval FD. Laval FD protects about 425,000 population, has nine engines, 254 firefighters all paid, no fireboats. Engines carry 4x50 feet of four inch diameter, similar 2.5 inch and 1.5 inch hose, hard suction, no hose tenders, mutual aid with MFD for heavy rescue, etc. Regarding the water system, it was consolidated 2 years ago; low pressure, drafting is practised; it relies on alternative water supplies. Heating is about 25% oil, remainder gas or electricity.

2.4.2 Gas and liquid fuel pipelines

Crossing the study area are several major gas and liquid fuel transmission lines, shown in Figure 42. The major gas transmission line is the TransCanada Mainline, which began supplying eastern Canada with gas from western Canada in 1958. This line supplies the natural gas distribution network, which is discussed below.

The major liquid fuels transmission line is the Trans-Northern pipeline, which began daily operations in 1952 supplying transmission of refined products from the Island of Montreal to points west and currently supplies an average of 172,900 barrels per day of refined fuel products. Concerns exist as to the condition of the pipeline. An older pipeline previously supplied crude oil from Portland ME (USA) but has now largely been replaced by the Enbridge 30” crude oil pipeline from western Canada, which has a capacity of about 36,000 cu. m. per day.

The study area is supplied with natural gas by Énergir (formerly known as Gaz Métro, a diversified energy company and the largest natural gas distribution company in Quebec). This energy is mostly used for cooking, heating, industrial processes and is also employed at filling stations (as a carburant). The primary sources of information on the gas system was Mr. Rémi Beylot, Adviser, Risk Prevention, Emergency Measures and Business Continuity – Énergir.

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13 While the figure is from a Canadian government source, it may not be completely current or up-to-date. It is presented simply to indicate major gas and liquid fuel transmission lines across the study area.


17 https://en.wikipedia.org/wiki/Enbridge_Pipeline_System
There are over 1,000 km of gas and about 200 km of liquid fuel buried transmission pipelines in the study area (https://www.neb-one.gc.ca/sftvrmnt/sft/ dshbrd/mp/index-eng.html). Trans-Northern liquid fuel pipeline begins on the Island of Montreal and has a branch line supplying the airport.

Énergir serves 205,000 customers province wide (approximately half are within the study area) through 2,600 km of buried pipelines whose pressures vary from less than 700 kPa (100 psi) to more than 2400 kPa (350 psi). Transmission is greater than 2,400 kPa, up to 9,900 kPa. Énergir provided a map of the system, Figure 43, which showed that a large part of the study area has gas service, with about two-thirds of the pipe system being polyethylene, and one third steel (there is no cast iron). The network is considered relatively new (mostly installed after 1980). Facilities are designed based on the CSAZ662 requirements (that considers seismic hazard). There are two LNG tanks (Usine LSR) at the east end of Montréal Island (near the petroleum refinery). Valves within the delivery stations can be activated remotely by the Gas Control Centre. Other valves can be closed manually by technicians to isolate smaller areas. Fire fighters are also able to close gas valves for a house or a building. More than 100 technicians would be rapidly available for emergencies. Énergir has evaluated the number of breaks given an earthquake. While there is no specific earthquake plan, Énergir would respond to an earthquake with an emergency plan that is regularly exercised.

Figure 43: Gas transmission (green), feeder (pink) and distribution (blue) networks.
Source: Énergir
2.4.3 Water supply

Adequate firefighting water supply is essential to prevent ignitions from growing into conflagrations following an earthquake. Water supply may be severely impacted by the scenario event.

2.4.3.1 Montreal water supply

The primary sources of information on the Montreal water system (MWS, Service de l’eau) were Mr. Normand Hachey, Division Chief, Investment Planning, Water Services, City of Montreal and Ms. Annie Carrière, Section Chief, Asset and Project Management, Infrastructure Division, Water Services, City of Montreal. In summary, MWS takes in water from the St. Lawrence river at several locations, either directly or via the Canal de l’Aqueduc (Figure 44 and Figure 45) and pumps the treated water to a number of tanks and reservoirs serving pressure zones, Figure 46, from which it is distributed via 5,400 kilometres of transmission and distribution pipe to over 400,000 customers, Figure 47. Water for firefighting is accessed from over 29,000 hydrants, Figure 48.
Figure 45: City of Montreal water intake and treatment plants: (top) Usine Atwater; (bottom) Usine Charles-J.-Des Baillets.
Source: Google Earth

Figure 46: Example of buried distribution reservoir – McTavish Reservoir on McGill University campus and serving downtown Montreal. In 2013 it suffered a pipe break causing significant damage to the university and flooding portions of the downtown area.

**McTavish Reservoir**
Built 1932, capacity 148 million litres
Figure 47: Water distribution pipe network, remaining life: (red) less than 40 years; (orange) 40 to 60 years; (green) more than 60 years.

Figure 48: Montreal fire hydrants.
Key aspects affecting provision of firefighting water to hydrants are:

- **Pump stations:** It is not known if the main pump stations have backup power. However, due to the size of the demands, it is unlikely that a significant portion of the pump capacity has backup power so that, in the event of an earthquake when commercial power would fail, the only system capacity for firefighting would be the tank and reservoir contents. This is not atypical of most systems.

- **Tanks and reservoir seismic stability:** MWS indicated that their reservoirs are currently undergoing earthquake analysis. The reservoirs do not appear to have seismic shutoff valves, so that distribution breaks would likely drain the reservoirs until outlet valves could be closed, either remotely or manually. It is not known if the outlet valves have backup power for this purpose (some large batteries would suffice).

- **Distribution piping:** The frequency of remaining life is shown in Figure 49, based on which the frequency of date of installation was inferred. Until about the 1960s cast iron (CI) was used ubiquitously for water distribution pipe, after which a transition to ductile iron (DI) pipe occurred (more recently, PVC and other plastic materials are sometimes used). Cast iron is brittle and is well known to have a high failure rate in earthquake (ALA 2001; O’Rourke and Liu 2012; O’Rourke et al. 2014; Scawthorn et al. 1992). From Figure 49 it can be seen that 40% to perhaps as much as 60% of MWS’s distribution network is composed of CI. This was confirmed by MWS who indicated that 68% of their system was CI with about 30% DI, while trunk and transmission lines greater than 16” diameter were typically steel or reinforced concrete cylinder pipe. Figure 49 is further confirmed by historic population growth, Figure 50, which shows that Montreal’s water infrastructure would have been largely “built out” by the 1970s’, while Laval and Longueuil likely have more modern infrastructure. That MWS’s infrastructure is older is well-known and a concern\(^8\), and Montreal in 2012 began a 10-year improvement program for the distribution system.

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2.4.3.2 Laval water supply

The primary sources of information on the Laval water system were Messrs. Pascal Lessard of Civil Security and Rene Daigneault, Director, City of Laval FD. The water system was consolidated from smaller agencies about two years ago, and is a low-pressure system. The fire department practises drafting and is practised in relying on alternative water supplies.

2.4.3.3 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, although they could not furnish a comprehensive list or map of such AWS. The question therefore exists, how many and where are likely AWS that could be used following an earthquake? To answer this question, a review was made of water bodies and swimming pools, finding a significant part of the City of Montreal has access to AWS, with lesser access for other jurisdictions, as shown in Figure 51. While some of the AWS is from lakes and ponds, most of the AWS is from swimming pools (there are a number in Montreal, although some are outdoors and presumably are empty in the winter) and from the St. Lawrence River.
AWS from the St. Lawrence is by two means: (a) fire engines drafting from the river, or (b) several tugboats, each of which can pump 10,000 gpm, Figure 52. Discussions with MFD indicate that there are a number of locations where MFD engines can access the river, that the water level of the river doesn’t typically fall so far as to preclude access, and that MFD would likely be able to access St. Lawrence river water even in the winter – “it rarely freezes solid anymore since the Coast Guard has icebreakers to keep the river open for navigation. It has to get extra cold for several days before the river freezes, but we are likely to get ice along the shoreline and in calm areas. We have drills to make openings in the ice and (worst case) portable pumps that could be used to help move water from the holes to our pumper. We have never had occasion to use them.” (Routley, personal communication). It may be concluded that the St. Lawrence is a reliable AWS although, if the fire is not very close to the shore, water will then have to be conveyed inland through fire hoses. As noted earlier, MFD is restricted in not having LDH (which neighbouring departments do have). That is, smaller hose can only convey water so far before pressure losses require pressure being boosted, by another fire engine in relay. This is very asset-intensive and reduces the capacity of the department. MFD indicated that, “if given enough time”, firefighters could convey water in relays more than one to two kilometres inland. Given the time pressures following an earthquake, a practical distance of 300 m from AWS was used for this analysis.

Figure 51: Analysis grid cells with access to Alternative Water Supplies (AWS).

Figure 52: Tugboat Ocean Serge Genois, one of several port tugboats equipped to pump 10,000 gpm and capable of supplying landlines. Note monitors.
2.4.4 Weather

An important factor in large conflagrations is weather (NFPA 1951; TCEEE 2005), where hot, dry windy weather (“red flag” days) are especially critical for the occurrence of large fires. The climate of Montreal may be summarized as “continental and humid, with hot summers and cold winters; the mean annual precipitation is 950 mm, of which 25 percent (240 cm) falls in the form of snow. The mean daily maximum and minimum temperatures are respectively 26 degrees C and -4 degrees C; extreme yearly maximum and minimum temperatures are typically 32 degrees C and -30 degrees C. Frosts occur between 1 October and 15 April; the average season of snowfall is from mid-November to end of March. Annually, there are approximately 2,000 hours of sunshine, 4,470 degree-days below 18 degrees C, and 930 degree-days below zero degrees C. Winds vary from west to southwest, with a monthly maximum velocity of 20 km per hour (winter) and a monthly minimum velocity of 15 km per hour (summer)” (Boyer et al. 1985).

These patterns are shown by hourly data for the period 2008-2019 in Figure 53 and summarized by month in Figure 54 with cumulative frequencies for windspeed, temperature and humidity shown in Figure 55. It can be seen that subfreezing temperatures occur 30% of the time in Montreal. Correlations of temperature, humidity and windspeed were examined to determine if “red flag” days were a significant concern in Montreal, finding that such occurrences are very infrequent. This finding was confirmed by MFD. It should be noted however that such conditions are not impossible – they occurred and were a major factor in the Great Montreal Fire of 1852. Strong winds, even if not accompanied by hot, dry conditions, are an important factor in conflagrations, and are probabilistically accounted for in the analysis. Humidity and temperature also affect fire spread and are accounted for in the analysis.

Figure 53: Montreal windspeed, temperature and humidity cumulative frequencies, based on 100,000 hourly readings.
Data source: Weatherstats Canada, https://montréal.weatherstats.ca/download.html

Temperature degree C
Montreal, 100k hourly readings Jan. 2008 – June 2019

Wind speed km/h
Montreal, 100k hourly readings Jan. 2008 – June 2019

Relative humidity
### Figure 54: Montreal weather pattern.

<table>
<thead>
<tr>
<th>Month</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recent high °C (°F)</td>
<td>12.0 (53.5)</td>
<td>15.9 (59.6)</td>
<td>26.8 (79.6)</td>
<td>30.1 (86.2)</td>
<td>34.0 (93.2)</td>
<td>36.6 (97.9)</td>
<td>36.0 (96.8)</td>
<td>35.6 (96.1)</td>
<td>35.6 (96.1)</td>
<td>35.6 (96.1)</td>
<td>22.2 (72.0)</td>
<td>17.0 (62.6)</td>
<td>25.6 (78.1)</td>
</tr>
<tr>
<td>Average high °C (°F)</td>
<td>−5.4 (22.9)</td>
<td>−3.7 (26.9)</td>
<td>2.6 (36.7)</td>
<td>11.0 (51.8)</td>
<td>18.0 (64.4)</td>
<td>25.7 (78.3)</td>
<td>28.4 (82.9)</td>
<td>34.6 (94.5)</td>
<td>36.0 (96.8)</td>
<td>35.6 (96.1)</td>
<td>35.6 (96.1)</td>
<td>35.6 (96.1)</td>
<td>35.6 (96.1)</td>
</tr>
<tr>
<td>Daily mean °C (°F)</td>
<td>−8.9 (19.6)</td>
<td>−7.2 (19.9)</td>
<td>−1.2 (29.9)</td>
<td>7.0 (44.6)</td>
<td>14.5 (58.1)</td>
<td>23.2 (73.8)</td>
<td>30.8 (87.4)</td>
<td>35.7 (96.3)</td>
<td>35.7 (96.3)</td>
<td>35.7 (96.3)</td>
<td>35.7 (96.3)</td>
<td>35.7 (96.3)</td>
<td>35.7 (96.3)</td>
</tr>
<tr>
<td>Average low °C (°F)</td>
<td>−12.4 (10.7)</td>
<td>−10.0 (12.9)</td>
<td>−4.8 (23.4)</td>
<td>2.9 (37.2)</td>
<td>10.9 (51.6)</td>
<td>14.9 (58.8)</td>
<td>17.8 (64.0)</td>
<td>16.7 (61.9)</td>
<td>11.9 (53.4)</td>
<td>9.9 (49.8)</td>
<td>−6.2 (17.4)</td>
<td>−9.6 (19.9)</td>
<td>3.5 (38.3)</td>
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<tr>
<td>Record low °C (°F)</td>
<td>−43.5 (−45.7)</td>
<td>−33.3 (−27.7)</td>
<td>−38.9 (−37.9)</td>
<td>−17.4 (−2.5)</td>
<td>−5.1 (23.0)</td>
<td>1.1 (34.0)</td>
<td>7.8 (46.0)</td>
<td>6.1 (43.0)</td>
<td>0.5 (32.6)</td>
<td>−7.2 (19.6)</td>
<td>−37.8 (−38.7)</td>
<td>−31.9 (−25.3)</td>
<td>−31.5 (−25.7)</td>
</tr>
<tr>
<td>Average precipitation mm (inches)</td>
<td>33.6 (1.3)</td>
<td>72.9 (2.9)</td>
<td>84.3 (3.3)</td>
<td>74.9 (2.9)</td>
<td>84.6 (3.3)</td>
<td>87.6 (3.4)</td>
<td>68.2 (2.7)</td>
<td>100.8 (3.9)</td>
<td>84.3 (3.3)</td>
<td>53.6 (2.1)</td>
<td>101.0 (3.9)</td>
<td>100.7 (3.9)</td>
<td>100.7 (3.9)</td>
</tr>
<tr>
<td>Average rainfall mm (inches)</td>
<td>49.4 (1.9)</td>
<td>23.7 (0.9)</td>
<td>42.7 (1.7)</td>
<td>52.2 (2.0)</td>
<td>30.5 (1.2)</td>
<td>67.5 (2.7)</td>
<td>100.0 (3.9)</td>
<td>180.6 (7.1)</td>
<td>160.9 (6.3)</td>
<td>88.1 (3.5)</td>
<td>68.9 (2.7)</td>
<td>44.4 (1.7)</td>
<td>834.5</td>
</tr>
<tr>
<td>Average snowfall cm (inches)</td>
<td>45.5 (18.0)</td>
<td>46.6 (18.3)</td>
<td>35.8 (14.1)</td>
<td>11.8 (4.6)</td>
<td>5.6 (2.2)</td>
<td>0.0 (0.0)</td>
<td>0.0 (0.0)</td>
<td>0.0 (0.0)</td>
<td>2.0 (0.8)</td>
<td>4.8 (1.9)</td>
<td>10.0 (3.9)</td>
<td>7.0 (2.8)</td>
<td>25.5 (9.9)</td>
</tr>
<tr>
<td>Average days ±0.2 mm</td>
<td>15.6 (15.6)</td>
<td>12.4 (12.4)</td>
<td>10.6 (10.6)</td>
<td>12.5 (12.5)</td>
<td>12.9 (12.9)</td>
<td>13.6 (13.6)</td>
<td>12.8 (12.8)</td>
<td>12.0 (12.0)</td>
<td>9.3 (9.3)</td>
<td>3.0 (3.0)</td>
<td>2.0 (2.0)</td>
<td>1.4 (1.4)</td>
<td>0.0 (0.0)</td>
</tr>
<tr>
<td>Average snowfall inches</td>
<td>14.3 (0.6)</td>
<td>4.3 (0.2)</td>
<td>7.4 (0.3)</td>
<td>12.8 (0.5)</td>
<td>15.4 (0.6)</td>
<td>12.7 (0.5)</td>
<td>12.7 (0.5)</td>
<td>11.6 (0.5)</td>
<td>6.5 (0.3)</td>
<td>122.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean monthly hours</td>
<td>12.7 (0.5)</td>
<td>11.1 (0.4)</td>
<td>8.3 (0.3)</td>
<td>3.0 (0.1)</td>
<td>3.0 (0.1)</td>
<td>3.0 (0.1)</td>
<td>3.0 (0.1)</td>
<td>3.0 (0.1)</td>
<td>3.0 (0.1)</td>
<td>3.0 (0.1)</td>
<td>3.0 (0.1)</td>
<td>3.0 (0.1)</td>
<td>3.0 (0.1)</td>
</tr>
</tbody>
</table>

### Figure 55: Montreal windspeed, temperature and humidity cumulative frequencies, based on 100,000 hourly readings. Abscissa is windspeed (km/h), relative humidity (%) or temperature (degr. C) while ordinate is percentage of observations.
Data source: Weatherstats Canada, [https://montréal.weatherstats.ca/download.html](https://montréal.weatherstats.ca/download.html)
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 56:

- **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 are 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, it moves on to the next incident. If the fire department is not successful, it continues 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 56: Flow chart of fire-following-earthquake process (TCLEE 2005).](image-url)
This process is also shown in Figure 57, 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 57: 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 58. 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 others 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 58: 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 unheeded, 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, Scawthorn and Mileti 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 the Island of Montreal (Tamima and Chouinard 2017), finding that debris typically added about 4 minutes to travel time, with another 4 minutes added by bridge closures (i.e., a total of about 8 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 quite limited. One data point is the 1985 so-called “MOVE” incident in Philadelphia when an ignition occurred as the result of a civil disturbance due to which there was no fire service intervention for several hours, resulting in the spread of fire to 65 houses, Figure 60. The density and similarity of construction with some Montreal neighbourhoods (e.g., Le Plateau Mont-Royal district) is striking, Figure 61. While there is a higher fraction of buildings in this district with noncombustible facades (i.e., brick, stone), rear alleyways tend to have accumulations of combustibles, flammable cladding and stairways and other avenues for rapid firespread, Figure 62. Spread from block-to-block – that is, across streets and other fuel breaks – can easily occur in the absence of firefighting, Figure 59. Estimates of large fires are presented in section 4.
Figure 60: Aftermath of Philadelphia “MOVE” incident fire, a rare case of modern urban fire without fire service intervention. Note fire-resistant party walls, around which the fire extended.

Figure 61: Le Plateau Mont-Royal district.
Source: Google Earth

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. Using methods in (Porter 2018), median estimates of the number of buried pipe repairs in the study region vary from 7,000 to 9,000 repairs, the precise number and location depending on the scenario event. Repairs in this case mean leaks as well as breaks – the rule of thumb 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”) as shown in Figure 63 for Scenario 1 (Mw 6.5, downtown Montreal), where serviceability is the fraction of required flow actually 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 Scenario 1 is shown in Figure 64.

Figure 62: Le Plateau Mont-Royal district: Facades, and rears.

Figure 63: Water system serviceability for Scenario 1, Mw 6.5 downtown Montreal (effectively, likelihood of water at a hydrant).

Figure 64: Water Supply Factor (WSF) for Scenario 1, Mw 6.5 downtown Montreal (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, most of Montreal 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 fuels transmission lines are not accounted for in this study.

A particular concern is the energy complex in Montreal East, Figure 65. When strongly shaken, oil refineries and tank farms have typically had large fires that have burned for days. Examples include the Showa refinery in the 1964 Niigata (Japan) earthquake, the Tüpraş refinery in the 1999 Marmara (Turkey) earthquake (Scawthorn 2000), and the Idemitsu Kosan Hokkaido refinery fire in the 2003 Tokachi-oki earthquake, Figure 66. Earthquake impacts on petroleum refineries in Montreal are not explicitly dealt with in this study.

Figure 65: Petroleum refinery, Montreal East.
Source: Google Earth

Figure 66: Typical post-earthquake petroleum refinery fires: (left) Tüpraş Refinery following 1999 Mw 7.6 Marmara, Turkey, earthquake; (right) Idemitsu Kosan fire following 2003 Mw 8.3 Tokachi-Oki, Japan, earthquake.

Photo courtesy of G. Johnson. Photograph from Hokkaido Shim bun.
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 – Montreal suffers occasional severe snowstorms – the effect of these on response is complex and has not been considered.

3.6 Regional response

The scenario earthquakes primarily affect the study area, although eastern North American earthquake ground motions attenuate slower than other regions, meaning effects are felt more widely. As noted earlier, there are a large number of fire agencies within a few hours of Montreal 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 (Ottawa, Quebec City, Toronto…) 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. While MFD has cited the petroleum refinery as having LDH and special pumps, there is a significant possibility these resources will be required at the refinery.
  - 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 St. Lawrence 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

4.1.1 Scenario 1 Mw 6.5

The above methods and data have been employed to estimate ignitions, fire agency response, fire spread and final burnt area and losses for the three scenarios. Table 3 summarizes the results for Scenario 1, while Figure 67 to Figure 72 show the distribution of Ignitions (Igns.) by grid cell and Fire Response Area (FRA), Large Fires (LF), Final Burnt Area (FBA) and final dollar losses (Loss) for the Scenario 1 event. The figures present the median deterministic losses, while Table 3 presents median results for three analyses considering uncertainty – that is:

- “Deterministic” refers to the losses calculated using median ground motions and daytime mild weather (20 degr. C., 5 km/h windspeed and 70% relative humidity). Referring to Figure 53, it will be noted that these meteorological parameters are not median values but rather are somewhat warmer and milder than median conditions. No uncertainty on ground motions, weather or other factors is considered in this result.

- “Comprehensive” refers to losses calculated using all 100 realizations of the ground motions, without consideration of any other uncertainty and based on the same favourable conditions as used in the Deterministic analysis. Losses resulting from simply considering only the spatial correlation of the ground motions are more than double the Deterministic result, showing how significant is the uncertainty and correlation in ground motion.

- “Stochastic” refers to losses calculated considering not only correlation in ground motion but also uncertainty in temperature, windspeed and humidity. These results are comparable to the Comprehensive results, showing that this uncertainty is less a factor than that for ground motion including correlation.

All results are median values, where median is that value that has a 50% probability of being exceeded (or not exceeded).

Table 3: Results Scenario 1 MC1 Mw 6.5.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>MC1 Mw 6.5</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Igns.</td>
<td>LF</td>
</tr>
<tr>
<td>Deterministic</td>
<td>264</td>
<td>48</td>
</tr>
<tr>
<td>Comprehensive</td>
<td>373</td>
<td>68</td>
</tr>
<tr>
<td>Stochastic</td>
<td>385</td>
<td>69</td>
</tr>
</tbody>
</table>
Figure 67: Scenario 1 distribution of mean ignitions, entire study area.

Figure 68: Scenario 1 distribution of ignitions, Montreal.
Figure 69: Scenario 1 distribution of ignitions by Fire Response Area.

Figure 70: Scenario 1 distribution of large fires by Fire Response Area.
Figure 71: Scenario 1 distribution of final burnt area by Fire Response Area.

Figure 72: Scenario 1 distribution of final losses by Fire Response Area.
Figure 73: Scenario 1 histogram of 500 realizations: mean $24.6 and median $11.8 billion. Note the scale in the figure is in terms of hundreds of billions of dollars, so that the point on the axis at a value of 1 represents $100 billion.

Figure 73 is the histogram of the stochastic analysis showing losses are highly skewed towards lower values (70 or 14\% of the realizations had zero loss).

4.1.2 Scenario 2 Mw 7.0

Table 4 summarizes the results for Scenario 2, while Figure 74 shows the distribution of Ignitions (Igns.) by grid cell. The figures present the median deterministic losses, while the table presents median results for three analyses considering uncertainty.

Table 4: Results Scenario 2 NW2 Mw7.0.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>NW2 Mw7.0</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Igns.</td>
<td>LF</td>
</tr>
<tr>
<td>Deterministic</td>
<td>213</td>
<td>113</td>
</tr>
<tr>
<td>Comprehensive</td>
<td>349</td>
<td>196</td>
</tr>
<tr>
<td>Stochastic</td>
<td>344</td>
<td>173</td>
</tr>
</tbody>
</table>
Figure 74: Scenario 2 distribution of ignitions by grid cell.

Figure 75: Scenario 2 histogram of 500 realizations: mean $36 billion and median $27.7 billion.
4.1.3 Scenario 3 Mw 7.0

Table 5 summarizes the results for Scenario 3, while Figure 76 shows the distribution of Ignitions (Igns.) by grid cell. The figures present the median deterministic losses, while the table presents median results for three analyses considering uncertainty.

Table 5: Results Scenario 3 SW3 Mw7.0.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Igns.</th>
<th>LF</th>
<th>FBA (mills. sq. m)</th>
<th>Loss ($ mills.)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deterministic</td>
<td>207</td>
<td>78</td>
<td>3.0</td>
<td>$12,558</td>
<td>single realization, no uncertainty, daytime mild weather (20 degree C, 5 km/h wind, 70% relative humidity)</td>
</tr>
<tr>
<td>Comprehensive</td>
<td>306</td>
<td>121</td>
<td>7.3</td>
<td>$30,655</td>
<td>100 realizations of spatially correlated ground motions, daytime mild weather (i.e., no uncertainty on weather)</td>
</tr>
<tr>
<td>Stochastic</td>
<td>320</td>
<td>126</td>
<td>7.0</td>
<td>$29,453</td>
<td>500 realizations of spatially correlated ground motions, uncertainty on weather and time of day</td>
</tr>
</tbody>
</table>

Figure 76: Scenario 3 distribution of ignitions by grid cell.
4.2 Summary of all scenario events

Median Loss results for all scenarios are presented in Table 6. Financial loss (total value of structure, non-structural components and contents) vary from about $12 billion to $30 billion.

Table 6: Median results by scenario (in billions $).

<table>
<thead>
<tr>
<th>Scenario</th>
<th>S1 MC1 Mw6.5</th>
<th>S2 NW2 Mw7.0</th>
<th>S3 SW3 Mw7.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deterministic</td>
<td>$4,215</td>
<td>$14,706</td>
<td>$12,558</td>
</tr>
<tr>
<td>Single realization, no uncertainty, daytime mild weather (20 degree C, 5 km/h wind, 70% relative humidity)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Comprehensive</td>
<td>$11,723</td>
<td>$29,646</td>
<td>$30,655</td>
</tr>
<tr>
<td>100 realizations of spatially correlated ground motions, daytime mild weather (i.e., no uncertainty on weather)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stochastic</td>
<td>$11,766</td>
<td>$27,653</td>
<td>$29,453</td>
</tr>
<tr>
<td>500 realizations of spatially correlated ground motions, uncertainty on weather and time of day</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4.3 Comparison with previous studies

Section 1 of this report summarized previous studies of earthquake loss for the study area. To the extent it is possible, it is of interest to compare this study's results with those previous studies. Table 7 summarizes these previous studies, from which it can be seen that the only studies to explicitly examine fire following earthquake in Montreal were the RMS 1995 and AIR 2013 studies. The AIR 2013 study examined Quebec City, a smaller region subjected to lower shaking than considered in this study. Only the AIR study clearly considered uncertainty – the RMS and Swiss Re studies are silent on this.

Table 7: Summary of previous studies.

<table>
<thead>
<tr>
<th>Study</th>
<th>Exposure / Event</th>
<th>Peril(s)</th>
<th>Loss ($ billions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yu et al 2016</td>
<td>Montreal city buildings only, 2% in 50 years</td>
<td>Shaking only</td>
<td>$1.4</td>
</tr>
<tr>
<td>Rosset et al 2019</td>
<td>Montreal residential buildings, six scenarios</td>
<td>Shaking only</td>
<td>$1~10</td>
</tr>
<tr>
<td>Swiss Re 2017</td>
<td>Montreal region, Mw5.8 event</td>
<td>Primarily shaking</td>
<td>$45</td>
</tr>
<tr>
<td>RMS 1995</td>
<td>Montreal region Mw7.5 event</td>
<td>EQ incl. FFE</td>
<td>$5*</td>
</tr>
<tr>
<td>AIR 2013</td>
<td>Quebec City, Mw7.1 event, MMI VI-VII</td>
<td>EQ incl. FFE</td>
<td>$0.725*</td>
</tr>
</tbody>
</table>

* This result is only the reported fire following earthquake portion of the loss.

It would be useful to adjust these studies' results for comparison with the findings of this study. Because of many differences between the parameters of the current study and previous studies, quantitative adjustment and comparison is not possible, so that we provide a brief qualitative discussion.

The Swiss Re study provides no details except an event magnitude that is considerably less than considered in this study (Swiss Re magnitude 5.8 vs. this study's 6.5). Moreover, the focus of the study was shaking, not fire following. Any adjustment would be to increase the $45 billion loss upward, although how much cannot be quantified.

The RMS study results would also be adjusted upward, at least by an exposure value factor of 450% to account for increases in exposure value since the time of the RMS study (1995), so that the RMS results would be perhaps $22 billion, although this would also need to then be adjusted downward due to the magnitude of the RMS event (magnitude 7.5 vs. this study's 6.5 for Scenario 1 and magnitude 7 for Scenarios 2 and 3).

The AIR study results for Quebec would need adjustment upward for exposure (a factor of 4 given the difference in size of the metropolitan areas) and intensity (the AIR intensity in Quebec is lower than considered in this study). While the adjustments would increase the AIR loss amounts, even an approximate adjustment cannot be estimated.
4.4 Insurance aspects

Earthquake insurance penetration in Quebec is quite low, but fire following earthquake is generally covered under the fire policy, not earthquake, or through a fire following earthquake endorsement. Therefore, loss due to fire following earthquake is generally covered for home insurance policy holders. The Swiss Re report takes its cue from (Le Pan 2016) and discusses this in some detail, as well as the misunderstanding by many people that they are covered for earthquake shaking damage under their ordinary fire or homeowner policy.

Overall, the situation appears ripe for a financial catastrophe – on the one hand, many people believe they are insured for earthquake, but aren’t. On the other hand, insurers have significantly greater exposure due to fire following earthquake than they understand and may fail given a major earthquake and subsequent fires. As Le Pan notes, these failures may ripple through the Canadian financial industry, to the extent that Swiss Re, one of the leading global reinsurers, speaks of “financial contagion”:

“Earthquake triggered mortgage impairment and further credit contagion risk are currently not accounted for on any balance sheet (private or public), nor properly assessed to contain contagion. On the contrary, credit default mutualization has the potential to accelerate contagion effects in a highly systemic scenario as an earthquake, putting more Canadians at financial disadvantage, even if not directly impacted by the earthquake.”

This report seeks to inform fire officials in Montreal about the fire risk and what they can do to reduce it. The information will be of interest to the insurance industry and it is hoped the industry will work with the fire service toward this end.
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 Quebec is modern, advanced, well-equipped and of a high caliber in its organization, methods and tactics. On the other hand, the earthquake risk, while understood by some to be a concern, does not appear to be a major concern for some fire departments. The following opportunities exist for improvement.

5.1.1 Fire station vulnerability

We recommend that all fire stations and related facilities in the study area requiring immediate post-earthquake functionality be evaluated according to the requirements of the National Building Code of Canada, including provisions for Post-disaster important buildings.

For example, a number of MFD buildings date from before WW1, the oldest being 1891, Figure 41, and about 43 or almost two-thirds were built before 1980, which is generally considered the beginning of modern seismic design. Lastly, the headquarters building is a 1932 Unreinforced Masonry Building which also houses the Emergency Operations Centre.

Fire station seismic vulnerability and its effects, directly on firefighter health and safety and indirectly on the ability of the fire apparatus to respond, has long been recognized, as shown in Figure 78 and is now well quantified, Figure 79. San Francisco, Los Angeles, Vancouver, B.C., Seattle and other cities have spent millions of dollars reinforcing and replacing aged stations, specifically due to seismic vulnerability concerns, Figure 80.

Figure 78: Fire station collapse, 1933 Long Beach (CA) earthquake. Note MFD's headquarters building dates from 1932.
5.1.2 Firefighting water capacity

Although the City of Montreal is surrounded on all sides by water, so 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. Why? Because, similar to the Ancient Mariner, while ‘water water [was] everywhere’, San Francisco could not move the water to where the fires were. A similar situation may exist in Montreal in that MFD, unlike neighbouring fire departments, does not have Large Diameter Hose (LDH) and currently would have significant difficulty in pumping/relaying water from the St. Lawrence river to say Le Plateau Mont-Royal (about 3 km). This situation is not unique (Scawthorn 2011) but is also not acceptable.

Alternative water supply sources need to be better identified, and access and water transport capabilities enhanced. Large Diameter Hose (LDH) systems, comparable to San Francisco Fire Department’s or Vallejo FD’s Portable Water Supply System (PWSS) Figure 81 or Vancouver, B.C.’s new LDH hose reel system, Figure 82, should be developed on a regional basis. Note that a PWSS has wider applicability than just earthquake – it can be used in the case of water main breaks to provide potable supply, for wildfires and for dewatering of flooded areas.

MFD cited the petroleum refinery in Montreal East as having LDH, but there will be competition for this resource following an earthquake, and MFD should have its own capabilities. Note that Laval FD carries larger hose than MFD.
Figure 81: Example of Portable Water Supply System (PWSS) (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.

Figure 82: Vancouver (B.C.) Fire and Rescue new LDH reel system – each trailer-mounted motorized reel carries 6000 ft. of 6" hose.
Photo: Scawthorn, 2019

5.2 Water service opportunities

Montreal's water service is an older system that has its challenges, in response to which in 2012 it began a 10-year improvement program for the distribution system. MWS is also performing analyses of its reservoirs for seismic stability.

It is recommended that MWS analyze its entire system for earthquake effects. For this study we estimate over 2,500 repairs, including about 500 breaks, will occur in the Montreal buried pipe network. Including seismic considerations in MWS’s improvement program is recommended, as well as considering development of a resilient network (Davis 2019; Multihazard Mitigation Council 2018).

Such an analysis is overdue. Most North American water systems in seismic zones have already assessed their seismic vulnerability, many quite some time ago, and are in the process or have completed seismic improvements, Figure 83.
5.3 Building standards opportunities

Almost all high-rise buildings in Montreal are sprinkled, to the region’s credit. However, these sprinklers rely on buried water mains for supply. In an earthquake, water mains may lose pressure, so that sprinklers will have no supply, Figure 84. 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

It is unclear if a similar requirement exists in the National Building Code of Canada although the benefit of such a requirement is clear and should be considered for Quebec.
5.4 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 Montreal East. Nevertheless, 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 Province of Quebec: (1) a review of the overall seismic vulnerability and reliability of major energy facilities; (2) review by Énergir of its ability to control and isolate its transmission and distribution networks in the event of a major earthquake.

Figure 84: 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).
6. Concluding remarks

The Geological Survey of Canada assesses the Montreal 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 5.8 in a 1732 earthquake which shook Montreal strongly and caused significant damage. In 1852 the City lost half its housing in a Great Fire.

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 three scenario events – a magnitude 6.5 event centred in downtown Montreal and magnitude 7 events to the Northwest and Southwest of Montreal – were determined and found to cause very strong ground motions in the study area, resulting in hundreds of breaks in the water distribution systems and hundreds of fires.

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 of between $10 billion and $30 billion. These are median estimates – there are smaller 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 can be significantly reduced. Montreal has begun to understand the threat of an extreme earthquake – this is demonstrated for example by the examination of the seismic stability of its water reservoirs. The initial work however is limited and has focused on the risk of damage from shaking. There is also a risk from fire. Specific actions can be taken now to reduce the risk of fire damage. The potential loss involved represents a local, provincial and national threat.

The province of Quebec has a strong commitment to fire safety[19]. It is our hope that the local, provincial and national governments will work together to implement the proposed solutions. A small investment now can greatly reduce the risk of loss.

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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Appendix A: Montreal building types

As noted above, a survey of buildings was conducted within Montreal, Laval and Longueuil for this study, in order to identify typical building types with regard to their earthquake and fire vulnerabilities. The survey was limited to a “windshield” survey of building exteriors and other visible attributes, particularly:

(a) for earthquake vulnerability: building age, lateral force resisting system, presence of soft story, materials of construction particularly of the lateral force resisting system, building separation and building height;
(b) for fire vulnerability: building age, materials of construction particularly of cladding, building density and spacing, building height, occupancies, vegetation.

While rapid visual surveys are no substitute for detailed structural and fire protection engineering analyses, important information and a general categorization of vulnerability can be readily acquired (FEMA 154 1988; FEMA 154 2002; FEMA 154 2015; Scawthorn 1986; Scawthorn 1988). The specific routes and areas surveyed are shown in Figure 85.

Figure 85: Sites and routes during Montreal visit: general photo locations are shown by icons.

In the following we shall use some terminology by which buildings are categorized for seismic and fire considerations.

Regarding seismic types of construction, so-called “Model Building Types” (MBTs) are often categorized as shown in Table 8, in which an “MnH” system is used, where “M” refers to the material of the lateral force resisting system (S for steel, M for masonry, C for Concrete, W for wood, etc.), “n” is a number referring to a type of lateral force resisting system (1 for moment frame, 2 for braced frame, etc) and “H” refers to height (typically L for Low, M for Moderate and H for High).
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<th>Height</th>
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Regarding fire-related types of construction, buildings are categorized by “Type” (IBC 2009) which, in a very simple way, are:

**TYPE I:** Fire Resistive Non-combustible (Commonly found in high-rise and mid-rise buildings).

**TYPE II:** A: Protected Non-Combustible (e.g., school buildings) B: Unprotected Non-Combustible (typ. commercial buildings).

**TYPE III:** Protected Combustible (known as “ordinary” construction, these are typically with brick, block or concrete walls and wooden roof or floor assemblies).

**TYPE IV:** Heavy Timber (“mill” construction).

**TYPE V:** A: Protected Wood Frame (Commonly used in the construction of newer apartment buildings; there is no exposed wood) B: Unprotected Wood Frame (Typ. single family homes and garages).

References to fire spread in the following are in the context of a subnormal fire department response – that is, no or very limited suppression. Selected neighbourhoods of the study region are discussed, numbered as shown to Figure 86, with a mixture of photos from the survey and Google Earth.

**Figure 86: Selected locations.**

1. **Old Montreal and downtown:** Building ages transition from 18th and early 19th C. Old Montreal stone and URM buildings to late 19th C older steel framed high rises with stone cladding, to early and then mid-20th C. mid- and high-rise buildings.

   Seismic vulnerabilities: older buildings are typically URM or S2 and have no seismic design. Pre-1980s buildings mid- and high-rise are S or C buildings and probably seismically inadequate. Newest buildings will have some seismic design. Pounding and great cladding damage, collapse potential for older buildings.
Fire vulnerabilities: Older buildings typically Type III with early 20th C high-rises being Type I, mid rises typically Type II and low-rises Type III. Problems include density and lack of separation, no secondary water supply for high-rises, narrow streets.

Fire spread is relatively rapid due to exposures via radiant heat.
2. **Plateau Mont-Royal**: Predominantly dense low-rise Type III URM row houses, non-combustible facades but rears sometimes have wood cladding, staircases, much vegetation, other fire hazards. Fire spread very rapid, especially via rear exposures due to very high radiant heat emission from rapid-growth large fires. Alley ways also receptive to secondary firebrand ignitions.
3. **Cartierville**: Newer, less dense area, combination of low-rise Type III URM duplexes and row houses, newer Type I and II, C1 to C3 apartment buildings, Type V single family dwellings. Fire spread in high-rises not so rapid but eventually complete if sprinkler water supplies fail and/or no fire department response. Fire spread in duplexes and row houses similar to what is expected in Plateau Mont-Royal, perhaps not quite so rapid, but result not dissimilar. Fire spread in single family dwellings not very rapid, but definitely possible esp. given adverse meteorological conditions.
4. **St. Leonard – Anjou**: Lower density mixture residential, light industrial largely Type III. If no fire suppression, fire spread sometimes confined to block of origin.
5. **Roxboro – Dollard des Ormeaux**: Lower density largely residential with Type III and V dwellings and supporting low-rise Type III commercial centres. If no fire suppression, fire spread sometimes confined to block of origin.