

DEVELOPMENT AND APPLICATION OF THE CANRISK INJURY  
MODEL AND A DISASTER SPATIAL DECISION SUPPORT SYSTEM  
(SDSS) TO EVALUATE SEISMIC RISK IN THE CONTEXT OF  
EMERGENCY MANAGEMENT IN CANADA: CASE STUDY OF  
OTTAWA, CANADA

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# List of Acronyms

ATC – Applied Technology Council  
CERT – Community Emergency Response Teams  
CDMS – Comprehensive Data Management System  
CKSZ – Charlevoix Kamouraska Seismic Zone  
CTUID – Census Tract Unique Identifier  
EM – Emergency Management  
EERI – Earthquake Engineering Research Institute  
ELE – Earthquake Loss Estimation  
ELER – Earthquake Loss Estimation Routine  
ESRI – Environmental Systems Research Institute Inc.  
FEMA – Federal Emergency Management Agency  
FOOSH – Falling On Out-Stretched Hands  
FSE – Fuzzy Synthetic Evaluation  
GIS – Geographic Information System  
GPS – Global Positioning System  
Hazus – Hazards United States  
HUSAR – Heavy Urban Search and Rescue  
HVAC – Heating, Ventilation, and Air Conditioning  
ICD – International Classification of Diseases  
ISS – Injury Severity Score  
LSAR – Light Search and Rescue  
LSLSZ – Lower St. Lawrence Seismic Zone  
M – Moment Magnitude  
M<sub>L</sub> – Richter / Local Magnitude  
M<sub>N</sub> – Magnitude Nuttli  
M<sub>S</sub> – Surface Wave Magnitude

MMI – Modified Mercalli Intensity  
MRI – Magnetic Resonance Imaging  
MUSAR – Medium Urban Search and Rescue  
NAD – North American Datum  
NASZ – Northern Appalachian Seismic Zone  
NCR – National Capital Region  
OBG – Ottawa Bonnechere Graben  
OD Matric – Origin-Destination Matrix  
OFC – Operational and Functional Components  
OR – Operating Suite  
PGA – Peak Ground Acceleration  
PGV - Peak Ground Velocity  
PTSD – Posttraumatic Stress Disorder  
R/C – Reinforced Concrete  
SA – Spectral Acceleration  
SAR – Search and Rescue  
SDSS – Spatial Decision Support System  
SGLSZ – Southern Great Lakes Seismic Zone  
SLRS – St. Lawrence Rift System  
SZ – Seismic Zone  
TELES – Taiwan Earthquake Loss Estimation System  
Urban Rat – Urban Rapid Assessment Tool  
URM – Unreinforced Masonry  
USAR – Urban Search and Rescue  
USFA – United States Fire Administration  
WQSZ – Western Quebec Seismic Zone

# Abstract

Approximately 43% of Canada's population reside in urban centres at most seismic risk. This research creates practical and proactive tools to support decision making in emergency management regarding earthquake risk. This proactive approach evaluates the potential impact of future earthquakes for informed mitigation and preparedness decisions. The overall aims are to evaluate a community's operational readiness, reveal limitations and resources gaps in the emergency plan, test potential mitigation and preparedness strategies and provide a realistic earthquake scenario for training activities. Two models, the CanRisk injury model and a disaster Spatial Decision Support System (SDSS), were designed and developed to further evaluate seismic risk on a community scale.

The injury model is an extension of the engineering-based CanRisk tool and quantifies an individual's risk to injury, the number of injuries, and provides an injury profile of life-threatening injuries at the building scale. The model implements fuzzy synthetic evaluation to quantify seismic risk, mathematical calculations to estimate number of injuries, and a decision-matrix to generate the injury profile.

The SDSS is an evidence-based model that is designed for the planning phase to evaluate post-earthquake emergency response. Loss estimations from Hazus Canada and the CanRisk injury model are combined with community geospatial data to simulate post-earthquake conditions that are important for immediate post-earthquake response. Fire services, search and rescue operations (including urban search and rescue and police services), emergency medical services, and relief operations are all modelled.

A case study was applied to 27 neighbourhoods in Ottawa, Canada, using a M6.0 and M7.25 scenarios. The models revealed challenges to all emergency response units. A critical threshold exists between the M6.0 and M7.25 scenarios whereby emergency response moves from partial but manageable functionality to a complete system breakdown. The models developed in this research show great utility to emergency managers in Canada.

# Acknowledgements

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*“The roots of education are bitter, but the fruit is sweet.”*

*-Aristotle, quoted by Diogenes Laertius in Lives of Eminent Philosophers*

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# Introduction

## Rationale

Both the developing and developed worlds have witnessed numerous devastating earthquakes in the 21<sup>st</sup> century. In fact, the first decade of this century measured more earthquake fatalities than any decade in the previous century. The frequency of earthquakes is not increasing, but rather there is better instrumental coverage, reporting, and larger populations living in high seismic risk regions. Seismic risk in western Canada is well-documented (e.g. Bruneau, 1990; Adams and Halchuk, 2003; Adams and Atkinson, 2003; Monk, 2007; Goda et al., 2011). In eastern Canada, however, seismic risk is compounded by the exposure of a largely unaware and unprepared population who lacks a sense of urgency to take mitigation and preparedness actions (Bruneau, 1990; Bruneau and Lamontagne, 1994). Eastern North America is located in an intraplate setting and has experienced several large and devastating earthquakes including the 1663 ~M<sub>L</sub>7.0 Charlevoix-Kamouraska earthquake, the 1886 ~M<sub>L</sub>7.3 Charleston, South Carolina earthquake and the 1811-1812 New Madrid earthquake sequence that included four earthquakes greater than M7.0. Recently, the 2011 M6.3 Christchurch, New Zealand, earthquake exemplifies the impact of a devastating earthquake near an urban centre, and is comparable to a potential event in North America.

Seismic risk incorporates the notions of hazard, vulnerability and exposure. Fundamental seismic risk questions are: (1) why and where do earthquakes occur; (2) what other hazards are associated with these earthquakes; (3) how vulnerable is the built environment to strong earthquake shaking; and (4) how vulnerable is the population to earthquake consequences. The answers to these questions can promote earthquake awareness in a community and provide a guideline to assist in the development of an emergency plan.

Emergency management (EM) provides a governmental structure and applies science, technology and coordination to deal with large-scale emergency events. Traditionally, EM has had a tendency to focus on the urgent aspects of a disaster; however, it is now accepted

that EM is comprehensive and multifaceted (Erden and Coskun, 2010). Preparedness, planning, and mitigation are quickly moving to the forefront of emergency management with the goal of preventing or reducing future losses.

The relationship between disaster research and emergency management have been widely discussed (e.g. Mileti, 1999; Stallings, 2002; Rodriguez et al., 2007). However, a research gap exists between seismic risk assessment and EM strategies. There are different approaches to seismic risk assessment, one of which is the use of loss estimation tools. The growing movement of these tools has demonstrated the value of their outputs in EM. The two main types of earthquake loss estimations (ELE) tools are proactive (preparedness and mitigation focus) and reactive (near real-time focus). Their utility is closely related to its history as the needs and demands of the users have shifted over time and has been influenced by key historical events.

### **A brief history of earthquake loss estimation research**

A timeline of key events in ELE research is illustrated in Figure I1. ELE research began in 1932 in California and was motivated by the insurance industry (Khater et al., 2003). In the 1960s, the insurance industry was still the impetus for such research. Traditional loss estimations implemented a deterministic /scenario-based approach that produced a highly-tailored report but provided little opportunity to update estimations to reflect changes in the inventory and input data (Anagnos et al., 1996).

Throughout the 1960s and following decades, there was a pronounced influence from the earthquake engineering sectors which transformed loss methodology from a deterministic approach toward a probabilistic one to enhance building codes (Campos Costa et al., 2010). Milestone loss estimation studies of high risk American urban centres such as San Francisco and Los Angeles were conducted in the 1970s (Seligson and Shoaf, 2003) and formed the basis for national policy-making and disaster relief / recovery operations in the United States (Khater et al., 2003).

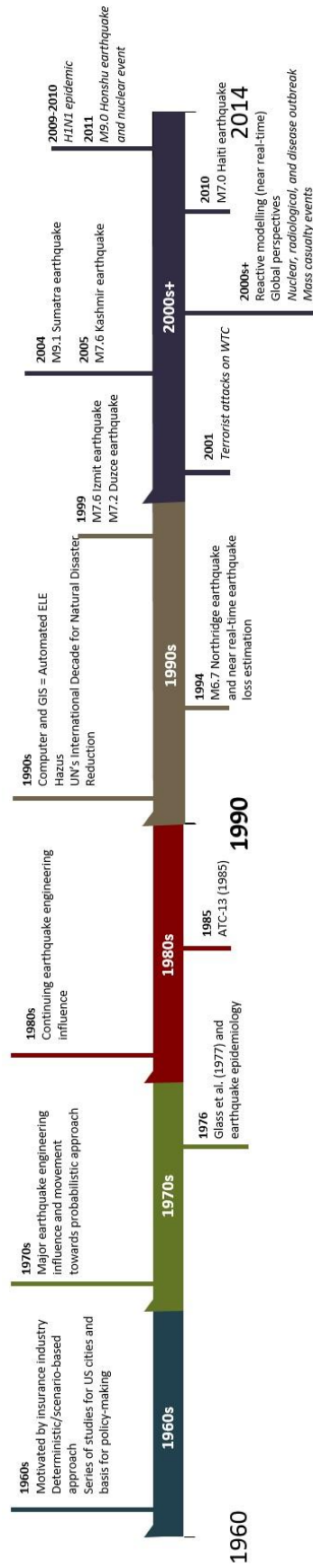


Figure I1: Timeline of important events that influenced earthquake loss estimation methodology and the development of loss estimation models and decision models in general.

In the late 1970s, earthquake epidemiology, the study of the distribution and causes of earthquake casualties was born when Glass et al. (1977) researched earthquake injuries following the 1976 M<sub>s</sub>7.5 Guatemala earthquake (Petal, 2011).

In the 1980s, the Applied Technology Council (ATC) published ATC-13 (1985), a revolutionary document on ELE methodology (Petal, 2011) with the intent to estimate the economic losses in California (Seligson and Shoaf, 2003). This effort, and similar efforts of the time were primarily led by the engineering community. Tierney (1990) noted that “if over the years there had been even one-tenth of the number of persons working on the problem of earthquake casualties as were working on building effects, real progress might have been made on casualty estimations; but this is not the case”.

The 1990s had several notable developments in ELE research. Firstly, computer functionality and its accessibility as well as the Internet, relational database management, and GIS facilitated the automation of loss estimation tools (Seligson and Shoaf, 2003). The development and implementation of Hazus (Hazards United States) was a landmark event in ELE methodology. Hazus uses seismic hazard and structural responses to estimate physical, social and economic losses from earthquakes.

Secondly, this decade marked the “International Decade for Natural Disaster Reduction”, a United Nations initiative for international action to study natural disaster characteristics with focus on their social impacts (Petal, 2011). During this time, interest was generated in multi-disciplinary research to better understand disaster risk (e.g. Blaikie et al., 1994; Davidson, 1997). Additionally, Durkin et al. (1991b) published a cohort-study of 24 survivors (60% of the survivors) of a reinforced concrete building that collapsed during the 1985 M8.0 Michoacan (Mexico City) earthquake to better understand the cause of earthquake injuries, as well as type of injury sustained. Retrospective epidemiologic research was also published regarding the 1989 M6.9 Loma Prieta earthquake (e.g. Durkin et al., 1991a).

Significant events that influenced the progression of ELE research were the 1994 M6.7 Northridge earthquake where response and early recovery decisions were supported by near real-time loss estimations (Blais et al., 1996; Eguchi et al., 1997), and the 1999 >M7.0s

earthquakes in Turkey which generated a significant Euro-Mediterranean research interest (Elnashai et al., 2008).

In the 21<sup>st</sup> century, earthquake epidemiology and casualty loss estimation research is continuing to progress (e.g. Duzgun et al., 2011; Koyama et al., 2011), but at a slower pace than earthquake engineering, cost-benefit analysis, and economic loss estimation methodology. A series of significant events has created trends in general loss estimation research.

- Mass casualty and global scale events - The 11 September 2001 World Trade Centre Terrorist attacks where Frykberg (2003) noted that North America required better emergency management strategies and guidelines for mass casualty events.
- Mass casualty events and reactive modelling - Other mass casualty events were the 2004 M9.1 Sumatra earthquake, the 2008 M7.6 Kashmir earthquake and the 2010 M7.0 Haiti earthquake which required early decision making for humanitarian assistance.
- Nuclear, radiological and chemical releases, and disease outbreaks – Significant events such as the 2009-2010 H1N1 outbreak and 2011 M9.0 Honshu earthquake and nuclear event influenced the development of many health services-related models.

### **Gaps in earthquake loss estimation and decision support models**

Strasser et al., (2008) and Daniell (2011) provide brief reviews of earthquake loss estimation tools. Seismic hazard, earthquake engineering and/or economic losses are the core focus of most tools (e.g EPEDAT, PAGER, LNECloss, methodology from Stehle et al. (2002), and Badal et al. (2005)); few incorporate complex social characteristics for casualty estimation.

Examples include: (1) Coburn et al. (1992) who incorporate variables to account for post-earthquake search and rescue (SAR) efficiency, and (2) Zhao and Zheng (2000) who assess the progression of injury during entrapment and integrate factors such as injury severity, trap surroundings, physique of the occupant, and time. Hazus, although monumental, only

account for population distributions and time of day as non-building factors in casualty estimations. Additionally, Hazus only estimates casualties as a function of building damage.

Recently, the fast-paced progression of ELE research and tools has focused on reactive/near real-time models and global / regional scales (e.g EPEDAT (Eguchi et al., 1997; Seligson and Shoaf, 2003), PAGER (Jaiswal et al., 2011), APE-ELEV (Astoul et al., 2013), OPAL (Daniell, 2011), and ELER (Hancilar et al., 2010) rather than proactive models and community scales.

Several models focus solely on loss estimations which neither address mitigation and response needs (Thomas et al., 2007) nor ask ‘what do these numbers mean for my community’. Surprisingly, there are very few decision support models that evaluate post-earthquake conditions relevant for emergency first response. Some examples are: (1) Hazus which addresses some regional impacts such as fire following, shelter requirements, and critical facility functionality; (2) Aleskerov et al., (2005) which estimates shelter needs; (3) Kuwata and Takada (2004) which models post-earthquake traffic management; and (4) Duzgun et al., (2011) which considers the accessibility of critical facilities in each neighbourhood. Presently, loss estimation and decision support models in general, are influenced by recent global events (e.g. mass casualty events (Arboleda et al., 2007; Amram et al., 2012), and nuclear, radiological and disease outbreak events (Scheulen et al., 2009; Coleman et al., 2013; Lee et al., 2013; Koerner et al., 2014).

Clearly, there is a lack of both proactive earthquake casualty loss estimation models that account for both building and social risk factors, and decision support models that evaluate response capacity at a local scale. These types of models would establish a meaningful context between seismic risk assessment and EM strategies, and be of great benefit to decision makers.

Other challenges in applying disaster research (including seismic risk assessment) and emergency management (EM) are: (1) the development of partnerships and the engagement of the community; (2) the emphasis on preparedness and mitigation strategies; (3) the use of data and GIS as best practice; and (4) the importance of building on successes as well as

considering the ‘lessons learned’ and challenges from relevant case studies. Acknowledging these challenges in model design is opportune.

### **Application of loss estimation and decision models in emergency management**

Many models have been implemented and used in the emergency management community. For example, PAGER is now embedded in the USGS near real-time earthquake map and is used as a global post-earthquake disaster alert system to facilitate informed decision making and coordination regarding humanitarian assistance (Frolova et al., 2011; Jaiswal et al., 2011). ELE models used in the LESSLOSS project have identified neighbourhoods of higher seismic risk in Istanbul whereupon targeted strategies have been applied, and have also supported decision making regarding mitigation strategies in Lisbon (Spence, 2007; Zonno et al., 2009). Another example of the application of ELE models was the use of Hazus in the “Great ShakeOut”, one of the most widely known earthquake drills. The “Great ShakeOut” Scenario uses loss outputs to support realistic, large scale and comprehensive scenario development for Southern California (Jones and Benthien, 2011).

The benefits of proactive loss estimation and response capacity models is that they can help concentrate efforts to maximize effective preparedness and mitigation strategies (e.g. Spence, 2007; Zonno et al., 2009; Campos Costa et al., 2010). These models can also facilitate policy making (Khater et al., 2003), better gauge thresholds that may require humanitarian assistance (e.g. Jaiswal et al., 2011), and provide a basis for training exercises and simulations (e.g. Scawthorn, 2003; Barnett et al., 2005; Rosenfeld et al., 2009).

### **Description of Research and Original Contributions**

The purpose of this research was to create proactive and practical tools for decision makers in emergency management regarding earthquake risk. The overall aim of the models is to facilitate informed decision making in EM by evaluating a community’s operational readiness, revealing limitations and resources gaps in the emergency plan, testing potential

mitigation and preparedness strategies, and providing a realistic earthquake scenario for training activities. In this PhD dissertation, two models were designed and developed to further evaluate seismic risk with applications to proactive emergency management. Both models are designed for Canada, but have international application. Additionally, both models were designed using an evidence-based approach, that is, both models implemented empirical qualitative and quantitative data as a basis for conceptual and model frameworks.

The research in this dissertation has the following objectives (the two major original contributions are italicized):

- *To design and develop an evidence-based earthquake injury model that quantifies the risk to injury, the number of injuries, and provides an injury profile at a building scale for the CanRisk program*
- *To design and develop an evidence-based disaster Spatial Decision Support System (SDSS) that incorporates high resolution loss estimations and geospatial community resources to facilitate informed decision making regarding proactive strategies for immediate post-earthquake response*
- To apply the CanRisk injury model and disaster SDSS using a case study of Ottawa, Canada, and critically evaluate the results in the context of EM
- To recommend a set of common proactive strategies for immediate post-earthquake response of fire services, search and rescue operations, emergency medical services and relief operations for Canadian communities

This dissertation follows an article-based format. The overall flow of the document consists of (1) a literature review on seismic risk in eastern Canada as there is insufficient literature that summarizes its comprehensive risk, (2) methodological approach used and description of the development of the CanRisk injury model and (3) the disaster SDSS, (4) the application of these original models using a case study of Ottawa, Canada, and (5) research and management conclusions using examples from the case study as well as a discussion on future research directions.

Chapter 1 is a review paper on seismic risk pertinent to major eastern Canadian urban centres. I am the sole author and only contributor. This paper is intended for an academic journal that encourages multi-disciplinary perspectives.

Chapter 2 is the description of the CanRisk injury model including its rationale and development. I am the primary author and contributor. My responsibilities were to determine the risk factors via a comprehensive literature review, and the compilation and analysis of injury datasets. I also designed, developed and tested the injury model in the MATLAB environment. Amid Elsabbagh is second author as we were both working on CanRisk models at the same time, and he advised me on the use of MATLAB and fuzzy synthetic evaluation. Amid designed and developed the CanRisk masonry model. Murat Saatcioglu is third author and oversees the development of the CanRisk software program. The last author is Michael Sawada who provided assistance with the analysis of the injury dataset. This paper is intended for a seismological focused journal.

Chapter 3 is the description of the disaster SDSS. I am the primary author and contributor. My responsibilities were to determine the model components via an intensive literature review, and designed and developed the SDSS using ArcGIS's Model Builder. Michael Sawada is second author and provided advice and assistance regarding GIS techniques and tools. Murat Saatcioglu, the last author, also collaborated on this model. This paper is intended for a general natural hazards/disasters journal as the first of a two-part paper.

Chapter 4 is a critical discussion on the application of the CanRisk and disaster SDSS using a case study of Ottawa, Canada. I am the sole author and only contributor. This paper is intended for general natural hazards/disasters journal as the second of a two-part paper.

Chapter 5 are the main research conclusions and recommended future research directions. Additionally, general guidelines for post-earthquake emergency response planning are included. I am the sole author and only contributor. This chapter is not intended for publication; however, the guidelines of qualitative observations and conclusions of this research are for community use.

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# Chapter 1

## Literature Review: *Seismic risk in eastern Canadian urban centres*

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*“Civilization exists by geological consent, subject to change without notice.”*

*-Will Durant*

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**Abstract:** Seismic risk is a broad term that incorporates the physical impact of an earthquake hazard, vulnerability (e.g. unaware and unprepared population, response capacity, etc.) and the exposure of the elements at risk. Of the six Canadian urban centres at greatest seismic risk, Montreal, Ottawa, Quebec City and Toronto are located in eastern Canada. These urban centres are situated in intraplate settings yet still experience seismicity. In eastern Canada, moderate-to-large earthquakes have occurred in the past, and evidence indicates that seismicity will continue. The historical nature of these urban centres has compounded risk with the presence of historical buildings, many of these built with unreinforced masonry and prior to seismic provisions in the National Building Code of Canada. The large unaware and unprepared population exposed to seismic hazard, will also contribute to risk in several ways including being injured by inappropriate actions taken during earthquake shaking (e.g. rapidly exiting a building). By understanding earthquake risk, a community can better develop its ability to mitigate, prepare for, respond to, and recover from an earthquake.

**Keywords:** *earthquake risk, seismic risk, eastern Canada*

## 1.1 Introduction

Large earthquakes ( $M > 6.0$ ) in intraplate regions such as Australia, the United Kingdom, and central and eastern North America represent significant seismic risk partly due to unaware and unprepared populations (e.g. Bruneau and Lamontagne, 1994; Musson, 2003; Blong, 2004). Seismic risk in eastern North America is further compounded by population and infrastructure growth (Bruneau and Lamontagne, 1994). Seismic hazard assessments have been established in Canada and promotes awareness and preparedness initiatives (Bruneau, 1990; Monk, 2007). In eastern Canada however, there is a distinct lack of urgency (Bruneau, 1990) and a false perception of the seriousness of the threat since eastern Canadian earthquakes occur infrequently and historically have caused little damage (Bruneau and Lamontagne, 1994). As of early 2014, the major urban centres of eastern Canada have not experienced a damaging earthquake in the 20<sup>th</sup> or 21<sup>st</sup> century, but previous experience from other contemporary North American earthquakes has shown the possible consequences of a moderate-to-large earthquake (e.g 1989 M6.9 Loma Prieta earthquake, 1994 M6.7 Northridge earthquake).

Although there are excellent review papers of the various aspects of eastern Canadian earthquakes such as seismic hazards (e.g. Tuttle et al., 1990, Adams and Basham, 1989), seismicity (e.g. Mereu et al., 2002; Adams, 1989), and building damage (e.g. Paultre et al., 1993; Bruneau and Lamontagne, 1994), very few review papers exist on the comprehensive seismic risk within eastern Canada. A necessary review must discuss the following key questions:

- Why and where do earthquakes occur in eastern Canada, including past, present and future?
- What other hazards are associated with these earthquakes?
- How vulnerable is the built environment to earthquakes?
- How vulnerable is the population to earthquake consequences?

Discussing these questions provide a clearer and bigger picture of seismic risk especially to urban centres and can facilitate informed decision making for emergency management. The

purpose of this chapter is to provide a review of the current seismic risk of the major urban centres of eastern Canada. This chapter will discuss (1) seismic hazard and its associated hazards from geological and seismological perspectives, and (2) seismic vulnerability and exposure including (a) building performance and unsafe building characteristics as well as operational and functional components from an engineering perspective, and (b) casualties from previous eastern Canadian earthquakes and other relevant case studies from a medical perspective. Casualties is a term inclusive of fatalities and injuries.

## **1.2 Risk definitions**

Risk can be generally defined as the damage / impact that will be caused by a future earthquake in a given area, and is the product of hazard, vulnerability and exposure. Hazard is a measure of the intensity of the earthquake effects in that region and includes aspects of fault rupture, energy release (magnitude), seismic wave attenuation and amplification, landslides, liquefaction, etc. Vulnerability is a measure of the capacity for a society to cope, withstand, or recover from the impacts of a future earthquake. There are many aspects that influence vulnerability such as socio-economic factors, unaware and unprepared populations, a community's response capacity, etc. Exposure is a measure of the elements at risk that could be impacted by the seismic hazard and includes population, buildings, infrastructure, etc.

## **1.3 Why do earthquakes occur in eastern Canada?**

Continental eastern Canada is at great distances from any plate margin, but it still experiences significant seismic activity (e.g. 1663 ~M<sub>L</sub>7.0 Charlevoix-Kamouraska earthquake, the 1886 ~M<sub>L</sub>7.3 Charleston, South Carolina earthquake). Seismic activity in eastern Canada is not random, but concentrates near pre-existing crustal weaknesses (Sykes, 1978). These crustal weaknesses are associated with embedded geological structures such as ancient rift

zones and margins, igneous intrusions, continent-ocean transitions, continental slopes (Hasegawa, 1991), and impact craters (Rondot, 1971).

A major crustal rupture (also known as a relic rift system) in eastern Canada is the St. Lawrence Rift System (SLRS) that includes the Ottawa-Bonnechere Graben (OBG) (Kumarapeli and Saull, 1966; Kumarapeli, 1985) (Figure 1.1). The SLRS is estimated to be approximately 2,200 km in length (Kumarapeli and Saull, 1966) and is the byproduct of a triple rift junction centered at Mont Sutton near Montreal with arms extending northwestward through the Ottawa Valley to Lake Timiskaming, eastward through the Gaspé Peninsula, and southward through Lake Champlain (Sykes, 1978; Adams and Basham, 1989; Kamo et al., 1995).

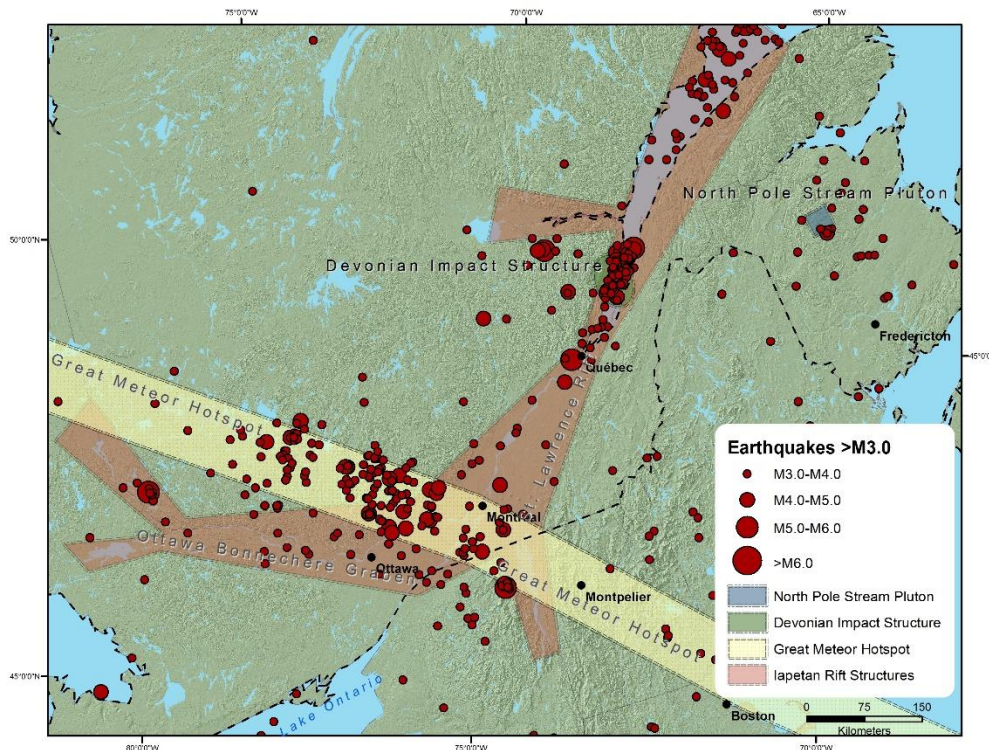


Figure 1.1: Crustal weaknesses affecting major urban centres in eastern Canada. The following are approximate boundaries for (1) Iapetan rift structures (SLRS and OBG), (2) the Great Meteor Hotspot track and/or the general orientation of the suspect igneous intrusions, (3) the Devonian Impact Structure, and (4) the North Pole Stream Pluton/igneous intrusion (modified from Kumarapeli and Saull, 1966; Rondot, 1971; Burke et al., 1989; Ma and Eaton, 2007) (Data sources: ESRI, [www.earthquakescanada.nrcan.gc.ca](http://www.earthquakescanada.nrcan.gc.ca)).

Triple rift junctions occur during supercontinental breakup, where two arms open to form an ocean, while the third arm fails. The SLRS and the OBG were initially formed by the continental breakup/fragmentation of Rodinia and the formation of the Iapetus Ocean during the late Precambrian and early Paleozoic (Kumarapeli, 1985). A complex series of orogenies sealed proximal faults and reactivated distal faults (Kumarapeli, 1985) thus creating newer but smaller fault systems that offset the main rift system (Adams and Basham, 1989; Tremblay et al., 2003; Rimando and Benn, 2005). These processes continued during the continental rifting of the subsequent supercontinent of Pangaea throughout the Mesozoic (Sykes, 1978; Rimando and Benn, 2005) and into the Cretaceous (Daneshfar and Benn, 2002).

The intrusion of igneous bodies also defines unique crustal weaknesses in eastern Canada. Examples of such igneous intrusions exist in (1) the Miramichi region of New Brunswick (Burke et al., 1989; Hasegawa, 1991), and (2) western Quebec (Figure 1.1). The North Pole Stream Pluton in the Miramichi region of New Brunswick was emplaced during the Acadian orogeny and covers approximately 800 km<sup>2</sup> (Burke et al., 1989). The western Quebec intrusions run parallel to the OBG, and are thought to be either (1) byproducts of continental rifting and fracture zones (Kumarapeli and Saull, 1966; Kumarapeli, 1985), or (2) the passage of a hotspot (Crough, 1981; Ma and Eaton, 2007). It is suggested that igneous intrusions are stronger and more brittle than the surrounding rock and can concentrate ambient plate stresses (Hasegawa, 1991). In the case of a hotspot, however, its passage would have created local uplift that thermally stressed and fractured the crust thus creating or reactivating crustal weaknesses (Ma and Eaton, 2007).

Another notable crustal weakness is the Late Devonian meteorite impact crater which is located between Baie-Saint-Paul and La Malbaie, Quebec (Rondot, 1971; Hasegawa, 1991) (Figure 1.1). This event caused ring faulting and intense fracturing within and immediately surrounding the impact crater (Adams, 1989; Adams and Basham, 1989; Baird et al., 2009).

## 1.4 Where do earthquakes occur in eastern Canada?

Crustal weaknesses can be thousands of kilometres long, but only sporadically active; this creates spatial clustering of seismic activity (Basham et al., 1979). In Canada, the only definitive active fault sources are the Cascadia subduction zone and the Queen Charlotte Fault along the west coast of British Columbia (Atkinson and Goda, 2011). In eastern Canada, there are numerous earthquake zones (Figure 1.2). Table 1.1 summarizes notable pre-historic and historic earthquakes in eastern Canada.

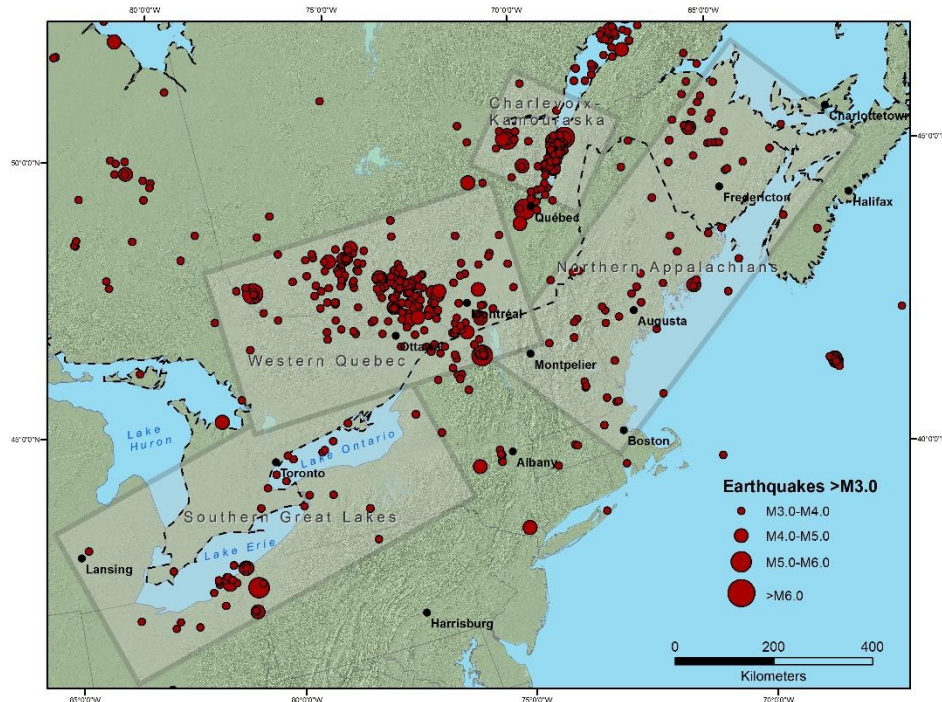


Figure 1.2: Selected seismic zones in eastern Canada that affect major urban centres. Those seismic zones (SZ) are the (1) Southern Great Lakes SZ, (2) Western Quebec SZ, (3) Charlevoix-Kamouraska SZ, and (4) North Appalachians SZ. Adams et al. (2002) noted that Montreal, Ottawa, Quebec City, and Toronto constitute four of the top six urban populations at most seismic risk in Canada (Data sources: ESRI, [www.earthquakescanada.nrcan.gc.ca](http://www.earthquakescanada.nrcan.gc.ca)).

Table 1.1: Summary of some notable earthquakes and related seismic hazards in the Western Quebec Seismic Zone, Charlevoix-Kamouraska Seismic Zone, and the Northern Appalachians Seismic Zone. Other relevant hazards that were not located in these SZs are (a) surface faulting (e.g. Adams et al., 1991; Lamontagne, 2002), (b) tsunami, notably, the 1929 M7.2 Grand Banks tsunamigenic earthquake that killed 28 people in the Burin Peninsula, NL, and (c) snow avalanches as the 1999 M<sub>N</sub>5.1 Lower St Lawrence SZ earthquake may have triggered a snow avalanche but it could not be documented (Lamontagne, 2009).

Magnitude	Year	Location	Landslide	Liquefaction	Other Hazard	References
<b>Western Quebec Seismic Zone</b>						
~M <sub>6.5</sub> ~M <sub>7.0</sub>	Pre	Ottawa Region	Retrogressive	Liquefaction		Aylsworth et al., 2000; Aylsworth and Hunter, 2004; Doig, 1991;
~M <sub>N</sub> 5.8	1732	~Metro Montreal, QC				Doughty et al., 2010; Hodgson, 1945a,b; Hunter et al., 2007;
~M <sub>6.1</sub>	1935	Témiscaming, QC	Rockfall			Lamontagne, 2002, 2009;
			Embankment			Lamontagne et al., 2007; Leblanc, 1981; NRCan, 2010
			Sub-aqueous			
~M <sub>5.6</sub>	1944	Cornwall, ON				
M <sub>5.0</sub>	2010	Val-des-Bois QC	Retrogressive			
			Embankment			
M <sub>N</sub> 5.2	2013	Shawville, QC				
<b>Charlevoix-Kamouraska Seismic Zone</b>						
Large	Pre	Gouffre, Malbaie, Ouelle, QC		Liquefaction		Cauchon-Voyer et al., 2011;
~M <sub>L</sub> 7.0~M <sub>L</sub> 7.5	1663	Baie-Saint-Paul, QC, Region	Retrogressive	Geysers	Backflood	Desjardin, 1980; Ebel, 2011; Evans, 2001; Hodgson, 1945a;
			Sub-aqueous		Outburst flood	Lamontagne, 2002, 2009;
					Tsunami	Lamontagne et al., 2007; Lefbvre et al., 1992; Mitchell et al., 1990;
~M <sub>L</sub> 6.5	1870	Baie-Saint-Paul, QC, Region	Rockfall	Geysers		Legget and LaSalle, 1978; Syvitski and Schafer, 1996; Tuttle and Atkinson, 2010; Tuttle et al., 1990
~M <sub>6.2</sub>	1925	Ile aux Lièvres, QC	Sub-aqueous	Liquefaction	Tsunami	
M <sub>5.9</sub>	1988	Saguenay, QC	Rockfall	Liquefaction		
			Embankment			
<b>Northern Appalachians Seismic Zone</b>						
M <sub>N</sub> 5.8, M <sub>N</sub> 5.5	1982	Miramichi Highlands, NB				Burke et al., 1989; Lamontagne et al., 2007

### 1.4.1 Southern Great Lakes Seismic Zone and the Northern Appalachians Seismic Zone

The Southern Great Lakes Seismic Zone (SGLSZ) is currently a region of low to moderate seismicity ( $M < 5.5$ ) and encompasses the western edge of Lake Ontario that is composed of numerous urban centres including Toronto (Mohajer et al., 1992; Ebel and Tuttle, 2002). In this seismic zone, the mechanism of seismicity is elusive and greatly debated; it has been attributed to ancient rifting (Kumarapeli and Saull, 1966; Ebel and Tuttle, 2002), glaciotectonics (Adams et al., 1993), and fluid induction (Mereu et al., 2002). Although many small seismic events have occurred in the SGLSZ, historical records and pre-1970 instrumental data cannot accurately locate epicentres. Consequently the post-1970 earthquake record is too short to define spatial patterns (Stevens, 1994; Mereu et al., 2002). No paleoseismic evidence of large ( $M > 6.0$ ) events has been documented in this zone (Ebel and Tuttle, 2002). However, it has been noted by many (Mohajer et al., 1992; Wallach et al., 1998) that the potential for a significant earthquake should not be dismissed, as even quiescent faults are known to become active (Leonard and Clark, 2011).

The Northern Appalachians Seismic Zone (NASZ) encompasses a large area including most of New Brunswick and extends into the New England States (Adams, 1989). This zone tends to

have uniform seismicity with a concentration of activity in the Miramichi highlands (Adams, 1989).

#### **1.4.2 Western Quebec Seismic Zone**

The Western Quebec Seismic Zone (WQSZ) encompasses many urban centres including Montreal and Ottawa, and represents a significant contribution to seismic risk in eastern Canada (Adams et al., 2002). Seismicity consists of two bands: (1) the first trends northwest along the OBG and has experienced large historical earthquakes (e.g. 1944 M5.6 Cornwall earthquake), and (2) the second trends parallel 200 km north of the OBG and is aligned with the emplacement of igneous intrusions (Adams, 1989).

#### **1.4.3 Charlevoix-Kamouraska Seismic Zone**

Historically, the Charlevoix-Kamouraska Seismic Zone (CKSZ) is the most seismically active area in eastern Canada and encompasses numerous urban centres along the St. Lawrence River including La Malbaie and Riviere-du-Loup (Lamontagne, 2002). It has been identified that this zone is the most probable location of a future large earthquake (Bent, 1992; Onur et al., 2008). In the CKSZ, earthquakes tend to be focussed beneath the St. Lawrence River and associated with the SLRS; this area is further complicated by the presence of the Late Devonian meteorite impact structure (Adams, 1989; Hasegawa, 1991; Tuttle and Atkinson, 2010).

#### **1.4.4 Important considerations**

The scientific evidence and descriptions via written or oral accounts of previous earthquakes including both pre-instrumental and instrumental events, provide clues as to the potential impacts of future eastern Canadian earthquakes and provide direction with respect to seismic risk (Lamontagne, 2008a). The reporting of many of the early historical earthquakes

in eastern Canada may show preference to regions of human settlement along the lower St. Lawrence, Quebec City and Montreal (Hodgson, 1945a; Basham et al., 1979).

The earthquake record in eastern Canada is short and it is probable that some crustal weaknesses / seismogenic structures have not yet been revealed by the short period of observation (Ebel et al., 2008; Tuttle and Atkinson, 2010). Kafka and Walcott (1998) suggested that two out of three earthquakes greater than M5.0 occur in the vicinity of active areas. However, most earthquakes in eastern North America, including those that are  $M \geq 7.0$  (e.g. the 1811-1812 New Madrid earthquake sequence, 1886  $\sim$ M7.3 Charleston, South Carolina earthquake), are related to ancient rift structures (Ebel and Tuttle, 2002), and these structures are the most likely source of future earthquakes (Tuttle and Atkinson, 2010). Many suggest (Adams and Basham, 1989; Bent, 1992; Onur et al., 2008) that the Charlevoix-Kamouraska Seismic Zone is considered to be a likely location of a future large earthquake. However, Ma and Atkinson (2006) noted that the wide range of focal depths within the WQSZ, particularly along the Ottawa River Valley may have the potential to produce a large rupture. New international research establishes that earthquakes in extended stable continental regions such as the SLRS and OBG can experience large earthquakes of up to  $M7.65 \pm 0.1$  (Leonard and Clark, 2011). Currently, Canadian hazard maps assume a maximum possible magnitude of M7.2 (e.g. Nastev et al., 2015, *In Preparation*), however updated hypotheses suggest that a higher magnitude event is possible anywhere along the relict rifted zones (Atkinson and Goda, 2011).

## **1.5 What other hazards are associated with earthquakes?**

Other hazards associated with ground motion have been documented in eastern Canada. Interestingly, the highest number of fatalities have been caused by these associated hazards rather than the shaking itself. The most lethal event was the earthquake-generated tsunami following the 1929 M7.2 Grand Banks earthquake that killed 27 people (Lamontagne et al., 2007). Therefore, a short discussion on the various geological hazards that can affect eastern Canadian urban centres such as seismic wave amplification and mass movements is merited

Table 1.1 outlines these hazards as well as the observation of surface rupture, liquefaction, snow avalanches, flooding, and tsunamis.

### **1.5.1 Seismic wave amplification**

A basic component of earthquake ground motion is the potential of the underlying rock and sediment to attenuate or amplify an incoming seismic wave. The frequency content of seismic waves, crustal attenuation properties, and the surficial geological deposits play a significant role in the amplification of these waves as dramatically observed in North American earthquakes (Bruneau, 1990), including eastern Canadian earthquakes (Hodgson, 1945a; Paultre et al., 1993; Lamontagne, 2002). In particular, softer sediments increase the likelihood of wave amplification.

Soil characteristics can be classified using microzonation or simulations of soil dynamic response such as seismic reflection and refraction studies, which establish the underpinnings for detailed maps of soil conditions (Lamontagne, 2008a). In Canada, soil microzonation maps are available for Vancouver, Victoria, Montreal, Ottawa and Gatineau (Adams and Halchuk, 2004; Chouinard and Rosset, 2007; Hunter et al., 2007). In eastern Canada, the presence of soft sediments (e.g. Leda clay) is of particular interest because if disturbed and on a slope, the soil can lose its strength and flow (Hunter et al., 2007). Additionally, these sensitive sediments demonstrate exceptionally low shear wave velocities (40 to 150 m/s), and are among the lowest measured worldwide (Hunter et al., 2007). Microzonation studies and other seismic-related research have revealed that portions of major eastern Canadian urban centres (Lamontagne, 2002) including heavily urbanized neighbourhoods in Quebec City (Bruneau and Lamontagne, 1994), Ottawa (Hunter et al., 2009; Lamontagne, 2010), and Montreal (Durand and Robillard, 1998) are underlain by these hazardous soft sediments.

### 1.5.2 Mass movements

Mass movements are a well-known associated seismic hazard, and can happen on land or under water (sub-aerial or sub-aqueous). Earthquake-generated rockfalls/rockslides are common and can be triggered by ~M4.0 events and/or high-frequency shaking. Historically, these types of mass movements pose a great threat to linear infrastructure such as transportation systems and lifeline networks (e.g. Pierre and Lamontagne, 2004; Ebel et al., 2008).

In eastern Canada, particularly along the St. Lawrence River, Ottawa River and their tributaries, retrogressive slides in soft sediments are common (Desjardins, 1980; Aylsworth et al., 2000; Evans, 2001; Aylsworth and Hunter, 2004) (Figure 1.3). There are numerous examples of earthquake-induced retrogressive slides but the majority occur without earthquake shaking (e.g. Eden et al., 1971; Evans and Brooks, 1994). Examples of earthquake-generated retrogressive slides are presented in Table 1.1.



Figure 1.3: Photograph of the earthquake-induced retrogressive slide near Notre-Dame-de-la-Salette following the 2010 M5.0 Val-des-Bois earthquake (Photograph: S.K. Ploeger).

Subaqueous mass movements are not well reported because they are more difficult to document (Keefer, 1984). These earthquake-generated sub-aqueous landslides have occurred in various eastern Canadian waterway settings such as fjords (e.g. 1663 ~M<sub>L</sub>7.0 CKSZ earthquake in the Saguenay basin (Syvitski and Schafer, 1996), estuaries (e.g. prehistoric and the 1663 earthquake along the St. Lawrence estuary (Cauchon-Voyer et al., 2011), rivers (e.g. agitated and discoloured water from various historical events (Hodgson, 1945a), and lakes (e.g. M6.1 WQSZ earthquake in Lac Tee and Kipawa (Doig, 1991; Doughty et al., 2010)).

Though earthquake-generated mass movements have never been reported in urban centres of eastern Canada, the threat does exist. Cliffs and other steep slopes have the potential to produce rockslides/landslides if certain endogenic and exogenic characteristics exist. The Cap Diamant slides in urban Quebec City (1841, 1582, 1864, 1889) are examples of this hazard. Both pre-historic and historic mass movement scars are visible and have been documented along numerous waterways in the Ottawa area (e.g. Aylsworth et al., 2000). Cauchon-Voyer et al. (2011) noted that Highway 138, which follows the north shore of the St. Lawrence River and intersects the CKSZ and the Lower St. Lawrence Seismic Zone (LSLSZ), crosses a historic landslide scar and other vulnerable sediment complexes. Mass movements in manmade slopes (i.e. embankments) have also been known to damage and obstruct transportation networks (Hodgson, 1945a; Bruneau and Lamontagne, 1994; Lamontagne et al., 2007; Ebel et al., 2008). These occurrences can hamper a post-earthquake response efforts and relief supplies.

## **1.6 How vulnerable is the built environment to earthquakes?**

The performance of structural systems during earthquake shaking is not only an important component of risk to the built environment, but also to the population since building failure is the leading cause of casualties in earthquakes. Therefore, the enhanced resistance of structures to ground motion is the most prudent strategy in earthquake protection (Coburn and Spence, 2002). In developed countries such as the United States, Canada, and Japan, the

building codes are not only superior but also strictly enforced. Unfortunately, building codes apply to new buildings only and are not being applied retroactively. Therefore, except in special circumstances, many of the older buildings are not necessarily capable of withstanding earthquake shaking without damage. Historical buildings (pre-1940) tend to be exceptionally vulnerable to earthquake damage as witnessed in previous eastern Canadian earthquakes and in the recent 2011 M5.8 Virginia earthquake (Table 1.2). By investigating damage from previous earthquakes, vulnerable buildings can be identified for mitigation and retrofit programs. During the 1989 M6.9 Loma Prieta earthquake, retrofitted buildings performed well during the earthquake, while adjacent buildings that did not adopt such measures performed poorly (Bruneau, 1990).

Various building types (masonry, timber, concrete and steel) have discrete structural characteristics and thus behave differently during earthquake shaking (see Coburn and Spence, 2002; FEMA, 2012). Construction materials are central to the design of structural systems due to various characteristics of their relative strength, stiffness and ductility. Earthquake-resistant designs rely on materials with high ductility, high strength-to-weight ratios, and low cost (Duggal, 2007).

Table 1.2: Summary of some historical buildings that were damaged during eastern North American earthquakes in the 20<sup>th</sup> and 21<sup>st</sup> century.

Magnitude	Year	Building Location	Building	Reference
M <sub>4.3</sub> , M <sub>5.5</sub> , M <sub>4.3</sub> , M <sub>6.2</sub> , M <sub>6.1</sub>	1908, 1914, 1917, 1925, 1935	Ottawa, ON	Museum of Nature	Lamontagne, 2010
M <sub>6.2</sub>	1925	Quebec City, QC	Gare du Palais	Mitchell et al., 1990
M <sub>5.8</sub>	1988	Quebec City, QC	Hippodrome	Mitchell et al., 1990
		Montreal, QC	Montreal-east City Hall	
M <sub>5.8</sub>	2011	Washington, DC	Washington Monument (Figure 1.4) Washington National Cathedral	Horton and Williams, 2012



Figure 1.4. Restoration work in the spring of 2013 on the Washington Monument in Washington DC following the August 2011 M5.8 Virginia earthquake (Photograph: S.K. Ploeger).

### 1.6.1 Masonry buildings

Masonry is used in many aspects of building design such as load-bearing and non-load bearing walls, infill panels, partitions, and decorative elements, and primarily consists of bricks, blocks or stones. Historically, unreinforced masonry (URM) buildings perform poorly during earthquakes (see Bruneau and Lamontagne, 1994; Monk, 2007; Lamontagne, 2008b; Lamontagne, 2010) due to these structures' (1) brittle nature, (2) high mass and therefore large inertial forces, (3) stiffness, and (4) quality of construction (Coburn and Spence, 2002; Duggal, 2007). Masonry buildings are common to downtown cores of eastern Canadian urban centres and their exceptionally poor performance in earthquakes has been noted in all moderate-to-large eastern Canadian earthquakes (see Hodgson, 1945a; Lamontagne et al., 2007). The most common damage to masonry buildings are severe diagonal tension cracking,

roof joists or beams sliding off their supports, out-of-plane failures of top-walls and exterior wythes, and building failure (Bruneau, 1990; Bruneau and Lamontagne, 1994; EERI, 2011b).

Out-of-plane failures are widely and arguably the most reported type of masonry damage in eastern Canadian earthquakes even at great distances (250 km) (Bruneau and Lamontagne, 1994). These failures are due to the application of inertial/lateral force causing the walls to bend and deform (Coburn and Spence, 2002). The lack of adequate anchorage or ties between the masonry walls / wythes to diaphragms creates poor load pathways and therefore diminishes structural integrity of the building (Paultre et al., 1993; Bruneau and Lamontagne, 1994). Building failure (partial or complete collapse) has been observed in both American and eastern Canadian earthquakes (e.g. Bruneau, 1990; Bruneau and Lamontagne, 1994; Lamontagne, 2008b). Although considered non-structural, chimney damage is extremely common in eastern Canadian earthquakes (Bruneau and Lamontagne, 1994). The observation of masonry damage in earthquakes demonstrates the need for additional earthquake protection in these historical building types (Mitchell et al., 1990). Previous retrofit programs in North America have proven to increase the earthquake resistance of such building types (Bruneau, 1990).

### **1.6.2 Timber buildings**

Timber is an ideal and economical material for constructing earthquake-resistant low-rise buildings due to (a) its strength and light weight characteristics, (b) its high ductility, and (c) its flexibility which allows for absorption of energy (Coburn and Spence, 2002; Duggal, 2007). Timber buildings should perform very well during earthquakes (Bruneau, 1990). However poor maintenance of the building and/or its foundation can increase the risk of damage (Bruneau and Lamontagne, 1994; Coburn and Spence, 2004) as observed during the 1988 M5.9 Saguenay earthquake (Paultre et al., 1993). Older timber buildings may experience deterioration and decay of the wood which can lead to unfavourable behaviour (Coburn and Spence, 2002); quality construction and preservation can lessen this behaviour (Paultre et al.,

1993; Duggal, 2007). Of note, the seismic design of timber-framed residential buildings was only recently introduced into the National Building Code of Canada in 2010.

### **1.6.3 Concrete buildings**

Reinforced concrete (R/C) is the most widely used construction material for mid- and high-rise buildings because of its easy availability, low cost, stiffness, and versatility (Duggal, 2007). Concrete is better known for its strength, rather than its ductility and energy absorbing capabilities (Duggal, 2007). The addition of steel reinforcement improves its ductility (Coburn and Spence, 2002). Consequently, North American earthquakes have demonstrated that older non-ductile R/C structures are vulnerable (Mitchell et al., 1995).

R/C structural systems typically consist of a combination of beams and columns, and may also include shear-walls (Duggal, 2007). Moment-resistant frames are commonly used in medium to low seismic regions, and can be found in older construction. In such structural systems, the lateral forces are transmitted by the bending of columns and beams (Coburn and Spence, 2002; Duggal, 2007). Framing systems can be further strengthened by the addition of shear-walls, braces and/or well-integrated load-bearing walls (Duggal, 2007).

Firstly, shear-walls transmit lateral forces to the foundation while stiffening the structure and thereby reducing lateral drift (Duggal, 2007). Structural systems with an adequate number of shear-walls oriented in both directions and adequate diaphragm connections generally perform well (Mitchell et al., 1995). As observed in previous western North American earthquakes, the lack of shear-walls or irregularly placed shear-walls can lead to extensive damage and render a building unsalvageable; similar design deficiencies are likely present in Canadian R/C structural systems (Mitchell et al., 1995). For example, during 1994 M6.7 Northridge earthquake, the Kaiser Permanente Building in Granada Hills had a ‘pancake’ collapse of the second storey; this is a common structural design that has likely been implemented in Canada (Mitchell et al., 1995).

Secondly, bracing systems can also be incorporated to strengthen moment-resisting frames. These systems transfer lateral forces via tension and compression members (Coburn and

Spence, 2002). Nonetheless, omitted members can lead to unfavourable behaviour such as the buckling of compression elements and rupturing of tension members, potentially resulting in excessive displacements (Mitchell et al., 1990).

Lastly, infill panels can be either integrated into the structural system or carefully isolated from the lateral force resisting systems (Coburn and Spence, 2002); however in R/C moment frame buildings they are infrequently integrated into the structural system. Infill walls are vulnerable to earthquake shaking and fail in a brittle manner causing damage to the structure and injuring occupants (Coburn and Spence, 2002). R/C buildings with masonry infills have been notably damaged in previous eastern Canadian earthquakes. For example, following the 1988 M5.9 Saguenay earthquake, a school in Chicoutimi reported cracks in nearly every masonry wall and out-of-plane failures; in addition to an institutional residence that reported cracking in infill panels (Mitchell et al., 1990).

The leading cause of failure in R/C structural systems is the crushing of concrete and excessive yielding of reinforcement which lead to the degradation and the reduction of stiffness and henceforth the reduction in its energy absorbing capabilities (Duggal, 2007). Damaged concrete columns with excessive spalling of cover concrete, diagonal tension cracking caused by shear, and bar buckling have been reported in previous eastern Canadian earthquakes (Mitchell et al., 1990). Additionally, parking structures are renowned for their structural vulnerability in earthquakes due to irregularity, specifically short column effects, which was observed (i.e. structural failures) during the 1994 M6.7 Northridge earthquake (Mitchell et al., 1995).

#### **1.6.4 Steel buildings**

Steel structural systems are highly ductile, light, strong, and flexible and therefore, a desirable construction material for earthquake-resistant buildings (Coburn and Spence, 2002; Duggal, 2007). Steel is a favourable construction material in multi-storey buildings, but due to its high cost it tends to be more prominent in low-rise buildings (Duggal, 2007). Traditionally, steel buildings perform well and rarely collapse during earthquakes.

However, structural weaknesses in steel buildings and resultant damage have been observed in eastern Canadian earthquakes. For example, damage to an industrial building in Quebec City during the 1925 ~M6.2 CKSZ earthquake caused an approximately 8 cm displacement of a steel column and the buckling of steel angles (Bruneau and Lamontagne, 1994). Significant buckling to a steel bracing system was also observed in a church bell tower following the 1988 M5.9 Saguenay earthquake (Mitchell et al., 1990).

### **1.6.5 Operational and Functional Components**

Operational and functional components (OFCs) include non-structural building elements and building contents. The three main classes of OFCs are architectural, mechanical and electrical, and general building content. Recent experience in North American and eastern Canadian earthquakes has demonstrated that the majority of damage is due to the failure of operational and functional components (Bruneau and Lamontagne, 1994; Coburn and Spence, 2002). In many cases, a building may have only incurred minor/slight structural damage, but extensive damage to OFCs can render the building unusable (Duggal, 2007).

Architectural components include (1) design elements such as non-bearing walls, partitions, and non-integrated infill walls, (2) decorative elements such as parapets, veneers, and cladding, and (3) generic elements such as doors, windows, glass, staircases, and chimneys (Duggal, 2007). There has been exceptional documentation of the performance of architectural components in eastern Canadian earthquakes because of their prevalence in historical neighbourhoods. The most common architectural damages are the failure of masonry walls, parapets, cornices, exterior cladding and decorative elements, (Bruneau, 1990; Pierre and Lamontagne, 2004) and the toppling of chimneys (Bruneau and Lamontagne, 1994). The damage to chimneys has been reported in nearly all moderate-to-large eastern Canadian earthquakes (e.g. Hodgson, 1945a; Hodgson, 1945b; Mitchell et al., 1990; Paultre et al., 1993; Bruneau and Lamontagne, 1994; Pierre and Lamontagne, 2004) within a distance of 400 km to the epicenter (Bruneau and Lamontagne, 1994). A notable example occurred during the 1944 M5.6 Cornwall-Massena earthquake where approximately

2,000 chimneys out of a building stock of 3,081 were damaged in the municipality of Cornwall (Hodgson, 1945b; Lamontagne et al., 2007). Falling glass from high-rise buildings is another common architectural OFC failure due to the structure's movements (i.e. swaying and rotation) during earthquake shaking (Coburn and Spence 2002). Broken windows have also been reported in eastern North American earthquakes as low as M5.0 (Pierre and Lamontagne, 2004), and in eastern Canadian earthquakes at great distances (150 km) (Bruneau and Lamontagne, 1994).

Mechanical and electrical components include ceiling systems and lighting fixtures, Heating, Ventilation and Air Conditioning (HVAC), pipes and plumbing systems, electrical wiring, and elevators. The failure of ceiling systems has been well documented in both American and eastern Canadian earthquakes, and commonly involve fluorescent lights and their fixtures, suspended ceilings and their tee-bar system, and plaster board ceilings (Mitchell et al., 1990; McKeivitt et al., 1995). The failure of ventilation and HVAC systems due to excessive oscillations or subsequent power outages has also been documented. For example, following the 1988 M5.9 Saguenay earthquake the emergency control venting at an industrial facility in the Saguenay region did not function, and led to the leakage of eight tons of hydrofluoride gas (Mitchell et al., 1990). As observed from the 1994 M6.7 Northridge earthquake, the proper anchorage of HVAC systems may significantly improve recovery time from weeks to days (McKeivitt et al., 1995).

Pipes and plumbing systems are vulnerable to ruptures or failures at bends or junctions (Duggal, 2007). In developed regions, the failure of plumbing systems can have widespread consequences as documented with ruptured (1) wastewater and potable water lines as observed following the 2011 M6.3 Christchurch earthquake (EERI, 2011a), (2) water trunk lines and localized flooding (Scawthorn et al., 1996), (3) pipes and sprinkler systems in hospitals leading to full facility evacuations, and (4) ammonia piping at an industrial facility following the 1994 M6.7 Northridge earthquake (McKeivitt et al., 1995).

Damage to electrical substations and transformers, most notably to ceramic/porcelain insulators, fallen or displaced transformers, surge arrestors, bushings, and damaged buswork

have been reported after both American and eastern Canadian earthquakes (Mitchell et al., 1990; Bruneau and Lamontagne, 1994; McKevitt et al., 1995; Pierre and Lamontagne, 2004). Subsequent power loss has occurred due to physical damage to the system, simulated power surges, vulnerable electrical poles, failure of backup generators and dislodged battery backup systems (Mitchell et al., 1990; McKevitt et al., 1995; Pierre and Lamontagne, 2004). Elevators are also vulnerable components as guide rails can be damaged, and counterweights or the car can become misaligned (Duggal, 2007) as noted at a hospital in Quebec City following the 1988 M5.9 Saguenay earthquake (Mitchell et al., 1990).

The most common type of OFC damage is to building content because they tend to be unfastened and unanchored and can easily topple. The movement and rotation of heavy furniture, statues, and cemetery monuments without being overturned are common in eastern Canadian earthquakes (Hodgson, 1925). McKevitt et al. (1995) noted many examples of damage to building content following the 1994 M6.7 Northridge earthquake, such as (1) the tumbling of books and content off shelves, (2) the failure of shelves, racks, and large storage racks, (3) the displacement and overturning of industrial reservoirs, stockpiles, and pressurized tanks, and (4) the overturning heavy office furniture such as filing cabinets.

## **1.7 How vulnerable is the population to earthquake consequences?**

Earthquake-related casualties are complex consequences of the event and are influenced by three primary factors (1) seismological and geological properties of the earthquake, (2) characteristics of the structural/building system and OFCs, and (3) social factors (Ohashi and Ohta, 1984; Alexander, 1996). In eastern Canadian earthquakes, there are no reports of direct earthquake casualties with the exception of two fatalities sustained in structural failures during the 1870 ~M<sub>L</sub>6.5 CKSZ earthquake (Lamontagne, 2008b). However, eight fatal cardiac events were documented from the 1925 CKSZ and 1988 Saguenay earthquakes (Lamontagne et al., 2007). The following discussion on casualties is expanded to include relevant case studies.

### 1.7.1 Mechanism of injuries

International case studies clearly establish that the structural aspects of the built environment are the most notorious mechanism of earthquake casualties. However, developed regions with superior and enforced building codes have recorded fewer casualties in major earthquakes of comparable size, which supports the premise that well-developed building codes reduce injuries (Eberhart-Phillips et al., 1994). Structural failure is the primary cause of fatal-injuries in North American earthquakes (e.g. 1989 M6.9 Loma Prieta and 1994 M6.7 earthquakes), but constitute less than 10% of non-fatal injuries (e.g. Durkin et al., 1991). In developed regions, OFCs are likely to be one of the primary mechanisms of injury (Durkin, 1985). Architectural components such as parapets and chimneys, tend to be heavy and blunt and thus can cause the most serious and life-threatening injuries. Building contents cause most injuries; Durkin (1985) noted a 3:1 ratio between being injured by building contents (e.g. books, filing cabinets and furniture) versus other OFCs. Similar to architectural OFC injuries, the overturning and falling of heavy contents, and household objects/furniture can also cause serious injuries (e.g. Durkin et al., 1991; Peek-Asa et al., 1998). During the 1994 M6.7 Northridge earthquake, OFCs were responsible for approximately five fatalities (~9%) and over 7,000 injuries (~28%) (McKevitt et al., 1995).

Earthquake injuries are also influenced by human behaviour and is dependent on choices made before, during, and after strong earthquake shaking. Contrary to popular belief, there is generally enough time to react between the onset of ground motion and peak motion (Lomnitz, 1970; Roces et al., 1992; Armenian et al., 1992; Durkin and Thiel, 1992). The most common reactions to ground motion are to either rapidly exiting the building, or take protective action (Ohta and Ohashi, 1980; Archea et al., 1984).

Rapidly exiting a building can have serious safety implications. Firstly, this action can increase an occupant's likelihood of being struck by a falling object. Unlike regions with inferior building codes and/or inadequate code enforcement, building designs in developed regions use modern building codes that are more earthquake-resilient, and structural failure is not

common. The failure of exterior masonry walls, masonry architectural features, and falling cladding/glass are serious built environment hazards to the population, and often cause serious- or fatal-injury (e.g. Du Ree, 1941; Durkin et al., 1991).

Secondly, rapidly exiting a building can increase an occupant's likelihood of falling. Based on contemporary North American earthquakes, falling is the most common mechanism of injury (Durkin, 1985; Durkin et al., 1991; Pointer et al., 1992; Peek-Asa et al., 1998). Falls tend to occur (1) on stairways when occupants are attempting to rapidly exit a building and/or evacuate down damaged and darkened stairways, (2) falling/jumping from a height, and (3) by the force of the earthquake shaking (Durkin et al., 1991). Stairways are notoriously hazardous (e.g. Noji et al., 1990) and damaged stairways have been observed in eastern Canadian earthquakes (Mitchell et al., 1990). Many fall-related injuries are minor and do not require hospital admission; however serious fall-related injuries (Durkin et al., 1991; Peek-Asa et al., 1998), and fatal-injuries (McKevitt et al., 1995) have been observed in American earthquakes. Earthquake-induced mass panic is rare (Durkin, 1985; Mawson, 2005) but this behaviour has been documented in a North American earthquake that led to a trampling-related fatality (Peek-Asa et al., 1998). The likelihood of mass panic can increase (1) in high-rise buildings (Durkin, 1985), (2) in schools (Roces et al., 1992), and (3) by being among unfamiliar people or in unfamiliar locations (Mawson, 2005).

Protective action by taking cover ("drop, cover and hold on") is often effective. It is generally the safest and most prudent action and is widely recommended by public safety agencies. These actions may increase the likelihood of minor injuries such as sprains/strains (Durkin, 1985; Durkin and Thiel, 1992; Roces et al., 1992); they also have the potential to significantly reduce the risk of more serious injuries especially from fall-related incidents and being struck by falling objects. For example, during the 2011 M5.8 Virginia earthquake, injuries were reported when teachers and their classes evacuated their school and were hit by falling debris (EERI, 2011b); these injuries were likely avoidable. Therefore, prior education in earthquake safety via training and drills is a crucial step in learning the appropriate reactions to strong ground motion (Durkin, 1985) and reducing casualties. Additionally, research suggests that taking protective action under sturdy furniture during a structural failure can

increase the chance of survival because it can create void spaces (Durkin and Murakami, 1988; Durkin and Thiel, 1992).

### 1.7.2 Types of injury

The majority of earthquake injuries are related to physical traumas, but the manifestation or exacerbation of medical conditions and psychological impacts are also notable (e.g. Pointer et al., 1992; Salinas et al., 1998). In earthquakes with predominantly OFC damage such as those reported in North America, the majority of injuries are minor and consist of superficial injuries, sprain/strains and open wounds. Sprains and strains are typically due to falls and protective action, while superficial and open wounds are typically due to bumping into, or being struck by objects (Durkin et al., 1991).

In general, head and upper body injuries are more likely to occur during daytime earthquakes. Of the documented head injuries in American earthquakes, concussions and closed injuries are common and likely associated with falling building content (Shoaf et al., 1998). Life-threatening head injuries are generally fatal (Beinin, 1985; Tanaka et al., 1999; Coburn and Spence, 2002). For example, the leading cause of death from the 1994 M6.7 Northridge earthquake was fatal-head injuries (Peek-Asa et al., 1998).

The majority of spinal/back injuries are strains caused by taking protective action or falling. Spinal fractures are also common in earthquakes with (1) predominantly OFC damage and occur when the occupant's back is exposed to falling objects (Maruo and Matumoto, 1996), and (2) fall-injuries (Peek-Asa et al., 1998). Serious fractures and spinal cord injuries are due to being struck by heavy objects or during structural failure (Glass et al., 1977; Beinin, 1985; Durkin et al., 1991; Maruo and Matumoto, 1996; Coburn and Spence, 2002; Dhar et al., 2007).

Trunk injuries include those of the thoracic and abdominal regions. As observed in night-time earthquakes, the individual's sleeping position strongly influences the type of trunk injury as the ribs, the shoulder girdle and pelvic area are more exposed to falling objects (Sheng, 1987; Maruo and Matumoto, 1996). The occurrence of serious intra-trunk injuries (i.e.

internal thoracic and abdominal) is uncommon, as they tend to be fatal (Peek-Asa et al., 1998; Tanaka et al., 1999).

Injuries to the extremities are the most common and typically occur during daytime earthquakes. Injuries to the upper extremities are generally related to the exposure of the arms while catching or reaching for objects, bracing themselves or property (Ohashi and Ohta, 1984; Durkin, 1985; Mahue-Giangreco et al., 2001), and falling, also known as FOOSH injuries (Falling On Out-Stretched Hands). Injuries to the lower extremities are typically related to falls, stepping on broken objects, and jumping from height (Durkin et al., 1991; Shoaf et al., 1998; Dhar et al., 2007).

The manifestation or exacerbation of illness also constitutes a significant number of earthquake casualties; particularly cardiovascular events. Cardiovascular events can increase fivefold and generally occur within one hour following an earthquake (Beinin, 1985; Leor et al., 1996; Muller and Verrier, 1996; Kloner et al., 1997; Matsuoka et al., 2000). The increase in cardiovascular events, both non-fatal and fatal, has been documented in American earthquakes (Durkin et al., 1991; Pointer et al., 1992; Eberhart-Phillips et al., 1994) and eastern Canadian earthquakes (Lamontagne, 2008b). Importantly, in earthquakes that do not cause significant structural damage, cardiac events may be the leading cause of earthquake-related fatality in eastern Canada (Lamontagne et al., 2007) due to emotional stress (Leor et al., 1996; Kloner et al., 1997).

The psychological and psychosocial effects of earthquakes are often overlooked (Alexander, 1996) but are universal (de Bruycker et al., 1985; Carr et al., 1996; Dhar et al., 2007).

Individuals and society as a collective will have emotional reactions to earthquakes and the degree of post-earthquake stress will likely be associated with the strength of the mainshock (Goenjian et al., 1994), the number of aftershocks, and their earthquake awareness (Durkin, 1985; Tierney, 1988; Lamontagne et al., 1992). Post-Traumatic Stress Disorder (PTSD) is a common psychological effect (de Bruycker et al., 1985; Goenjian et al., 1994) and tends to be associated with intense and vivid experiences related to sensorial stimuli (Pynoos et al., 1993; Goenjian et al., 1994), and/or the separation from affiliations (Mawson, 2005) rather

than the violent ground motions. One of the most common psychosocial reactions following North American earthquakes is mass anxiety (Hodgson, 1945a; Carr et al., 1996). Common manifestations to anxiety are: (1) the fear of aftershocks (Hodgson, 1945a; Carr et al., 1996), (2) depression due to property loss (loss of life is not common in North American earthquakes) (Tierney, 1988; Lamontagne et al., 1992), and (3) post-earthquake violence (Pointer et al., 1992; Carr et al., 1996; McArthur et al., 2000).

## 1.8 Conclusion

The evaluation of seismic risk in any region of the world is complex, and influenced by many factors. Seismic risk of eastern Canada is no different and only a few key questions were discussed in this chapter. In eastern Canada, ongoing seismicity supports that the threat of a moderate-to-large earthquake to major urban centres exists. The combination of population growth and urbanization increases the exposure of the population and the built environment to potential seismic losses. Adams et al. (2002) shows that four of the top six Canadian urban populations at greatest seismic risk are located in eastern Canada. The seismic vulnerability of eastern Canada is due to the high number of unreinforced masonry buildings, a widely documented building type recognized to perform poorly in earthquakes. Finally, the discussion on how the population is vulnerable to being injured in the built environment clearly establishes that social losses can be reduced with earthquake safety education and retrofit programs.

This chapter provided a review of the major factors that contribute to the seismic risk of major eastern Canadian urban centres. The following recommendations are not new and have been emphasized for decades. However, throughout the process of this review and extensive research in seismic risk, the author views these recommendations as absolutely necessary to reduce earthquake risk and easily achievable.

First, access to, and synthesis of case studies and the sharing of successes, challenges, 'lessons learned' can help researchers and decision makers understand seismic risk and

design emergency management strategies. In addition, data from multiple perspectives such as management, medicine, engineering, geoscience, social science, and the public are relevant. Even case studies from moderate earthquakes, such as the 2010 M5.0 Val-des-Bois earthquake, can provide vital information as to the vulnerabilities within the communication and transportation sectors in addition providing an overall indication of earthquake awareness / preparedness within a community.

Second, the key to reducing potential seismic losses in eastern Canada is education of the population. Earthquake awareness is the foundation of a series of proactive steps to create a safety-oriented society (Bruneau and Lamontagne, 1994). As children, we are taught in school via repetitive lectures, activities and drills, the appropriate reactions to fires and fire safety. As an adult, fire safety is engrained in our memories, so it is no longer a matter of reviewing emergency plans or reformulating our behaviour, but virtually a natural and unconscious response. In Japan, earthquake safety is taught in the school and home environments and Shaw et al. (2004) demonstrated that learning in those environments played a vital role in reinforcing Japan as an earthquake safety-oriented society. Increased knowledge in earthquake safety alters our perception and allows us to become aware. Earthquake awareness therefore provides the stepping stones to reduce future earthquake losses and build community resilience by earthquake preparedness and other proactive emergency management strategies.

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# Chapter 2

## *Development of the CanRisk earthquake injury model*

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*“Captain FitzRoy and some officers were at the town during the shock, and there the scene was more striking; for although the houses, from being built of wood, did not fall, they were violently shaken, and the boards creaked and rattled together. The people rushed out of doors in the greatest alarm. It is these accompaniments that create that perfect horror of earthquakes, experienced by all who have thus seen, as well as felt, their effects.”*

*-Charles Darwin in The Voyage of the Beagle*

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**Abstract:** CanRisk is an existing seismic assessment tool that integrates building vulnerability, site seismic hazard, and building exposure from detailed building-specific engineering data. Modules that support the individual evaluation of reinforced concrete, masonry and timber-frame buildings have been recently developed. The injury model presented in this chapter is an extension of the CanRisk tool to quantify an individual’s risk to injury, the number of injuries, and provide an injury profile of life-threatening injuries at the building scale. The model uses an evidence-based and multi-disciplinary approach to identify risk factors that affect an individual’s risk to injury. The model implements fuzzy synthetic evaluation to quantify seismic risk, calculations to estimate number of injuries, and a decision-matrix to generate the injury profile. The model is also designed to include the ability to test the benefits of mitigation strategies such as the retrofit of operational and functional components and earthquake safety campaigns.

**Keywords:** *seismic risk, earthquake injury, fuzzy synthetic evaluation, fuzzy inference system,*

## 2.1 Introduction

Earthquake casualties are the consequences of the intensity of ground shaking, earthquake resistance of buildings, and operational and functional components (OFC), as well as human behaviour. Seismic events being unique and dynamic, the causal factors of injuries vary, and as such, the estimation of earthquake-related injuries is difficult. In order to underpin casualty loss estimation methodologies and better support emergency management, detailed information of risk factors from case studies must be compiled and studied. The estimation of injuries and their risk factors are of considerable interest to emergency managers. Identifying and understanding the causative factors of injuries can aid in the development of effective mitigation and preparedness strategies such as earthquake safety campaigns and retrofit programs to reduce an individual's risk to injury. Additionally, understanding risk factors can reduce the overall number of injuries and can improve the response capacity of an emergency agency. For example, a municipal fire brigade can implement active earthquake safety training among their firefighters and/or retrofit programs to reduce losses and maximize their resources for post-earthquake deployment. Secondly, the estimation of injuries and injury profiles (a short summary of injury details) provides critical information to emergency managers, especially those responsible for medical care facilities/hospitals and paramedic operations. Hospitals must remain open and operational to cope with a surge of incoming casualties. Injury estimations allow hospitals to identify the amount of resources required to manage that surge capacity. Injury profiles, on the other hand, offer vital insight on the various resources needed, such as specialized medical personnel, equipment, and pharmaceuticals.

This chapter presents the rationale and development of an evidence-based injury model for the CanRisk program (see Tesfamariam and Saatcioglu, 2010; Elsabbagh, 2013). The purpose of the CanRisk earthquake injury model is to quantify the risk to injury, the number of injuries, and provide a profile of life-threatening injuries at the building scale. The risk to injury output can equally apply to a single unit within a building or to an entire structure and is dependent on the earthquake preparedness decisions of the 'owner'. The overall aim of the model is to facilitate informed decision making in emergency management (EM) by

testing potential mitigation and preparedness strategies and providing loss estimations that will aid in the development of a realistic earthquake scenario. This injury model is designed for the CanRisk program, but its underlying evidence-based theory has international application.

Hazus and CanRisk are two loss estimation programs that are applicable to Canadian settings. Hazus is a leading program in loss estimations and is available in the United States and Canada. The benefits of the Hazus casualty loss estimation methodology are: (a) it is calibrated for North America (although based solely on Californian earthquakes), (b) it is continuously updated to include recent earthquakes, and (c) it provides empirically-derived multipliers to estimate the number of casualties within each severity class (Severity 1 (minor injuries), Severity 2 (serious), Severity 3 (life-threatening), and Severity 4 (fatal)). Some limitations of this methodology are that: (a) it does not provide details of injuries within each severity class, and (b) it does not estimate fall injuries, which have been the primary mechanism of injury in North American earthquakes. Nonetheless, Hazus is a monumental achievement in earthquake loss estimation methodology.

CanRisk is seismic assessment tool that integrates building vulnerability, site seismic hazard, and building exposure from detailed building-specific engineering data. CanRisk is modular in that it can include modules to evaluate the risk of various aspects of the built environment. It currently includes modules to evaluate the earthquake resistance of reinforced concrete buildings (Tefamariam and Saatcioglu, 2010), unreinforced masonry buildings (Elsabbagh, 2013), timber-frame buildings (Komsari, 2014), and steel buildings (Saatcioglu 2014 personal communication) and the injury module detailed herein. Unlike Hazus, CanRisk utilizes more detailed structural parameters in its evaluation of building performance which leads to a more accurate estimation of damageability (the estimated amount of damage that a building suffers; a value between 0 and 1). CanRisk also evaluates buildings individually rather than over an aggregated area. The outputs of CanRisk and Hazus both offer valuable insight to facilitate informed decision making.

## 2.2 Rationale

The three primary factors that influence earthquake injuries are (1) earthquake shaking characteristics (e.g. magnitude, attenuation, amplification), (2) the performance of structural building systems (e.g. seismic force resisting system, building design, quality of construction, irregularities, year of construction) and their OFCs (e.g. architectural, mechanical/electrical, building contents), and (3) social factors (e.g. patterns of human activity, earthquake awareness / preparedness, and human behaviour) (Ohta and Ohashi, 1980; Alexander, 1996; Peek-Asa et al., 2003).

Firstly, the majority of earthquake injuries occur during 'felt' ground motions (Durkin et al., 1991a). In general, the prevalence of injury is greater closer to the epicenter and decreases with epicentral distance. Peek-Asa et al. (2003) found that for every ~1 km increase in epicentral distance, there was a 10% decrease in the risk to injury. However, isolated concentrations of injuries have been documented and are commonly related to soil conditions and poor building resistance. In Canada, seismic wave amplification from soft soil conditions is well documented. For example, approximately 95% of reported damage during the 1988 M5.9 Saguenay earthquake occurred on soft soils, up to distances of 350 km (Paultre et al., 1993; Lamontagne, 2002).

Secondly, structural performance of buildings during strong ground motion is a key predictor of injuries. In regions with superior / modern and enforced building codes, the primary cause of serious and fatal injuries is building failure (partial or complete), although there are only a few documented cases of sensational building failures (e.g. the 1989 M6.9 Loma Prieta earthquake, the 1994 M6.7 Northridge earthquake, the 2011 M6.3 Christchurch earthquake) (Alexander, 1996). Building failures typically cause fewer than 10% of non-fatal injuries in developed regions (Durkin et al., 1991a; Ardagh et al., 2012).

In buildings more structurally resilient to lateral forces, operational and functional components (OFCs) are more likely the sources of most injuries (Ohashi and Ohta, 1984; Durkin, 1985). OFCs are classified as (1) architectural and non-structural, (2) mechanical and electrical, or (3) general building content. Durkin (1985) noted a 3:1 ratio between being

injured by building contents (e.g. desks, filing cabinets and furniture) versus other OFCs. Serious injuries are generally caused when people are struck by heavy building contents, other heavy components, and unreinforced masonry elements (Durkin et al., 1991a; Peek-Asa et al., 1998). In North American earthquakes, a high proportion of damage is due to OFCs (Bruneau and Lamontagne, 1994; Coburn and Spence, 2002). For example, during the 1994 M6.7 Northridge earthquake, OFCs were responsible for approximately five fatalities and over 7,000 injuries (McKevitt et al., 1995). Therefore, the primary factor of injury prevention is the development of superior building codes that are strictly enforced (Lomnitz, 1970; Coburn and Spence, 2002) as well as active and timely implementation of structural and non-structural retrofits (Bruneau 1990; Mitchell et al., 1995).

Thirdly, human behaviour and choices made before, during, and after earthquake shaking also influence the risk of injury. In earthquakes of all magnitudes, there is generally enough time to react before peak motion (Lomnitz, 1970; Roces et al., 1992; Armenian et al., 1992; Durkin and Thiel, 1992). During North American earthquakes, one of the common reactions is to rapidly exit a building during shaking. Such reaction increases an individual's risk to injury from falling OFCs such as masonry elements and cladding/glass (Du Ree, 1941; Durkin et al., 1991a). Based on recent case studies of Californian earthquakes, falling is the most common mechanism of injury (Durkin et al., 1991a; Peek-Asa et al., 1998; McArthur et al., 2000). Falling occurs in stairways, when falling/jumping from a height, or by the intensity of earthquake shaking (Durkin et al., 1991a).

In developed regions, taking protective cover ('Drop, Cover, and Hold On') is the most prudent action during earthquake shaking. These actions may cause superficial injuries (e.g. sprains/strains) (Durkin, 1985; Durkin et al., 1991a; Durkin and Thiel., 1992; Roces et al., 1992), but have the potential to significantly reduce the risk of serious or fatal injuries (Durkin and Murakami, 1988). Therefore, active knowledge in earthquake safety does play a major role in the reduction of earthquake injuries.

## 2.3 Methodology

The CanRisk injury model is a proactive (mitigation and preparedness) tool for decision makers from the household to the municipal levels. It serves three main functions: (1) to evaluate the risk of injury, (2) to profile life-threatening injuries (a short summary of injury details), and (3) to estimate the number of injuries by both building and non-building factors (Figure 2.1). Additionally, the model is designed to evaluate the outcomes of specific mitigation decisions, such as how OFC retrofits and earthquake safety / preparedness strategies affect risk to injury. The primary framework of the injury model uses fuzzy synthetic evaluation (FSE) to determine the risk to injury. Life-threatening injury (i.e. severity 3) profiles are evaluated using a decision matrix, and the estimation of number of injuries is calculated using a combination of Hazus methodology (FEMA, 2012) and the CanRisk risk to injury FSE output.



Figure 2.1. Conceptual framework of the CanRisk Injury model.

### 2.3.1 Risk Factors

Risk factors are evidence-based and derived from case studies and reports which provide qualitative evidence of the indicators of risk. For example, 'lessons learned' offer constructive comments on the challenges and successes of the earthquake impact, such as the importance of OFC retrofits (e.g. McKeivitt et al 1995) or consequences of OFC failure (Du Ree, 1941). The synthesis and analysis of data from medical case studies also help determine risk factors. An earthquake injury dataset consisting of 44 international case studies of 19 earthquakes was compiled (see Appendix 2.1). The injury dataset represents over 50,000 individual injuries and was coded to include information on: (a) time of day; (b) ICD-10 taxonomy (International Classification of Diseases); (c) body location of injury (upper body, trunk or lower body); (d) inferred severity (minor, serious, and life-threatening); and (e) most frequently observed damage state of buildings in the case study region. To account for inter-earthquake variability in the absolute counts of injuries, proportions of the sum of all injuries for each earthquake were used. For example, two case studies were used to describe the 1989 Loma Prieta earthquake; however, the sum of injuries for both case studies was used in the proportion calculations to represent the injuries observed from this earthquake. Wilcoxon signed-ranked test was used in R (R version 3.0.1) to determine significant differences in proportions of injury characteristics within the datasets. Appendix 2.2 provides a summary of all tests that were performed. As expected, many results are statistically marginal due to the nature of the quantification of earthquake injuries in case studies such as their inherent incomplete and ambiguous nature and the lack of published datasets. However, the stronger results show effects / patterns of injuries that are further contextualized and supported by medical insights from case studies to support the inclusion of parameters, membership functions and weights.

The CanRisk injury model is designed to incorporate two broad concepts that contribute to injury, and are (1) the influence of building structural and OFC damage factors, and (2) non-building influences, such as various psychological, environmental and social factors. The following discussion focusses on the risk factors for the risk to injury FSE and their influence on life-threatening injuries.

### 2.3.1.1 Building Influence

#### *Damageability*

Building factors include both structural and non-structural (OFC) elements. Traditionally, one of the most influential predictors of serious and fatal injury is building failure. This effect is also noted in the statistical analysis results (see Appendix 2.2). Building performance during ground motion, and therefore its damageability, is the primary contributor to risk to injury. In CanRisk, damageability is a direct output from the engineering models and is between 0 (no damage) and 1 (complete damage) (see Tesfamariam and Saatcioglu, 2010; Elsabbagh, 2013). Hazus linguistic outputs are also compatible. For example, ‘extensive building damage’ translates to a ~0.7 damageability factor.

#### *Building type*

The injury dataset was coded to include a parameter related to the most frequently observed damage state from each case study: (1) Light damage which is primarily non-structural damage with few structural failures, (2) moderate damage which is primarily structural failures of ‘moderate material’ (e.g. timber frame) and/or low-rise buildings, and (3) heavy damage which is primarily structural failures of ‘heavy material’ (e.g. reinforced concrete) and/or mid- to high-rise buildings. Year of construction and the design code are not considered as it is assumed that construction material (building type) characteristics and their behaviour during ground motion will generate distinct injuries. For example, the collapse of a timber-frame building in a region with superior and enforced building codes will likely have similar injury patterns as a collapsed timber-frame building with sub-standard codes. The statistical analysis of this risk factor revealed that severity of injuries is influenced by the type of building material (see Appendix 2.2). In the FSE, this risk factor is represented by building type because it is a reflection of (1) the construction material and its weight, (2) building height and its potential volume of debris, and (3) challenges of debris removal which affects entrapment time. An overview of building type classifications is presented in FEMA (2012, Chapter 3).

### ***Operational and Functional Components hazards and Retrofit Decisions***

Historically, mass building failure is not common in developed regions and therefore OFCs tend to be one of the leading causes of injury. The statistical analyses and case study observations support that risk to minor injuries (severity 1) is more likely in buildings that do not experience partial or complete failure. Low damage does not preclude the occurrence of serious injury, however.

In order to enhance CanRisk's mitigation potential, the injury model not only includes the influence of OFCs, but also has the ability to evaluate how OFC retrofits can affect the risk to injury. The three classes of OFCs within each occupancy class are generalized and assigned values to represent 'no retrofit' or 'full retrofit' of OFC components. Retrofit decisions can be made for each OFC group. For example OFC values can be calculated if retrofits were only conducted on building content and not architectural or electrical/mechanical features.

Damageability and retrofit decisions are also important indicators of life-threatening injuries (see Appendix 2.3). A damageability of  $<0.7$  (meaning the building is still intact) is more influential to survivable life-threatening head and spinal injuries, as building failure and prolonged entrapment would likely be fatal within hours (Beinin, 1985; Tanaka et al., 1999; Coburn and Spence, 2002). Case studies suggest that lower thoracic and lumbar fractures are more frequently caused by falls (Peek-Asa et al., 1998). Spinal cord injuries are arguably more common at the onset of architectural OFC failure or failure of other heavy OFCs, and/or damageability of  $>0.7$  (Glass et al., 1977; Beinin, 1985; Durkin et al., 1991a; Maruo and Matumoto, 1996; Coburn and Spence, 2002; Dhar et al., 2007). However, these life-threatening injuries can quickly become fatal when vital physiological functions become impaired. Serious orthopedic injuries such as compound fractures, are more common in damageability  $<0.7$  as they are likely high-impact fall/FOOSH injuries (Falling on Out-Stretched Hands) on stairways or from a height. Most fall-related injuries are serious (severity 2) and characterized by fractures and dislocations of hands, arms, shoulders, feet, ankles and legs (Nordell et al., 2000; Daniels II et al., 2004). At the onset of building failure, orthopedic injuries typically progress to crush injury. Life-threatening trunk injuries are also

associated with the failure of architectural elements and building failure (Coburn and Spence, 2002) (see Appendix 2.2).

### **2.3.1.2 Socio-environmental influences**

#### ***Familiarity***

The risk to injury can increase when the occupant is among the ‘unfamiliar’ that is, in an unfamiliar place or with unfamiliar people at the time of the earthquake (Mawson, 2005). An effective example to show psychological influence is mass panic. Although rare, this behaviour can be attributable to unfamiliarity (place and/or people) (Mawson, 2005) and has been reported in previous earthquakes (e.g. Roces et al., 1992; Peek-Asa et al., 1998). Each occupancy class was ranked as being either familiar, moderately familiar, or unfamiliar. For example occupancy classes such as retail stores, restaurants, and theaters are examples of locations that are unfamiliar, while residences are familiar, and being among co-workers in an office setting is an example of moderately familiar.

#### ***Previous Earthquake Experience***

Previous earthquake experience influences the personal decision making process in many ways, such as taking proactive steps to increase the safety of one’s family (securing heavy objects, family emergency planning and drills), and providing an experiential knowledge on the psychological intensity of an earthquake event (Dooley et al., 1992; Russell et al., 1995; Nguyen et al., 2006). In order to prepare for earthquakes, Shaw et al., (2004) proposes that knowledge is acquired by earthquake experience and education. The experience factor in this model is designed to represent the ‘human experience’; that is: (1) ‘human’ and the associated psychological effects of previous earthquake losses such as the loss of a family member or home; and (2) ‘experience’ which reflects the perceived intensity of the ground shaking. Earthquakes can be frightening experiences, and intense earthquake shaking and associated losses can have a profound effect on the human psyche.

To measure previous earthquake experience, earthquakes between 1985 and 2013 with a greater than magnitude M5.0 for the six Canadian urban centres at greatest seismic risk:

Vancouver, Montreal, Ottawa, Victoria, Quebec City and Toronto (Adams et al., 2002) were mapped in GIS. The Modified Mercalli Intensity Scale (MMI) was used to define the perceived intensity of the earthquake. The MMI scale classified intensity into to four groups as (1) shaken ( $MMI \leq V$ ; M5.0), (2) primarily OFC damage (MMI VI; M5.1-5.5), (3) primarily OFC damage with injuries (MMI VII; M5.6-6.2), and (4) structural failure and injuries ( $MMI \geq VIII$ ;  $M \geq 6.3$ ). The Injury Severity Score (ISS) procedure which is used in emergency medicine (Baker et al., 1974) was adapted to help quantify previous earthquake experience. Each earthquake was assigned a rank of 1 through 4 as define above. The three strongest earthquakes within 250 km of each city were selected and squared. Table 2.1 denotes the summed ranks for each city. Previous earthquake experience does not always result in a reduced risk to injury as some individuals may have a negative reaction due to previous trauma or the exacerbation of a mental illness such as Post Traumatic Stress Disorder.

Table 2.1: Top six Canadian urban centres in terms of seismic risk according to Adams et al. (2002) and their three strongest earthquakes. In parentheses is the assigned rank: (1) shaken, (2) OFC damage, (3) OFC damage and injuries, (4) structural failure and injuries. The summed ranks also have an assigned linguistic class. Note that any earthquake with a rank of (4) will automatically be assigned a summed rank of 28 as this is assumed to be a traumatizing human experience.

Urban Centre	Earthquake1	Earthquake2	Earthquake3	Summed rank	Experience <sup>1</sup>
Montreal	M5.1(2) <sup>2</sup>	M5.2(2) <sup>2</sup>	M5.5(2) <sup>2</sup>	12	Some
Ottawa	M5.0(1) <sup>2</sup>	M5.2(2) <sup>2</sup>	M5.5(2) <sup>2</sup>	9	Little
Quebec City	M5.1(2) <sup>2</sup>	M5.4(2) <sup>2</sup>	M5.9(3) <sup>2</sup>	17	Some
Toronto				0	Very Little
Vancouver	M5.5(2) <sup>2</sup>	M6.1(3) <sup>2</sup>	M6.8(4) <sup>2</sup>	28	Sufficient
Victoria	M5.5(2) <sup>2</sup>	M6.1(3) <sup>2</sup>	M6.8(4) <sup>2</sup>	28	Sufficient

<sup>1</sup>Term assigned to describe amount of earthquake experience. These have subsequent ranks of 1-5 for input into the fuzzy synthetic evaluation.

### ***Time of day***

Research reveals that the time of day of an earthquake influences the risk to injury because of human activities (e.g. Tierney, 1990; Zuccaro and Cacace, 2011). In developing regions, night-time earthquakes tend to produce a greater number of casualties because many are inside their homes that may not have adequate earthquake resistance and enforced building codes (Lomnitz, 1970). In North America and in developed regions, daytime earthquakes will

likely produce more casualties due to mass evacuations (evacuations for high-rise buildings, shopping malls, theaters, etc.), traffic light failure, road damage, and falling OFCs (Peek-Asa et al., 1998). Therefore, the CanRisk injury model accounts for the time of day when the earthquake occurs.

Time of day is also an influential factor of life-threatening injuries, because it is an indicator of body positioning. Head and spinal injuries are more common during daytime earthquakes when the occupant is sitting, standing, or leaning and their head and back are exposed to falling OFCs (Maruo and Matumoto, 1996). Severe orthopedic and lower spinal injuries are also common in daytime earthquakes when occupants tend to rapidly exit a building and fall which is not the correct action to take. However, occupants who awake in the night and sit up in their beds or fall in the dark are also at risk of these types of injuries (Sheng, 1987). Life-threatening trunk injuries are common in night-time earthquakes when occupants are sleeping and in lateral or supine positions (Maruo and Matumoto, 1996) and falling OFCs and/or building elements strike the occupant in the thoracic regions, most notably the rib cage, and pelvic region (Sheng, 1987; Maruo and Matumoto 1996). Crush injury is common in night-time earthquakes (see Appendix 2.2), though generally requires buildings with a damageability index of  $>0.7$ .

#### ***Air temperature - Core body temperature***

Core body temperature characterizes two important factors of risk to injury: (1) exposure and the development of hypothermia, and (2) the development and progression of crush syndrome. Hypothermia occurs when the core body temperature decreases due to ambient air temperature or other stimuli such as severe trauma or hemorrhagic shock. A normal body temperature is  $\sim 37^{\circ}\text{C}$ , and mild hypothermia develops as the body temperature decreases below  $36^{\circ}\text{C}$ . Symptoms of severe hypothermia begin to develop at  $\sim 33^{\circ}\text{C}$  and can greatly compound an individual's health.

A thermometric model was utilized to show the relationships between ambient air temperature and core body temperature. Details of the ancillary thermometric model are not discussed in this dissertation; however, the model is adapted from Iampietro (1961), Bell et al. (1992) and ISO 8996 (2004). In the CanRisk injury model, the user can either select the

month of the earthquake whereupon the average monthly temperature for that city is used, or select a temperature range. These ambient air temperatures are translated to core body temperatures in the thermometric model and are classed as either normal body temperature, mild or severe hypothermia after a three hour exposure.

Case studies and medical research suggests that core body temperature can also influence the development of crush syndrome. Crush syndrome is a severe complication of crush injury and occurs when compressed muscle tissue breaks down into intracellular components which are then released into circulation during reperfusion (Sever and Vanholder, 2012). These intracellular components include myoglobin and potassium which can adversely affect heart and kidney function, as well as other internal organs (Michaelson, 1992).

Animal research suggests that cooling can affect post-traumatic microcirculation, degeneration and inflammation of a muscle tissue (Takagi et al., 2001; Schaser et al., 2006). This evidence, in addition to the use of therapeutic hypothermia and the van't Hoff-Arrhenius Law, may support the medical observation by Mulvey et al. (2008) that a cooler air temperature (and thus body temperature) may inhibit the development of crush syndrome. Sever and Vanholder (2012) indicate that hypothermia should be treated immediately in crush syndrome patients, as the prognosis of survivability is low due to the onset of serious physiologic conditions. However, the onset of many of these conditions begin when the core body temperature decreases below  $\sim 33^{\circ}\text{C}$ . Therefore, the CanRisk injury model considers mild hypothermia as a positive influence to crush syndrome development.

### ***Earthquake safety education***

The risk to injury due to human behaviour during earthquake shaking is arguably the most influential non-building factor (Durkin, 1985; Murakami and Durkin, 1988). Beinin (1985) noted that more than 50% of traumatic injuries may be due to inappropriate behaviour, such as jumping from buildings and panic-stricken flight. The number of, and certain types of, injuries are assumed to be linked to earthquake safety education, because those who are educated on the appropriate behaviour will likely take protective action rather than exiting the building during the shaking (USFA, 1992). Proactive mitigation strategies and earthquake

preparedness are known to reduce earthquake losses (Durkin, 1985; Tierney, 1988; USFA, 1992; Shaw et al., 2004). The injury model ranks four levels of earthquake preparedness / safety education, (1) active (drills), (2) physical (guest speaker, informational video), (3) reading (memorandum, internet search) and (4) none. It is widely accepted that interactive, visual-based and experiential forms of learning are more effective at developing skill sets than traditional reading. Active education is widely recognized to be the most successful form of safety training (Shaw et al., 2004) and is reflected in the rule-based knowledge of the FSE.

Knowledge on appropriate behaviour during shaking (i.e. 'Drop, Cover and Hold On') plays a lesser but still important role in the risk of life-threatening injuries, with the exception of serious orthopedic injuries. In this model, serious orthopedic injuries are assumed to be fall-related and associated with high impact fall/FOOSH injuries.

### **2.3.2 Evaluation of risk to injury and Fuzzy Synthetic Evaluation**

Quantitative-based methods are common approaches in risk management (e.g. Ahmed et al., 2007), but generally require high-resolution numerical data (Abdul-Rahman et al., 2013). These methods may not be suitable for the evaluation of disaster-related risk because data tends to be limited, ambiguous or deficient. Fuzzy logic is a method that can systemically handle the inherent limitations of disaster-related risk. Fuzzy Synthetic Evaluation (FSE) is a type of fuzzy method that calculates a single output from multiple quantitative and qualitative inputs, as well as expert judgment. In this research, FSE incorporates risk factors that influence an individual's risk to being injured and generates a single output between 0 (low risk) and 1 (high risk). FSE is also the basis of the engineering modules of the CanRisk program.

The CanRisk injury model was constructed in the MathWorks<sup>®</sup> MATLAB environment using the Fuzzy Logic Toolbox. An overview of the hierarchical framework of the risk to injury FSE and its risk factors are presented in Figure 2.2. First, the input variables / risk factors that influence risk to injury are identified and represented as rounded rectangles in Figure 2.2.

For example, input variables of damageability and building type represent ‘structural influence’. Each risk factor is defined linguistically (e.g. damageability can be defined as none, slight, moderate, extensive, complete), and with a range (e.g. ‘none’ damageability is defined by input values between 0.0 and 0.3). These ranges are called membership functions.

Second, fuzzification is the process where input variables are transformed into the fuzzy sets (Figure 2.3). A fuzzy set consists of membership functions where an input factor can have partial membership in multiple ranges. For example, a building with a damageability of 0.65 can be considered both moderately and extensively damage. Membership functions are an extension of Boolean logic where logic moves away from inclusion or non-inclusion to a set with an input having a degree of inclusion to numerous sets (Wang et al., 2009; Mi et al., 2001). The CanRisk injury model sets are defined by triangular fuzzy numbers as they are common, simple and effective when input data is subjective and vague (Abdul-Rahman et al., 2013).

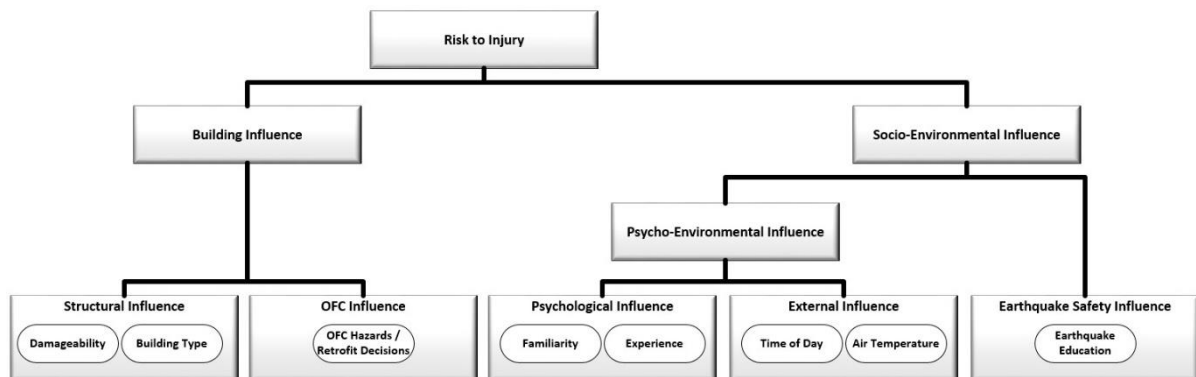


Figure 2.2: Overview of the hierarchal framework of the risk to injury FSE.

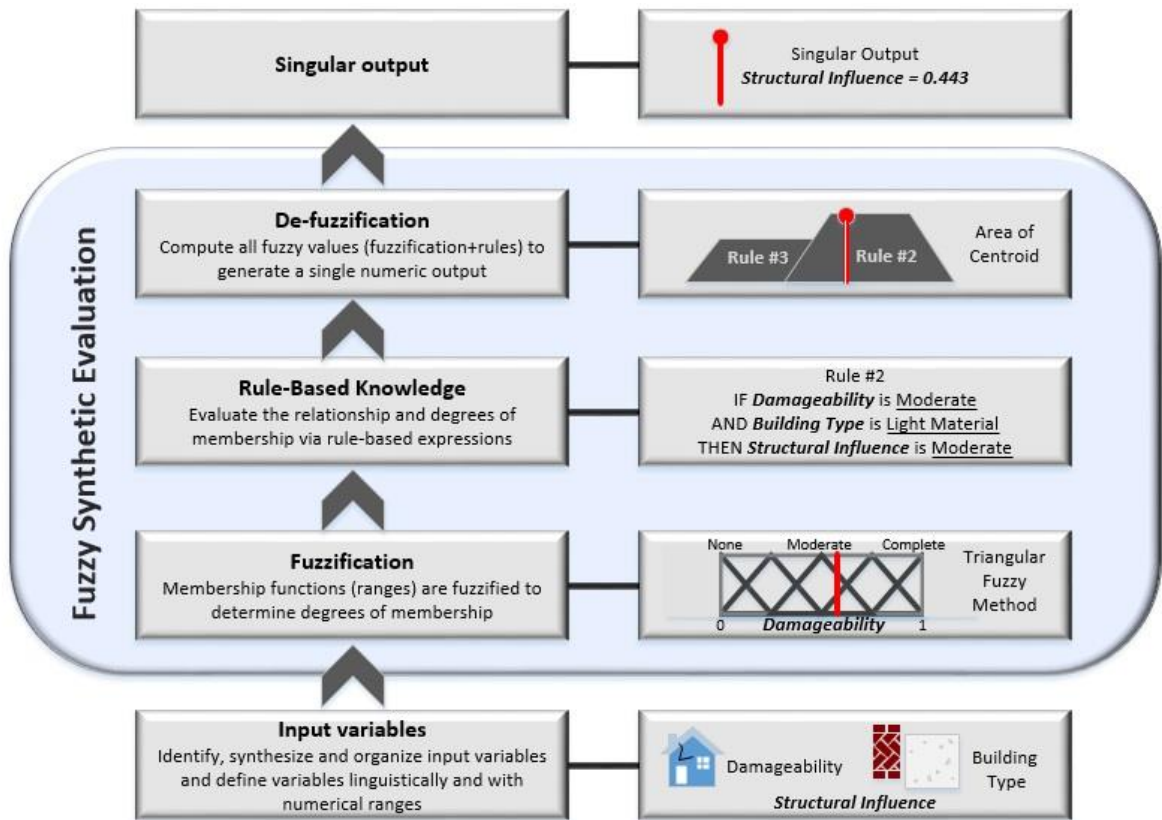


Figure 2.3: Overview of the fuzzy synthetic evaluation method using the Mamdani Implication Method.

Third, rule-based knowledge evaluates the relationship and degrees of membership of the input values by using IF-THEN rules determined by expert judgment. An inference engine assesses how the two independent input variables derive the outcome based on the IF-THEN rules. For example, if the building damageability is moderate and the building type is constructed with light material then the ‘structural influence’ is moderate. Finally, de-fuzzification involves the evaluation of the processed fuzzy values to generate a single numeric output. The risk to injury FSE output ranges from 0 to 1; 0 being the lowest risk to injury and 1 being the highest risk to injury. A summary of the FSE risk/input factors, fuzzy groups, membership functions and range is presented in Table 2.2.

Table 2.2: Summary of the FSE risk factors and their fuzzy groups, membership functions and range.

<b>Risk Factors /Input Variables</b>	<b>Fuzzy Groups</b>	<b>Membership Functions</b>	<b>Membership Range</b>
Damageability	None, Slight, Moderate, Extensive, Complete	0.0-0.3-0.5-0.7-1.0	0.0-1.0
Building Type	Light, Moderate, Heavy	0.15-0.375-0.6	0.15-0.6
OFC Hazards / Retrofit Decisions	Low, Moderate, High, Very High, Exceptional	0.0-0.375-0.75-1.125-1.5	0.05-1.5
Familiarity	Familiar, Moderately Familiar, Unfamiliar	1.0-2.0-3.0	1.0-3.0
Earthquake Experience	Sufficient, Some, Little	1.0-3.0-5.0	1.0-5.0
Time of Day	Night, Day	1.0-2.0	1.0-2.0
Body Temperature	Normal, Mild, Serious	1.0-2.0-3.0	1.0-3.0
Earthquake Education	Active, Visual, Read, None	0.0-4.0-8.0-9.0	0.0-9.0
<b>Fuzzy Evaluation Groupings</b>			<b>De-Fuzzification Range</b>
Structural Influence	Very Light, Light, Moderate, Serious, Critical, Imminent	0.0-0.2-0.4-0.6-0.8-1.0	0.0-1.0
Building Influence	Numerical 1-8	8 Equal Intervals	0.0-1.0
Psychological Influence	Low, Moderate, High, Very High	0.0-0.3-0.6-1.0	0.0-1.0
Environmental Influence	Low, Moderate, High, Very High	0.0-0.3-0.6-1.0	0.0-1.0
Psycho-Environmental Influence	Very Low, Low, Moderate, High, Very High	0.0-0.25-0.5-0.75-1.0	0.0-1.0
Socio-Environmental Influence	Numerical 1-6	6 Equal Intervals	0.0-1.0

### 2.3.3 Life-threatening injury profile

Life-threatening injuries create an exceptional demand on medical resources including medical equipment, pharmaceuticals and specialists. They are also of interest to emergency managers, especially those responsible for medical care facilities/hospitals and paramedic operations because of their unique requirements. For these reasons, life-threatening head/spinal, trunk, orthopedic, and crush injuries were selected for evaluation.

The injury profiles are constructed using a decision matrix of the varying risk factors. The risk factors are earthquake safety education, time of day, OFC hazards / retrofit decisions, damageability, ambient air temperature, and building type. Each risk factor has various parameters to describe their states (see Table 2.3), for example time of day is either day or night. For each type of injury, the parameters are ordered from best case (lowest value) to worst case (highest value) and normalized. Some of these 'orders' are straightforward such as education, OFC hazards and building type (i.e. active training is more effective than no education), however, the time of day, damageability, and temperature parameters vary because they may influence some types of injuries more than others (e.g. orthopedic injuries are more likely to occur during the day and crush injuries are more likely at night). A summary of risk factors for each type of injury and the most significant risk factor parameters is presented in Appendix 2.3 including key evidence from both statistical tests and case studies. Ranking is based on qualitative and quantitative evidence, and expert judgment. Next, each risk factor is weighted relative to its influence on the given type of

injury as ordered in Appendix 2.3. For example, life-threatening head/spinal injuries have four associated risk factors; the most influential is OFC hazards / retrofit decisions and the least is earthquake education. Therefore, the OFC hazards is multiplied by four, while earthquake education is multiplied by one. The sum of the risk factors for each type of injury will determine if the risk of life-threatening head/spinal, trunk, orthopedic, and crush injuries is low, moderate or high.

Table 2.3: Risk factor parameters ranks and normalized value (in brackets) for the injury profile decision matrix.

Risk Factors		Type of Injury			
Main Factor	Parameter	Head/Spinal	Trunk	Orthopedic	Crush
Education	Active	1 (0.5)	1 (0.5)	1 (0.5)	1 (0.5)
	Visual	2 (1)	2 (1)	2 (1)	2 (1)
	Read	3 (1.5)	3 (1.5)	3 (1.5)	3 (1.5)
	None	4 (2)	4 (2)	4 (2)	4 (2)
Time	Night	1	2	1	2
	Day	2	1	2	1
OFC Hazards / Retrofit Decisions	Low	1 (0.4)	1 (0.4)	1 (0.4)	1 (0.4)
	Moderate	2 (0.8)	2 (0.8)	2 (0.8)	2 (0.8)
	High	3 (1.2)	3 (1.2)	3 (1.2)	3 (1.2)
	Very High	4 (1.6)	4 (1.6)	4 (1.6)	4 (1.6)
	Exceptional	5 (2)	5 (2)	5 (2)	5 (2)
Damageability	<0.7	2	1	2	1
	>0.7	1	2	1	2
Temperature	Normal	NA	NA	NA	1 (1.33)
	Mild	NA	NA	NA	2 (0.67)
	Serious	NA	NA	NA	3 (2)
Building Type	Light	NA	1 (0.67)	NA	1 (0.67)
	Moderate	NA	2 (1.33)	NA	2 (1.33)
	Heavy	NA	3 (2)	NA	3 (2)

### 2.3.4 Estimation of number of injuries

CanRisk's estimation of the number of injuries combines Hazus methodology with the aforementioned risk to injury FSE output. Hazus casualty methodology utilizes North American datasets to calculate injuries, however, it only considers injuries due to structural and OFC damage. Considering the primary cause of injury in North American earthquakes is

related to non-building factors such as attempting to rapidly exit a building and falling, the FSE output of the risk to injury is used as an indicator for these types of injuries.

A ‘mechanism of injury’ dataset was compiled and represented 21 international case studies of 17 earthquakes. Of these, only 16 case studies were selected for analysis because they contained fall-related (non-building related) injuries. A histogram of the proportions (the number of fall-related injuries divided by the total number of reported injuries for the earthquake) revealed a non-normal distribution (Figure 2.4). Due to the nature of the histogram, the range of possible fall injuries was determined by the 10<sup>th</sup> (0.096) and 90<sup>th</sup> (0.502) percentiles. However, as seen in previous earthquakes (e.g. 1964 M7.6 Niigata, Japan earthquake (Ohashi and Ohta, 1988), and the 1994 M6.7 Northridge earthquake (Peek-Asa et al., 1998; McArthur et al., 2000; Mahue-Giangreco et al., 2001), fall-related injuries can constitute more than 50% of all injuries. Equation 2.1 denotes the calculation of the number of non-building injuries in the CanRisk model where upper and lower represent the percentile bounds:

$$Inj_{Non-building} = \left( \left( \frac{0.502_{upper}}{0.096_{lower}} * Risk_{Inj} \right) * [N_{occupants} - (Inj_{sev1} + Inj_{sev2} + Inj_{sev3} + Inj_{sev4})] \right) \quad [2.1]$$

Where  $Inj_{Non-building}$  is the total number of non-building (e.g. fall-related) injuries,  $Risk_{Inj}$  is the CanRisk FSE output of ‘Risk to Injury’ (0-1),  $N_{occupants}$  is the number of occupants within the building, and  $Inj_{sev\eta}$  is the total number of injuries for each severity class.

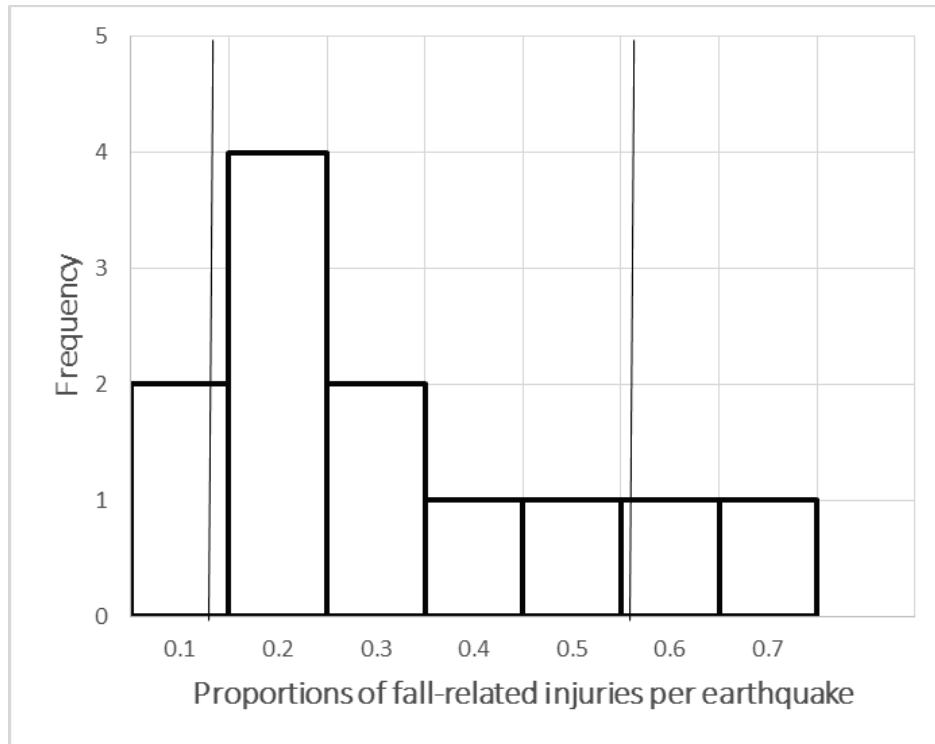


Figure 2.4: Histogram of fall-related injuries for 16 earthquakes showing the 10<sup>th</sup> and 90<sup>th</sup> percentile.

It is acknowledged that the above equation may seem disproportional as the fewer number of people injured by building factors (Hazus methodology) increases the chance of being injured by non-building factors (risk to injury multiplier). In most cases, the injuries sustained by the onset of building and OFC failure supersedes those from non-building factors. For example, a serious (severity 2) FOOSH injury is not comparable to the severity and medical resources needed to treat a crush injury. However, in earthquakes with few building failures as often seen in North America, non-building injuries like falls can represent a major stressor on medical and emergency response resources.

The distribution of fall / non-building injuries in each severity class (minor, serious, and life-threatening) is determined by trends observed in the injury dataset. All injuries consistent with FOOSH/fall-related characteristics were extracted from the injury dataset (Appendix 2.4). Severity 1 (minor) and severity 2 (serious) injuries included all arm, shoulder girdle, and leg injuries; minor injuries also included all general sprains and strains. Severity 3 (life-

threatening) injuries included the entire severity 3 orthopedic injury dataset which does not include crush injury. It is assumed that the majority of these injuries were sustained from non-building factors (i.e. tripping, falling or jumping). Under these assumptions, an ordinal logistic regression using R (R version 3.0.1) was used to determine the probabilities of sustaining a minor, serious or life-threatening non-building injury. Fatal injuries are not accounted for as these types of injuries were not included in the injury dataset and therefore could not be calculated. The ordinal logistic regression included two categories, damage (see ‘Building Influence’ – Building Type) and earthquake education (see ‘Earthquake Safety Influence’). These categories were selected because more damage leads to additional obstacles during and after shaking and increases an occupant’s chance of tripping, and earthquake education is an indicator if an occupant will attempt to rapidly exit a building. The results of the ordinal logistic regression are summarized in Table 2.4. Although no fatal fall injuries were included in the ordinal logistic regression, these types of injuries are possible (McKevitt et al., 1995).

Table 2.4: Summarizes the results of the ordinal logistic regression of non-buildings (i.e. fall-related) injuries.

Categories			Injury Severities Probabilities		
Damage	Earthquake Safety	Number of earthquakes	Sev 1 (Minor)	Sev2 (Serious)	Sev3 (Life-Threatening)
Light	Active, Visual	3	0.882407	0.060022	0.057571
Light	Read, None	2	0.983169	0.011608	0.005223
Moderate	Active, Visual	1	0.022632	0.272597	0.704771
Moderate	Read, None	6	0.152729	0.677022	0.170249
Heavy	Active, Visual	0	N/A	N/A	N/A
Heavy	Read, None	4	0.153245	0.774433	0.072322

## 2.4 Sensitivity analysis and validation

A sensitivity analysis of the risk to injury FSE was performed using an iterative process. A select number of numeric inputs were chosen that best represent each risk factor (Table 2.5). All possible combinations of these inputs were evaluated to determine the sensitivity of each risk factor. As anticipated, the most sensitive input is damageability, followed by OFC hazards / retrofit decisions; represented by the building influence axis in Figure 2.5.

Literature clearly documents damageability as the primary predictor of injuries; injuries due to OFCs are also clearly established. Earthquake safety education is the most influential non-building factor (socio-environmental influence). Familiarity, previous earthquake experience, time of day and body temperature are less sensitive. This is partially due to (1) the emphasis placed on known influences in the fuzzy rule-based knowledge, and (2) the hierarchal framework as the aforementioned factors undergo the most fuzzy inferences. However, combinations of the most influential parameters of these factors (unfamiliar, little experience, daytime earthquake, and/or serious hypothermia) increase sensitivity.

Table 2.5: Selected sensitivity test inputs that best represent each risk factor.

<b>Risk Factor</b>	<b>Linguistic Representation</b>	<b>Numeric Inputs</b>
Damageability	None, Slight, Moderate, Extensive, Complete	0.01, 0.25, 0.5, 0.75, 0.98
Building Type	Light, Moderate, Heavy	0.25 0.375 0.6
OFC Hazards / Retrofit Decisions	Low, Moderate, High, Very High, Exceptional	0.1, 0.375, 0.75, 1.125, 1.5
Familiarity	Familiar, Moderately Familiar, Unfamiliar	1, 2, 3
Previous earthquake experience	Sufficient, Some, Little	1, 2, 3
Time of Day	Night, Day	1, 2
Body Temperature	Normal, Mild, Serious	1, 2, 3
Earthquake Safety Education	Active, Visual, Read, None	0, 4, 8, 9

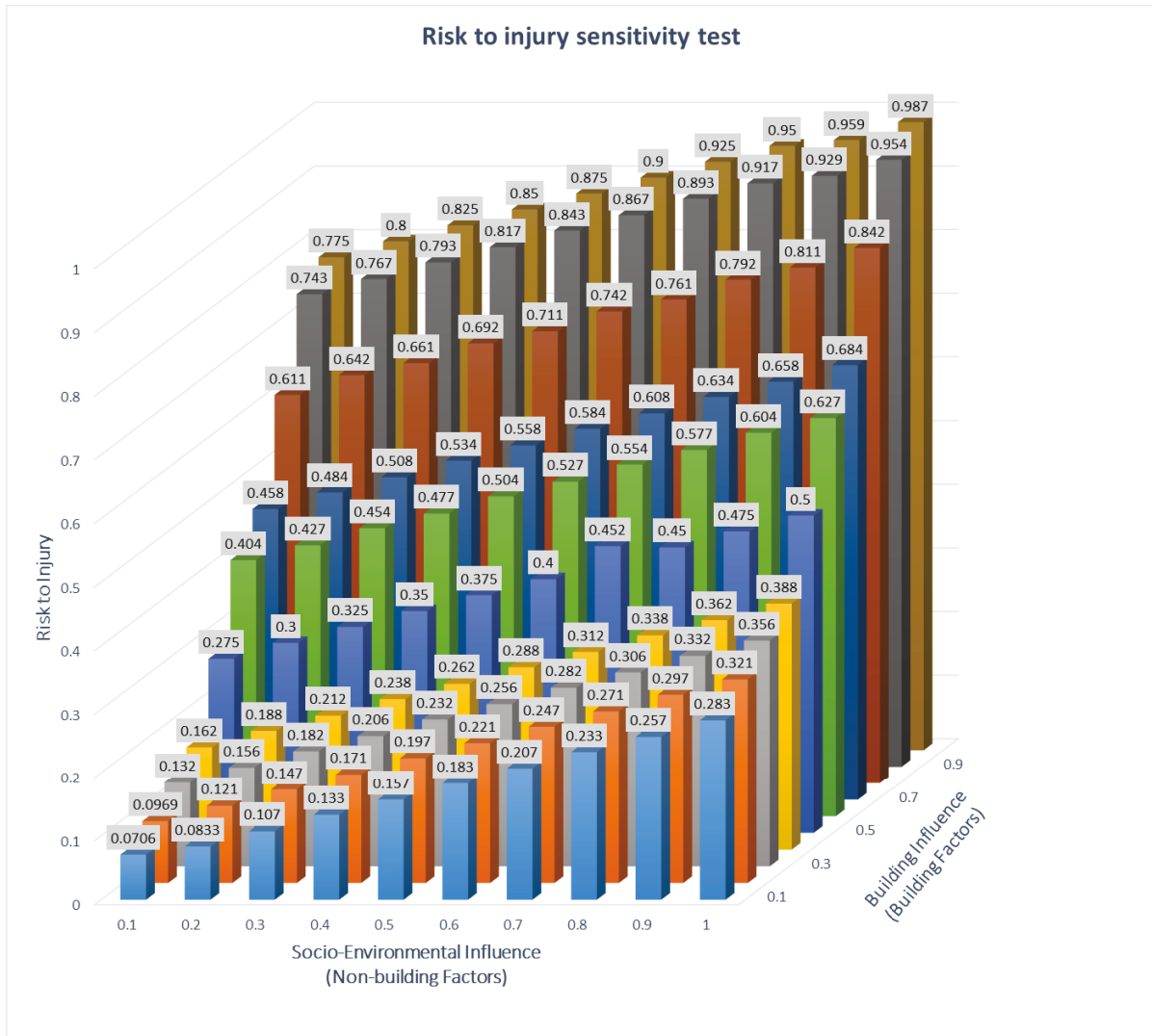


Figure 2.5: Sensitivity analysis results of building versus non-building factors.

There are very few case studies that provide an extensive epidemiology of earthquake injuries, that is, all documented injuries for a building where many risk factors are known. Durkin et al. (1991b) presents an example of such a case study which details the injuries of 22 survivors of an eight-storey reinforced concrete medical resident dormitory that collapsed during the 1985 M8.0 Michoacan (Mexico City) earthquake (Table 2.6). In this case study many survivors sustained multiple injuries, but only the most serious injury was considered.

Table 2.6: Comparison of estimated and observed injuries from a medical resident dormitory following the 1985 M8.0 Michoacan earthquake (Durkin et al., 1991b). A total of 76

casualties are reported, 36 of which sustained fatal injuries and 18 declined or were not available to be surveyed. The CanRisk risk to injury output was estimated to be 0.862.

Injury Type	Estimated	Estimated with Fall	Observed
<b>Number of Casualties n = 76</b>			
Severity 1	30.4 (40.0%)	30.6-31.6 (~40-42%)	6 (7.9%)
Severity 2	15.2 (20.0%)	16.3-21.2 (~21-28%)	6 (7.9%)
Severity 3	3.8 (5.0%)	3.9-4.4 (~5-6%)	10 (13.2%)
Severity 4	7.6 (10.0%)	N/A	36 (47.4%)
Unknown			18 (23.7%)
<b>Risk to Life-threatening (Severity 3) Injuries</b>			
Head/Spinal	Moderate		1(10%)
Trunk	High		1 (10%)
Orthopedic	High		4 (40%)
Crush	High		4(40%)
Risk to Injury	0.862		

In this example, there are inconsistencies in the estimation of the number of injuries which is expected because the Hazus methodology is calibrated to Californian earthquakes. For example, as dictated in the Hazus methodology, the complete collapse of a reinforced concrete building would cause the following distribution of injuries, 40% minor, 20% serious, 5% life-threatening, and 10% fatal. On the other hand, the risk to injury and the life-threatening injury profiles are more consistent with actual observations. Head and spinal injuries received moderate risk, while trunk, serious orthopedic, and crush injury are ranked as high risk. Serious orthopedic and crush injury (including compression) had the highest observations, while trunk injuries only had one observation. However, upon further inspection, two crush injuries and two orthopedic injuries were located in the trunk.

## 2.5 Limitations in model approach

The computation of earthquake risk is a complex task, and for this reason it is exceptionally difficult to model. Assumptions and limitations are intrinsic to the development of loss estimation and risk to injury methodology. Outlining the assumptions and limitations helps define reproducibility, and more importantly, to highlight the challenges within this research field. The following key assumptions/limitations used in this model:

1. Traditional casualty loss estimation methodology is empirical and frequently based on previous experience (e.g. Fulford et al., 2002; Spence et al., 2011; FEMA, 2012). In North America, there are very few contemporary earthquakes and even fewer in Canada with which to assemble a comprehensive injury database. International case studies only consists of a few relevant earthquake datasets. The lack of these datasets and the reporting of earthquake injuries is attributable to the lack of standardized methods to collect data, the interpretations of injury severity, lack of epidemiological data of the patient, and the chaotic nature of post-earthquake situations (Alexander, 1985; Durkin, 1985; Alexander, 1996; Peek-Asa et al., 1998; Ramirez and Peek-Asa, 2005; Auf der Heide, 2006; Stallings, 2002; Ardagh et al., 2012). Mahue-Giangreco et al. (2001) noted however, that case studies are better than simulated injury data because they can provide more appropriate recommendations for emergency managers.
  
2. Coded factors in the injury dataset are generalized. Examples of generalizations are listed: (1) Upper body refers to injuries of the head, neck, arm and shoulder girdle. Trunk refers to injuries of the thorax, abdomen and pelvis. Lastly, lower body refers to injuries of the legs and hips. Pelvic injuries were included as part of the trunk because it cradles the lower abdominal organs. Hip injuries were considered as lower body as many of these injuries were to the top of the femur. (2) Damage is coded as light, moderate and heavy which is based on most observed damage state of buildings in a given case study region. 'Light damage' is modelled to assume primarily OFC damage. This statement, however, does not consider that many serious/life-threatening injuries may be generated by a few sensational building failures. Moderate damage involves widespread building failures of light (e.g. timber-frame, URM) and/or low-rise buildings, while heavy damage involves heavy (e.g. concrete) and/or high-rise buildings. (3) The severity of injury was determined from:

- a. Severity 1 (minor) included all sprains, strains, contusions, open wounds, and soft tissue injuries.
- b. Severity 2 (serious) included all closed fractures with the exception of skull, pelvic and spinal fractures, general burns, dislocations, general closed head injuries, and complicated open wounds.
- c. Severity 3 (life-threatening) included spinal injuries, intra-abdominal and intra-thoracic injuries, skull fractures, compound and open fractures, pelvic fractures, severe burns, traumatic brain injuries (TBI), and crush injuries.

Lastly, it is acknowledged that the coded injury severity can vary, where minor injuries can be serious and/or life-threatening, and vice-versa.

3. The statistical analysis of the injury dataset yielded few definite results (Appendix 2.2). Statistical tests were used to help identify effects / trends rather than making a definitive statement of reality (Nuzzo, 2014). However, all strong results were supported by first-hand / primary qualitative observations made in medical case studies and reports.
4. Case studies can provide qualitative evidence of the risk factors. Multi-perspective and international observations of an earthquake are beneficial and offer unique insight of 'lessons learned', but are subject to jurisdictional bias. Each case study must be judged for its relevance in a Canadian context. For example, when considering the risk factor of earthquake education, running out of a building may be a prudent action in developing regions or regions with adobe buildings (e.g. de Bruycker et al., 1985; Armenian et al., 1992), but increases the chance to serious or fatal injury in developed regions.
5. Limitations in the epidemiology of injuries lead to assumptions in the translation of the dataset to risk factors. For example, in order to estimate the number of non-building (fall) injuries and their severity distribution, all injuries characteristic of fall

injuries were extracted for analysis. This method may not have included all actual injuries from falls and/or included injuries that were caused by another mechanism.

6. An unanticipated trend was observed in ordinal logistic regression results of the probabilities of minor, serious, and life-threatening non-building injuries (see Table 2.4); the chances of minor injuries increase when earthquake safety education is low. There are three possibilities for this trend. (1) In the dataset used to for the ordinal logistic regression analysis, light damage and low earthquake education was represented by two earthquakes, one of them was the 2011 M6.3 Christchurch earthquake. Research and data reporting from this earthquake has been exemplary, and may offer better recording/reporting of earthquake injuries (minor to life-threatening) and therefore skewed towards minor injuries. All three earthquakes representing light damage and high earthquake education were 20<sup>th</sup> century earthquakes from California (1989 Loma Prieta, 1992 Landers, and 1994 Northridge earthquakes). Researchers have noted that a significant number of minor injuries were likely treated but not reported (Durkin and Thiel, 1992; McKeivitt et al., 1995; McArthur et al., 2000). (2) Moderate damage is classified as primarily structural failures of moderate material (e.g. timber-frame) and/or low-rise buildings. Only one earthquake represented moderate damage and high earthquake education which was the 1995 M6.9 Great Hanshin (Kobe) Japan earthquake. This particular earthquake had numerous timber-frame building collapses. Most earthquakes with moderate damage and low earthquake education had URM building collapses. It is possible that there is a fundamental difference in the epidemiology of injuries with these conditions and therefore they cannot be compared. For example, perhaps life-threatening orthopedic injuries in URM collapses are less survivable which leads to fewer injuries being reported, while these types of injuries in timber-frame collapses have higher chances of survival. Other fundamental differences are that injuries from developing and developed regions cannot be compared due to different post-earthquake medical treatment and advanced care capacities. (3) Another possibility

could be that one or both of the categories (damage and earthquake safety education) do not influence non-building /‘fall-related’ injuries. Though this possibility would oppose observations from international earthquake injury literature.

7. Risk factors are generalized. Some examples of these generalizations are: (1) The base calculation of OFC numeric inputs assumes that all occupancy classes contain the same OFCs. For example, all single family dwellings are assumed to have a porch, URM cladding, a chimney, and wall partitions. (2) All professional and technical services (i.e. offices) are classified as moderately familiar under the assumption that the occupant will not know all of their colleagues in a large office complex. This assumption may not be the case for smaller businesses. (3) Experience is based on the urban centre’s seismicity since 1985. This risk factor assumes that the population have memories of the intense  $M > 5.0$  earthquakes within their respective urban centres. Naturally, populations change over time and many people may not have experienced these baseline earthquakes. Additionally, earthquakes that are located on the outer region of the 250 km buffer may not generate the same type of experience as their group designation (shaken, OFC damage, etc).
8. In Equation 2.1, the 0.096 and 0.502 values were determined by the ‘mechanism of injury’ dataset in which all case studies with documented fall-related injuries were selected and used to construct a histogram. This variable was calculated using the 10<sup>th</sup> and 90<sup>th</sup> percentile which can change when newer data becomes available. Additionally, these variables do not consider the unique circumstances where significantly more fall-related injuries are possible. However,  $Risk_{inj}$  should encapsulate additional factors that reduce the risk of non-building injuries such as earthquake education.
9. The observation of Canadian earthquake injuries has been rare. Additionally, historical Canadian earthquakes have produced few reported injuries due to small

damage. Therefore model calibration and validation for Canadian scenarios are not as well constrained.

The following are recommendations for future work:

1. Casualty loss estimation methodology is underpinned by evidence-based research and analysis. Therefore, it is imperative that case studies are assembled and made available. With larger datasets and qualitative observations, loss estimation methodology can be better refined, including the contributions detailed in this chapter.
2. An international framework for recording, standardizing and reporting earthquake injuries is needed. Even contributions from a single institution are useful in loss estimation research. Therefore, we encourage medical care facility emergency management committees to facilitate and support a framework to record earthquake-related injuries. This can be accomplished in several ways including tailored medical charts (i.e. how were you injured?), an assigned personnel or volunteer to record such information, or a pre-tested standardized questionnaire to collect relevant data after the earthquake.
3. A partner-enabled approach to case studies is also beneficial. Pre-tested standardized questionnaires can be constructed and given to participating institutions, agencies, and businesses to enable a cohort study of injuries and their mechanisms.
4. Researchers should make a better effort to publish earthquake case studies that include injuries. Even small earthquakes such as the 2010 M5.0 Val-des-Bois that affected the Ottawa region can provide important observations, challenges, successes, and 'lessons learned'.

## 2.6 Conclusion

Earthquakes present a significant exposure to danger and threaten the integrity, security and well-being of communities. Earthquake risk is complex and infused with imprecision, ambiguity and limited data, making it difficult to model. However, modelling is a useful exercise and can facilitate informed decision making in emergency management. The CanRisk injury model enables decision makers to test potential mitigation and preparedness strategies which can aid in the design of effective emergency plans and promote community and medical care facility resilience. Additionally, the CanRisk injury model outputs can aid in the development of a realistic earthquake scenario that can be utilized as an educational tool and for training purposes (e.g. tabletop exercise).

The CanRisk injury model is designed for a Canadian setting, but it has international application in other developed regions. The validation results of the model are promising, but loss estimation studies must rely mostly on future damaging earthquakes for validation. Nonetheless, the CanRisk injury model risk factors are supported not only by an extensive review on multi-perspective, international scholarly case studies but also on the compilation and analyses of injury and mechanism datasets.

## 2.7 Acknowledgements

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<sup>1</sup>Only found in Chapter 2 appendices

# Chapter 3

## *Disaster Spatial Decision Support System (SDSS) for emergency management decision making for immediate post-earthquake emergency response*

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*“An ounce of prevention is worth a pound of cure.”*

*-Benjamin Franklin*

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**Abstract:** Preparedness, planning, and mitigation are quickly moving to the forefront of emergency management with the goal of preventing or reducing future losses. The growing movement of loss estimation programs such as Hazus, have demonstrated the value use of estimation outputs in emergency management. Although loss estimation studies can aid in the emergency management cycle, they rarely address mitigation and response needs. Conceptually, the disaster Spatial Decision Support System (SDSS) asks “what do these numbers mean for my community?” The SDSS is an evidence-based model that is designed to facilitate informed decision making in regard to proactive strategies that can enhance response capacity. Loss estimations from Hazus Canada and the CanRisk injury model are combined with community geospatial data to simulate realistic post-earthquake conditions that test a community’s operational readiness, reveal limitations and resources gaps in the emergency plan, and test potential mitigation and preparedness strategies.

**Keywords:** *seismic risk, SDSS, earthquake preparedness, earthquake planning, earthquake response*

### 3.1 Background information

The first 72 hours following a damaging earthquake are crucial in emergency management, especially with regard to response operations. Primary concerns within these hours are the treatment of injuries, extrication of entrapped persons, and the suppression of follow-on hazards that threaten the health and the safety of the community. A third crucial concern is the establishment of shelters to house the unharmed families who cannot occupy their homes. Other demands that require attention include the restoration of power, communications, clean water, and waste water facilities. Typically after 72 hours, response operations slowly return to baseline conditions or shift to recovery efforts in North American earthquakes; an exception would be large aftershocks.

Emergency management (EM) provides a governmental structure and applies science, technology and coordination to deal with large scale emergency events. Traditionally, EM had a tendency to focus on the urgent aspects of a disaster, however it is now accepted that EM is comprehensive and multifaceted (Erden and Coskun, 2010). Preparedness, planning, and mitigation are quickly moving to the forefront of EM with the goal of preventing or reducing future losses (e.g Mileti, 1999). As noted by many, including Scawthorn et al. (1996) and Ramirez and Peek-Asa (2005), there is a need to understand the risk in order to design strategic and useful mitigation and preparedness programs. The synthesis of post-earthquake qualitative observations from scholarly and governmental documents not only provide 'lessons learned' and recommendations from previous earthquakes, but also achievements that can be built upon. The evidence collected from these observations can improve our understanding and facilitate the development of a conceptual framework to model risk. A Geographic Information System (GIS) is a useful tool that can organize, analyze and visualize community and emergency resources. GIS can also integrate a conceptual framework to answer spatial questions, identify spatial trends and patterns, and model possibilities (Dash, 2002; Thomas et al., 2007). Consequently, the use of GIS is quickly becoming best practice in EM.

A research gap exists between the translations of seismic risk assessment into management strategies. Loss estimations are an important step towards these translations, but generally do not address mitigation and response needs (Thomas et al., 2007) nor ask “what do these numbers mean for my community?” The purpose of this chapter is to present the underpinnings and development of a proactive evidence-based disaster Spatial Decision Support System (SDSS). This SDSS integrates high resolution (Tier-2) loss estimations with community-specific inventories, resources, and post-earthquake qualitative observations, to establish a meaningful context between seismic risk assessment and EM strategies. Tier-2 (or Level 2) loss estimations incorporate more detailed datasets such as updated building inventories and expert-based hazard conditions. This disaster SDSS will output realistic post-earthquake disaster conditions that are important for response operations which can facilitate informed decision making by testing a community’s operational readiness, revealing limitations or resource gaps within emergency plans, testing potential preparedness and mitigation strategies, and providing a realistic earthquake scenario for training purposes.

## **3.2 Rationale**

Damaging earthquakes create a unique set of circumstances in which an entire community can be physically, socially and economically crippled with no warning. With this, the mobilization and deployment of emergency services may be atypical, for example not all fire resources may be accessible or deployable. Almost all aspects of traditional coordination is affected including reporting incidents (e.g. calling 911), dispatching responding units and having unaffected personnel and equipment available to respond, en-route obstacles and delays, and coverage issues. The following discussion summarizes key observations from previous relevant case studies that are integrated into the subsequent model.

### **3.2.1 Delays in reporting and responding emergency units**

In general, communication systems are severely impacted during moderate-to-large ( $M > 5.0$ ) earthquakes due to damaged communication infrastructure and system saturation / congestion (Tierney, 1988; Haynes et al., 1992; Scawthorn et al., 1996; Tanaka, 1996). Call volume to 911, and the telephone and cellular systems in general, increases between four to fifty times versus the regular call volume (Durkin et al., 1991; Durkin and Thiel, 1992; Ukai, 1997). Communication systems tend to regain their capacity by 72 hours (Ukai, 1997), but can be disrupted for much longer periods of time depending on the degree of infrastructural damage (Kirsch et al., 2010). The failure of communications has been identified as a challenge leading to 'lessons learned' in many past earthquakes. In the event of a communications failure, emergency response units have been known to self-dispatch to nearby fires (Garcia et al., 1994).

Previous North American earthquakes have also demonstrated that en-route obstacles delay responding emergency units following a large earthquake. These obstacles include jammed vehicle bay doors, flooded streets due to ruptured water main/truck lines, ignited gas lines, debris, downed power lines, and bridge damage (Garcia et al., 1994; USFA, 1992; USFA, 1994; Scawthorn et al., 1996; Ukai, 1997; Scawthorn, 2008).

### **3.2.2 Post-earthquake fires**

Following a large and damaging earthquake, fire services in major urban centres can be completely committed within minutes (Garcia et al., 1994) because it is common to have simultaneous fire ignitions (e.g. USFA, 1994; Scawthorn et al., 1996). Most urban fire services are not equipped to deal with multiple simultaneous fire ignitions (Scawthorn, 2008). The key to effective fire suppression is rapid response, therefore delays in response due to communication saturation and en-route obstacles can lead to uncontrolled fires or the possibility of conflagrations which can be initiated in as little as an hour or two (Scawthorn et al., 1996). Additionally, physical damage to lifeline infrastructure such as water/trunk line ruptures can leave fire crews without access to an adequate water supply.

Therefore, alternative sources of water need to be identified and utilized. Sources of water can be swimming pools, local creeks, helicopter water drops, and fire boats (Bruneau, 1990; Scawthorn et al., 1996; Ukai, 1997). In past earthquakes, in neighbourhoods with no alternative water supply, entire residential blocks have been left to burn (USFA, 1994).

### **3.2.3 Search and Rescue (SAR)**

The greatest demand for emergency response units (fire, ambulance and police) occurs within the first 24 hours when the health and well-being of people are the most affected. SAR operations commence at the onset of structural and non-structural failure. One of the most critical factors in the rescue of entrapped survivors is the structural system / building type that failed. Light SAR (LSAR) operations are commonly undertaken by emergent groups of survivors and volunteers who use their bare hands and simple tools such as shovels, ladders, and rope for extrication (de Bruycker et al., 1983; Durkin and Murakami, 1988; Noji et al., 1990; Roces et al., 1992). These operations are most suitable for masonry or timber-frame structural failures such as houses and small businesses. Structural failure of complex buildings such as reinforced concrete (R/C) or steel requires specialized SAR task forces and equipment. These requests are generally undertaken by Urban Search and Rescue (USAR) task forces (e.g. USFA, 1992; USFA, 1994). Canada has five heavy USAR (HUSAR) task forces stationed in Vancouver, Calgary, Winnipeg, Toronto and Halifax and they can be rapidly deployed. The City of Ottawa has a medium USAR (MUSAR) task force. MUSAR task forces are self-sustainable for at least 24 hours and have the resources to treat numerous minor, serious and life-threatening injuries.

### **3.2.4 Medical treatment and medical care facilities**

In the hours following a damaging earthquake, saturated 911 and other communication systems, as well as damaged transportation systems, can delay the delivery of advanced medical treatment. As previously observed in North America, the majority of the requests for paramedic services are usually not answered. For example following the 1989 M6.9 Loma

Prieta earthquake, paramedics only transported one-in-three calls in the Santa Cruz area (Durkin and Thiel, 1992).

All medical facilities within the affected region tend to get a surge of injured persons that can be five times greater than baseline conditions (Salinas et al., 1998; McArthur et al., 2000). In previous American earthquakes, the majority of the medical care capacity was able to meet the demand; however some medical facilities were overwhelmed and neared the demand-supply threshold (Pointer et al., 1992). In these earthquakes, the highest demand for medical treatment occurs within the first 24 hours of the event, typically with 50-70% of the injuries being minor, ~ 5-10% requiring hospitalization, and ~1-2% requiring major surgery (Roces et al., 1992; Coburn and Spence, 2002); in extreme cases, up to ~10% may require major surgery (Roces et al., 1992).

Medical care facilities are not exempt from earthquake damage as structural, non-structural, and both fire and water damage have been observed in modern facilities in Japan (Tanaka, 1996), the United States (Tierney, 1988; Schultz et al., 2003), Canada (Mitchell et al., 1990), and New Zealand (EERI, 2011; Ardagh et al., 2012). Non-structural / operational and functional component (OFC) damage such as burst pipes, and failed HVAC (Heat, Ventilation, Air Conditioning) systems can force an evacuation of a medical facility (e.g. Durkin et al., 1991; Haynes et al., 1992; Schultz et al., 2003; Ardagh et al., 2012). Additionally, possible damaged equipment such as MRI units (Magnetic Resonance Imaging), hemodialysis machines, X-ray machines, oxygen gauges, and microscopes can diminish the diagnostic and treatment capacity of modern medical care facilities (e.g. Pointer et al., 1992; Roces et al., 1992; Ukai, 1997). In some instances, hospitals can remain functional but many not accessible thus leading to diversions and the potential of overcrowding neighbouring facilities (Ukai, 1997).

Deployable medical personnel, trained volunteers and field facilities can significantly decrease the number of incoming patients to a medical care facility by more than 80% (Coburn and Spence, 2002; Dhar et al., 2007). A significant number of earthquake injuries are minor and can be treated using first aid. Deployable medical resources can also provide

advanced medical care to seriously injured persons prior to their arrival to a medical care facility (Schultz et al., 1996; Dhar et al., 2007). A tiered medical response system that included first aid field posts, mobile medical team/facilities, and field hospitals (e.g. Schultz et al., 1996), has been implemented with success in past earthquakes in Tangshan and Kashmir (e.g. Sheng, 1987; Dhar et al., 2007).

### **3.2.5 Management of convergent volunteerism**

Convergent volunteerism, particularly emergent groups of survivors, is a worldwide phenomenon following large earthquakes (Glass et al., 1977; Olson and Olson, 1987), including American earthquakes (USFA, 1992; Garcia et al., 1994; USFA, 1994; Scawthorn et al., 1996). Volunteers will not only offer their skill sets but also their resources to assist in the greater effort (Pointer et al., 1992). Emerging groups of volunteers can be an asset to SAR operations, but can also become a great hindrance (Garcia et al., 1994; Cone et al., 2003). The rapid coordination of volunteers by authority figures, notably law enforcement officers, can make them a valuable emergency response asset (Auf der Heide, 2006).

### **3.2.6 Shelters**

Relief efforts and shelters are one of the most important resources to unharmed survivors. Observations from contemporary American earthquakes have demonstrated the need of these efforts. For example, following the 1994 M6.7 Northridge earthquake, over 34,000 dwellings were vacated and thousands of unharmed survivors required shelters (Carr et al., 1996). Following both the 1989 M6.9 Loma Prieta earthquake and the 1987 M5.9 Whittier Narrows earthquake, over 10,000 survivors were displaced and/or required shelters (Tierney, 1987; Bruneau, 1990; Brady and Perkins, 1998).

### **3.3 Methodology**

This disaster SDSS was developed in ESRI® ArcGIS using ModelBuilder. The underpinnings and development of this framework is evidence-based, integrating post-disaster and multi-perspective observations. The implementation of this evidence establishes realistic and meaningful context for decision makers in emergency management. This approach also facilitates the adaptability of the recommendations and guidelines into community emergency planning (Swanson and Bhadwal, 2009). Additionally, mitigation strategies and preparedness planning can be cycled through the model to test decisions.

The SDSS framework (see Figure 3.1) combines community geospatial data with loss estimations to determine mobilization and deployment challenges, en-route obstacles, passability and accessibility to emergency sites, and assess possible coverage issues or decision making consequences. Table 3.1 presents a summary of all required community geospatial data. The SDSS will evaluate the above issues for fire services, SAR operations such as the USAR task force, emergency medical services and police services, medical care facility operations, and relief operations.

#### **3.3.1 Pre-earthquake situational awareness**

Pre-earthquake situational awareness can be an indicator of the operational readiness of emergency response services. Situational awareness is constructed using (1) essential community data such as roads and buildings, (2) emergency resources and assets such as the fire stations, the number of trucks/personnel per station, and the fire services mandated response time, and (3) loss estimations from Hazus and CanRisk.

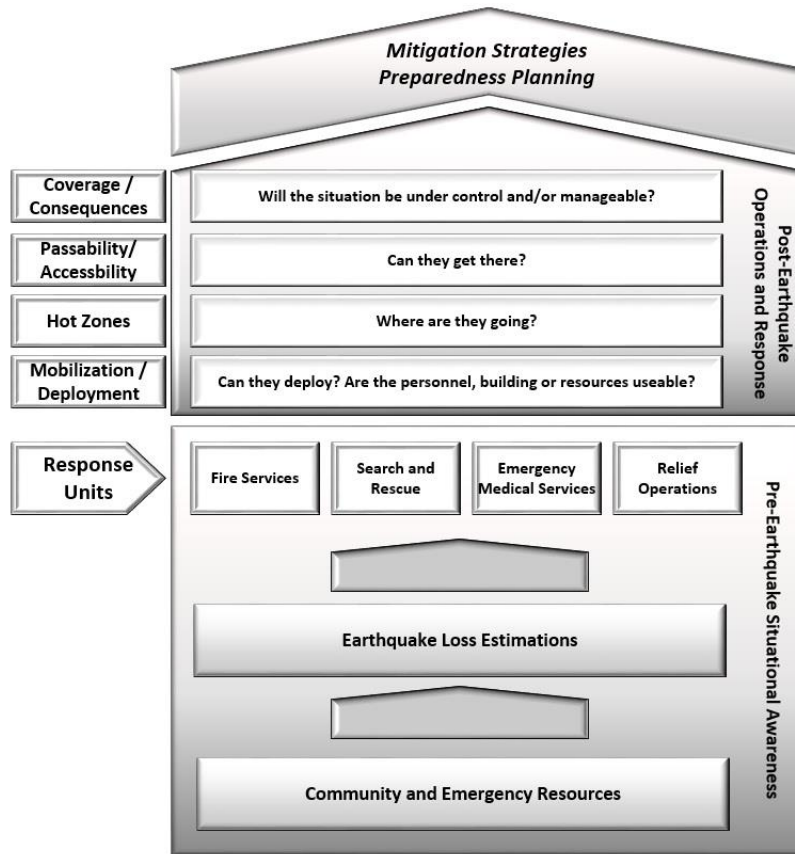


Figure 3.1: Conceptual overview of the disaster SDSS. Pre-earthquake situational awareness accounts for the community and emergency resources as well as earthquake loss estimations to model post-earthquake conditions for response purposes.

Table 3.1: List the required community geospatial and attribute data.

Name	Feature Class	Required Attribute Data
Bridges	Point	Bridge type (overpass, bridge), owner (municipal, provincial, federal)
Building Footprints	Polygon	None
Building Inventory	Point	Building type (see FEMA 2012, Chapter 3), number of storeys, occupancy class
Census Tracts	Polygon	CTUID, Hazus tract ID
Fire Hydrants	Point	None
Fire Stations	Point	Fire station ID, name, number of fire trucks and personnel
Hospitals	Point	hospital ID, name, number of beds, hospital type (acute, chronic), number of patients, number of OR suites, number of X-rays, severity level (1,2,3), mass capacity
Natural Waterways	Polygon	Volume
Open Areas	Polygon	e.g. Parking lots and parks

Paramedic Posts	Point	Paramedic post ID, name, number of ambulances and personnel
Private Pools	Point	Volume
Public Pools	Point	Volume
Routes	Line	Requisite network data
Shelters	Point	Shelter ID, name
Soils	Polygon	Class letter (A,B,C,D,E)
USAR Station	Point	USAR station ID, number of truck and personnel

### 3.3.1.1 Community essentials

Community geospatial data is required for every aspect of the SDSS as it defines inventory, boundaries and routes. Census tracts provide the boundaries necessary to clip all other geospatial data because they are the smallest available unit in Hazus Canada. Census tract geospatial data must contain Census Tract Unique Identifiers (CTUIDs) and their Hazus Census IDs. Building footprints allow for the calculation of building area and number of buildings per footprint. The building inventory provides important information regarding each building and is also required by Hazus and CanRisk. Urban RAT was used to collect the building inventory in Ottawa (Sawada et al., 2013; Ploeger et al., 2014 *Accepted*). Urban RAT integrates the virtual environment and mobile smart devices to facilitate the rapid visual screening of building structural parameters. The roads spatial data must have the requisite information to create a network dataset which provides the ability to model transportation networks.

### 3.3.1.2 Response unit and medical care facility jurisdictions

Jurisdictions represent an approximate ‘catchment area’ for each emergency responder facility such as a fire station or a paramedic post. These provide the foundation for supply-demand calculations to evaluate coverage and consequences. If jurisdictions are not provided, the SDSS utilizes the Network Analyst extension in ArcGIS to create them using a facility service area model. Mandated or estimated response times are utilized to create fire, police, and paramedic service jurisdictions for each facility. Hospital jurisdictions are generated using the same procedure, however, the jurisdictions represent the closest hospitals for the citizens to travel to under the assumption that injured persons can and will

travel to the closest hospital. Lastly, the catchment area for shelters is generated with the assumption that citizens requiring shelter are willing to walk for one hour which is equivalent to approximately five kilometres.

#### **3.3.1.3 Debris by road segment**

To establish the vulnerability of each road segment to debris requires information on the number of general building types per segment and road width. Appendix 3.1 depicts the major steps used to determine debris by road segment. A road segment is the road located between two intersections (junctions). Debris is representative of building types (timber, masonry, steel and concrete): Type A debris consists of wood and masonry, and Type B consists of concrete and steel. The primary difference between these two debris types is the mechanism by which they are removed. Type A can be removed with simple hand tools and common construction equipment, while Type B requires specialized equipment to break long steel members and large concrete slabs (Ploeger, 2008). Classifying debris by Type A and Type B buildings is similar to Hazus methodology (see FEMA, 2012 Chapter 12) and promotes interoperability between Hazus and the disaster SDSS.

The potential for debris along a road segment is determined by the number and proportion of Type A and Type B buildings. The proportion of buildings along each segment will be used to distribute the tonnage of debris given by Hazus. Kuwata and Takada (2004) suggested that roadways greater than 12 m generally do not become completely obstructed. Buffers representing 8, 12 and 16 m road widths were created for each road segment. All buildings that intersected each buffer were calculated. These values will be used to rank post-earthquake road passability.

#### **3.3.1.4 Fire threat by block**

Threat zones for post-earthquake fire ignition have been derived based on observations from previous earthquakes (Scawthorn, et al., 1996; Scawthorn et al., 2005; and Scawthorn, 2008). In the SDSS, fire threat zones are defined at the community block level, and therefore the entire block shares the same threat. A community block is the geographic area that is

bounded by connecting road segments and is known as a city block in an urban area. Each occupancy class (see FEMA, 2012 Chapter 3) was classified as having a Level 1, Level 2 or Level 3 threat of fire ignition. As such, all Level 3 occupancy classes as defined by Scawthorn et al. (1996) are single family home and duplexes, repair shops, and all industrial locations. The residential occupancies have an increased vulnerability because they are typically timber-framed and can easily rotate off of their foundations (Durkin, 1985) and sever gas lines (Scawthorn et al., 1996), or are prone to electrical arcing and gas leaks from appliances and furnaces (Scawthorn, 2008). Repair shops and industrial facilities are also vulnerable due to ruptured gas lines (e.g. Mitchell et al., 1990; McKeivitt et al., 1995), buckling of tanks, and overturning of cylinders (Perkins and Wyatt, 1994). Each level is linearly weighted and classified as a “High”, “Moderate”, or “Low” threat by community block. Appendix 3.1 depicts the major steps used to determine fire threat by block.

#### **3.3.1.5 Conflagration threat by block**

Large fires or fires that lack suppression resources can quickly spread and become conflagrations within hours following an earthquake (Scawthorn et al., 1996). In highly urbanized areas with dominant older timber-frame construction such as Japan and parts of eastern North America, the potential for conflagration is high (Oppenheim, 1984). The spread of a fire is influenced by fuel layouts which include building density, spacing between buildings, construction materials as well as wind speed and humidity (Oppenheim, 1984; Scawthorn, 2008). Building density is measured by the ratio of building plan area and open space within each block. However, only timber-framed buildings are included in these ratio calculations due to their inherent vulnerability to fire. Ratios above 0.3 are considered to be high density blocks (Scawthorn et al., 2005). Appendix 3.1 depicts the major steps used to determine conflagration threat by block. A limitation to this approach is that garages and tree density are not considered nor are meteorological conditions.

Open areas that are greater than 100 m can be designated as firebreaks and can slow or halt fire progression. This width is a modest estimation that accounts for situations with no fire suppression and light winds (see FEMA, 2012 Chapter 10). Available geospatial data of open

areas such as parks or parking lots can be assessed within the SDSS to determine if they meet the 100 m requirement. The combination of firebreaks and building density by city block are combined to determine the conflagration threat by community block.

### 3.3.1.6 Emergency resources

The distribution of emergency resources characterize the type and location of emergency response assets throughout a community. A summary of resources and their default values are listed in Table 3.2. Successes and challenges outlined in post-earthquake reports indicate that special capabilities and equipment must also be seriously considered in emergency planning. Examples of special capabilities and equipment are: (1) In fire services, drafting capabilities allow for fire units to draft water from alternative water sources if fire hydrant water is not accessible. Therefore, the location of alternative water sources for fire suppression is considered. (2) The number of X-ray machines and operating suites provides an estimation of a medical care facility’s capacity to treat serious (severity 2) and life-threatening (severity 3) injuries, respectively ([www.bt.cdc.gov](http://www.bt.cdc.gov)).

Table 3.2. List of emergency resources required for the SDSS (dots). There are no default values for the location of buildings as this is information contained in the geospatial data. The italicized parameters denote default estimations.

Parameters	Emergency Response and Relief Services					
	Fire	USAR	Police	Paramedic	Medical Care Facilities	Shelters
Location of buildings	•	•	•	•	•	•
Number of Emergency Vehicles <sup>1</sup>	•	•	•	•		
	<i>2-3 per station</i> <sup>2</sup>	<i>Convoy</i>	<i>Estimation</i> <sup>3</sup>	<i>1 per post</i> <i>3 per hospital</i>		
Number of Emergency Personnel <sup>1</sup>	•	•	•	•		
	<i>4 per truck</i>	<i>Min. Deployment</i>	<i>1 per car</i>	<i>2 per truck</i>		
Mandated Response Times <sup>4</sup>	•		•	•		
	<i>8 minutes</i>		<i>30 minutes</i>	<i>30 minutes</i>		
Special Capabilities / Equipment	<i>Drafting = Yes</i>				<ul style="list-style-type: none"> <li>• Number of Patients</li> <li>• Number of Beds</li> <li>• Mass Capacity (<i>Beds*3</i>)</li> <li>• Number of Operating Suites</li> <li>• Number of X-Ray Machines (<i>Beds/10<sub>A</sub>, 50<sub>C</sub></i>)</li> <li>• Nearest hospitals</li> </ul>	• Shelter Capacity (250)

<sup>1</sup> For responding vehicles or personnel only

<sup>2</sup> 3 trucks per station for urban areas, 2 trucks per station for rural areas

<sup>3</sup> Estimated by publicly available satellite imagery

<sup>4</sup> Mandated response times are times denoted by the community. 30 minute defaults are used to ensure coverage throughout the community without overlap.

A,C A-Acute medical care facilities, C-Chronic/Long-term medical care facilities

Water is a necessary resource for fire suppression and is traditionally obtained from fire hydrants. However, experience in previous North American earthquakes reveal that hydrants are susceptible to both direct and indirect damage. For example, following the 1994 Northridge earthquake there was infrastructural damage to the water system that included at least six ruptures in the main trunk line, and ~1400 line leaks, all of which led to a shortage of water and water pressure at many hydrants (Scawthorn et al., 1996). This reinforces the need for innovative water sources such as swimming pools and natural waterways (Scawthorn et al., 1996; Ukai, 1997). Geospatial data of natural waterways and public pools may be available from the municipal office. A separate remote-sensing model was used to detect all backyard swimming pools and estimate the volume of available water in each pool (Brian Bancroft, personal communication 2013). This model is not discussed in this article. However, any geospatial layer that denotes pools and a volume estimate can be used.

### 3.3.1.7 Loss estimations

The SDSS integrates tabular loss estimation outputs from Hazus and CanRisk. The tabular data is joined to geospatial data by census tract identifiers or pre-determined facility identifiers. Table 3.3 provides a summary of the required loss estimation tabular data.

Table 3.3: Summary of tabular data from loss estimation programs. The circles represent loss estimations from Hazus, and squares represent loss estimations from CanRisk.

Parameters	Fire Station	Hazus Losses	Hospital	Paramedic Posts	Shelter	USAR Losses	USAR Rescue
Facility ID	○		○	○	○	○	
Damage	○ <sup>1</sup>	○ <sup>2</sup>	○ <sup>1</sup>	○ <sup>1</sup>	○ <sup>1</sup>	○ <sup>1</sup>	
Functionality	○		○	○	○	○	
Number of injuries	□	○	□	□		□	□
Debris		○					
Critical Exposure							□

<sup>1</sup>-None, Slight, Moderate, Extensive and Complete for an individual building

<sup>2</sup>-None, Slight, Moderate, Extensive and Complete for all buildings that are wood, masonry, steel and concrete

### **3.3.2 Post-earthquake operations and response**

The operational readiness of emergency services is evaluated when newly-generated disaster conditions threaten a community. The introduction of loss estimations and earthquake intensity data provide the foundation to translate these SDSS inputs into post-earthquake conditions such as en-route obstacles, post-earthquake fires, SAR hot zones and rescue efforts, and the capacity of medical care facilities. This approach allows for emergency plans to be exercised and assessed for gaps and limitations in resources and planning.

#### **3.3.2.1 Mobilization and deployment**

Response unit facilities, as well as their personnel and equipment, are not immune to losses during earthquakes. These factors are evaluated to determine the ability to deploy, which can affect coverage within their respective jurisdictions. Some response units must also mobilize before deployment including volunteer fire brigades and USAR task forces. The ability to deploy is determined by the number of uninjured personnel and the availability of undamaged equipment; both factors are considered for each facility. Each calculation is performed under the assumption that the personnel are located at a specific facility (i.e. fire fighters in a fire station). Additionally, this calculation is only used for deploying fire services, paramedic services, and USAR task forces. It is assumed that the majority of police officers and their vehicles will be on patrol at the time of the earthquake.

The number of deployable personnel is an important factor to consider because some emergency response vehicles require a certain number of personnel to operate. Loss estimation outputs include the number of injuries per building. In order to account for various 'crew' sizes, the number of deployable personnel is ranked. For 'crews' greater than 10 members, ranks are assigned based on the percent of injured personnel. For example, a full complement receives a rank of 0, and a loss of 25% is 1, 50% is 2, 75% is 3, and greater than 90% is 10 as this is considered to be non-operational. Paramedics, on the other hand,

are assumed to work in pairs, one ambulance per post and three ambulances per hospital. If one paramedic is injured, then the ambulance cannot deploy as one crew member must drive and the other tends to the injured. Ranks are assigned as 0 or 3 for a paramedic post (i.e. the single ambulance can or cannot deploy), or 0 to 3 for a hospital as uninjured paramedics can partner if another is injured.

The number of deployable trucks is also an important consideration. The day 1 functionality estimation is the primary value for this calculation. Functionality was used in lieu of building damage because it provides a robust indication of a fire station's ability to function. For example, a building may not have sustained any structural damage, but the failure of operational and functional components (OFCs), or jammed vehicle bay doors can render trucks unusable (e.g. USFA, 1994). The following is the algorithm that was created to determine the number of useable fire and USAR trucks ( $Truck_{Deploy}$ ) [3.1]:

$$Truck_{Deploy} = (Func_{Day1}/100) * \text{Number of Trucks} \quad [3.1]$$

The number of usable trucks is proportional to the functionality of the facility. The personnel threat and number of usable trucks are combined to determine the number of deployable trucks. Once more, the deployment of ambulances has a slightly different procedure. As functionality decreases by 25%, approximately one ambulance becomes unusable. The combination of available paramedics and ambulances determines the final number of deployable ambulances.

Decision makers must also consider the well-being of unharmed persons who require temporary shelter. Shelters are evaluated to determine if they can receive displaced families and a functionality value greater than 50% is considered to be operational.

### **3.3.2.2 Hot zones**

There are two types of hot zones considered in this SDSS - post-earthquake fires and collapsed buildings. Appendix 3.2 depicts the major steps used to determine hot zones. First, the number of post-earthquake fires is determined by implementing the Scawthorn (2008) fire model. This model establishes the general rules for fires and is derived using Modified

Mercalli Intensity (MMI) and floor area. The former is a reflection of damage and the latter of available fuels (Scawthorn et al., 1996). Total floor area is calculated for each census tract by multiplying the plan area by the number of storeys for each building within a census tract. The user defines MMI. Table 3.4 denotes the relationship between approximate fires rates and MMI that is applied in this SDSS.

Table 3.4. The approximate ignition rate for MMI VII, VIII, IX, and X (Scawthorn et al., 2005; Scawthorn, 2008).

MMI	VII	VIII	IX	X
1 ignition per million sq. ft. of building floor area	18	10.5	4.5	1.5

Once the number of fires per census tract is calculated, the location of these fires must be approximated. All buildings with a high fire threat are extracted from the dataset and using the ‘Create Random Points’ tool, random buildings representing the number of fires per census tract are selected. The approach to utilize random point selection allows for more robust exercising of emergency plans and testing of strategies as well as helps to identify potential response challenges. For example, not all fires will be in the vicinity of alternative water sources if traditional water sources are not available.

The location of building failures is based on loss estimations. Generally, failures of wood and masonry structural systems will not require USAR, though there are exceptions. Therefore, USAR and LSAR hot zones are determined for LSAR-type (Type A) or USAR-type (Type B) buildings and the total number of failures of each type per census tract. Random points representing the number of LSAR and USAR hot zones are generated. The USAR task force deploy location is randomly selected from the USAR hot zones.

To determine shelter needs, the number of extensively and completely damaged homes are summed per census tract. Only easily identifiable family residences such as traditional timber-frame or unreinforced masonry buildings are considered in this case study. Families within these damaged homes are assumed to be displaced and require shelter. However, individuals in large concrete multi-dwellings (i.e. apartments and condominiums) may also

require shelter. The population of each household is assumed to be an average family of four. These estimations will be used to determine shelter coverage.

### **3.3.2.3 Passability and accessibility**

One post-earthquake condition that collectively affects all response units is en-route obstacles. These are defined as obstacles that emergency responders may experience while en-route to a scene or medical care facility that can delay arrival or isolate sites. Common en-route obstacles are damaged bridges and overpasses, debris on the roadways, and fire (Appendix 3.3).

Loss estimations of bridges and overpasses are not included in this disaster SDSS, as the data is not currently available with Hazus or CanRisk. However, the SDSS can be adapted in the future to be inclusive of such loss estimations. Therefore, in order to account for damaged and/or closed bridges / overpasses, assumptions can be made based on observations from previous earthquakes. In the absence of information, the default assumptions in this SDSS are that all bridges / overpasses with the following attributes are vulnerable to damage or closure, and extracted from the dataset, (1) on soil class E, (2) provincially owned, and (3) all over-water bridges.

Firstly, soil class 'E' refers to the soil conditions at a particular site where the soil is 'soft', that is, the soil has a low shear wave velocity that amplifies incoming earthquake waves.

Yashinsky (1998) noted that 85% of the damaged bridges during the 1989 Loma Prieta earthquake were located on soft soils. Secondly, provincially-owned bridges / overpasses typically represent the major highways systems that run throughout the community.

Observations from previous American earthquakes have documented damages to state-owned bridges (e.g. van Anne and Scawthorn, 1994) and the closure of state highways (Yahinsky, 1998). Lastly, Bruneau (1990) reported that the 1989 Loma Prieta earthquake caused damage to over-water bridges which is relevant to Canada as many older Canadian bridges are built with pre-code seismic design levels. The user has the option to choose the number of damaged bridges from the extracted point dataset. This choice allows the user to account for any automatic closures for bridge / overpass inspections. However, the default

value is ~5% and is based on observations from Canadian and American communities. In the 1989 Loma Prieta earthquake, 100 bridges of the 2,000 affected by shaking were damaged, of which 12 were closed (Yashinsky, 1998). Collectively, bridge / overpass damage and closures are referred to as bridge barriers and represents impassable points along the road network.

A second type of en-route obstacle that can delay response units, is a debris filled roadway. There are three primary factors considered, (1) the amount of debris per segment, (2) the number of building collapses per segment, and (3) the number of intersecting buildings at 8, 12, and 16 m road widths per segment. Hazus loss estimations provide the estimated tonnage of Type A and B debris per census tract. The combination of Type A and B building distributions per census tract and per segment (Appendix 3.1) as well as debris data per census tract (Appendix 3.3) allows for the amount of debris per segment to be approximated.

Hazus loss estimations provide the total number of buildings in each damage state including 'complete damage' per census tract. It is assumed that buildings in the 'complete damage' class have experienced at least a partial or complete collapse. LSAR and USAR hot zones already represent building failures and these are summed along each segment.

The width of the roadways including sidewalks are also accounted for as narrow roadways are likely to become impassable if building or OFC failures occur. Pre-earthquake situational awareness has already determined the number of intersecting buildings at 8, 12 and 16 m road widths. To determine if a road segment is "Most Likely Passable", "Likely Passable", "May Be Passable" or "Not Likely Passable", debris tonnage, collapses and intersecting buildings are ranked and summed along a road segment (see Appendix 3.3).

Post-earthquake fires are also obstacles. However, fires along road segments are considered separately because fire services would be responding to these scenes rather than avoiding them. If these segments were to be included in the overall road passability model, it would interrupt Network Analyst calculations for calculating en-route delays for fire services.

Collectively, road passability and fire roads are referred to as types of line barriers and represent impassable segments along the road network.

The delay of emergency vehicles can occur when point or line barriers cause a diversion while en-route to emergency scenes. Delays for responding fire services, paramedic services, and USAR task forces are evaluated using origin-destination (OD) matrix analyses available from ESRI’s Network Analyst extension. Table 3.5 outlines the parameters for each analysis. Each ‘route’ begins at a fire station, paramedic post / medical care facility, or USAR facility, and ends at the fire scene or USAR hot zone. Each route is calculated both without and with obstacles, and delays can be deduced if the cost with obstacles is greater than the cost without obstacles. Cost refers to an attribute that measures delays (i.e. impedences) along a network. The OD matrix analyses of fire service and paramedic routes use meters as an impedance attribute. The USAR team, on the other hand, uses minutes as this will be used in further calculations to determine critical exposure of entrapped persons. All evaluated routes will output as either “No Expected Obstacles” or “Expected Obstacles”.

Table 3.5: Outlines the parameters used in the origin-destination matrix analyses for responding emergency units.

Origins	Point Barriers	Line Barriers		Destinations	Cost
	Bridges/ Overpasses	Road Passability	Fire Roads		
Fire Stations	○	○		Fires	Meters
Paramedic Posts/ hospitals	○	○	○	USAR hot zones	Meters
USAR facility	○	○	○	USAR hot zones	Minutes

In addition to the evaluation of the passability and accessibility to hot zones, the SDSS also considers the accessibility of medical care facilities. Accessibility is modelled using the Network Analyst extension. A one kilometer service area is extended along the roadways surrounding each medical care facility. All point and line barriers within each service area are counted and classified into groups representing “Accessible” “Relatively Accessible”, “Not Easily Accessible”, and “Serious Accessibility Issues”. Since most medical care facilities have

multiple entrances, any hospital with “Serious Accessibility Issues” have greater than six barriers within one kilometer of them.

#### **3.3.2.4 Coverage and consequences**

The evaluation of coverage and consequences is the most valuable aspect of the SDSS as it provides useful indicators of gaps and limitations within an emergency plan. The outcome of mitigation strategies and preparedness planning is also apparent in this section. Coverage is the term that represents whether a responding unit can cope with all the emergencies within its jurisdiction, while consequences explore the outcome of the lack of coverage (see Appendix 3.4).

##### ***Fire services***

Fire service coverage is evaluated by the number of fires within its service jurisdiction and the number of available units which are able to respond. That is, are there enough deployable fire trucks to suppress the fires within their jurisdiction? This SDSS accounts for operational and non-operational communication systems to dispatch fire units and allows the decision maker to consider if the investment in redundant communication systems is a beneficial strategy. Appendix 3.4 depicts the major steps used to determine fire service coverage and consequences. If communication systems are functioning then it is assumed that fire units will dispatch according to the priority of the fire; priority is determined by the combination of occupancy class, total building area, and the number of attached buildings. Examples of high priority occupancy classes are those with a high density of occupants such as high rise buildings, critical facilities such as medical care facilities and schools, government buildings, industrial facilities, and banks. High priority is also assigned to buildings with larger floor areas and multiple attached buildings. Priority for all three factors are ranked and assigned as either “Highest”, “Moderately High”, “Moderately Low”, or “Lowest” priority. Therefore, it is assumed that the lowest priority fires may be left unattended. Alternatively, if communication systems have failed and/or self-dispatching occurs, it is assumed that units will respond to the nearest fires since these are visible from the station or are close enough

for the residents to self-report. Therefore, the fires farthest from the fire station may be left unattended.

If there are insufficient response units to suppress all post-earthquake fires, the result may be that some unattended fires are at risk of progressing to a conflagration. If these unattended fires are located in a conflagration threat zone, then they are flagged as potential conflagrations.

Currently, this disaster SDSS does not account for lifeline and utility network damage with the exception of roads and bridges. It does, however, account for damaged or inaccessible fire hydrants due to building or architectural OFC failure. Therefore, all fire hydrants along road segments labeled as “Not Likely Passable” are considered to be inoperative.

Additionally, this SDSS assesses if alternative water supplies are sufficient to suppress a building fire. All water sources within 250 m of a fire are determined and include the number of operable fire hydrants and the cumulative water volume of alternative water sources. It is assumed that the water needed to suppress the average house fire is ~94,635 litres (~25,000 gallons). All evaluated fires will output to either have “Adequate Water Availability” or “Inadequate Water Availability” with respect to alternative water.

### ***Search and Rescue***

Search and rescue operations encompasses both light SAR (LSAR) and urban SAR (USAR) operations. The coverage and consequence of each of these is covered by emergency medical services (i.e. paramedic services), police services and USAR task forces. Appendix 3.4 depicts the major steps used to determine SAR coverage and consequences.

Generally, LSAR operations do not require specialized personnel and equipment. As observed in previous earthquakes, the majority of entrapped survivors are rescued by emergent groups of volunteers who use their bare hands and simple tools for extrication. USFA (1992) and Auf der Heide (2006) concluded that the presence of authority figures, notably law enforcement officers, is warranted and that these figures are the most suitable for the coordination of volunteers. As such, this disaster SDSS assumes that police officers will be the primary responders to LSAR sites and operations. If the number of LSAR hot zones

outnumber the available responding police units then the jurisdiction is labeled as having “Unmanaged Volunteers”. If there are a sufficient number of responding units, the area is labeled as “Under Control”.

USAR operations require specialized personnel and equipment since these usually deal with the failure of large and complex buildings. Consequently, these types of collapses are also the most likely to cause life-threatening injuries. Minor, serious, life-threatening and fatal injuries can be determined by both Hazus and CanRisk; Hazus outputs are used as they provide estimations over an entire census area. Paramedic services are the responding unit that can provide the most valuable pre-hospital treatment for life-threatening injuries. Paramedic coverage is measured by the number of available ambulances and the number of life-threatening injuries within each jurisdiction. Life-threatening injuries were selected because they require advanced pre-hospital treatment while less severe injuries, though serious, generally require first aid and limb mobilization, and do not necessarily require ambulance transport. Emergency medical care coverage is labeled as being either “All Covered”, “Just Covered”, or “Not Covered”.

Lastly, if a USAR task force is based within the affected community it generally deploys to only one location. Therefore, lengthy delays are likely if a community does not have a USAR task force or requires additional support from a national USAR task force. In any international region, any delays in a USAR-type rescue can have lethal consequences for the entrapped survivors. In Canada, exposure to cold temperatures is a real threat during the cold season. The USAR rescue model within this SDSS considers (1) the time it takes for a local USAR-task force to travel to the USAR hot zone including a four hour delay for mobilization, and (2) a 48 hour delay for arrival of any national task forces. Critical exposure is calculated using the CanRisk injury model which outputs the number of hours for the core body temperature to drop below 33°C; below this temperature, serious hypothermia and the onset of life-threatening symptoms can occur. These times are compared with USAR mobilization delays (i.e. 4 hrs or 48 hrs). The entrapped survivors at the USAR hot zone will have either a “Survivable”, “Imminent”, or “Lethal” stage of exposure. However, it is important to note

that once on scene, the rescue of entrapped survivors can take hours or days that are not accounted for.

### ***Medical care operations***

Medical care facility operations are essential in the flow of life-saving treatment. Any loss of facility functionality can significantly diminish the diagnostic and treatment capacity of a modern facility. The evaluation of mass capacity, functional X-ray machines and operating suites are indicators of a facility's capacity to treat minor, serious and life-threatening injuries, respectively (<http://www.bt.cdc.gov/>). Each medical care facility is ranked according to its day 1 functionality to represent threat levels. For example, a Level 4 signifies that the facility is too badly damaged (structural or OFC) to remain fully functional and has a high likelihood of evacuation. Figure 3.2 shows the breakdown of threat levels and its relationship to X-ray and operating (OR) suite functionality.

Facility functionality on day 1 is used to deduce the number of useable X-rays and operating suites. Initially, as hospital functionality diminished by 12.5%, the functionality of the equipment decreased by 25%, which led to no useable X-ray machines or OR suites with a facility functionality of less than 50%. Observations from previous relevant earthquake case studies have demonstrated that some capacity to treat serious injuries continues even with a low facility functionality. Considering this, the proportions of useable X-ray machines within a threat level 4 designation were adjusted to reflect these possibilities. Coverage of serious injuries is calculated by the total number of functioning X-ray machines and the number of serious injuries within that facility jurisdiction for four hours. It is assumed that six patients can be X-rayed per hour ([www.cdc.gov](http://www.cdc.gov)).

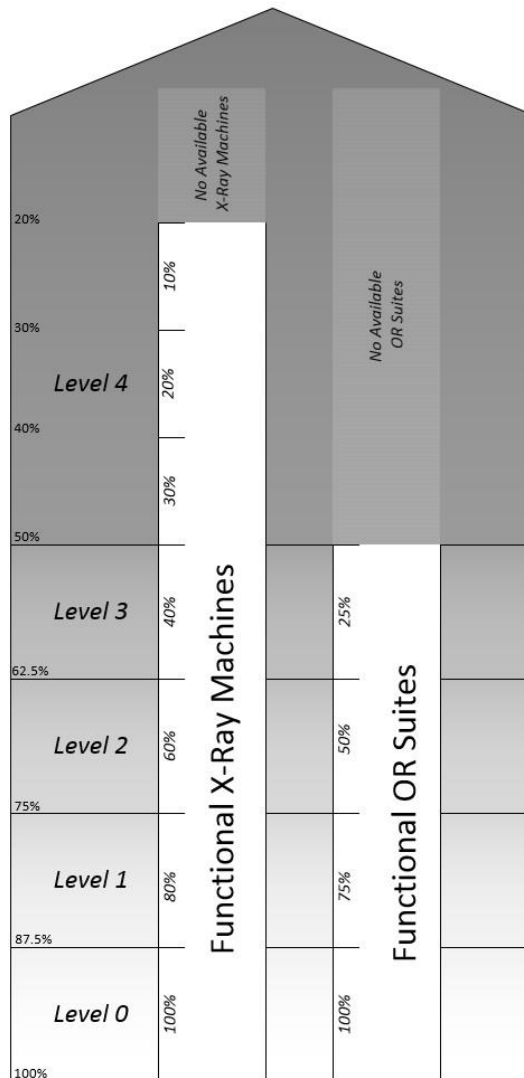


Figure 3.2: Outlines the relationship between hospital threat levels and functionality on day 1, as well as its relationship to usable equipment. Each level (0-4) is classified according to the facility functionality on day 1. The functional X-ray machine and OR suite bars depict the percent of useable equipment at a given threat level. Note that Level 0 represents a fully functional facility while Level 4 represents a facility that is non-operational due to structural damage and/or OFC damage such as burst pipes and power outages.

Operating suites have more sophisticated equipment and are in sensitive environments.

Unless facility emergency plans include contingencies for make-shift or field OR suite alternatives, then minor OFC damage such as a burst water pipes, gas lines or HVAC failures can lead to the contamination of the suite and/or the evacuation of the facility (e.g. McKeivitt et al., 1995). Therefore, if facility functionality is below 50%, then no OR suites are available

(Figure 3.2). The coverage of life-threatening injuries at each facility is determined by the number of functional OR suites and the number of incoming life-threatening injuries over the span of four hours. However, it is assumed that one OR suite can treat one patient per hour.

For the initial coverage within a facility's jurisdiction, day 1 facility functionality is not considered for the treatment of minor injuries as these can be easily treated in or outside the facility. Coverage for minor injuries is based on the facility's mass capacity and the number of injuries within each facility jurisdiction. Each medical care facility is also tagged as being "Under Capacity", "At Capacity", or "Over Capacity" for both serious / life-threatening injuries and its overall capacity (i.e. all earthquake-related injuries and pre-earthquake facility patients).

Using the SDSS outputs, an emergency manager can construct a profile for each medical facility that contains information on (1) its ability to cope with injuries generated within its jurisdiction, (2) the three nearest facilities to be used as potential locations for transfers and/or evacuations, and (3) the potential resource capacity of its facility and the three nearest facilities. The deduction of a facility's coverage and its ability to cope has already been discussed. However, observations from relevant case studies shows that some facilities must transfer patients to other hospitals that have a greater capacity to treat injuries (Tanaka, 1996; Dhar et al., 2007). For each facility, the Network Analyst extension was used to calculate the three closest facilities for transfers and/or evacuations. Key questions to determine which of the three closest facilities transfers / evacuees would be transported are (1) is the facility still functional, and if it is still functional, (2) does it have capacity to treat incoming transfers? However, some communities may only have one hospital. In these cases, the model can consider facilities in neighbouring communities but additional assumptions will have to be made as to the functionality and capacity of each.

The first factor to determine the nearest available facility for transfers / evacuation, is its operational capacity (i.e. threat level less than 4). If all three nearest facilities are non-operational, then the SDSS flags the initial facility as "Assess". Figure 3.3 shows the cascading

procedure for the hospital transfer model. The cascading effect occurs when the nearest facility is evaluated to see if it has the capacity to treat transferred patients, if it does not, then the next closest facility is evaluated, and so on. General transfers and evacuations are modelled separately. General transfers including minor, serious and life-threatening injuries can be independently evaluated but follow a similar cascading procedure. If one facility cannot cope with the transfers, then they are directed to the next facility. As previously mentioned, mass capacity, functional X-ray machines and operating suites are the key indicators to determine a facility's capacity to injuries. The facility that intakes the transfers is also evaluated to see if it "Meets Demand" or "Partially Meets Demand"; the latter occurs when some but not all of the incoming injuries can be treated.

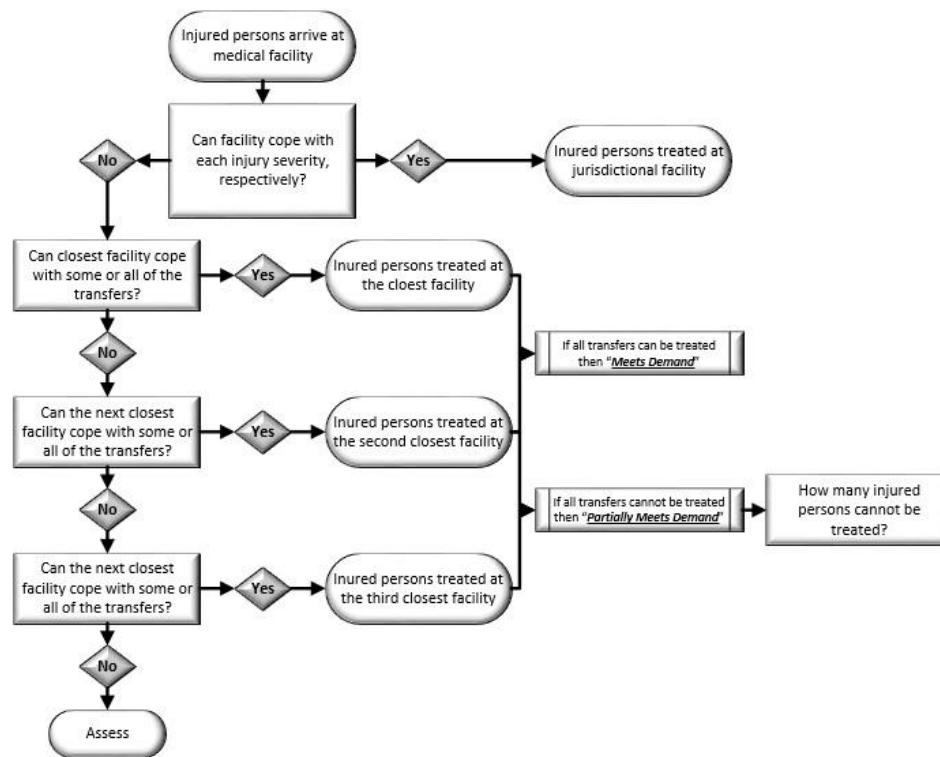


Figure 3.3: The overview of the procedure to transfer injured persons to neighbouring facilities. This procedure is also similar to the evacuation procedure.

The procedure to model evacuations is very similar, except when injured persons arrive at the hospital, the facility is assessed by its threat level. Any hospital with a threat level of 4 is

evacuated, and injured persons are transported to the next closest facility. The consequences of seasonality is also considered in the evacuation procedure. Evacuations during the 'cold' season require the transfer of all patients and injured persons to the neighbouring medical facility. During the 'warm' season, only serious and life-threatening injuries, as well as critical pre-earthquake patients are evacuated. It is estimated that 25% of pre-earthquake patients are critical and require immediate transfers.

Finally, the potential resource capacity to manage serious and life-threatening injuries of the jurisdictional facility and its three nearest facilities is evaluated. For example, not all hospitals have the capacity to treat life-threatening injuries. The attributes of each medical care facility contain information on its capacity to treat injuries, a Level 1 represents the ability to only treat minor injuries, Level 2 can treat serious injuries, while a Level 3 can treat life-threatening injuries. Each facility profile evaluates its capacity as well as the capacities of the three nearest facilities and categorizes it as: (1) "Worst case", where all the nearest hospitals can only treat minor injuries; (2) "Critical Resources"; (3) "Promising Resources", where resources to treat serious and/or life-threatening injuries are available at the jurisdictional or three nearest hospitals; (4) "Best Case", where there is a strong likelihood that the jurisdictional and/or the nearest hospitals have the resources to treat all incoming injuries.

The deployment of medical teams has been identified as a successful strategy in many past earthquakes. An assumption is that pre-established collection points at recognizable landmarks within neighbourhoods will reduce the strain on medical care facilities (e.g. Haynes et al., 1992). To model this, it is assumed that a medical field base is established within each hospital jurisdiction which should reduce the facility's anticipated surge of walk-in patients by 50% for all minor injuries and 25% for all serious injuries. Life-threatening injuries would still be transported to medical care facilities. Appendix 3.4 depicts the major steps used to evaluate the strategy to deploy medical field teams. The same procedure for hospital coverage is used, but with the adjusted number of incoming patients.

### ***Relief operations***

Like other critical facilities, shelters are not exempt from damage. All shelters with a day 1 functionality of greater than 50% is considered open and can receive displaced persons. The jurisdictions of all open shelters are updated and coverage is calculated by the number of displaced persons within that area and available space in the shelter. Each open shelter is tagged as either being “Under Capacity”, “At Capacity”, or “Over Capacity” (see Appendix 3.4).

### 3.4 Conclusion

The disaster SDSS presented in this chapter attempts to translate various aspects of seismic risk assessment into a meaningful context for decision makers in emergency management. Upon review of several case studies, this SDSS was designed to build upon previous experience by acknowledging successes, challenges and ‘lessons learned’. An evidence-based approach to disaster modelling is supported by many researchers (e.g. Durkin, 1985; Quarantelli, 1985; Ramirez and Peek-Asa, 2005; Auf der Heide, 2006). Additionally, by including multi-perspective observations, the SDSS becomes a realistic and practical tool for decision makers.

The immediate and direct applications of this SDSS are presented below. The SDSS can:

1. Test the operational readiness of a community and reveal gaps and limitations in emergency plans. These and testing preparedness and mitigation strategies can support informed decision making within a community, enhance response capacity, and promote community resilience. Proactive strategies include investing in redundant communication systems for fire coordination, alternative water sources for fire suppression, and community emergency response teams (CERT) / field medical teams. In combination with the CanRisk injury model, additional strategies include OFC retrofit programs and earthquake safety campaigns for emergency response units within a community.

2. Establish a realistic earthquake scenario, which not only provides insight into the widespread impact and operational readiness of a community, but is also a powerful educational tool. Visualization, in itself, can quickly and effectively communicate important information to a wide audience. Maps and/or tabular loss estimations can engage community conversation about a shared vision to prevent and reduce future losses.

A realistic scenario also offers research-based, scientific injects for active training such as table top exercises of emergency plans. As identified in Ontario's Emergency Management and Civil Protection Act, all communities require an emergency plan and an annual exercising / training of that plan as part of the Community's Emergency Management Program. However, plans / exercises developed in isolation can be based on misinformation and inaccurate knowledge (Mileti, 1999). The outputs of this SDSS can provide realistic details and injects for these mandated table-top or field exercises.

### 3.5 Acknowledgements

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# Chapter 4

## *Application of the CanRisk injury model and the disaster SDSS: a case study of the City of Ottawa*

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*“Bad times have a scientific value. These are occasions a good learner would not miss... What had been ever since our memory, solid continent, yawns apart, and discloses its composition and genesis. We learn geology the morning after the earthquake, on ghastly diagrams of cloven mountains, upheaved plains, and the dry bed of the sea.”*

*– Ralph Waldo Emerson*

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**Abstract:** The application of the CanRisk injury model and the disaster SDSS in a Canadian context supports the models’ utility for decision makers in emergency management. Both models were applied to 27 neighbourhoods in Ottawa, Canada, using a M6.0 and M7.25 scenario. In general, the SDSS revealed that all emergency response units will be challenged following a large earthquake. However, there is a critical threshold that exists between the M6.0 and M7.25 scenarios where emergency response will move from partial but manageable functionality to a complete breakdown of the system.

**Keywords:** *seismic risk, SDSS, earthquake preparedness, earthquake response, City of Ottawa, loss estimations, Hazus, CanRisk*

## 4.1 Introduction

A damaging earthquake presents a unique challenge to emergency management (EM) because it generally involves community-wide physical and social losses. In addition to these losses, an earthquake can instigate widespread chaos, impromptu activities, and uninformed behaviour. Among the many consequences of a poorly-coordinated response is a potential 10-fold increase in fatalities (Coburn and Spence, 2002). However, with mitigation, preparedness, and response strategies, negative consequences can be prevented, reduced or managed.

Emergency management applies science, technology, and oversight to mitigate, prepare for, respond to, and recover from extreme events that may become disasters. Historically, EM has been reactive, with a tendency to focus on the urgent aspects of a disaster and short-term goals, because it is easier to justify spending money in the short-term on the urgent effects of the disaster rather than long-term mitigation strategies (Huppert and Sparks 2006). Over the last few years, preparedness, planning, and mitigation are quickly gaining momentum as it is in everyone's best interest to prevent or reduce future losses (Mileti, 1999).

The CanRisk injury model and the disaster Spatial Decision Support System (SDSS) (see Chapters 2 and 3) are tools designed to facilitate informed decision making in emergency management in Canada regarding earthquake risk. The injury model is an extension to the CanRisk seismic assessment tool and quantifies an individual's risk to injury, the number of injuries, and provides an injury profile at the building scale. Embedded in this model is the ability to test the effect of proactive (mitigation and preparedness) strategies, specifically operational and functional component (OFC) retrofits and earthquake safety campaigns. The disaster SDSS is a GIS-based model, designed for the preparedness phase, to simulate disaster conditions relevant to immediate post-earthquake response. The SDSS focusses on fire services, search and rescue operations which include police services, emergency medical services which include paramedic services and medical care facilities, and relief/shelter

operations. The purpose of this chapter is to apply both models in Ottawa, Canada, as a case study region.

## 4.2 Case study

The City of Ottawa was selected as a case study, but Hazus Canada, the CanRisk injury model and the SDSS are applicable anywhere in Canada where the necessary data sources exist. Apart from the City of Ottawa being a convenient and strategic location with major academic institutions and government, it also is the centre of other relevant seismic risk pilot projects including the seismic microzonation of soils, ShakeMaps, and Urban RAT. Additionally, the Ottawa region has historically experienced several earthquakes (Lamontagne, 2010).

The classification of soils has become an important risk factor as a result of the 2005 National Building Code of Canada. The Geological Survey of Canada and Carleton University have evaluated the shear wave velocity of soil and rock and produced a seismic microzonation map of the National Capital Region (NCR) (Hunter et al., 2009). This revealed the geographic distribution of five soil classes (hard rock to soft soil) that exist within the study region. The presence of soft soils are of concern because they can amplify incoming seismic waves.

The three urban centres with the highest seismic risk in eastern Canada are located in the Ottawa - Quebec City corridor (Adams et al., 2002). Many agencies and universities are currently studying the various aspects of seismic risk within this corridor including the Geological Survey of Canada, Carleton University, and Western University who have developed ShakeMaps for Canada. ShakeMaps predict regional patterns of ground motion for a given earthquake magnitude and location (Pal and Atkinson, 2012). A series of high resolutions ShakeMaps were created for the National Capital Region (Pal and Atkinson, 2012) and used in this research (see Appendix 4.1).

Urban RAT is another project that was developed to evaluate seismic risk, particularly seismic vulnerability of buildings. Urban RAT was designed and developed at the University of Ottawa with support from Natural Resources Canada. This tool integrates the virtual

environment and mobile smart devices to facilitate the rapid visual screening of building structural parameters (Sawada et al., 2013; Ploeger et al., 2014). The City of Ottawa was selected as a pilot location because the development of Urban RAT was congruent with its active use. In April 2014, the Urban RAT dataset contains approximately 50,000 buildings.

The study region boundaries are dictated by the available data, in this case, the Urban RAT inventory. This dataset is further constrained by census tract boundaries that are a requisite for Hazus (Figure 4.1). Sixty-one fully-inventoried census tracts are selected, which represents ~46,500 buildings and 27 neighbourhoods. The entire geographic area measures ~81 km<sup>2</sup> and contains a population of ~227,000 citizens. The study region contains a rich mixture of historical and modern buildings, and includes Ottawa's primary tourist neighbourhood (Byward Market), the central business district and Parliament Hill (Centretown), many historical neighbourhoods (e.g. Glebe – Dow's Lake, Ottawa-South), culturally-diverse neighbourhoods (e.g. West Centretown), and large academic institutions including Algonquin College, Carleton University and the University of Ottawa.

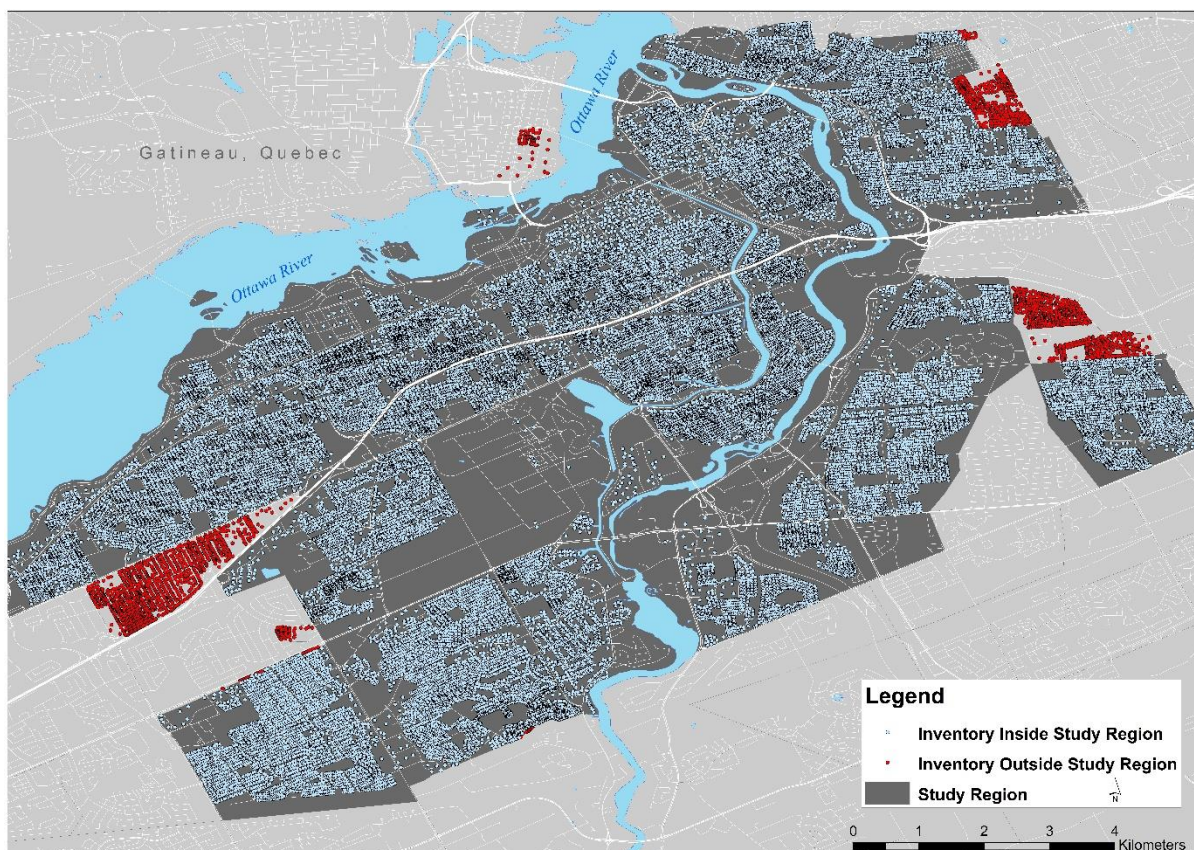
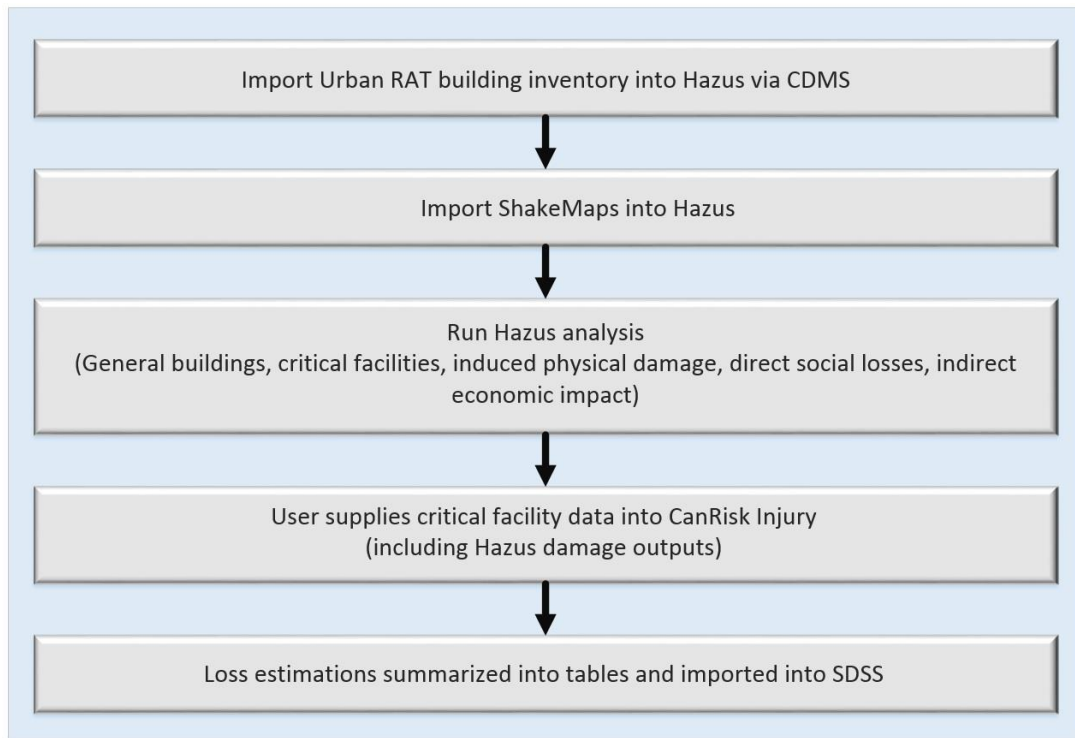


Figure 4.1: Study region within the City of Ottawa for the case study. The study region is constrained by the available building inventory from Urban RAT and census tracts.

Two scenarios were developed, and their parameters are described below. ShakeMaps (Sa(0.3s), Sa(1.0s), PGA, and PGV) were input into Hazus to represent a M6.0 (distance ~10-15 km) and M7.25 (distance ~25-30 km) earthquake (Appendix 4.1). The first scenario (M6.0) represents a realistic and 'expected' event with a 2% chance of being exceeded in a 50 year period. The second scenario (M7.25) represents a maximal value for geological regions like Ottawa (i.e. extended stable continental). The ShakeMaps were constructed using a combination of probabilistic and deterministic methods using Geological Survey of Canada hazard estimates, Atkinson and Boore (2011) ground motion prediction equations, and amplification factors to reflect soil conditions (Nastev et al., 2015). The selected ShakeMaps represent the upper limit of realistic ground motions for each scenario. These ground motions are large and plausible; a similar approach was used for "The ShakeOut Scenario" for Southern California (Perry et al., 2011).

The CanRisk injury model is used to determine the number of injuries per critical facility to support SDSS deployment calculations, and USAR hot zones to project the strain on emergency medical services. CanRisk building parameters are specific to each critical facility. However, proactive strategies were tested to see the effect of including or not, earthquake safety education and non-structural retrofits. Hazus loss estimations were also implemented. Figure 4.2 shows the procedure used to calculate loss estimations that are input into the disaster SDSS.

Figure 4.2: The procedure used to calculate loss estimations from Hazus and CanRisk.



## 4.3 Results

### 4.3.1 Loss estimations

Loss estimations are primarily generated by Hazus Canada, however building-specific injuries are from CanRisk (Table 4.1); all loss estimation results are presented in Appendix 4.2. Firstly, Hazus loss estimations summarize losses within each census tract (see Appendix 4.2A). Table 4.2a,b presents a summary of total damaged buildings by general building type and occupancy class. In the M6.0 scenario, approximately 32% of the building stock is damaged with less than 0.5% of these being partial or complete building collapses. In the M7.25 scenario, 63% is damaged with less than 1.0% of those being collapses. Unreinforced masonry (URM) buildings are the most vulnerable to damage; this building type is traditionally the most vulnerable in eastern Canada and worldwide. The least vulnerable building type is steel. Occupancy class does not affect building damage which is reflected in the results. However, religious buildings and schools are slightly more vulnerable because they generally involve masonry elements. The Sandy Hill neighbourhood incurs the highest

proportion of damage due to the high number of URM buildings and soil class D (stiff / soft soils) (Figure 4.3).

Table 4.1: Summarizes which program, Hazus or CanRisk, generated loss estimations.

Loss Estimations	Hazus	CanRisk
Building Damage	•	
Building Functionality	•	
Debris	•	
Injuries by Area	•	
Injuries by Building		•

Table 4.2: Summarizes Hazus buildings losses by general building type and occupancy class for an (a) M6.0 and (b) M7.25 scenario. The percent of buildings included in each damage state is *italicized* in (). Note that Hazus calculates losses based on probabilities, therefore the building values do not always add up between scenarios and is demarcated by ~.

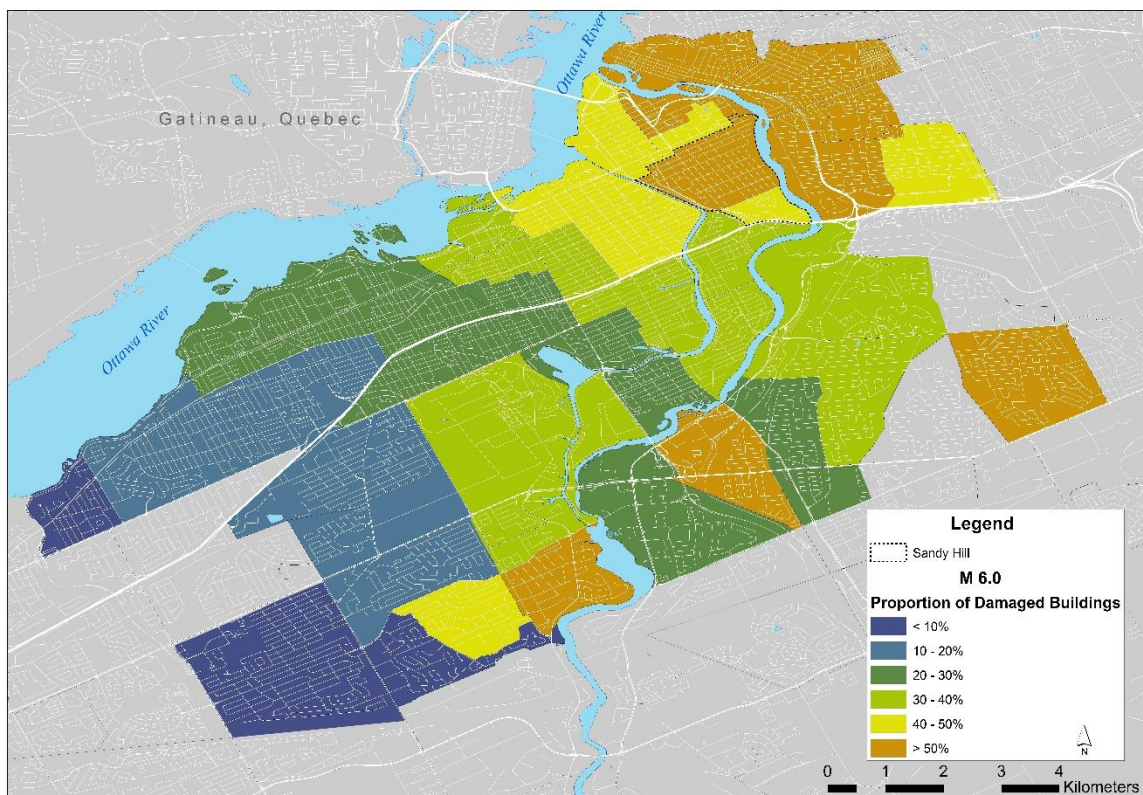
(a)

M6.0					
General Building Type					
Type	None	Slight	Moderate	Extensive	Complete
Concrete	892 (2.8)	348 (2.6)	114 (6.9)	4 (8.2)	0 (0.0)
Steel	476 (1.5)	101 (0.8)	27 (1.6)	1 (2.0)	0 (0.0)
Masonry	710 (2.2)	708 (5.3)	392 (23.7)	36 (73.5)	1 (100.0)
Timber	29357 (93.4)	12117 (91.3)	1124 (67.8)	8 (16.3)	0 (0.0)
General Occupancy Class					
Residential	29598 (94.2)	12355 (93.1)	1413 (85.3)	37 (75.5)	1 (100.0)
Commercial	1450 (4.6)	729 (5.5)	172 (10.4)	8 (16.3)	0 (0.0)
Industrial	41 (0.1)	16 (0.1)	4 (0.2)	0 (0.0)	0 (0.0)
Agricultural	2 (0.0)	1 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
Religious	94 (0.3)	53 (0.4)	19 (1.1)	1 (2.0)	0 (0.0)
Government	140 (0.4)	67 (0.5)	27 (1.6)	2 (4.1)	0 (0.0)
Education	109 (0.3)	57 (0.4)	22 (1.3)	2 (4.1)	0 (0.0)
<b>Total ~</b>	<b>31435</b>	<b>13274</b>	<b>1657</b>	<b>49</b>	<b>1</b>

(b)

M7.25					
General Building Type					
Type	None	Slight	Moderate	Extensive	Complete
Concrete	340 (2.0)	493 (2.2)	465 (7.2)	59 (12.4)	2 (6.7)
Steel	226 (1.3)	208 (0.9)	150 (2.3)	21 (4.4)	1 (3.3)

Masonry	128 (0.7)	503 (2.2)	904 (14.0)	286 (60.2)	26 (86.7)
Timber	16311 (95.9)	21250 (94.6)	4935 (76.5)	109 (22.9)	1 (3.3)
<b>General Occupancy Class</b>					
Residential	16244 (95.5)	21184 (94.3)	5615 (87.0)	340 (71.6)	22 (73.3)
Commercial	613 (3.6)	1037 (4.6)	616 (9.5)	89 (18.7)	6 (20.0)
Industrial	17 (0.1)	23 (0.1)	17 (0.3)	3 (0.6)	0 (0.0)
Agricultural	1 (0.0)	2 (0.0)	1 (0.0)	0 (0.0)	0 (0.0)
Religious	35 (0.2)	63 (0.3)	56 (0.9)	12 (2.5)	1 (3.3)
Government	55 (0.3)	80 (0.4)	84 (1.3)	16 (3.4)	1 (3.3)
Education	39 (0.2)	66 (0.3)	66 (1.0)	14 (2.9)	1 (3.3)
<b>Total ~</b>	<b>17005</b>	<b>22454</b>	<b>6454</b>	<b>475</b>	<b>30</b>



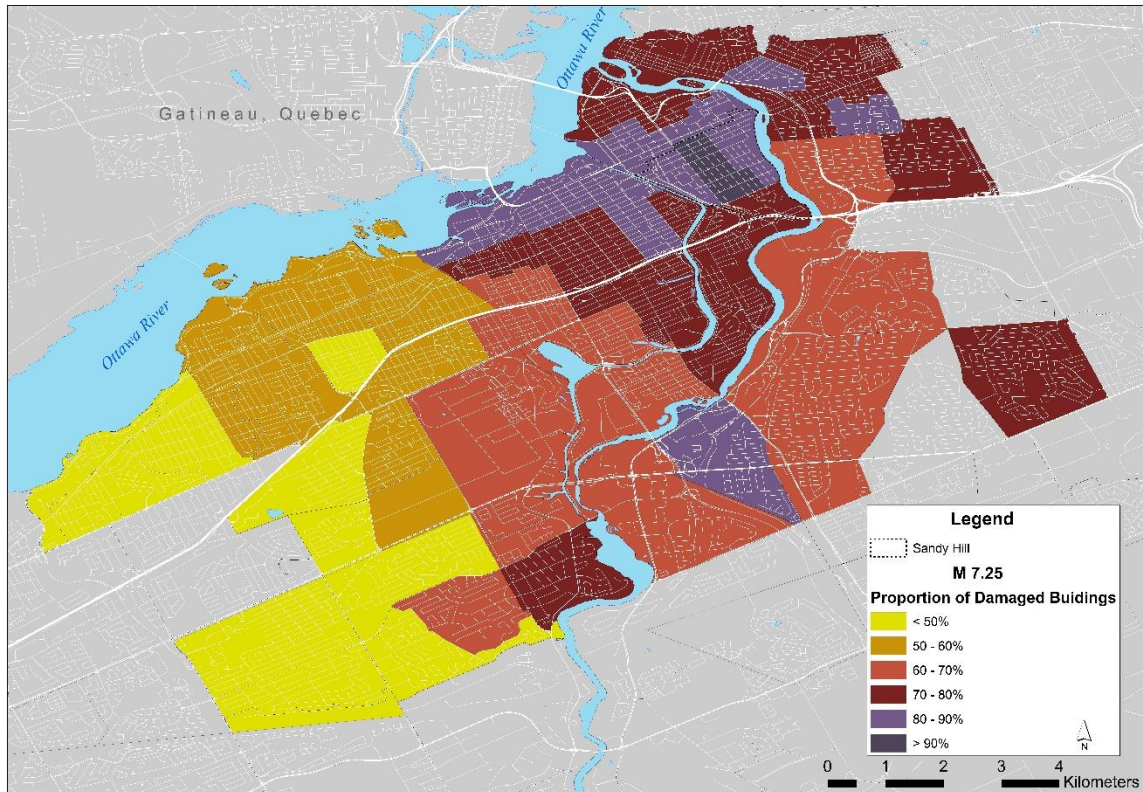


Figure 4.3: (a) Depicts the proportions of damaged buildings by census tract for the M6.0 scenario where the majority of damages are below 50% per census tract. (b) Depicts the same but for the M7.25 scenario where the most amount of damage is above 50%. In both cases, the Sandy Hill neighbourhood has the highest proportion of damage. (Data sources: DMTI spatial, Ottawa neighbourhood study, Hazus Canada).

Hazus distinguishes between debris types. Type A debris consists of wood and masonry, and can be removed with simple hand tools and common construction equipment. Type B debris consists of concrete and steel, and requires specialized equipment. Hazus results on the tonnage of debris provides two important points. Firstly, the M6.0 scenario shows that there are few extensively and completely damaged buildings. Additionally, the majority of the building inventory and damage is to timber-framed buildings. Therefore it is not surprising that more Type A debris is produced than Type B (see Table 4.3). Secondly, the M7.25 scenario generates a ten-fold increase in extensive and complete damage to steel and concrete buildings. However, there are still more timber and masonry building collapses. In this scenario, the tonnage of Type B debris is greater than the Type A debris. This may be due

to the fact that a complete collapse of a concrete structure will produce significantly more debris when compared with wood and masonry buildings.

Table 4.3: Summaries debris generation in thousands of tonnes for an (a) M6.0 and (b) M7.25 scenarios. The percent of debris type is *italicized* in ().

(a)

M6.0			
Debris Generation (thous. tonnes)			
	Type A	Type B	Total
Tonnage	112.97 (60.3)	74.5 (39.7)	187.45

(b)

M7.25			
Debris Generation (thous. tonnes)			
	Type A	Type B	Total
Tonnage	343.16 (44.0)	436.97 (56.0)	780.21

Casualties are grouped into four classes, severity 1 to 4 (minor, serious, life-threatening and fatal). The greatest number of injuries are minor, followed by serious, fatal and lastly, life-threatening. In both scenarios, over 85% of injuries are minor and approximately 10% are serious. While there are no recorded critical and fatal injuries in the M6.0 scenario, the M7.25 scenario estimates that ~ 2% are fatal and ~ 1% are life-threatening (see Table 4.4). The greater number of fatal injuries versus life-threatening injuries is dictated by Hazus methodology (FEMA, 2012) and based on ATC-13 (1985), and is likely due to the delay of advanced medical treatment and the extreme conditions in which people are injured (i.e. building collapses).

Table 4.4: Summarizes the distribution of casualties (minor, serious, life-threatening, and fatal injuries) for each general building type and occupancy class for an (a) M6.0 and (b) M7.25 scenarios. The percent of injuries by severity is *italicized* in (). Note that Hazus calculates losses based on probabilities, therefore the casualty values do not always add up between scenarios and is demarcated by ~.

(a)

M6.0	
General Building Type	

Type	Minor (Sev1)	Serious (Sev2)	Critical (Sev3)	Fatal (Sev4)
Concrete	17 (21.5)	1 (16.7)	0 (0.0)	0 (0.0)
Steel	7 (8.9)	0 (0.0)	0 (0.0)	0 (0.0)
Masonry	38 (48.1)	4 (66.7)	0 (0.0)	0 (0.0)
Wood	17 (21.5)	1 (16.7)	0 (0.0)	0 (0.0)
<b>General Occupancy Class</b>				
Residential	12 (15.2)	1 (16.7)	0 (0.0)	0 (0.0)
Commercial	59 (74.7)	5 (83.3)	0 (0.0)	0 (0.0)
Industrial	1 (1.3)	0 (0.0)	0 (0.0)	0(0.0)
Education	5 (6.3)	0 (0.0)	0 (0.0)	0 (0.0)
<b>Total ~</b>	79	6	0	0

(b)

<b>M7.25</b>				
<b>General Building Type</b>				
Type	Minor (Sev1)	Serious (Sev2)	Critical (Sev3)	Fatal (Sev4)
Concrete	75 (21.1)	9 (18.7)	1 (25.0)	1 (14.3)
Steel	40 (11.2)	5 (10.4)	0 (0.0)	0 (0.0)
Masonry	191 (53.6)	31 (64.6)	3 (75.0)	6 (85.7)
Wood	50 (14.0)	3 (6.2)	0 (0.0)	0 (0.0)
<b>General Occupancy Class</b>				
Residential	5 (1.4)	1 (2.1)	1 (25.0)	0 (0.0)
Commercial	283 (79.5)	39 (81.2)	3 (75.0)	6 (85.7)
Industrial	5 (1.4)	1 (2.1)	0 (0.0)	0 (0.0)
Education	22 (6.2)	3 (6.2)	0 (0.0)	1 (14.3)
<b>Total ~</b>	356	48	4	7

Critical facilities including fire stations, paramedic posts, medical care facilities, and shelters, were individually evaluated in Hazus; CanRisk was used to further evaluate fire stations and paramedic posts (see Appendix 4.2 B and C). Hazus loss estimations provides information on damage and functionality of each fire station and paramedic post; while CanRisk estimated the number of casualties (see Appendix 4.2 B and C). Both scenarios assumed to be in June with an air temperature above 10°C; conditions similar to the 23 June 2010 Val-des-Bois earthquake. It is also assumed that the buildings being evaluated do not have seismically retrofitted OFCs, and personnel that are not actively trained for earthquake events. The following is a brief summary of facility damage and personnel injuries (Appendix 4.2):

- Medical care facilities: In the M6.0 scenario, two of the eight facilities had a day 1 functionality below 50%. In the M7.25 scenario, all facilities have a day 1 functionality below 50%. A facility functionality of 50% is assumed to be the threshold for the capacity to perform emergency response tasks.
- Shelters: In the M6.0 scenario, five of the ten have a functionality greater than 50%. In the M7.25 scenario, all shelters but one have a functionality below 50%.
- Fire stations: In both scenarios, all stations incurred damage and injured personnel. In the M6.0 scenario, seven of the nine stations have a day 1 functionality above 50%. In the M7.25 scenario, only three are above 50%. In both scenarios, all fire stations have at least two injured fire fighters, however, some stations have up to ten injured fire fighters, including fatalities.
- There are nine paramedic posts, four of which are regular stand-alone posts, and five are acute care medical facilities. In the M6.0 scenario, eight of the nine posts have a day 1 functionality above 50%. All paramedics at regular posts receive no injuries, however, at acute care facilities, at least one paramedic crew will be injured. In the M7.25 scenario, all posts have a functionality below 50%. At least one paramedic is injured at each post except at some stand-alone posts.

#### 4.3.2 Disaster SDSS

The disaster SDSS results are presented in Appendix 4.3. The disaster SDSS has two main sections; the first is pre-earthquake situational awareness which is the same for both earthquake scenarios, and the second is post-earthquake conditions. Table 4.5 defines the use of Hazus and CanRisk loss estimations in the SDSS and denotes whether emergency resources are default or actual values for Ottawa (see Chapter 3 Table 3.2). Pre-earthquake situational awareness includes a summary of the fire and conflagration threat zones, the number of firebreaks and alternative water sources for each community block, and passability threats for each road segment. There are 3,353 community blocks in the study region. Of these, 2,235 have a low fire threat, 819 have a moderate fire threat and 299 have a high fire threat. There are 1,792 blocks with the highest threat for conflagrations. There are

only 41 community blocks that contain a firebreak with a width greater than 100 m. Additionally, there are only 305 blocks that have alternative sources of water. Note that some post-earthquake conditions generated from the disaster SDSS are randomized in that each time the model is run, a new set of locations are calculated (see Chapter 3) but provide credible representations of a possibility.

Table 4.5: Summarizes the use of Hazus and CanRisk loss estimations in the SDSS and whether emergency resources are default or actual values for the Ottawa case study. All shaded boxes denote non-applicability.

SDSS Hierarchy	Response Unit	Hazus		CanRisk		Emergency Resources <sup>1</sup>	
		Damage	Functionality	Debris	Injuries <sup>2</sup>	Injuries <sup>3</sup>	Actual
Deployment:	Fire Vehicles		•				•
	Fire fighters					•	•
Jurisdiction:	Fire					•	
Hot Zones:	Fire <sup>4</sup>						
Deployment:	USAR Vehicles		•				•
	USAR Personnel					•	•
Deployment:	Police Vehicles					• <sup>5</sup>	
	Police Officers					•	
Jurisdiction:	Police						•
Hot Zones:	USAR	•					
	LSAR	•					
	USAR Injuries/Exposure				•		
Deployment:	Ambulances		•			• <sup>6</sup>	
	Paramedics					•	
Jurisdiction:	Paramedic						• <sup>7</sup>
Jurisdiction:	Hospital						• <sup>8</sup>
Capacity:	Incoming Injuries				•		
	Threat Level		•				
	Mass Capacity						•
	X-Rays		•				•
	OR Suites		•			•	
Shelter	Capacity		•				•

<sup>1</sup> Based on Chapter 3 Table 3.2

<sup>2</sup> Injuries by census tract

<sup>3</sup> Injuries by building

<sup>4</sup> Fire hot zones are determined by MMI and total building area

<sup>5</sup> Actual values for municipal police services

<sup>6</sup> Ambulance and crews are actual but does not consider units at mobile locations

<sup>7</sup> Used the default value to be sure that model calculations would include all life-threatening injuries

<sup>8</sup> Most hospitals do not have a specific jurisdiction but support the region

#### **4.3.2.1 Passability**

Point and line obstacles can delay response units. There are 146 bridges and overpasses within the study region. In both scenarios, the SDSS indicated that more than one bridge over the Rideau River, Rideau Canal or Ottawa River was damaged and/or closed. In the M6.0 scenario, it is assumed that five are damaged and/or closed (see Chapter 3 Section 3.3.2.3). Three of these are bridges and two are overpasses. In the M7.25 scenario, an assumption is that seven bridges/overpasses are damaged. Five of these are bridges and two are overpasses. It is not the intent of the SDSS to specifically identify damaged bridges / overpasses, but rather to present the possibilities that can hinder the movement of emergency response units as experienced in previous earthquakes.

There are 10,284 road segments in the study region. Results indicate that 7,019 segments may have characteristics that increase the possibility of a road blockage due to debris (see Appendix 4.3A). In the M7.25 scenario, there are four segments that are not likely passable, and another 7,388 that have characteristics that increase the chance of a blockage.

#### **4.3.2.2 Fire services**

In the M6.0 scenario, all fire units can deploy at least one truck except for the station with a day 1 functionality of less than 10%. None of the stations can deploy all trucks. In the M7.25 scenario, only five stations can deploy a single truck, the rest can deploy no trucks (see Appendix 4.3B). In the M6.0 scenario, there are 20 simultaneous fires initiated immediately after the earthquake; 10 are unattended. All of the fires also occur within conflagration threat zones. In the M7.25 scenario, there are 34 simultaneous fires, 29 of these are unattended. All fires but two are located in conflagration threat zones (see Appendix 4.3B). In both earthquake scenarios, no fire units are delayed because of road blockages. Seasonality may play a factor in the occurrence and propagation of fires, however, this was not considered in the models.

The majority of unattended fires are in single family dwellings. In the M6.0 scenario, if fire communication systems are functional then all the unattended fires are located in residential

buildings. If communication systems are not functional then two fires are in non-residential buildings, an entertainment/recreation building (strip mall with over a dozen businesses), and another in a high school with over 1,000 students. All 4,730 fire hydrants are available if water trunk lines are intact. If water from hydrants is not available, only eight of the 20 fires have enough alternative water to suppress the average house fire.

In the M7.25 scenario, this case study indicates that if fire communication systems are functional then all but two of the unattended fires are located in residential buildings. Other unattended fires are located in a commercial strip mall with at least five businesses, and in a high school with over 1,000 students. However, six fires are in buildings with an unknown occupancy class that are likely garages or un-inventoried large buildings – a limitation of the Urban RAT dataset. All fire hydrants are available if water trunk lines are intact. If water from hydrants is not available, only 10 of the 34 fires have enough alternative water to suppress an average house fire. All unattended fires are located in a conflagration zone except for four fires.

#### **4.3.2.3 Search and Rescue operations**

In the SDSS, LSAR operations are directed by police services. It is assumed that most police units are on patrol, and therefore their ability to deploy cannot be measured by building damage. USAR operations, on the other hand, are directed by USAR task forces. In the M6.0 scenario, there is only one collapse of a masonry building. In this scenario, the LSAR operations are under control and there are no unmanaged volunteers. Since there are no collapses of steel or concrete buildings, the USAR task force is not required.

In the M7.25 scenario, there are 27 LSAR hot zones. For this scenario, there are not enough police units to manage volunteers resulting in situations of uncoordinated volunteer activities. There are three USAR hot zones, they are (1) a strip mall with three businesses, (2) a large shopping mall, and (3) a five-storey residential building containing 20-49 units. There are no expected en-route delays to USAR locations, but the Ottawa USAR task force can only deploy to one of these hot zones. Only one ambulance will experience an en-route delay to a

USAR hot zone due to a road blockage caused by a building fire. In the SDSS, it is assumed that ambulances will be prioritized to transport persons with life-threatening injuries; the number of life-threatening injuries is presented in Table 4.3. Since this scenario takes place in June with an air temperature above 10°C, there is no concern for environmental hypothermia.

#### **4.3.2.4 Emergency medical services**

There are eight medical care facilities in the study region, some of which are acute care facilities and others that are long-term care facilities. It is assumed that not all long-term care facilities have the capacity to treat serious and life-threatening injuries. In the M6.0 scenario, seven of the eight facilities have at least a threat level 1 meaning that some necessary equipment such as X-ray machines and operating suites (OR) are not available. Two are at a threat level 4, the highest of these levels and indicates a strong likelihood that this facility cannot provide adequate care to meet the entire surge in demand due to loss of equipment, pharmaceuticals and evacuation (see Appendix 4.2D). Of the study region hospitals, no transfers are required. A total of 170 patients need to be evacuated to facilities that have the capacity to treat critical illnesses and injuries. Two facilities are relatively accessible, meaning that some passability issues do exist within one kilometer of the facility (see Appendix 4.3E).

In an M7.25 scenario, all eight facilities are at a threat level 4. The facilities that are over capacity with serious and life-threatening injuries require 36 transfers. Approximately 600 critically injured and ill patients must be evacuated. Three of the facilities are relatively accessible. The deployment of field medical teams will reduce the number of injured persons seeking medical care at facilities by ~48%.

#### **4.3.2.5 Shelter operations**

There are ten shelters within the study region. In the M6.0 scenario, half are closed, but all remaining shelters are under capacity. In the M7.25 scenario, all shelters are closed except for one which is over capacity (see Appendix 4.3F).

## 4.4 Applications in Emergency Management

High resolution loss estimations from Hazus and the CanRisk injury model, and the SDSS establish a meaningful context to translate seismic risk assessments into management strategies. By maximizing the potential of loss estimation outputs and asking “what do these numbers mean for my community?”, an emergency manager can make informed decisions regarding earthquake mitigation, preparedness and response. The SDSS was designed to simulate immediate post-earthquake conditions that are important for immediate response operations. Such an approach can evaluate a community’s operational readiness, reveal limitations and resource gaps in emergency plans, and test potential proactive strategies enhance response capacity. Key results for each response unit will be discussed in further detail. An overview of the operational readiness of emergency services for the study region is presented in Appendix 4.4.

### 4.4.1 Fire services

Some aspects of the overall aim of the City of Ottawa Emergency Management Plan is to “protect the health and safety of responders, save lives, and reduce suffering” (City of Ottawa, 2010). Thus it is imperative to reduce potential injuries to fire fighters and preserve equipment functionality so they can, in turn, save lives and reduce suffering. Du Ree (1941) made important observations regarding fire station damage and the behaviour of fire fighters during the 1933 M6.4 Long Beach, California, earthquake. He noted that the fire crews had very little training on the appropriate actions to take during ground motion, and that there was an “every man for himself” mentality. At one station, the two fire fighters who sustained fatal injuries were struck by the falling non-structural brick facade as they rapidly exited the building. Garcia et al., (1994) noted that during the M6.9 1989 Loma Prieta earthquake, most fire station damage was non-structural. Non-structural / OFC damage can render trucks unusable because of jammed vehicle bay doors or large falling objects that can damage the fire trucks. Scawthorn et al., (1996) and USFA (1994) noted very little damage to

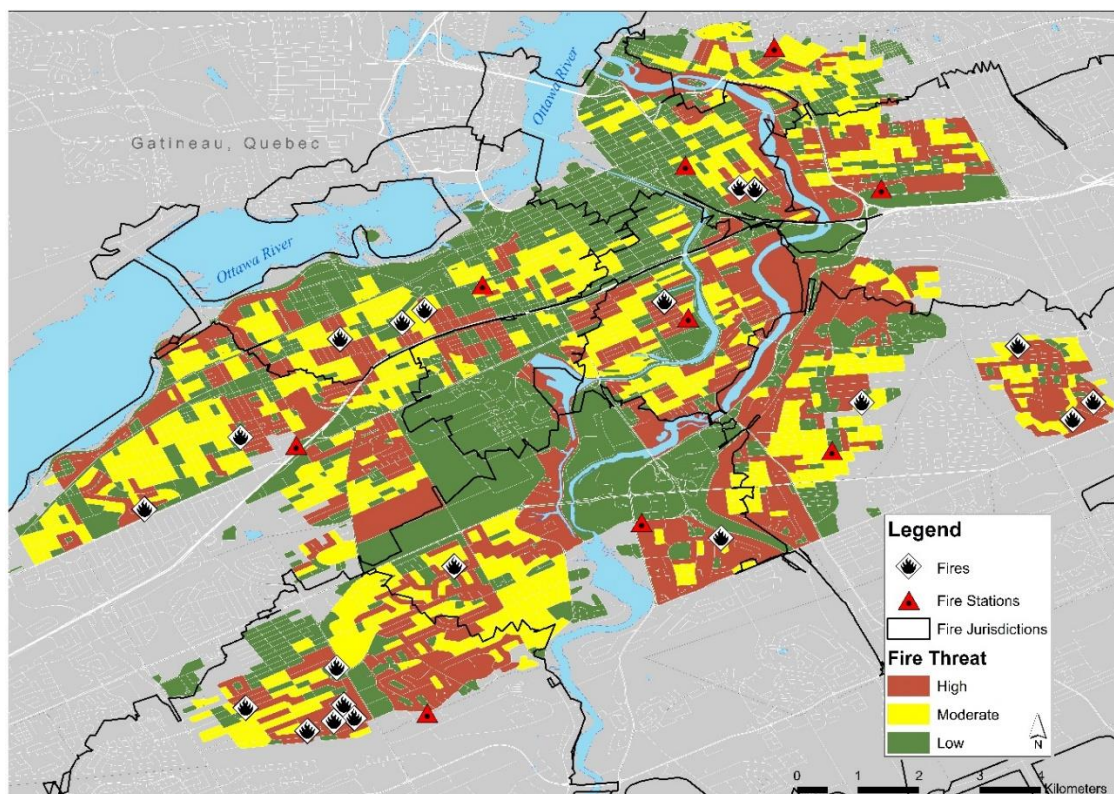
fire stations following the M6.7 1994 Northridge earthquake; the Los Angeles Fire Department had reviewed the earthquake safety of all stations before the event. These are important observations that chronicle the evolution of accepting earthquake risk (i.e. becoming aware) to implementing successful mitigation and preparedness strategies.

The default value of the number of fire fighters per station is twelve with four personnel per truck. The models reveal important information regardless if this default value is an over- or underestimation of personnel. In both scenarios, at least two fire fighters are injured per station. In the M6.0 and M7.25 scenarios, ~ 30% and 41% of fire fighters were injured, respectively. In both scenarios, at least one fire station incurred ten casualties of its twelve fire fighters. The CanRisk injury model reveals that with active earthquake safety training and the retrofit of non-structural elements of fire stations, fire fighter injuries can be reduced by 45% and 23%, respectively. These mitigation strategies are most effective for earthquakes that do not produce building failure. Naturally, to mitigate the consequences of a higher magnitude earthquake would require structural retrofits.

Scawthorn (2008) presented a general model for the number of post-earthquake fires based on the earthquake intensity and total building area. Large earthquakes are known to create simultaneous fires. For example, the 1994 M6.7 Northridge earthquake initiated 110 fires (Scawthorn et al., 1996) and the 1995 M6.9 Great Hanshin earthquake initiated ~ 100 fires (Scawthorn, 1996). The majority of post-earthquake fires occur within the first three hours (Scawthorn, 1996), but the restoration of power (e.g. USFA, 1994), and the use of furnaces/fireplaces on cold nights (e.g. USFA, 1992) can create a second wave of fires. Post-earthquake fires have been known to exhaust fire resources (personnel and trucks) within minutes following an earthquake (e.g. Garcia et al., 1994).

Under the assumption that there are three fire trucks per station, even with maximum deployment, there are not enough trucks to deal with all of the post-earthquake fires in either scenario. Additionally, some fire jurisdictions extend beyond the study region, therefore more fires can be expected to further stress the fire service units considered in this study (see Figure 4.4). Mitigation strategies can help reduce the number of fires. For

example, a retrofit strategy to anchor residential structures to their foundations may reduce the number of rotating buildings that sever adjacent gas lines (e.g. USFA, 1992). Another example is sustainable earthquake safety / preparedness campaigns that can instruct the public on how to turn off gas lines and to not to use furnaces/fireplaces unless proven safe. Alternatively, an effective planning strategy is to prepare pre-scripted messages that can inform the population about these potential fire hazards; Appendix 4.5 has an example of these messages from the Southern California Catastrophic Earthquake Response Plan (California Emergency Management Agency et al., 2010). Pre-scripted messages can be delivered in many forms including digitally (e.g. social media), manually (e.g. community bulletin boards), and verbally (e.g. radio). Planning strategies can also include multiple mutual aid pacts prior to an event. For example, following the 1994 Northridge earthquake, 102 mutual aid agencies participated in emergency efforts (Scawthorn et al., 1996). Pre-event pacts can be made with neighbouring municipal fire brigades and other fire agencies such as provincial forest fire crews, and businesses that can provide water tenders / tankers.



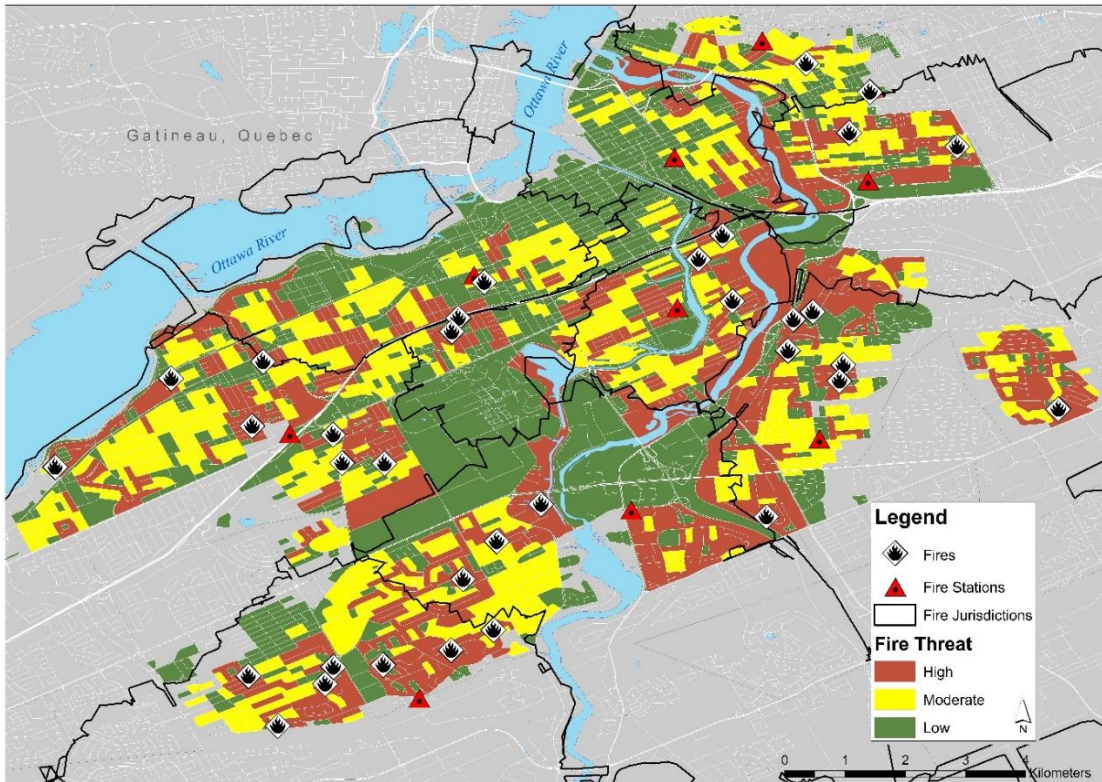


Figure 4.4: Overview of fire threat zones in the study region and the location of fire stations. The location of fires is also depicted for the (a) M6.0 and (b) M7.25 scenarios. (Data Sources: DMTI Spatial, City of Ottawa).

In both scenarios, there were no delays encountered by fire crews' en-route to the fire hot zones. However, people such as during evacuations, can become obstacles to traffic flow, but this was not modelled in the SDSS. In densely populated zones in Ottawa, people who have evacuated from high-rise buildings can block roadways and create delays. Additionally, parked or abandoned vehicles, downed electrical wires, flooded streets from broken water lines, and ruptured gas lines can create obstacles. Therefore, an earthquake during work and commuting hours will likely increase the number of en-route delays. Damaged bridges did not create delays in either scenario; it should be emphasized that the closure of any bridge would impede east-west travel due to the congestion of the re-directed traffic on the remaining passable bridges. Additionally, the closure of trans-provincial bridges would delay or prevent regional or inter-provincial aid or the movement of relief supplies.

The failure of communications, in general, has been identified as a challenge in many past earthquakes including the 2010 M5.0 Val-des-Bois earthquake. Due to these failures, fire units have been known to self-dispatch (e.g. Garcia et al., 1994). Even though many fires are left unattended, the ability to dispatch to the highest priority fires has intrinsic importance. For example, both SDSS scenarios involve fire at a high school with over 1,000 students. Therefore, investing in redundant communication systems are justly warranted.

In both scenarios the majority of fires, including unattended fires, are also in conflagration zones. The onset of a conflagration creates a cascading effect in emergency planning and is a logistical nightmare. For example, mass evacuations may need to take place, a designated route must therefore be identified and cleared, citizens must be informed, and people must be directed/transported to a safe location. Any conflagration would require extraordinary fire suppression measures including the need for water from non-traditional sources and the creation of firebreaks. Even without a conflagration, physical damage to lifeline infrastructure such as water / trunk line ruptures can leave fire crews without access to an adequate water supply. As recommended by others (Bruneau, 1990; Scawthorn et al., 1996; Ukai, 1997), the SDSS includes alternative water sources such as public / private pools and natural waterways. The City of Ottawa fire services have capabilities to draft water, however, not all communities may have the equipment for this. The results of the SDSS support that mapping alternative water sources and estimating water volume to be beneficial. Drafting from alternative water sources can help suppress 40% and 29% of the total number of house fires for the M6.0 and M7.25 scenarios, respectively. These percentages will change each time the model is run because of the random point tool used in the SDSS; however, even these modest reductions can be beneficial considering the number of fires located within conflagration zones. Other beneficial strategies may include water bladders or tenders in disaster caches or mutual aid pacts with companies that can supply water. Pacts and caches of water may also be useful in a winter scenario when pools and water bodies are empty and/or frozen.

Land use planning is a viable and sustainable long-term mitigation strategy to reduce the exposure of the built environment and population to hazards. For example, preserving or

creating green spaces in urban regions will not only promote environmental conservation, but will also act as natural firebreaks in the event of a conflagration. Implementing this strategy would be most beneficial in areas with a high conflagration threat.

#### **4.4.2 Search and Rescue and emergency medical services – Paramedic services**

The SDSS search and rescue units are composed of the USAR task force, paramedic and police services. Similar to fire services, earthquake safety training and non-structural retrofit programs at paramedic posts are beneficial and protect the health and safety of responders.

Ottawa's USAR task force is comprised of highly trained fire fighters, paramedics, and other members of the community. The USAR station is located at an active fire station just outside the study region. However, USAR personnel are not necessarily at this station during an earthquake because this team requires activation and mobilization. The assumption in this model is that all members are located at the USAR station. Damage and functionality of the USAR station is assumed to be similar to other fire stations losses located within the study region. These estimates will change as data becomes available and expands the study region. Under the assumption that 60 USAR members are available at the time of the earthquake, both scenarios reveal that 22% of USAR personnel are injured. Education and retrofit strategies would decrease injuries by ~ 61%, down to ~8%.

The default number of paramedics per post at all times is two (equivalent to one crew), with three crews at acute care facilities. Considering that the Ottawa Paramedic Service responds to approximately 12 calls per hour (City of Ottawa, 2012) and are subject to offload delays, it is not uncommon to have multiple crews at a single facility. Paramedic deployment is different from fire services, because they do not necessarily await dispatch at their posts. Ambulances and other support vehicles are often stationed at mobile locations and are dispatched from the main paramedic headquarters. In this case study, the main headquarters that houses ambulances is located just outside the study region. Staffing and coverage are also dependent on time of day; more than twice as many units are on duty during the day as oppose to the night hours. However, units can be reassigned throughout the community based on coverage needs.

Under the above assumptions, 26% and 37% of paramedics were injured during the M6.0 and M7.25 scenarios, respectively. In both scenarios, paramedics are more likely to be injured at a medical care facility due to the increased chance of being struck by falling building content. The CanRisk injury model reveals that with active earthquake safety training and the retrofit of non-structural elements at paramedic posts, paramedic injuries can be decreased by 50% and 36%, respectively.

Police services are also included in SAR operations. It is assumed that none of the police officers on patrol are injured during the earthquake. This assumption is due to Hazus casualty methodology being strictly dependent on building aspects (see FEMA, 2012). Within the study region, it is assumed that 15 municipal officers and 20 federal officers are on patrol. Provincial officers were not accounted for in these models as it is assumed the study region is not within their jurisdiction. Additional units can be deployed in emergency situations, however, these extra officers and vehicles are at police stations and are therefore subject to potential injury and/or damage. This would be an important issue in the M7.25 scenario where there are not enough officers to manage volunteers at LSAR hot zones.

In the SDSS, SAR operations are dependent on the number of collapsed buildings (LSAR and USAR hot zones). In the M6.0 scenario, Hazus estimated one LSAR hot zone and 27 were estimated for the M7.25 scenario. These results indicate that the M7.25 scenario would result in unmanaged volunteers. However, the responsibilities of police services as defined in the City of Ottawa emergency plan, would likely exhaust police service resources in both scenarios. In the post-earthquake response phase, examples of these responsibilities are (1) providing first aid, (2) directing vehicular and pedestrian traffic, (3) establishing site / perimeter security, (4) facilitating forensic identifications, and (5) maintaining public order.

One of the most common 'lessons learned' after an earthquake is the inherent altruistic behaviour of people that can greatly assist or hinder response operations. Law enforcement officers are ideal figures to best manage and direct convergent volunteers (Scawthorn et al., 1996). Preparedness strategies should include training police officers on how to effectively coordinate these volunteers. Ideally, a pre-earthquake program with registered volunteers at

any community level, would be most beneficial. Actively training and supplying volunteers with the skills and resources necessary to manage tasks in their neighbourhood whether in the workplace or at home, would greatly reduce the stress on police services. For example, registered volunteers could be trained on how to properly direct traffic and be supplied with coloured lights, flares and safety vests to aid in direction. Community groups can also be engaged as a volunteer asset. For example, a neighbourhood church group can be instructed on basic SAR training and protocols. Another example of a community-based strategy is volunteer training to help sort, manage and coordinate donations such as shovels, generators, construction vehicles, and food at pre-designated donation points. Community business owners are an integral part of a neighbourhood and may be willing to donate items such as flashlights, first aid kits, safety vests, and shovels. A community approach should also foster a shared vision of the well-being of their community as well as promote resilience.

A threshold exists between the M6.0 and M7.25 scenarios whereupon the occurrence of SAR hot zones significantly increases. For example, the 2011 M6.3 Christchurch earthquake produced two major failures of reinforced concrete (R/C) buildings that caused over half the fatalities reported from the earthquake (EERI, 2011). There are three USAR hot zones in the M7.25 scenario; (1) a strip mall with three businesses, (2) a large shopping mall, and (3) a five-storey residential building containing 20-49 units. These occupancies will change each time the model is run; however, there are important factors to consider.

Firstly, multiple USAR hot zones will likely require the support of the national USAR task force(s). The Ottawa USAR task force can mobilize in approximately four hours, but a national team, likely arriving from Toronto, will take significantly longer. Under the conditions of a daytime earthquake in June, adults and children are not likely to suffer from environmental exposure.

Secondly, if this earthquake scenario were to occur during the winter season, there is a strong possibility that entrapped survivors would become seriously hypothermic (body temperature  $<33^{\circ}\text{C}$ ). Table 4.6 provides a summary of how long it would take (in hours) for an adult or child to reach critical exposure. Considering that the Ottawa USAR team could

mobilize in approximately four hours, there are some conditions where entrapped individuals would be unlikely to survive due to exposure. Children are at a significantly higher risk to critical exposure than adults; however, night time earthquakes with a temperature below -20°C have severe consequences for both adults and children. For entrapped survivors who are awaiting the arrival of a national team, any winter earthquake may be lethal. However, Macintyre et al., (2011) argue that the question of “how long entrapped persons can survive?” should be avoided because there are many factors that affect survivability. Therefore critical exposure times listed in Table 4.6 should be considered one of many important factors.

Table 4.6: Summary of critical exposure in hours for an adult and child for six different temperature ranges. All estimates are approximate and based on being entrapped.

Temperature °C	Adult		Child	
	Day	Night	Day	Night
>10	72	72	72	14.25
0 - 10	72	11.75	21	6
-10 - 0	72	6.75	9	2.5
-15 - -10	11.75	4.5	6	1.75
-20 - -15	9.75	3.25	4.5	1.5
<-20	6.75	1.75	2.5	<1

Thirdly, the number of entrapped persons will vary by time of day and year. For example, the M7.25 scenario modeled a strip mall, large shopping mall and residential building as USAR hot zones. A daytime earthquake would cause more injuries in the commercial buildings and less in the residential building. A night time earthquake would cause more injuries in the residential buildings. In the retail occupancy class, the number of people would increase around key shopping seasons such as Christmas or ‘back to school’. Assuming an occupancy of 11-100 in the strip mall, 100-1000 in the large shopping mall, and 100-1000 in the residential building with 20-49 units, the injuries are estimated to be 8-86, 78-867, and 77-862, respectively. These occupancy ranges are from the Urban RAT dataset, and can be refined in the CanRisk injury model when exact occupancy is known. Injuries can decrease by approximately 3% with earthquake safety training and non-structural retrofits.

The primary factor to prevent injury is state-of-the-art and enforced building codes, and to complete structural and non-structural retrofits. URM buildings are the most vulnerable to damage and partial / complete failure. Mapping the distribution of these vulnerable building types may help focus structural and non-structural retrofit programs. In the study region, there is an abundance of URM buildings in the Sandy Hill, Centretown and Byward Market neighbourhoods, and along Bank Street (see Figure 4.5). Further consideration can be given to locations that may have a higher population density, economic and governmental importance, vulnerable population, key transportation networks, and other critical infrastructure. For example, Bank Street is a key route and commercial area with high pedestrian traffic within the city; investments in this location may decrease injuries and road blockages. Another location that would benefit from retrofits is the Sandy Hill neighbourhood, a region which includes student housing due to its proximity to the University of Ottawa and with stiff / soft soils. Post-secondary students are generally a vulnerable group because many come from outside the region and may not have the network necessary to seek shelter with family and friends, and may require sheltering (e.g. Lehman and Taylor, 1987). A higher demand for shelter can further stress emergency management operations.

The CanRisk injury model estimates that ~58 individuals will sustain life-threatening injuries within the collapsed shopping mall and residential building. Strategies to protect buildings against strong ground motion will reduce the number of life-threatening injuries which, in turn, will reduce demand on emergency medical services and the limited resources / medical staff at acute medical care facilities. In the M7.25 scenario, there are no hospitals with a day 1 functionality above 50%. This creates a strong likelihood that few or no operating suites are available to provide the life-saving treatment that these 58 survivors would require.



Figure 4.5: 3D view of the distribution of building types in downtown Ottawa and highlighting the Sandy Hill, Centretown and Byward Market neighbourhoods and Bank Street. (Data Sources: DMTI Spatial, City of Ottawa).

#### 4.4.3 Emergency medical services - Medical care facilities

Hazus casualty loss estimates provide the number of minor, serious, life-threatening and fatal injuries during a day, night and commuting time earthquake. Although more casualties are estimated during a daytime / commuting scenario, there are a significant number of injuries during a night time event. Therefore, earthquake safety campaigns and retrofit programs should be encouraged for both home and business owners. Moreover, it can be considered a good investment for a business to protect both employees and the inventory as it will facilitate resiliency, business continuity and reduce economic losses.

The SDSS evaluates the supply and demand for each of the eight medical care facilities located within the study region. Hazus casualty loss estimations (see Table 4.4) indicate a

total of 83 and 414 casualties in the study region for a daytime M6.0 and M7.25 scenario, respectively. These estimations should be considered the best case scenarios. Additionally, it is important to emphasize that the study region is only a portion of the City of Ottawa and casualty estimates would increase when considering the entire city. For example, post-earthquake case studies indicate that at least 24,000 were injured in the 1987 M5.9 Whittier Narrows (morning – daytime) earthquake, 16,100 in the 1989 M6.9 Loma Prieta earthquake (afternoon – daytime), and 240,000 in the 1994 M6.7 Northridge earthquake (night-time) (Shoaf et al., 1998). Furthermore, hospital medical records and workplace safety records exist for 1,543 individuals from the Loma Prieta earthquake (Durkin et al., 1991; Pointer et al., 1992); 1,140 from the 1994 Northridge earthquake (Durkin, 1996; Peek-Asa et al., 1998; McArthur et al., 2000; Mahue-Giangreco et al., 2001), and 6,659 records from the 2011 M6.3 Christchurch earthquake (Ardagh et al., 2011). Therefore, it is reasonable to assume that the number of injuries and those seeking treatment at medical care facilities will be substantially higher.

Hazus loss estimations input into the SDSS indicate six individuals with serious injuries but none where life-threatening in the M6.0 scenario, and 48 serious injuries and four life-threatening cases in the M7.25 scenario. While an individual evaluation of the M7.25 scenario USAR hot zones indicates that as many as 606 serious and 133 life-threatening injuries can be generated. There are two crucial factors to consider. First, there is an insufficient number of ambulances to cope with this demand as no ambulances will be available for immediate deployment within the study region following the M7.25 scenario. In the M6.0 scenario, there are nine available ambulances. Singular paramedic deployment, with one paramedic in an ambulance or support vehicle, can provide pre-hospital care but cannot transport injured persons. In either scenario, it is likely that most injured persons will be transported by privately-owned vehicles, police cars, buses, taxis or on-foot (Tanaka 1996; Auf der Heide 2006; Ardagh et al., 2012).

Second, both scenarios have hospitals with a threat level of 4 and have a strong likelihood that the facility cannot provide adequate care to meet the surge demand due to loss of equipment, pharmaceuticals and evacuation. In the M7.25 scenario, all hospitals are at this

threat level and approximately 19 functional X-ray machines may be available at these hospitals. This will allow for approximately 304 serious injuries to be diagnosed and treated over a four hour period. As a result, many seriously injured persons will have delayed diagnosis and treatment. The SDSS also reveals that no OR suites will likely be functional. Therefore, hospital emergency plans should include contingencies for make-shift or field OR suite alternatives. The CanRisk injury model can provide additional details regarding the type of life-threatening injuries. In the M6.0 scenario, the majority of damage involves residential homes and includes one collapse. The CanRisk injury profiles indicate that the most likely life-threatening injury will be orthopedic in nature. This would suggest that orthopedic surgeons, and dedicated OR suites for specialized orthopedic procedures such as debridement, fixation of compound fractures, and closed reductions should be considered in emergency plans (e.g. Dhar et al., 2007; Mulvey et al., 2008). Hazus estimates the collapse of three Type B buildings in the M7.25 scenario, and the SDSS provides their potential locations. Two of three were large reinforced concrete (R/C) buildings, one being a shopping mall and the other a 20-49 unit residential building. In both cases, the possibility of a life-threatening head/spinal, intra-trunk, crush and orthopedic injury are all high. When large R/C buildings collapse, crush injury is also common in these events. Highly specialized staff and equipment are needed to treat these types of injuries. For example, crush syndrome, a severe complication of crush injury, typically requires nephrologists, and specific pharmaceuticals and equipment to treat acute renal injuries.

The management of patient transfers and evacuations is problematic. No transfers are observed for the M6.0 scenario, and 36 are noted for the M7.25 scenario. Again, it is important to consider the underestimation of Hazus casualty estimations. Coordinating the transfer of patients between facilities requires adequate communication and transportation, which can be issues following a large earthquake. Both scenarios reveal a strong likelihood that at least two facilities would require evacuation due to either structural or OFC damage. Post-earthquake hospital evacuations present numerous logistical challenges. (1) Past American earthquakes document that anticipated in-facility evacuation routes are not accessible and alternate routes have to be found by non-engineers (Durkin, 1985).

Additionally, power outages or other utility damage can render elevators and staircase devices inoperable, therefore, staff will be moving patients using basic hospital equipment such as wheelchairs, backboards, mattresses and blankets (Walsh Chavez and Binder, 1996; Schultz et al., 2003). (2) In many cases, equipment, pharmaceuticals, hospital records, supplies, and food / water are compromised and/or left behind during an evacuation. Contingency planning to evacuate supplies and equipment or establish an alternate on-site cache should be considered. (3) Seasonality is an issue. During the warm season, the majority of patients can be moved to the adjacent space beside a hospital and only the most critical patients will require a transfer. Approximately 170 and 600 patients require evacuation to another facility following an M6.0 and M7.25 scenario, respectively. However, during the winter season, ~750 and ~2,800 patients would require evacuations due to the risk of hypothermia (see Appendix 4.3E) for the M6.0 and M7.25 scenarios, respectively. This presents critical logistical issues: How do we transport this number of patients? Where do we transport them to? (4) The movement of a large number of patients during either season can be a monumental task as many critical care patients require highly specialized care. A patient tracking system within community hospital plans may maximize resources and provide optimal care for those being transferred and/or evacuated.

Deployable medical personnel, trained volunteers and field facilities can significantly decrease the number of incoming patients to a medical care facility, and provide pre-hospital care to serious and critically injured persons. The SDSS estimates that the deployment of field medical teams will lessen the burden on the facilities by approximately 48% and 47% in the M6.0 and M7.25 scenarios, respectively. However, in order to maximize the benefit of deployed or activated teams, this strategy should be coordinated and included in the community emergency plan. Information regarding field teams and their locations should be disseminated to the public both before and after the earthquake. An unfamiliar location or lack of information can create confusion, or the perception that mobile medical teams are a lower-form of medical attention; thus leading injured persons to seek medical attention at the hospital rather than the mobile location (Auf der Heide, 2006). The extent of deployed / mobile medical teams can vary greatly. Community-based groups, organizations and

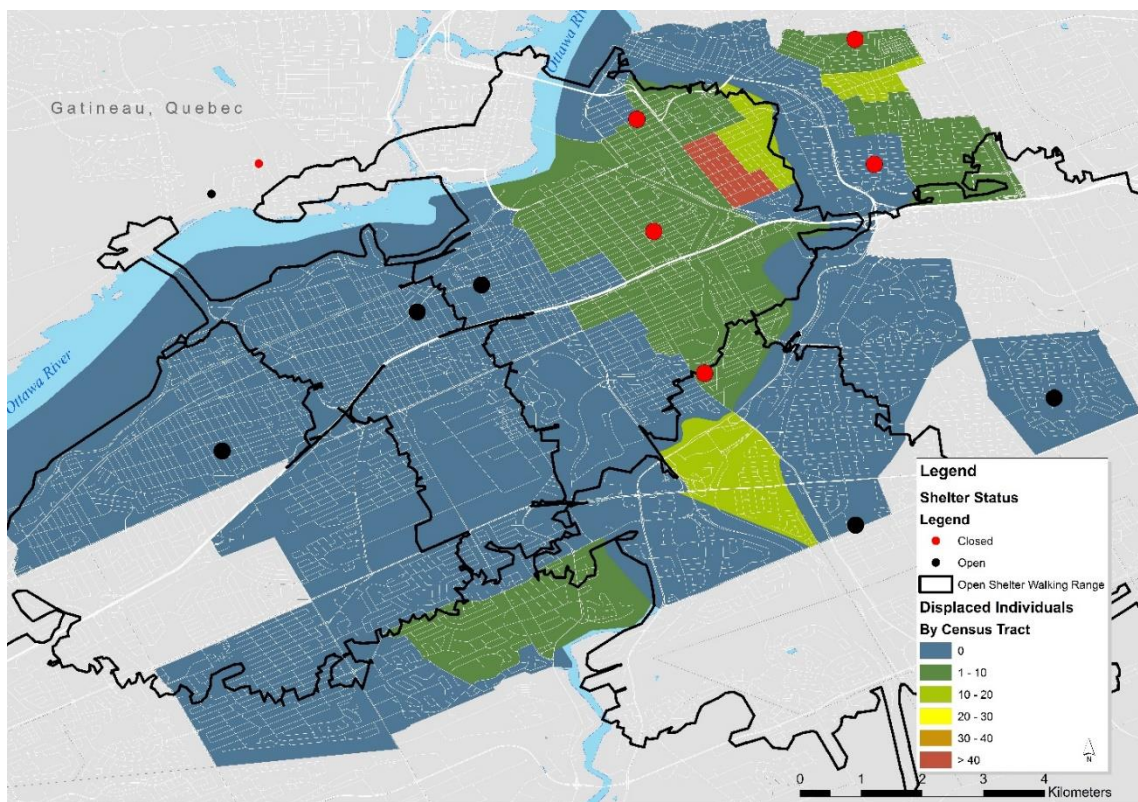
businesses can undergo first aid training which would be beneficial to reduce the number of ambulatory minor injuries. For example, a neighbourhood association / group can be given first aid training and supplies to help treat minor injuries. More organized teams such as Community Emergency Response Teams (CERT) or first response teams are also beneficial. CERT are registered volunteers who have trained with their local fire brigade to assist the community during an emergency or disaster. These volunteer teams have been implemented in various emergency plans in southern California. A tiered medical response system including first aid field posts, mobile medical team/facilities, and hospitals (e.g. Schultz et al., 1996), has also been implemented with success in past earthquakes (e.g. Sheng, 1987; Dhar et al., 2007).

Municipal, provincial and federal disaster caches such as the National Emergency Stockpile System should contain supplies to support the treatment of minor, serious, and life-threatening injuries. The result of these models demonstrate the need for make-shift OR suites and portable X-ray machines as well as the medical supplies, pharmaceuticals, blankets, tents, cots, generators, communication systems, food / water and sanitation provisions.

#### **4.4.4 Relief operations**

Relief efforts are one of the most important resources for uninjured survivors. Therefore, establishing shelters for individuals whose homes have been damaged is an important consideration in the immediate response phase (Tierney, 1988). Another group who may seek shelter are those with anxiety concerning aftershocks and have been known to camp in gardens, parks, vacant lots, alleyways, and even street medians (Hodgson et al., 1945; Carr et al., 1996). There are ten shelters within the study region. Both structural and non-structural damage can render a shelter unusable, therefore all shelters must be inspected prior to operation / activation. Additionally, shelters require resources such as potable water, sanitation disposal, and security. In the M6.0 scenario, ~ 680 individuals will require shelter. Although half of the shelters are expected to be closed, the remaining shelters are under capacity. Conversely, over 1,500 people require shelter in the M7.25 scenario (Figure 4.6). In

this case, all but one shelter are expected to be closed, surpassing its capacity, and leaving over 1,100 persons without shelter. It is important to note that only Type A buildings were considered in the calculation of displaced households, and it is therefore likely that more persons would require shelter. The greatest number of displaced households would occur in the Sandy Hill neighbourhood followed by Centretown and the Glebe. They are all adjacent to one another; this suggests that multiple shelters are needed in the downtown core. Under the premise that each shelter can support 250 people, at least four functional shelters would be required to house these three neighbourhoods alone.



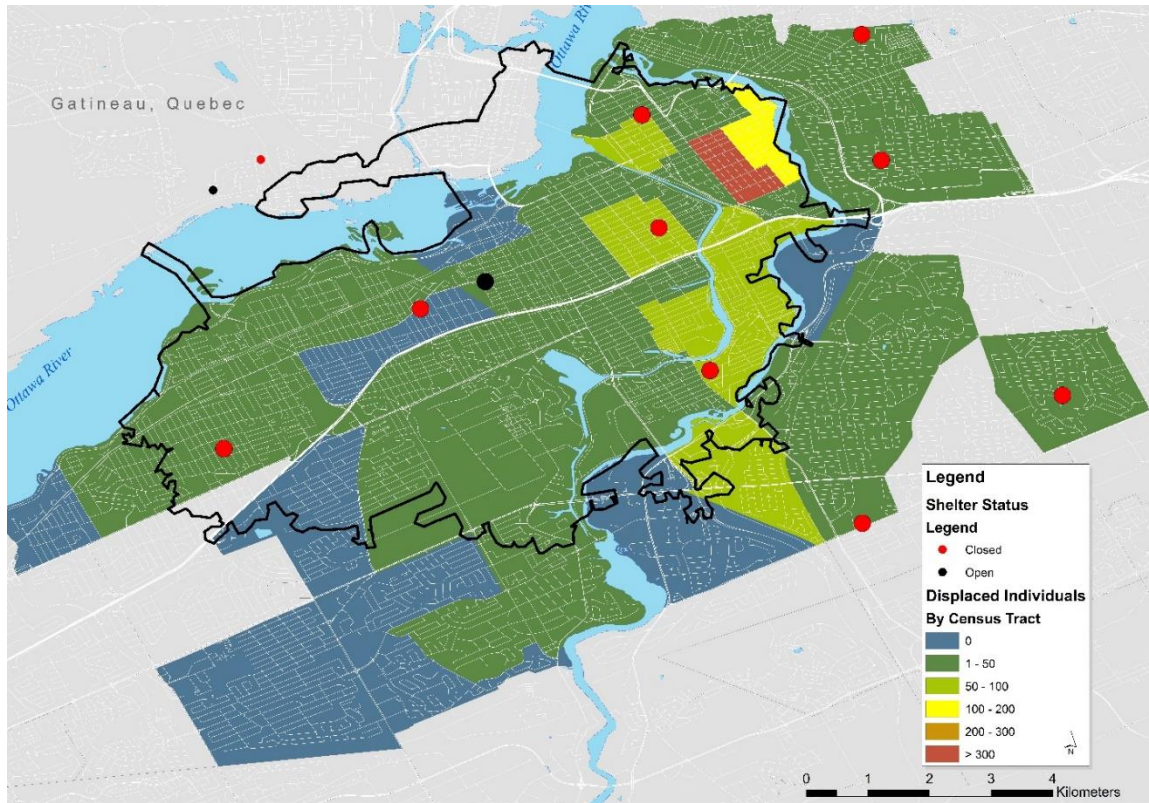


Figure 4.6: Shows an overview of the number of displaced individuals following the (a) M6.0, and (b) M7.25 scenarios. Additionally, the status of each shelter and its 5 km walking distance range is also shown. (Data Sources: DMTI Spatial, City of Ottawa).

The affected neighbourhoods are distinct and unique within the study region. Sandy Hill contains a large volume of student housing due to its proximity to the University of Ottawa. The vulnerability of post-secondary students has been studied; students tend to live in affordable and sub-standard housing and are often unaware of the earthquake threat (e.g. Lehman and Taylor, 1987). Additionally, they often come from elsewhere and can be uninformed about the seismic risk and may not have the necessary local connections; thus may require sheltering.

The Centretown neighbourhood consists of Parliament Hill and the central business district (CBD). CBDs and shopping neighbourhoods are noted to be exceptionally vulnerable to significant physical, social and economic losses due to its historical roots and dense environment (e.g. M6.3 Christchurch earthquake (EERI, 2011), M6.9 Loma Prieta earthquake

(Bruneau, 1990), M5.9 Whittier Narrows earthquake (Tierney, 1988)). The inherent vulnerability of these districts may cause more persons to be displaced as secured perimeters may be erected around heavily damaged city blocks. For example, following the M6.3 Christchurch earthquake, inspectors cordoned off over 100 square blocks in the CBD for at least ten days (EERI, 2011).

The Glebe-Dow's Lake neighbourhood is an eclectic and historical residential neighbourhood. The Glebe is family-oriented and has a strong community bond. FEMA (2012) notes that not all displaced persons will have the same need for sheltering. Households with higher income and that are predominately Caucasian (FEMA, 2012), are more likely to seek alternative shelter whether with family, friends or neighbours. As such, the Glebe neighbourhood fits these criteria within the study region. Therefore, not all displaced persons within these types of neighbourhoods are likely to seek community shelters.

Lastly, in both scenarios, hundreds of individuals may require shelters. A framework for a central registry, whether virtual and/or physical, would be beneficial to track these individuals so that families and friends can find out information about displaced persons.

## 4.5 Conclusion

The mitigation and preparedness phase of the EM cycle can prevent losses by eliminating potential threats, and reducing losses by anticipating and planning potential impacts. EM should not be practiced in isolation and community-involvement is an effective approach to foster sustainable community resilience. Both the CanRisk injury model and the disaster SDSS are practical and proactive tools to support informed decision making and enhance response capacity. Both tools are designed for Canadian settings, but also have international applications.

The City of Ottawa was selected as a study region because of its location near major academic institutions, strategic importance, and academic initiatives (seismic microzonation, ShakeMaps, and Urban RAT). A mixture of default and actual data was used in the models as

some information was publically available, and only a portion of Ottawa was modelled due to data limitations. However, the high-resolution loss estimations from Hazus and CanRisk are the first of its kind for the National Capital Region and Ontario. The application of these losses with the SDSS provides valuable insight as to the potential earthquake conditions following an M6.0 and M7.25 earthquake and their consequences in the immediate response phase.

In general, the SDSS revealed that all emergency response units will be affected and challenged following a damaging earthquake. This is not an unexpected observation, as this has been noted in many other relevant case studies. However, a critical threshold exists between the M6.0 and M7.25 scenarios where emergency response will move from partial and manageable functionality to a complete breakdown of the system. The consequences grow with the ground motion levels and include conflagrations, mass casualties, mass evacuations, and difficult black-tag triage decisions.

We, as a community, must know that progress is being made. The City of Ottawa has taken the initiative to generate a comprehensive emergency plan; this is above and beyond the mandated requirement. Additionally, the Office of Emergency Management has taken great interest in the earthquake threat that exists; earthquakes are identified as the number one threat to public safety in Ottawa. The City's initiative has also percolated into the public-private sectors. Several public and private agencies as well as various branches of government have recently conducted earthquake exercises. Hopefully this community conversation will continue to grow and foster a shared vision that will lead to sustainable and long-term mitigation and preparedness strategies.

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# Chapter 5

## *Research conclusions, future directions, and general guidelines for post-earthquake emergency response planning*

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*“Es ist nicht genug, zu wissen, man muss auch anwenden; es ist nicht genug, zu wollen, man muss auch tun.”*

*(“It is not enough to know, we must apply; it is not enough to have wishes, one must do.”)*

*- Johann Wolfgang von Goethe in Wilhelm Meisters Wanderjahre—Buch 3*

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### 5.1 Introduction

Seismic risk is comprised of hazard, vulnerability and exposure. Various levels of seismic risk exist across Canada. In eastern Canada, seismic risk is compounded by the presence of historical buildings, as well as the exposure of a large unaware and unprepared population (Bruneau, 1990; Bruneau and Lamontagne, 1994). Notably, communities in the Charlevoix-Kamouraska Seismic Zone and the Western Quebec Seismic Zone are at greatest risk. Currently, earthquakes cannot be predicted, and even if they could be, it is not feasible to relocate the population of an urban centre at risk. Therefore, effective long-term mitigation and preparedness strategies should be developed and implemented to reduce vulnerability. In developed countries, such as Canada, modern buildings codes and other mitigation strategies have resulted in the reduction of physical, social and economic losses (Mileti, 1999; Spence, 2007).

## 5.2 General challenges in disaster research and emergency management

The relationship between disaster research and emergency management has been widely discussed (e.g. Mileti, 1999; Stallings, 2002; Rodriguez et al., 2007). The design approach of the CanRisk injury model and the disaster spatial decision support system (SDSS) were, in part, a response to general challenges in disaster research and emergency management. Key concepts integrated into the approach are (1) the engagement of partnerships with the community, (2) the emphasis and intent of preparedness and mitigation strategies, (3) the need and use of data and geographic information systems (GIS) as best practice, and (4) the importance of building on successes, considering ‘lessons learned’ and challenges from relevant case studies. These common challenges which act as obstacles in the pursuit to prevent or reduce disaster losses have been identified and will be briefly discussed below in the context of this research.

### 5.2.1 Partnerships and community conversation

Emergency management should not be practiced in isolation (Mileti, 1999; McEntire, 2007). Such seclusion can lead to short-sighted and narrow-focussed strategies that lack an understanding of social science, the environment and technology (Mileti, 1999). The involvement of both vertical (municipal, provincial, federal) and horizontal (public, private, academic) partnerships builds community consensus which allows for a shared vision / commitment for the community and establishes common goals (Durkin and Thiel, 1992; Mileti, 1999; Davidson, 2002; Haque and Etkin, 2007; McEntire, 2007; Rotanz, 2007; Swanson and Bhadwal, 2009). When all stakeholders understand that there is a need to prevent / reduce losses, then individuals, households, organizations, and governments can work together and make decisions about a community’s future well-being. An excellent and promising example of community involvement is the “ShakeOut” earthquake drills which also promote awareness and practice “Drop, Cover and Hold On”. These drills began in California but have extended to British Columbia (“The Great British Columbia ShakeOut”), Quebec (“La

Grande Secousse du Québec”), and the eastern United States (“The Great SouthEast ShakeOut”).

The CanRisk injury model (see Chapter 2) and the disaster SDSS (see Chapter 3) incorporate multi-disciplinary and multi-perspective components into each model. The CanRisk injury model includes engineering, psychological, environmental, and social factors that influence an individual’s risk to injury. The disaster SDSS includes observations from various emergency response units, urban search and rescue (USAR) task forces, medical care facilities and emergency management as well as observations from scholarly disaster research to model immediate post-earthquake conditions. Additionally, these models are constructed with the cooperation and interest of municipal governments, the Ontario government, the Government of Canada, and various public and private organizations. Information and data is assembled with support from various government agencies and academic institutions.

Fostering collective concern and awareness in a community at seismic risk is difficult, especially in an intraplate setting with infrequent strong earthquakes. Visualization with tables and/or maps, in itself, is a powerful communication and educational tool because the recipient does not require technical or specialized knowledge to interpret the information. Loss estimations from Hazus, CanRisk, and the SDSS can engage the general public, public-private organizations, government and academia. Based on the experience gained during the process of designing, developing and implementing these two original tools, there is a shared and unified interest in reducing losses from future earthquakes in eastern Ontario.

### **5.2.2 Mitigation and preparedness strategies**

Mitigation and preparedness are widely known to be the most beneficial phases in the EM cycle; however, there is an overall emphasis generally placed on response and relief.

Mitigation efforts are sustained actions that help reduce losses, prevent consequences, and foster sustainability and resilience within a community. Two key approaches to mitigation are structural and social measures. Worldwide, the most important structural mitigation measures against earthquakes are superior / modern and enforced building codes and structural / non-structural building retrofits. In Canada, the National Building Code is both

superior and enforced, and advises as to the design and construction for new buildings. Unlike building codes, non-structural mitigation measures are neither 'centralized' nor 'standardized'. Arguably, long-term and sustainable educational campaigns are a social mitigation measures that show great promise (e.g. Shaw et al., 2004). The CanRisk injury model calculates an individual's risk to injury, and has the capacity to test whether non-structural retrofit programs and earthquake safety campaigns affect the overall risk to injury. Such knowledge can help decision makers at the household, business or municipal level investigate and implement various strategies to reduce future losses. The disaster SDSS, on the other hand, integrates both loss estimations and community resources, and asks the question 'what do these numbers mean for my community?'. This integration adds a meaningful context to loss estimations and helps translate seismic risk assessment into EM strategies.

Mitigation does not eliminate the need for preparedness (Mileti, 1999). Preparedness is the continuous process of developing strategies to eventually best manage an emergency or disaster. Planning is one of the major steps of the preparedness phase and attempts to anticipate the consequences of a hazard. This can facilitate informed decision making such as evaluating skills, resources, and agreements needed to build response capacity and enhance operational readiness.

The preparedness phase also encompasses the training and exercising of emergency plans; these are widely known to be successful strategies for reducing losses. Scenario building and simulations are analytically plausible accounts of future impacts and can be used as a training instrument to develop management strategies (Kleiboer, 1997). Additionally, these can be used to reveal weaknesses / gaps in emergency plans, and improve coordination and operational readiness. However, plans / exercises developed in isolation can be based on erroneous assumptions (Mileti, 1999).

The disaster SDSS is designed to be a proactive tool to enhance response planning as it specifically evaluates the pre-earthquake situational awareness and operational readiness of fire services, search and rescue operations including the urban search and rescue (USAR)

task force and police services, emergency medical services including paramedic services and medical care facilities, and shelters.

### **5.2.3 Data and technology**

The need for both qualitative and quantitative data to help define the risk have been expressed (e.g. Mileti, 1999; McEntire, 2007; Rotanz, 2007). The need for data is also identified in this research. For example, loss estimation methodology for Hazus and CanRisk require seismic hazard, building and infrastructure, and exposure data. Unfortunately, comprehensive building inventories are available in only a few urban areas and countries in the world (Erdik et al., 2011), even though these datasets produce more reliable loss estimates (FEMA, 2012; Ploeger, 2008). As such, the Urban Rapid Assessment Tool (Urban RAT) (see Sawada et al., 2013; Ploeger et al., 2014 *Accepted*) was designed, developed and implemented alongside this research in order to collect advanced engineering building data for Hazus and CanRisk loss estimations. Urban RAT is open source and available at <http://hazuscanada.ca>.

The use and/or compatibility of geographic information systems (GIS) and geomatics in loss estimation research is considered best practice and applied in many leading loss estimation methodologies, including Hazus (FEMA, 2012a), ELER (Hancilar et al., 2010), and TELES (Yeh et al., 2006). GIS-based loss estimation models and SDSSs such as those used in this research are valuable tools for all phases of EM (see Ploeger, 2014 *Submitted*). These show great promise in the development and implementation of mitigation and preparedness strategies since they can facilitate translations between research and practice (Mileti, 1999).

### **5.2.4 Evidence-based approach**

An evidence-based approach to disaster modelling is supported by many researchers (Durkin, 1985; Quarantelli, 1985; Ramirez and Peek-Asa, 2005; Auf der Heide, 2006). In disaster and loss estimation research, an evidence-based approach involves the use of empirical qualitative and quantitative data as a basis for conceptual and model frameworks.

Auf der Heide (2006) reviewed articles summarizing challenges and 'lessons learned' from previous disasters and determined that the same lessons seem to be 'learned' over and over again. Reviewing and compiling data from case studies can aid decision makers to avoid these management pitfalls and improve disaster planning (Auf der Heide, 2006). The following are examples of 'lessons learned' and successes identified in case studies that are implemented in the disaster SDSS: (1) Identifying alternative sources of water for fire suppression (USFA, 1992; Scawthorn et al., 1996; Scawthorn, 2008); (2) Accounting for self-dispatch of emergency units and the need for redundant / backup communication means (Scawthorn et al., 1996; Auf der Heide, 2006); (3) Assigning law enforcement officers to manage convergent volunteers (USFA, 1992; Auf der Heide, 2006).

The synthesis of post-earthquake qualitative observations from scholarly and governmental documents not only provides 'lessons learned' and recommendations of previous earthquake events, but also quantitative observations that can be assembled into datasets. Compiling and analyzing these datasets may reveal patterns and risk factors that will improve our understanding of seismic risk. For example, an earthquake injury dataset consisting of 44 international case studies on 19 earthquakes, which represent over 50,000 individual injuries, was compiled (see Appendix 2.1). Results from statistical analysis of this dataset, in addition to qualitative observations, supported risk factors used in the CanRisk injury model.

### **5.3 Research Conclusions**

The purpose of these models was to create pragmatic and proactive tools for decision makers in emergency management regarding earthquake risk that could translate seismic risk assessment to management strategies. Earthquake loss estimation and decision support models have direct application in emergency management and many have already been implemented in the decision making process (e.g. PAGER (Jaiswal et al., 2011), Hazus (Jones and Benthien, 2011), and LNECloss (Spence, 2007; Zonno et al., 2009)). The original tools developed in this dissertation, the CanRisk injury model and the disaster SDSS, were developed to facilitate informed decision making from the individual to community level.

Both tools are proactive in that they support a preparedness and mitigation approach to better prepare post-earthquake emergency response operations. Additionally, the CanRisk injury model can be used at the individual / household level to promote personal preparedness during an earthquake.

The overall aims of the models were to facilitate informed decision making in EM by:

- Evaluating a community’s operational readiness
- Revealing limitations and resources gaps in the emergency plan
- Testing potential mitigation and preparedness strategies
- Providing a realistic earthquake scenario for training activities.

The utility of these models is discussed in Table 5.1 in the context of the case study of the City of Ottawa applied in Chapter 4.

Table 5.1: Illustrates how the CanRisk injury and the disaster SDSS achieves these aims, using the case study of Ottawa as an example.

CanRisk injury model	Disaster SDSS
<b>Aim 1: Evaluate a community’s operational readiness</b>	
<i>General</i>	<i>Fire</i>
<ul style="list-style-type: none"> <li>• There would be injured paramedics and fire fighters that would impede deployment</li> <li>• There would be casualties throughout the study region</li> </ul>	<ul style="list-style-type: none"> <li>• There are more fires than available trucks</li> <li>• Fires in critical facilities are possible (e.g. high school with 1000+ students), important when considering dispatch priorities</li> <li>• If known, alternative water sources can suppress many fires</li> </ul>
	<i>SAR and paramedic services</i>
	<ul style="list-style-type: none"> <li>• Not all ambulances and paramedics will be able to deploy</li> <li>• USAR can deploy, with loss of some equipment and personnel</li> <li>• Unmanaged volunteers are probable</li> </ul>
	<i>Medical care facilities</i>
	<ul style="list-style-type: none"> <li>• Mostly accessible</li> <li>• Surge capacity may be exceeded with the loss of X-ray units and OR suites</li> </ul>

	<ul style="list-style-type: none"> <li>• Closure of facilities and evacuation are probable</li> </ul> <p><i>Shelters</i></p> <ul style="list-style-type: none"> <li>• Some, but not all, shelters can open</li> </ul>
<b>Aim 2: Reveal limitation and resource gaps in emergency plan</b>	
<i>Limitations</i>	<i>Limitations</i>
<ul style="list-style-type: none"> <li>• Promotion of earthquake safety training</li> </ul>	<ul style="list-style-type: none"> <li>• Need to coordinate volunteers and donated resources</li> <li>• Contingency planning for mass evacuation of hospitals</li> <li>• Secondary locations for shelters</li> </ul>
	<i>Resource gaps</i>
	<ul style="list-style-type: none"> <li>• Need mutual aid agreement for crews, trucks, and water (for fire suppression)</li> </ul>
<b>Aim 3: Test potential mitigation and preparedness strategies</b>	
<ul style="list-style-type: none"> <li>• Non-structural retrofit programs (critical facilities, workplace / household)</li> <li>• Preparedness campaigns and active training on what to do during an earthquake</li> </ul>	<ul style="list-style-type: none"> <li>• Invest in redundant communication system / procedures for fire services</li> <li>• Identify and map (in redundancy) all sources of alternative water</li> <li>• Train police officers and/or volunteers to coordinate convergent volunteers</li> <li>• Invest in deployable medical teams such as CERT, professional team (e.g. Schultz et al., 1996) or national teams (e.g. Germany' THW)</li> <li>• Provide resources for mass evacuation of medical care facilities</li> </ul>
<b>Aim 4: Provide a realistic earthquake scenario for training activities</b>	
<ul style="list-style-type: none"> <li>• Use loss estimations and model outputs presented in Appendix 4.2 and 4.3</li> </ul>	

The most immediate use of loss estimation and decision model outputs is as an educational tool to generate interest among decision makers. Presenting losses is an effective entry point to foster collective concern and engage in community conversation. This use of outputs has already proven to be effective not only within the National Capital Region but with decision makers in the public, private and government sectors across eastern Ontario.

Another straightforward use of the outputs is to build a realistic scenario for training purposes. Informed decision making in emergency management is based on experience and knowledge, and can be improved with training (Gonzalez and Brunstein, 2009). Tabletop

exercises and full-scale training are widely accepted and used in emergency management (Rosenfeld et al., 2009). In Ontario, all communities require an emergency plan and an annual exercising / training of that plan as part of the Community's Emergency Management Program. A scenario is an 'imagined form of reality' that provides plausible accounts of future risks (Kleiboer, 1997) and their design and execution are vital for tabletop and full-scale exercises (Scawthorn, 2003). These simulations offer real-life experiences that allow participants to enact roles in a fictitious context and partake in interactive and experiential learning (Kleiboer, 1997). The outputs of the CanRisk injury model and disaster SDSS provide realistic disaster conditions for this type of training. Previous research by Ploeger (2008) has been used in training exercises within eastern Ontario.

### **5.3.1 CanRisk Injury model**

The CanRisk injury model and the disaster SDSS are original contributions to further evaluate seismic risk with a contextualization for emergency management purposes. The CanRisk injury model contributes to the already existing CanRisk program, and accounts for fundamental limitations of the Hazus methodology. The injury model combines fuzzy synthetic evaluation, calculations, and a decision matrix, to estimate an individual's risk to injury, the number of injuries from building and non-building factors as well as an injury profile for life-threatening injuries at the building scale. The results from this injury model have a direct application for emergency management as they can provide insight into the benefits of implementing non-structural retrofit programs and earthquake safety campaigns. Additionally, casualty estimations and profiles can provide vital information for emergency management committees at medical care facilities, USAR task forces, and paramedic services to plan for earthquake disasters. The following are key conclusions from the development and implementation of the CanRisk injury model:

- Fuzzy synthetic evaluation (FSE) is an appropriate approach to modelling an individual's risk to injury because it can systematically handle the inherent ambiguous nature of seismic risk, incomplete and limited datasets, and expert judgment.

- The compilation and analyses of earthquake injury datasets revealed important risk factors, such as
  - The primary mechanism of earthquake injury in North American earthquakes is fall-related; the CanRisk estimation of fall injuries shows that non-building injuries (i.e fall-related) can be as high as 50%
  - Upper and lower body injuries are more predominant during daytime earthquakes likely due to body positioning and falls
  - Earthquakes with primarily operational and functional component (OFC) damage generate predominately minor injuries; the onset of building failure causes more serious injuries including crush injuries
  - Life-threatening injuries are more predominant with heavy damage (i.e. failure of large concrete and steel buildings) especially when the trunk is affected
  - Crush injuries are more predominant during large night-time earthquakes
- The FSE output of 'risk to injury' and the injury profile are consistent with Durkin et al., (1991) actual observations from the 1985 M8.0 Michoacan earthquake building collapse
- Building damage, OFC damage and earthquake safety education are the most influential risk factors in the 'risk to injury' FSE, however, the combination of less sensitive factors also affects the overall risk but at a lower level.

### 5.3.2 Disaster SDSS

The disaster SDSS is designed as a planning tool to enhance post-earthquake response. The SDSS incorporates tabular Hazus and CanRisk loss estimations with geospatial community / emergency resources to deduce pre-earthquake situational awareness and operational readiness. The model independently evaluates fire services, search and rescue operations, emergency medical services, and relief operations for immediate response activities. The SDSS is designed to evaluate specific strategies as 'lessons learned' from previous relevant earthquakes; these strategies include: the investment in redundant communication systems

for fire services; the deployment of field medical teams; and the use of alternative water sources for fire suppression. However, other important insights can also be deduced from the SDSS results. The following are key conclusions from the development and application of the disaster SDSS with emphasis on the case study of Ottawa. Since the SDSS uses random point selection to determine the location of hot zones and bridge passability, the case study conclusions may vary slightly for each scenario, however, the underlying conclusions will remain the same.

- Firebreaks (i.e. parks and parking lots greater than 100 m) reduce the number of conflagration threat zones
- The implementation of OFC retrofit programs of buildings and earthquake safety campaigns of personnel in fire services and paramedic services will reduce injuries
  - Depending on the earthquake scenario, the reduction can be as high as 45% (or 23 firefighters) for fire services and 50% (or 9 paramedics) for paramedic services
- It is likely that there will be more post-earthquake fires than the number of available fire units to adequately respond to them; many of these are also in conflagration threat zones
  - There were 10 and 29 unattended fires for the M6.0 and M7.25 earthquake scenarios in the Ottawa study region; nearly all are in conflagration threat zones
- It is beneficial to not only map alternative water sources, but also invest in drafting capabilities to manage post-earthquake fires
  - The use of alternative water sources has the capability of suppressing as much as 40% of post-earthquake fires in typical family homes
- The investment of redundant communication systems for fire services is more beneficial at reducing losses in critical facilities and large buildings in moderate-to-large earthquakes when there are less fires initiated; however, the capacity to dispatch to high-priority buildings is paramount

- In moderate-to-large earthquakes at short distances will likely cause partial or complete failures of timber-frame and unreinforced masonry (URM) buildings
  - The M6.0 scenario caused one 'light' failure (low-rise timber-frame or URM building) which had enough support from police services to coordinate convergent volunteers; however, the M7.25 scenario caused 27 'light' failures and had unmanaged volunteers
- In large earthquakes ( $M > 6.0$ ), there is a strong possibility of the collapse of multiple large reinforced concrete (R/C) buildings and USAR task forces will be required
  - In the M7.25 scenario, there were three USAR hot zones which would require Ottawa's USAR task force and at least one national USAR task force
- Multiple USAR hot zones may entrap a varying number of survivors depending on the time of day and year
  - In the M7.25 scenario, two commercial buildings and one residential building collapsed. A day time scenario suggests that there may be more trapped in the commercial building and inversely at night
- Delays in USAR mobilization and deployment have significant implications for entrapped survivors who are exposed to cold temperatures; children, night time earthquakes, and the cold season all have greater potential of critical exposure
- Multiple USAR hot zones will likely generate more life-threatening injuries that will severely strain emergency medical services
  - In the M7.25 USAR hot zones, the CanRisk injury model estimates that ~58 individuals will receive life-threatening injuries. There were no available ambulances (at posts or acute care facilities) to provide transportation in the simulation; however, single unit paramedics may provide pre-hospital care
- Mass capacity as well as the number of functional X-ray machines and operating (OR) suites, are useful indicators of a medical care facility's capacity to treat minor, serious and life-threatening injuries.
- Medical care facilities will likely incur damage in strong earthquakes and lose their functional capacity to treat and diagnose injuries / illnesses. A large earthquake may

lead to full facility evacuations that could be compounded by adverse weather conditions

- In the M6.0 scenario, two of the eight facilities have a functionality of less than 50%; while the M7.25 scenario has no facilities above 50%
- The M6.0 scenario establishes that there is a strong possibility that transfers and evacuations can be managed within the study region; however, the M7.25 scenario had serious implication for the health care system as many patients would have to be transferred and/or evacuated to other facilities (likely outside the city's jurisdiction)
- The deployment of field medical teams to known impacted locations can decrease the number of individual's seeking medical attention at hospitals by ~48%
- The presence of URM buildings is a useful indicator of a region that may require emergency sheltering, however, the absence of URM buildings does not preclude the need for shelters
- In strong earthquakes, the day 1 functionality of many shelters may be less than 50%, therefore many pre-designated shelters may not be operational
- There is a critical threshold that exists between the M6.0 and M7.25 scenarios where emergency response will move from partial and manageable functionality to a complete breakdown of the response system and capacity

## 5.4 Future Research Directions

### 5.4.1 CanRisk Injury model

Casualty loss estimation methodology is underpinned by evidence-based research and analysis. Therefore, it is imperative that case studies of future earthquakes are assembled and made available. With larger datasets and qualitative observations, loss estimation methodology can be refined, including the CanRisk injury model. The following are recommendations for future work.

### *Research-specific*

1. When more data becomes available to support risk factors, the CanRisk injury profiles can be designed using fuzzy synthetic evaluation
2. Formatting the injury and mechanism datasets to international standards and contributing them to an international repository for earthquake losses that will be accessible worldwide.

### *Field-specific*

1. Ultimately, an international framework for recording, standardizing and reporting earthquake injuries is ideal. However, even contributions from a single institution are useful in loss estimation research. Therefore, medical care facility emergency management committees should facilitate and support a framework to record earthquake-related injuries. This can be accomplished in several ways including tailored medical charts (i.e. how were you injured?), an assigned personnel or volunteer to record such information, or a pre-tested standardized questionnaire to collect relevant data after the earthquake.
2. A partner-enabled approach to case studies is also beneficial. Pre-tested standardized questionnaires can be constructed and given to participating institutions, agencies, and businesses to enable a cohort study of injuries and their mechanisms. The availability of any cohort building study with injury details can be used to calibrate and validate CanRisk's estimation of injuries and injury profile.
3. Researchers should make a better effort to publish earthquake case studies. Even small-to-moderate earthquakes such as the 2010 M5.0 Val-des-Bois that affected Ottawa can provide important observations, challenges, successes, and 'lessons learned'.

#### 5.4.2 Disaster SDSS

The Disaster SDSS is also an evidence-based model that incorporates common post-earthquake observations (successes, challenges, and ‘lessons learned’) from different perspectives and disciplines into its framework. Similarly to the CanRisk injury model, it is important that case studies are made available as these can help refine the model. Specific recommendations for future work are listed below.

##### *Research-specific:*

1. Many paramedic and police units are mobile at all times, and the assumption that all mobile units do not sustain damage / injuries may not be realistic. For example, in the M6.3 2011 Christchurch earthquake, partial collapses and out-of-plane failures onto adjacent roadways crushed a city bus and generated casualties. Therefore, these types of failures can introduce the possibility of injured personnel and/or damaged vehicles for mobile units. A study to determine how many units are mobile and their likely locations may provide (1) more realistic estimates as to the number of units in the study region, and (2) how many may be injured / damaged. On-board GPS units and publicly available data can provide this information which can be modeled with the SDSS’s debris by road segment model.
2. People in the streets are a significant en-route obstacle, especially in densely populated areas of an urban centre and should be considered as a line barrier in the SDSS. This can be modelled using building height, occupancy of a building, road width, and open areas; all of which are already integrated into the SDSS. Additionally, the CanRisk injury model can provide indicators of evacuation. For example, familiarity, previous experience, earthquake education, occupancy, and damageability can be used as indicators of a building evacuation. When the CanRisk outputs are combined with the SDSS, road segments at high risk of blockage due to people can be identified.

3. Limitations of the geographic boundary of the study region is dictated by the availability of data, in this case the Urban RAT dataset. It would be ideal to run the scenarios that include key critical facilities such as the paramedic headquarters, the USAR station, and the two other major medical care facilities in the City of Ottawa case study.
4. When the evaluation of all four building types (concrete, steel, masonry and wood) is available from the CanRisk program, the SDSS has been designed to be flexible and incorporate CanRisk losses with only a few modifications.
5. The passability and accessibility model for bridges should include more technical aspects of bridge vulnerability such as age, bridge design, number of spans, etc. Ideally, Hazus outputs or independent research conclusions can be adapted and implemented into the model to enhance accuracy.
6. The M5.0 2010 Val-des-Bois earthquake and the M<sub>N</sub>5.2 2013 Shawville earthquake may present an opportunity to validate the model. When data becomes available (e.g. ShakeMaps), the actual vs. estimated observations can be compared.

#### *Field-specific*

1. It would be ideal to implement SDSS results (culmination of Hazus, CanRisk and the SDSS) to support a table-top exercise and/or other relevant preparedness activities and have the 'players' evaluate these tools and provide feedback as to its practicality, weaknesses and strong-points. This information can refine the tool as well as point to future needs that may not have been identified in this research.

## **5.5 Calibration and validation of models**

It is widely accepted that loss estimation tools and outputs cannot be presented with total certainty (Spence, 2007). Furthermore, casualty estimation is one of the most complex issues

in earthquake loss estimation research (Zuccaro and Cacace, 2011). Nonetheless, loss estimation and decision support models are still valuable tools for decision makers. Tools can be calibrated, validated and refined with the use of empirical data. Calibration and validation of earthquake loss estimation models have utilized historical data (e.g. Frolova et al., 2011; Trendafiloski et al., 2011), and newly acquired data from recent and relevant earthquakes (e.g. Zuccaro and Cacace, 2011; Astoul et al., 2013; Sedan et al., 2013). However, many models (e.g. Jones and Dhu, 2002; Scheulen et al., 2009) including Canadian models (e.g. Ploeger, 2008) still require data for validation. Even with partially validated models, they would still benefit from additional earthquake data (e.g. Wald et al., 2011; Astoul et al., 2013; Sedan et al., 2013). Therefore, an inherent characteristic of loss estimation research is the lack of available data and having to wait for earthquakes to occur to test a model. Although complex and with inherent limitations, modelling earthquake risk cannot be disregarded. An evidence-based and multi-disciplinary approach combined with expert judgment does provide fundamental steps to understanding and modelling earthquake risk, and providing decision makers with useful emergency management tools.

Both models use software, data, and skill-sets that may not be available to all communities at risk. Although it is ideal to have these resources in order to obtain the most accurate estimations and insight for community specific management strategies, it is not always feasible. Appendix 5.1 presents general guidelines supported by observations and this research that any community can consider when reviewing their operational readiness and making decisions.

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# Appendices

Note that the appendices are labeled and ordered according to their respective chapter (i.e. there are no appendices for Chapter 1).

Appendix 2.1: Earthquake injury dataset consisting of 44 international case studies of 19 earthquakes.

EQID	Year	Urban Centre	Country	Magnitude	Injuries		Reference
					Case Study	Earthquake	
14	1948	Ashgabat	Turkmenistan	7.2	4111	4111	Beinin, 1985
25	1976	Santa Maria Cauque	Guatemala	7.5	38	38	Glass et al., 1977
23	1979	Tumaco Region	Columbia	8.1	5565	5565	Gueri et al., 1983
24	1983	Popayan	Columbia	5.5	228	228	Gueri et al., 1984
37	1985	Mexico City	Mexico	8.0	870	1034	Pan American Health Organization, 1991
38	1985	Mexico City	Mexico	8.0	142	1034	Pan American Health Organization, 1991
41	1985	Mexico City	Mexico	8.0	22	1034	Durkin et al., 1991b
9	1988	Spitak	Armenia	6.8	4799	4799	Noji et al., 1990
1	1989	Loma Prieta	United States	6.9	488	1543	Durkin et al., 1991a
2	1989	Loma Prieta	United States	6.9	1055	1543	Pointer et al., 1992
21	1990	Luzon	Philippines	7.7	295	295	Roces et al., 1992
36	1992	Landers	United States	7.3	146	146	Durkin, 1992
3	1994	Northridge	United States	6.7	330	1140	Mahue-Giangreco et al., 2001
4	1994	Northridge	United States	6.7	21	1140	McArthur et al., 2001
5	1994	Northridge	United States	6.7	153	1140	Peek-Asa et al., 1998
34	1994	Northridge	United States	6.7	636	1140	Durkin 1996
16	1995	Hanshin Region	Japan	6.9	90	7928	Ukai, 1997
17	1995	Hanshin Region	Japan	6.9	1948	7928	Matsuoka et al., 2000
18	1995	Hanshin Region	Japan	6.9	757	7928	Maruo and Matumoto, 1996
22	1995	Hanshin Region	Japan	6.9	5133	7928	Kuwagata et al., 1997; Oda et al., 1997; Tanaka et al., 1999
11	1999	Izmit Region	Turkey	7.6	50	464	Ozdogan et al., 2001
13	1999	Izmit Region	Turkey	7.6	414	464	Bulut et al., 1999
12	1999	Duzce Region	Turkey	7.2	9	9	Ozdogan et al., 2001
39	2003	Bam	Iran	6.6	713	3517	Salimi et al., 2009
40	2003	Bam	Iran	6.6	1322	3517	Mohebbi et al., 2008
52	2003	Bam	Iran	6.6	439	3517	Naghi, et al., 2005
53	2003	Bam	Iran	6.6	335	3517	Sabzehchian et al., 2006
55	2003	Bam	Iran	6.6	708	3517	Emami et al., 2005
6	2005	Kashmir	Pakistan	7.6	494	4437	Dhar et al., 2007
7	2005	Kashmir	Pakistan	7.6	468	4437	Mulvey et al., 2008
43	2005	Kashmir	Pakistan	7.6	298	4437	Sami et al., 2009
44	2005	Kashmir	Pakistan	7.6	291	4437	Bai and Liu, 2009
54	2005	Kashmir	Pakistan	7.6	2892	4437	Bozkurt et al., 2007
10	2008	Sichuan Province	China	7.9	243	13187	Wen et al., 2009
35	2008	Sichuan Province	China	7.9	3177	13187	Zhao et al., 2012
45	2008	Sichuan Province	China	7.9	196	13187	Jian et al., 2010
46	2008	Sichuan Province	China	7.9	1768	13187	Zhang et al., 2009
47	2008	Sichuan Province	China	7.9	533	13187	Yang et al., 2009
48	2008	Sichuan Province	China	7.9	1070	13187	Fan et al., 2011
49	2008	Sichuan Province	China	7.9	1862	13187	Xie et al, 2011
50	2008	Sichuan Province	China	7.9	4338	13187	Qiu et al., 2010
42	2009	Padang	Indonesia	7.5	374	374	Sudaryo et al., 2012
51	2010	Port-au-Prince	Haiti	7.0	841	841	Bar-On et al., 2011
33	2011	Christchurch	New Zealand	6.3	3002	3002	Ardagh et al., 2012

Appendix 2.2: Summary of statistical tests.

Test Name	Parameters		Pairings	p-value (proportion avg.)	P-value indicators	Test Represented		Major Observation
	A	B				EQs	Inj.	
Day(Loc)	Day	Body Location	Upper vs Trunk	0.0831 <i>(0.177 vs 0.126)</i>	Upper	11	18279	• During the day, upper and/or lower body injuries are predominant
			Upper vs Lower	0.7598				
			Trunk vs Lower	0.0972 <i>(0.126 vs 0.187)</i>	Lower			
Night(Loc)	Night	Body Location	Upper vs Trunk	0.7422		8	7196	
			Upper vs Lower	0.7998				
			Trunk vs Lower	0.6406				
Light(Loc)	Light Dmg	Body Location	Upper vs Trunk	0.402		7	3805	
			Upper vs Lower	0.675				
			Trunk vs Lower	1				
Mod(Loc)	Moderate Dmg	Body Location	Upper vs Trunk	0.8203		9	7065	
			Upper vs Lower	1				
			Trunk vs Lower	1				
Heavy(Loc)	Heavy Dmg	Body Location	Upper vs Trunk	0.313		6	14605	• In large and heavy building collapses, lower body injuries are predominant
			Upper vs Lower	0.844				
			Trunk vs Lower	0.219 <i>(0.101 vs 0.177)</i>	Lower			
Light(Sev)	Light Dmg	Severity	Sev 1 vs 2	0.078 <i>(0.409 vs 0.124)</i>	Severity 1	7	5240	• In earthquakes with little/no collapses, severity 1 injuries are predominant
			Sev 1 vs 3	0.219 <i>(0.409 vs 0.107)</i>	Severity 1			
			Sev 2 vs 3	0.375				
Mod(Sev)	Moderate Dmg	Severity	Sev 1 vs 2	0.29		8	12333	• At the onset of building collapse (moderate and high), severity 2 injuries are predominant, likely due to the progression of serious to fatal injury
			Sev 1 vs 3	0.57				
			Sev 2 vs 3	0.16 <i>(0.225 vs 0.118)</i>	Severity 2			
Heavy(Sev)	Heavy Dmg	Severity	Sev 1 vs 2	0.22 <i>(0.171 vs 0.278)</i>	Severity 2	6	13043	
			Sev 1 vs 3	0.69				
			Sev 2 vs 3	0.16	Severity 2			

Sev3(Dmg)	Severity 3	Damage	Low vs Mod Low vs High Mod vs High	0.44 0.13 0.22	High High	17	7113	• When severity 3 injuries are observed, it predominantly occurs in building collapses of large/heavy buildings
				(0.278 vs 0.132) (0.150 vs 0.185) (0.118 vs 0.185)				
Sev3(Loc)	Severity 3	Body Location	Upper vs Trunk Upper vs Lower Trunk vs Lower	0.047 0.351 0.024	Trunk Trunk	17	4807	• When severity 3 injuries are observed, it predominantly occurs in the trunk area
				(0.021 vs 0.072) (0.072 vs 0.019)				
Upper(Time)	Upper Body	Time	Day vs Night	0.17	Day	16	9842	• During the day, upper body injuries are predominant
				(0.216 vs 0.134)				
Trunk(Time)	Trunk	Time	Day vs Night	0.89		17	7210	
Lower(Time)	Lower Body	Time	Day vs Night	0.36		14	8423	
Crush(Dmg)	Crush	Damage	Low vs Mod Low vs High Mod vs High	0.2 0.64 0.55	Moderate	10	2086	• When crush injuries are observed, it predominantly occurs at the onset of building failure
				(0.014 vs 0.052)				
Crush(Time)	Crush	Time	Day vs Night	0.067	Night	10	2086	• When crush injury is observed, it predominantly occurs at night
				(0.0466 vs 0.137)				

Appendix notes:

‘Test Name’ and ‘Parameters’ is the abbreviated identifiers of each statistical test – Day-Day, Night-Night, Light-Light damage, Mod-Moderate damage, Heavy-Heavy damage, Sev3-Severity 3 injury (life-threatening), Upper-Upper body, Trunk-Trunk, Lower-Lower body, Crush-Crush injury, Loc-Body location, Sev-Injury severity (1,2,3), Dmg-Damage.

‘Pairings’ show the two parameters used in the Wilcoxon signed-ranked test.

'p-value (proportion avg.)' shows the p-value result of each sign-rank test, and in brackets in the average of each parameter. Note that the sum of the proportions were used as instead of absolute counts in order to account for inter-earthquake variability.

'P-value indicators' is the parameter that had the greatest effect.

'Test Represented' summarizes the number of earthquakes and injuries used in each test.

'Major Observation' is the statement of which factor had the greatest effect.

Appendix 2.3: Risk factors of life-threatening head/spinal, trunk, orthopedic, and crush injuries are listed in order of most influential to least influential. Key evidence to support each factor is abridged.

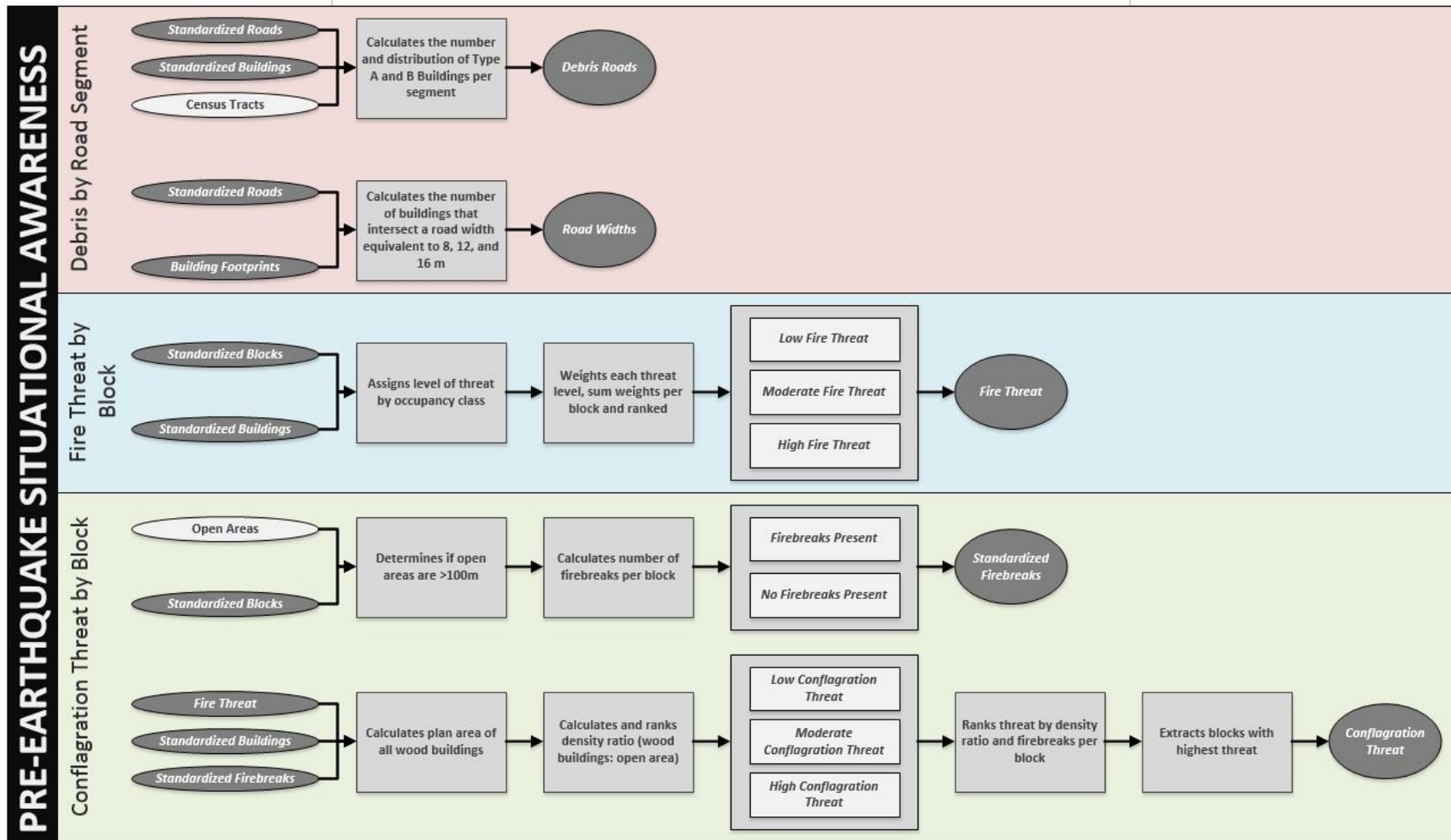
Injury Type	Risk Factor	Most Significant	Support
<b>Head/ Spinal</b>	Retrofit Decisions	No retrofits	Falling OFCs and building elements (Shoaf et al., 1998; Coburn and Spence, 2002)
	Time of Day	Day	Common in day when standing or sitting (Beinin, 1985; Sheng, 1987; Maruo and Matumoto, 1996; Papadopoulos et al., 2004)
	Damageability	<0.7	Likely fatal from building failure (Noji et al., 1990; Tanaka et al., 1999; Coburn and Spence, 2002)
	Earthquake Education	No education	Earthquake education reduces injuries (e.g. USFA 1992, El-Tawil and Aguirre, 2010)
<b>Trunk</b>	Damageability	>0.7	Likely with building failure or falling structural debris (Peek-Asa et al., 1998; Ozdogan et al., 2001; Coburn and Spence, 2002)
	Building Material	Heavy/Complex	Likely increases with building failure (Ozdogan et al., 2001) Supported by statistical tests - Sev3(Dmg), Sev3(Loc), Mod and High (Sev)
	Time of Day	Night	Common at night when in supine or lateral position (Sheng, 1987; Maruo and Matumoto, 1996; Papadopoulos et al., 2004)
	Earthquake Education	No education	Earthquake education reduces injuries in building failure (Durkin and Murakami, 1988)
	Retrofit Decisions	No retrofits	Void spaces from OFCs and structural elements play a role in survivability (Durkin and Murakami, 1988; Durkin and Thiel, 1992)
<b>Orthopedic</b>	Earthquake Education	No education	Common extremity injuries from attempting to protect property (Mahue-Giangreco et al., 2001) and falls (Durkin et al., 1991a; Durkin and Thiel, 1992; Shoaf et al., 1998)
	Time of Day	Day	As Above Supported by statistical tests - Day(Loc), Upper(Time)
	Retrofit Decisions	No retrofits	As Above
	Damageability	<0.7	Serious orthopedic injuries progress to crush injury with building failure
<b>Crush</b>	Damageability	>0.7	Mainly in failure of large R/C buildings (Tanaka et al., 1999; Coburn and Spence, 2002)

		Supported by statistical tests - Crush(Dmg), High(Loc), Mod and High(Sev) High(Loc) may support that lower body crush injuries are most common (Oda et al., 1997)
Building Material	Heavy/Complex	As Above
Time of Day	Night	Crush injury may be related to lying down and pinned, rather than standing/sitting Supported by statistical test - Crush(Time)
Body Temperature	Serious	Mild hypothermia may be beneficial may affect onset/progression of crush syndrome (Takagi et al., 2001; Schaser et al., 2006; Mulvey et al., 2008)
Earthquake Education	No education	Note: Earthquake education reduces injuries even in building failure (Durkin and Murakami, 1988)

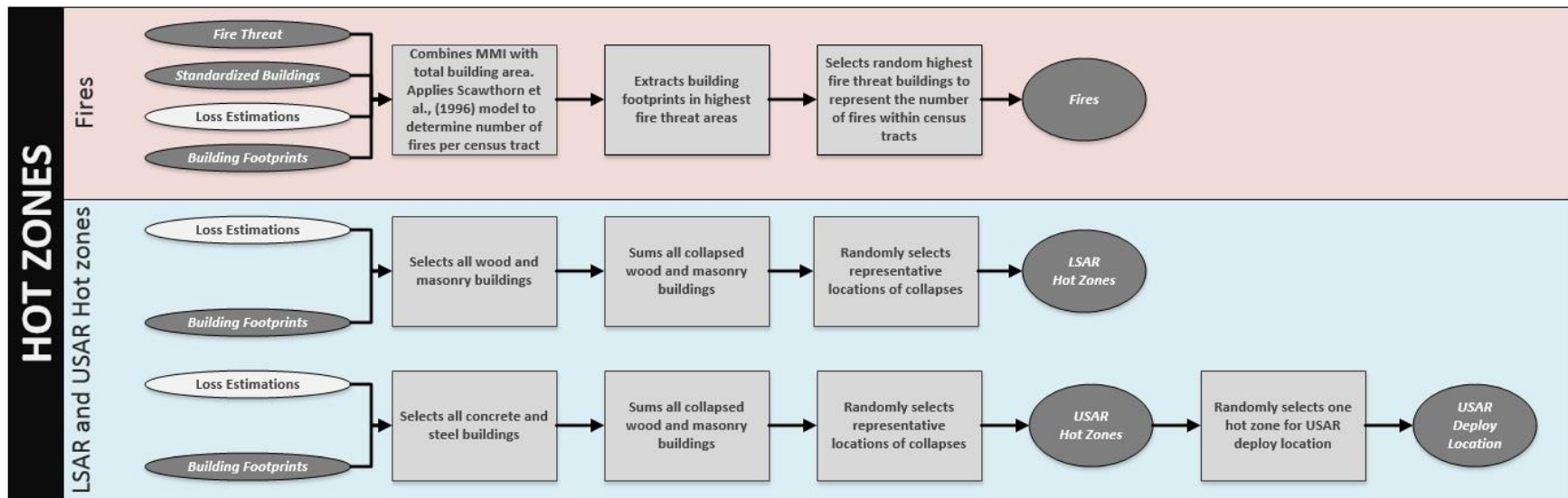
Appendix 2.4: Summary of case studies with injuries characteristic from falls.

Earthquake	Date	Damage	Education	Minor	Serious	Critical	Reference
Ashgabat, Turkmenistan	06 October 1948	Moderate	No		676		Beinin, 1985
Tumaco, Columbia	12 December 1979	Moderate	No			32	Gueri et al., 1983
Popayan, Columbia	31 March 1983	Moderate	No		31	36	Gueri and Alzate, 1984
Mexico City, Mexico	19 September 1985	Heavy	No	87	78	28	Pam American Health Organization, 1991
Spitak, Armenia	07 December 1988	Heavy	No	102	849		Noji et al., 1990
Loma Prieta, California, USA	17 October 1989	Low	Yes	287		10	Durkin et al., 1991a
Landers, California, USA	28 June 1992	Low	Yes	8			Durkin 1992
Northridge, California, USA	17 January 1994	Low	Yes	110	26		Durkin 1996
Kobe, Japan	17 January 1995	Moderate	Yes		33	133	Maruo and Matumoto, 1996; Ukai, 1997
Izmit, Turkey	17 August 1999	Moderate	No		70		Ozdogan et al., 2001
Duzce, Turkey	12 December 1999	Low	No		3	2	Bulut et al., 1999; Ozdogan et al., 2001
Bam, Iran	26 December 2003	Moderate	No	508	1044	136	Emami et al., 2005; Salimi et al., 2009;
Kashmir, Pakistan	08 October 2005	Moderate	No	28	541	373	Dhar et al., 2007; Mulvey et al., 2008; Bai and Liu, 2009
Sichuan, China	12 May 2008	Heavy	No	497	2816	250	Zhang et al., 2009; Fan et al., 2011; Zhao et al., 2012
Port-au-Prince, Haiti	12 January 2010	Heavy	No	98	219	92	Bar-On et al., 2011
Christchurch, New Zealand	22 February 2011	Low	No	2636	30	27	Ardagh et al., 2012

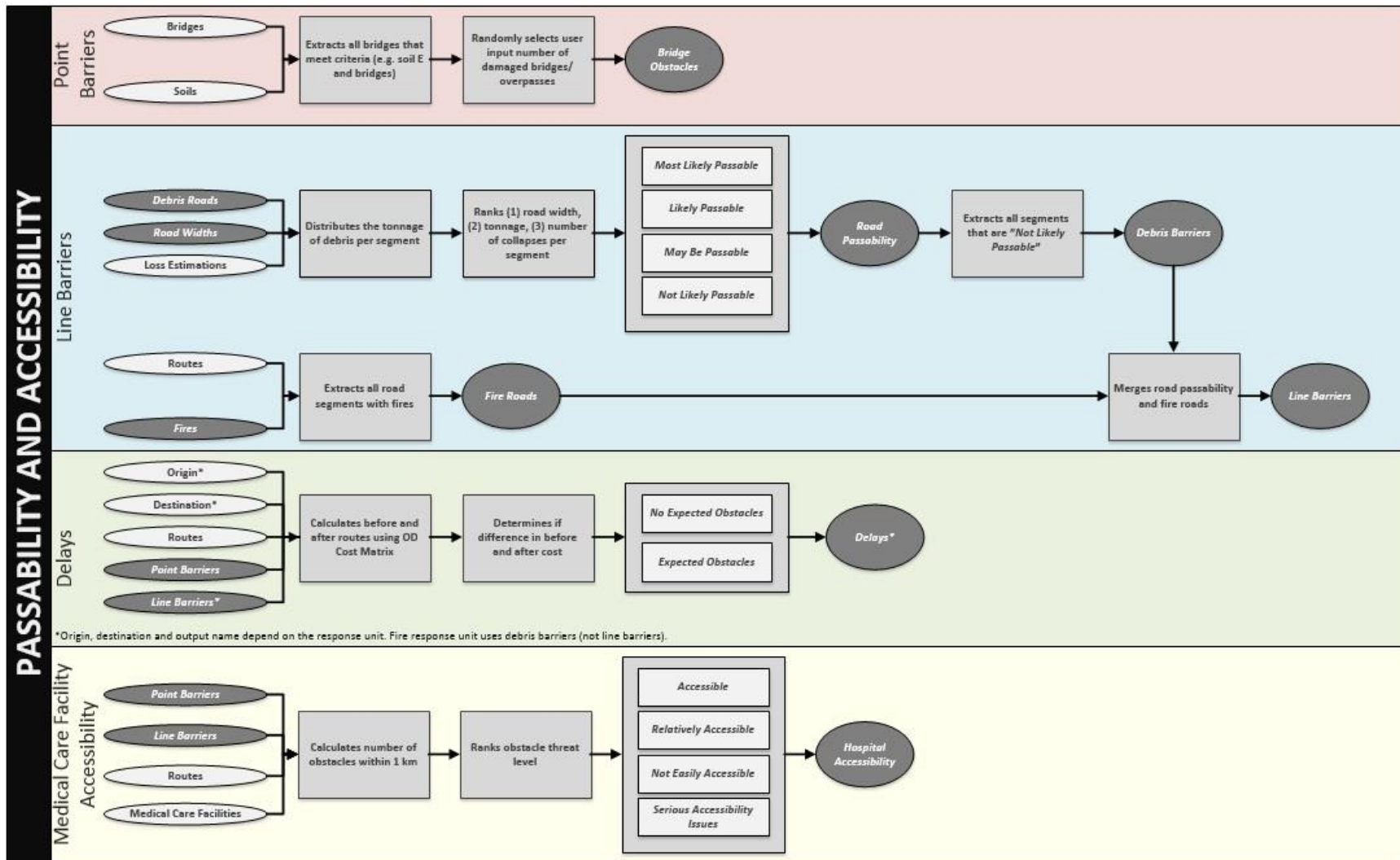
Appendix 3.1: Overview of the simplified procedure to calculate aspects of pre-earthquake situational awareness.



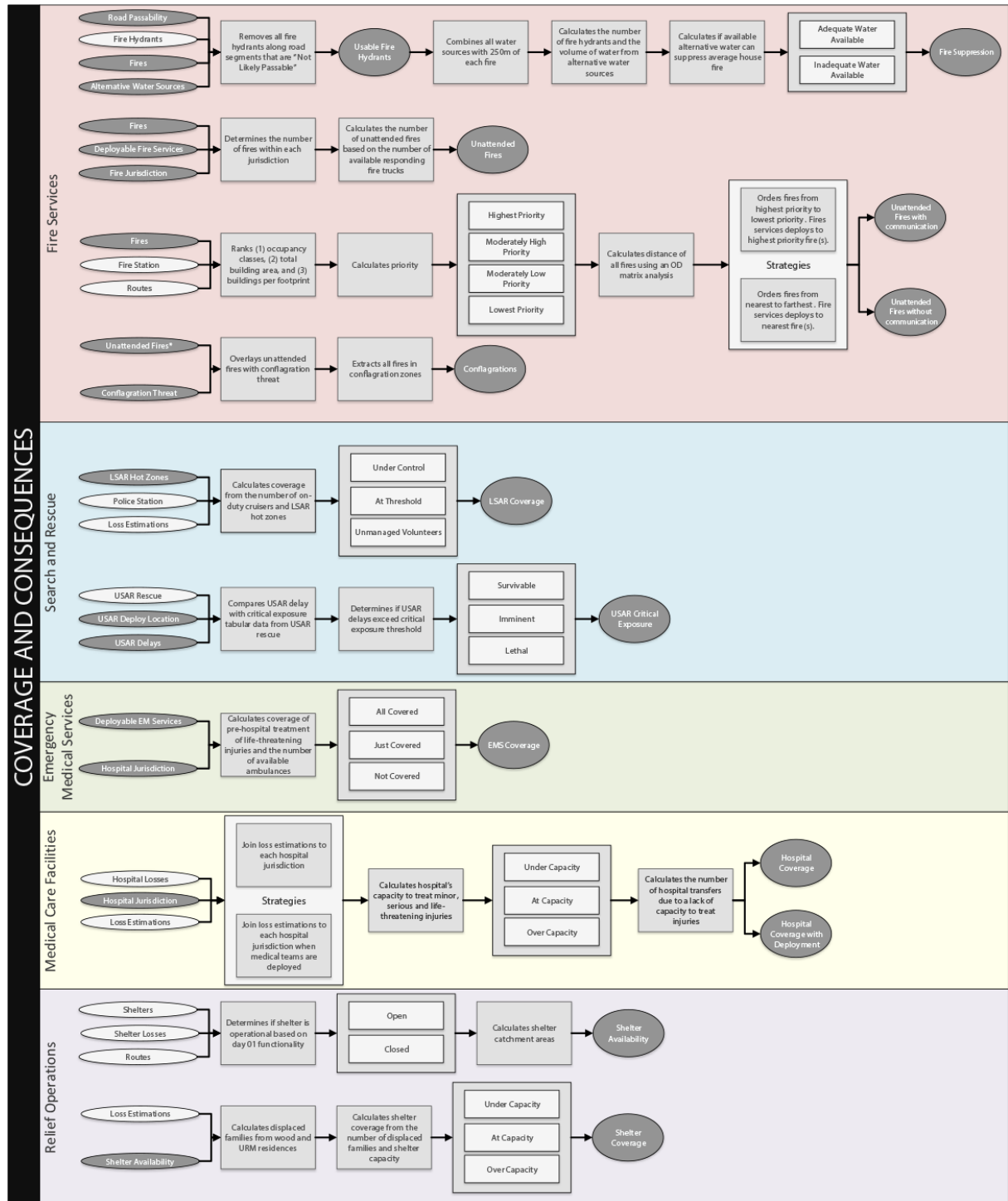
Appendix 3.2: Overview of the simplified procedure to calculate hot zones.



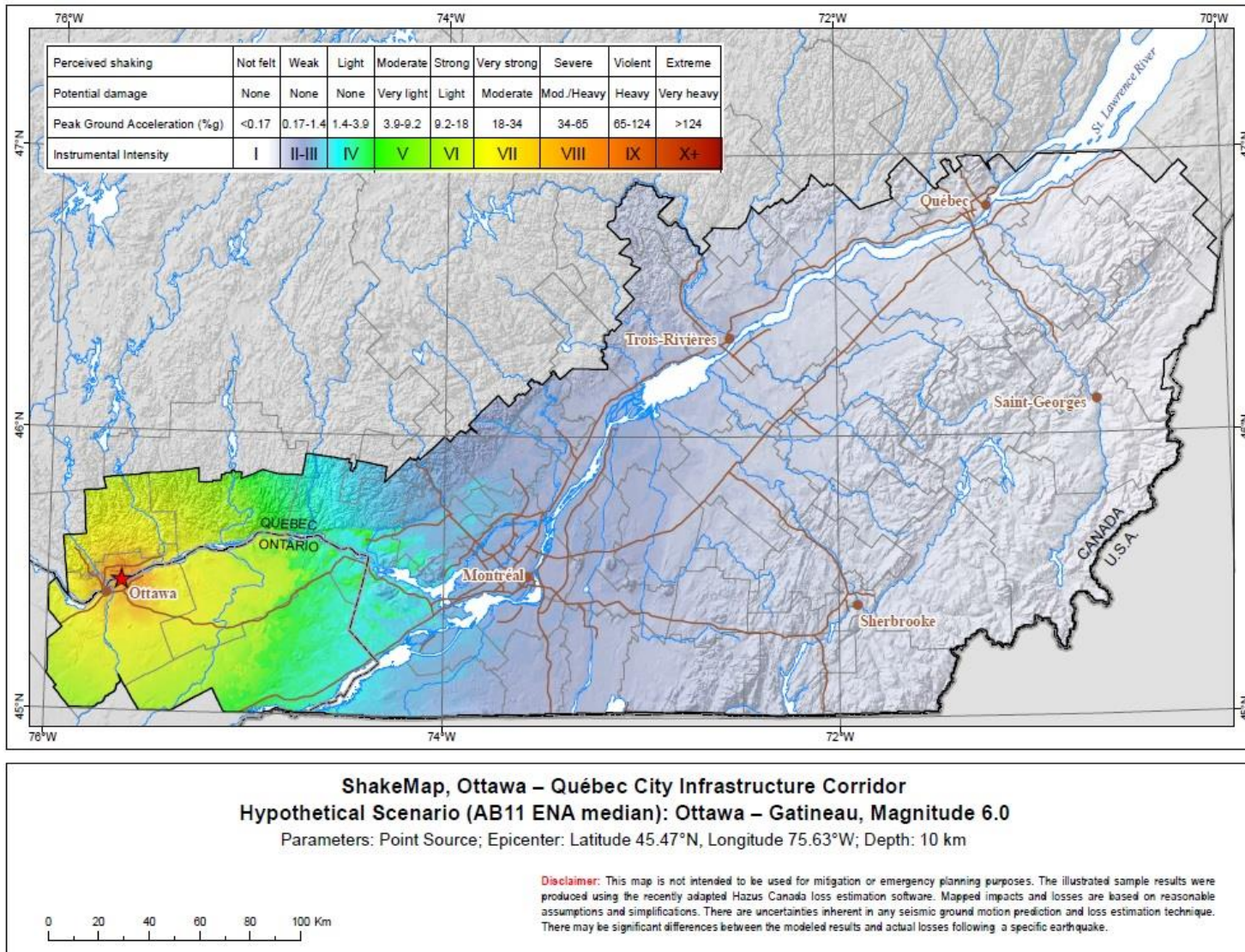
Appendix 3.3: Overview of the simplified procedure to calculate passability and accessibility issues.

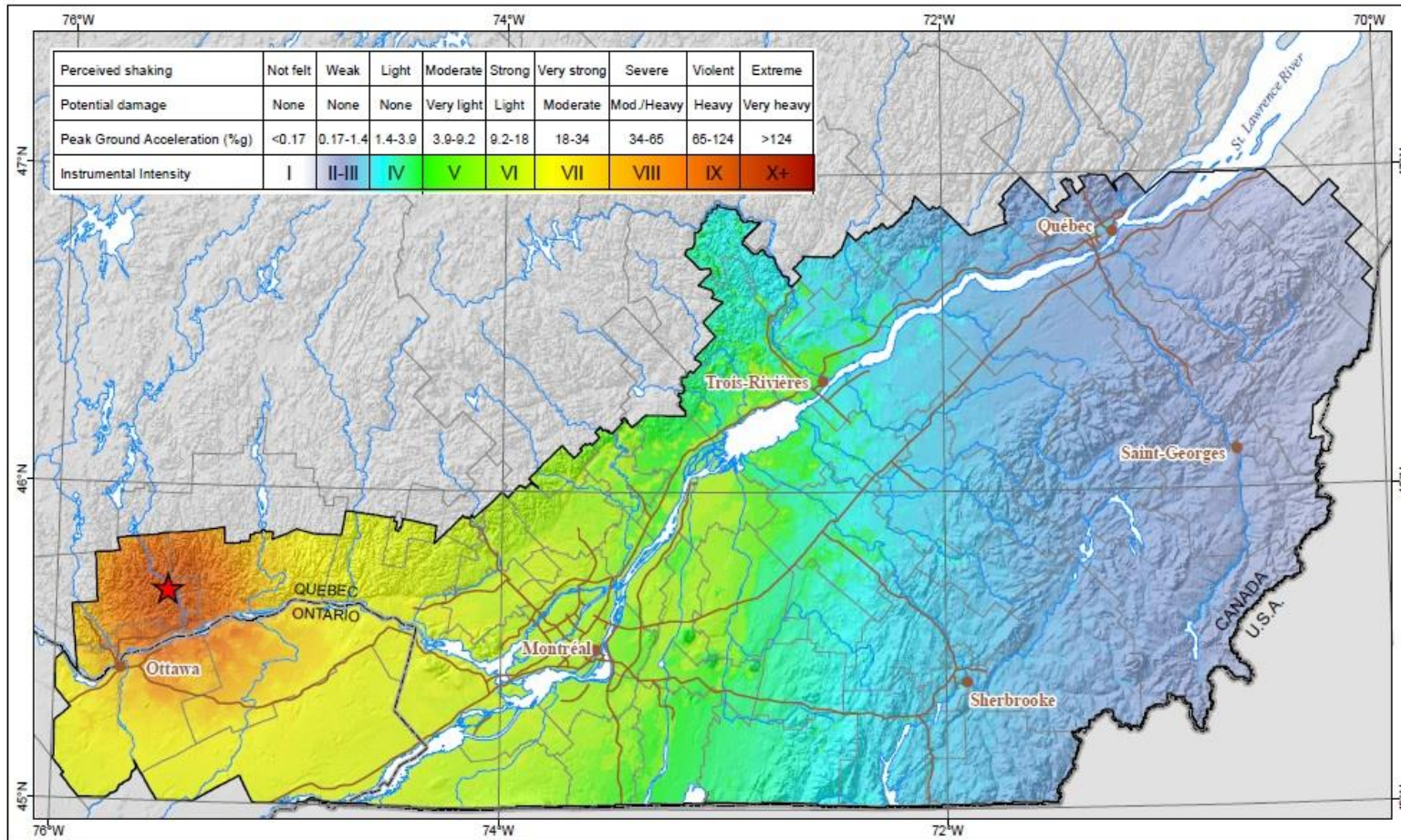


Appendix 3.4: Overview of the simplified procedure to calculate aspects of coverage and consequences.



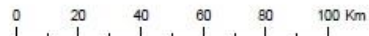
Appendix 4.1: ShakeMaps for the M6.0 (~10-15 km) and M7.25 (~25-30 km) (Nastev et al., 2015, *In Preparation*).





**ShakeMap, Ottawa – Québec City Infrastructure Corridor  
Hypothetical Scenario (AB11 ENA median): Ottawa – Gatineau, Magnitude 7.25**

Parameters: Point Source; Epicenter: Latitude 45.67°N, Longitude 75.5°W; Depth: 10 km



**Disclaimer:** This map is not intended to be used for mitigation or emergency planning purposes. The illustrated sample results were produced using the recently adapted Hazus Canada loss estimation software. Mapped impacts and losses are based on reasonable assumptions and simplifications. There are uncertainties inherent in any seismic ground motion prediction and loss estimation technique. There may be significant differences between the modeled results and actual losses following a specific earthquake.

Appendix 4.2: Summaries of loss estimations from Hazus Canada and the CanRisk injury model. [A] Summary of losses by census tract for the M6.0 and M7.25 scenarios in the Ottawa study region.

Census ID	Buildings		M 6.0												Debris (thous. tonnes)			Casualties												
			Concrete Buildings				Steel Buildings				Timber Buildings											Masonry Buildings								
Hazus	Total	Type A	Type B	None	Slight	Moderate	Extensive	Complete	None	Slight	Moderate	Extensive	Complete	None	Slight	Moderate	Extensive	Complete	None	Slight	Moderate	Extensive	Complete	Type A	Type B	Total	Minor	Serious	Life-Threatening	Fatal
35006000300	887	866	21	15	2	0	0	0	4	0	0	0	0	685	174	5	0	0	1	1	0	0	0	0.54	0.31	0.85	0	0	0	0
35006000400	786	771	15	1	4	2	1	0	3	2	2	0	0	264	405	87	2	0	2	5	4	1	1	1.48	1.88	3.36	3	1	0	0
35006000500	994	981	13	4	0	0	0	0	8	1	0	0	0	702	252	15	0	0	6	4	2	0	0	1.16	0.23	1.4	1	0	0	0
35006000600	1422	1421	1	1	0	0	0	0	0	0	0	0	0	974	418	29	0	0	0	0	0	0	0	0.66	0.05	0.71	2	0	0	0
35006000800	1240	1216	24	6	5	4	0	0	6	3	0	0	0	593	549	70	0	0	1	1	2	0	0	1.3	3.18	4.47	2	0	0	0
35006000900	1047	1040	7	0	2	2	1	0	1	1	0	0	0	481	499	60	0	0	0	0	0	0	0	1.09	0.72	1.81	1	0	0	0
35006001103	38	22	16	11	4	1	0	0	0	0	0	0	0	14	7	0	0	0	0	1	0	0	0	0.13	0.83	0.96	1	0	0	0
35006001104	747	733	14	10	3	1	0	0	0	0	0	0	0	477	237	18	0	0	0	1	0	0	0	1.21	0.62	1.83	1	0	0	0
35006001200	860	818	42	5	3	1	0	0	23	8	2	0	0	402	371	44	1	0	0	0	0	0	0	1.02	0.76	1.78	1	0	0	0
35006001300	978	946	32	17	10	4	0	0	0	1	0	0	0	467	429	48	0	0	0	1	1	0	0	1.14	2.31	3.45	2	0	0	0
35006001400	115	93	22	9	7	4	0	0	1	1	0	0	0	47	30	4	0	0	4	5	3	0	0	0.7	0.29	0.99	1	0	0	0
35006001500	876	826	50	17	12	4	0	0	14	3	0	0	0	463	235	21	0	0	43	43	20	1	0	3.23	0.85	4.08	2	0	0	0
35006001600	1605	1599	6	1	1	0	0	0	2	1	1	0	0	1008	437	33	0	0	54	47	19	1	0	1.44	0.22	1.65	2	0	0	0
35006001700	1086	1072	14	8	4	0	0	0	2	0	0	0	0	727	263	17	0	0	32	24	9	0	0	1.47	0.26	1.73	2	0	0	0
35006001800	836	824	12	5	2	0	0	0	4	1	0	0	0	507	219	16	0	0	36	32	13	1	0	2.06	0.54	2.6	2	0	0	0
35006001900	1032	1022	10	6	1	0	0	0	3	0	0	0	0	709	257	17	0	0	20	14	5	0	0	1.26	0.27	1.53	1	0	0	0
3500602001	746	686	60	33	14	4	0	0	6	2	1	0	0	415	247	20	0	0	3	1	0	0	0	1.06	3.74	4.79	1	0	0	0
3500602002	581	577	4	0	0	1	1	0	1	1	0	0	0	288	257	28	1	0	0	2	1	0	0	0.68	0.1	0.78	1	0	0	0
3500602100	1122	1100	22	13	1	0	0	0	8	0	0	0	0	917	176	6	0	0	1	0	0	0	0	0.42	0.05	0.48	0	0	0	0
3500602200	785	693	92	42	3	0	0	0	46	1	0	0	0	600	88	2	0	0	3	0	0	0	0	0.21	0.21	0.42	0	0	0	0
3500602302	530	525	5	3	0	0	0	0	2	0	0	0	0	456	67	1	0	0	1	0	0	0	0	0.27	0.04	0.31	0	0	0	0
3500603100	690	667	23	18	1	0	0	0	4	0	0	0	0	609	56	1	0	0	1	0	0	0	0	0.08	0.18	0.27	0	0	0	0
3500603201	526	508	18	15	1	0	0	0	2	0	0	0	0	435	55	1	0	0	13	3	1	0	0	0.26	0.12	0.39	1	0	0	0
3500603202	1413	1392	21	19	2	0	0	0	0	0	0	0	0	1192	186	5	0	0	7	2	0	0	0	0.33	0.18	0.51	0	0	0	0
3500603301	1187	1175	12	10	0	0	0	0	2	0	0	0	0	933	180	6	0	0	36	16	4	0	0	0.64	0.05	0.7	1	0	0	0
3500603302	867	859	8	3	0	0	0	0	5	0	0	0	0	695	133	4	0	0	18	7	2	0	0	0.37	0.04	0.41	0	0	0	0
3500603400	1209	1198	11	7	0	0	0	0	4	0	0	0	0	919	238	8	0	0	21	9	3	0	0	0.62	0.09	0.7	1	0	0	0
3500603500	632	594	38	25	5	0	0	0	7	1	0	0	0	413	149	9	0	0	11	9	3	0	0	1.79	0.77	2.56	1	0	0	0
3500603600	850	834	16	9	2	1	0	0	4	0	0	0	0	518	224	16	0	0	34	29	12	1	0	1.57	0.35	1.92	1	0	0	0
3500603700	386	301	85	38	21	5	0	0	16	5	0	0	0	121	60	4	0	0	46	47	22	1	0	7.59	3.68	11.26	3	1	0	0
3500603800	394	336	58	26	12	1	0	0	13	6	0	0	0	154	77	6	0	0	40	40	18	1	0	4.14	1.22	5.36	2	0	0	0
3500603900	610	596	14	8	2	1	0	0	2	0	1	0	0	397	173	13	0	0	6	5	2	0	0	0.69	0.17	0.86	1	0	0	0
3500604000	592	578	14	6	2	1	0	0	3	1	1	0	0	340	173	15	0	0	20	20	9	1	0	1.66	0.64	2.3	2	0	0	0
3500604100	588	559	29	20	4	1	0	0	3	0	1	0	0	360	155	13	0	0	14	12	5	0	0	1.1	0.36	1.46	1	0	0	0
3500604200	556	534	22	15	3	0	0	0	4	0	0	0	0	376	137	9	0	0	6	4	2	0	0	0.57	0.24	0.81	1	0	0	0
3500604300	952	918	34	20	2	0	0	0	11	1	0	0	0	713	188	8	0	0	5	3	1	0	0	0.64	0.19	0.83	1	0	0	0
3500604400	765	654	111	5	0	0	0	0	98	7	1	0	0	518	132	4	0	0	0	0	0	0	0	0.24	0.04	0.28	0	0	0	0
3500604500	1871	1746	125	46	9	0	0	0	66	4	0	0	0	1371	354	13	0	0	7	1	0	0	0	0.83	0.61	1.44	1	0	0	0
3500604600	736	706	30	21	5	0	0	0	4	0	0	0	0	510	176	9	0	0	5	4	2	0	0	0.59	0.65	1.23	1	0	0	0
3500604700	15	8	7	3	1	0	0	0	3	0	0	0	0	2	1	0	0	0	2	2	1	0	0	0.8	0.17	0.96	0	0	0	0
3500604800	226	74	152	64	38	8	0	0	25	14	3	0	0	9	4	0	0	0	25	25	10	1	0	18.03	16.37	34.41	2	0	0	0
3500604900	346	332	14	5	5	2	0	0	0	1	1	0	0	158	113	13	0	0	15	20	12	1	0	1.3	1.84	3.14	2	0	0	0
3500605000	131	96	35	14	11	5	0	0	3	1	1	0	0	31	23	2	0	0	13	17	9	1	0	5.87	7.02	12.89	1	0	0	0
3500605100	933	890	43	10	15	13	1	0	0	3	1	0	0	243	388	94	2	0	22	61	68	12	0	7.93	2.87	10.8	6	1	0	0
3500605200	834	802	32	11	9	4	0	0	5	2	1	0	0	333	241	28	0	0	62	84	50	4	0	4.22	1.87	6.09	4	1	0	0
3500605300	223	189	34	13	10	3	0	0	5	3	0	0	0	84	58	6	0	0	13	17	10	1	0	3.32	2.07	5.39	2	0	0	0
3500605400	270	208	62	29	15	4	0	0	8	4	2	0	0	78	54	5	0	0	22	30	18	1	0	4.73	3.32	8.04	1	0	0	0
3500605500	255	233	22	8	6	3	0	0	2	2	1	0	0	123	86	9	0	0	4	7	4	0	0	2.29	0.94	3.23	1	0	0	0
3500605600	348	331	17	7	6	3	0	0	0	1	0	0	0	148	143	21	0	0	4	8	6	1	0	1.55	0.85	2.4	3	1	0	0
3500605700	335	321	14	4	4	1	0	0	2	2	1	0	0	153	145	18	0	0	3	1	1	0	0	0.44	0.19	0.63	0	0	0	0
3500605800	758	731	27	11	7	2	0	0	4	2	1	0	0	346	322	38	0	0	6	10	9	0	0	8.19	2.12	10.31	5	1	0	0
35006010000	367	325	42	18	14	7	0	0	1	1	1	0	0	133	130	17	0	0	10	19	14	2	0	2.15	1.03	3.18	1	0	0	0
35006010100	498	434	64	15	11	5	0	0	22	9	2	0	0	204	194	24	0	0	2	5	5	0	0	1.12	3.86	4.98	1	0	0	0
35006010200	500	481	19	7	5	1	0	0	3	2	1	0	0	201	225	35	1	0	3	7	7	2	0	1.03	1.39	2				

M 7.25																																		
Census ID	Buildings				Concrete Buildings						Steel Buildings						Timber Buildings						Masonry Buildings						Debris (thous. tonnes)			Casualties		
	Hazus	Total	Type A	Type B	None	Slight	Moderate	Extensive	Complete	None	Slight	Moderate	Extensive	Complete	None	Slight	Moderate	Extensive	Complete	None	Slight	Moderate	Extensive	Complete	Type A	Type B	Total	Minor	Serious	Life-Threatening	Fatal			
35006000300	1270	867	403	7	389	2	0	0	0	2	3	0	0	0	445	386	35	0	0	0	0	0	1	0	1.99	3.69	5.67	2	0	0	0			
35006000400	782	768	14	0	2	4	1	1	0	1	2	2	1	90	390	261	15	1	0	0	4	5	2	4.48	13.5	17.98	17	3	1	1				
35006000500	994	981	13	2	0	0	0	0	0	4	3	4	0	353	508	107	1	0	0	5	5	2	0	3.82	1.99	5.81	7	1	0	0				
35006000600	1423	1421	2	1	1	0	0	0	0	0	0	0	0	466	771	180	3	0	0	0	1	0	0	2.02	0.4	2.42	8	1	0	0				
35006000800	1243	1221	22	1	2	9	2	0	1	3	3	1	0	262	684	261	9	0	0	0	2	3	0	3.55	19.27	22.82	12	2	0	1				
35006000900	1048	1045	3	0	0	1	1	0	0	0	0	1	0	265	610	165	3	0	0	0	0	1	1	2.42	3.53	5.95	4	1	0	0				
35006001103	39	23	16	5	7	4	0	0	0	0	0	0	0	7	12	3	0	0	0	0	1	0	0	0.42	4.29	4.71	4	0	0	0				
35006001104	743	731	12	3	5	4	0	0	0	0	0	0	0	246	394	89	1	0	0	0	1	0	0	3.31	4.04	7.35	3	0	0	0				
35006001200	861	816	45	2	4	4	1	0	11	14	8	1	0	225	465	124	2	0	0	0	0	0	0	2.16	3.34	5.5	4	0	0	0				
35006001300	980	946	34	6	12	14	2	0	0	0	0	0	0	319	520	104	1	0	0	1	1	0	0	2.04	7.46	9.51	5	1	0	0				
35006001400	115	95	20	3	7	7	0	0	2	1	0	0	0	24	43	13	1	0	0	1	4	7	2	1.92	1.58	3.51	4	1	0	0				
35006001500	874	827	47	3	10	14	3	0	7	6	4	0	0	195	398	123	3	0	7	31	55	14	1	10.54	6.15	16.68	8	1	0	0				
35006001600	1604	1599	5	0	1	1	0	0	0	1	2	0	0	445	810	219	4	0	9	37	59	15	1	4.79	1.75	6.55	9	1	0	0				
35006001700	1084	1072	12	1	4	4	1	0	0	0	1	1	0	342	536	127	2	0	6	21	31	7	0	5.44	2.52	7.96	12	2	0	0				
35006001800	829	821	8	0	3	2	0	0	0	1	2	0	0	223	406	108	2	0	6	24	41	10	1	6.81	3.01	9.82	10	2	0	1				
35006001900	1025	1022	3	2	0	1	0	0	0	0	0	0	0	334	524	123	2	0	3	14	18	4	0	4.75	2.66	7.42	7	1	0	0				
35006002001	746	685	61	9	19	19	5	0	2	4	2	1	0	227	372	83	1	0	0	1	1	0	0	3.8	26.66	30.47	7	1	0	0				
35006002002	587	582	5	0	0	0	1	1	0	1	1	1	0	137	334	101	3	0	0	0	2	3	2	1.65	0.68	2.33	4	1	0	0				
35006002100	1123	1100	23	7	5	2	0	0	5	4	0	0	0	543	490	65	1	0	0	0	1	0	0	1.66	0.68	2.33	2	0	0	0				
35006002200	788	696	92	23	16	7	0	0	30	13	3	0	0	396	272	23	0	0	2	2	1	0	0	1.08	2.61	3.69	2	0	0	0				
35006002302	533	524	9	3	2	0	0	0	3	1	0	0	0	303	204	16	0	0	1	0	0	0	0	1.07	0.55	1.62	1	0	0	0				
35006003100	691	664	27	9	9	3	0	0	4	2	0	0	0	384	257	22	0	0	1	0	0	0	0	0.55	4.54	5.09	2	0	0	0				
35006003201	529	509	20	8	8	2	0	0	1	1	0	0	0	276	195	21	0	0	4	7	5	1	0	1.48	2.23	3.71	5	1	0	0				
35006003202	1416	1394	22	10	8	4	0	0	0	0	0	0	0	721	593	70	1	0	2	4	3	0	0	1.51	2.87	4.39	2	0	0	0				
35006003301	1189	1175	14	6	4	0	0	0	2	2	0	0	0	536	514	68	1	0	8	21	23	4	0	2.86	0.71	3.57	3	0	0	0				
35006003302	869	859	10	2	1	0	0	0	4	3	0	0	0	370	403	59	1	0	3	10	11	2	0	1.87	0.56	2.43	1	0	0	0				
35006003400	1210	1200	10	4	3	0	0	0	2	1	0	0	0	539	557	68	0	0	8	12	13	3	0	2.25	0.79	3.04	7	1	0	0				
35006003500	635	594	41	10	13	8	0	0	2	4	4	0	0	202	302	66	1	0	2	8	11	2	0	6.62	6.79	13.42	6	1	0	0				
35006003600	850	837	13	2	4	3	0	0	2	1	1	0	0	230	417	111	2	0	6	23	38	9	1	5.21	2.51	7.72	6	1	0	0				
35006003700	381	301	80	9	25	27	2	0	3	6	8	0	0	53	102	28	1	0	7	33	61	15	1	25.88	24.94	50.82	16	2	0	1				
35006003800	394	336	58	9	15	13	0	0	5	9	7	0	0	66	132	37	1	0	6	29	51	13	1	13.46	8.49	21.95	10	1	0	0				
35006003900	603	594	9	2	2	4	0	0	0	0	1	0	0	175	318	86	2	0	1	4	6	2	0	2.26	1.39	3.66	5	1	0	0				
35006004000	587	576	11	1	3	3	0	0	0	1	3	0	0	158	289	78	1	0	4	15	25	6	0	4.91	3.13	8.04	8	1	0	0				
35006004100	585	557	28	8	9	7	0	0	0	1	3	0	0	161	286	78	2	0	2	10	15	3	0	3.7	3.03	6.72	5	1	0	0				
35006004200	554	535	19	6	7	3	0	0	1	1	1	0	0	179	278	65	1	0	1	4	6	1	0	2.08	1.87	3.96	3	0	0	0				
35006004300	951	915	36	9	10	4	0	0	5	4	4	0	0	410	435	63	0	0	1	3	3	0	0	2.5	1.96	4.46	4	0	0	0				
35006004400	766	655	111	2	1	1	0	0	59	36	12	0	0	336	289	30	0	0	0	0	0	0	0	0.74	0.47	1.21	1	0	0	0				
35006004500	1879	1748	131	22	25	13	0	0	36	25	10	0	0	785	840	115	2	0	2	3	1	0	0	3.27	7.19	10.46	4	0	0	0				
35006004600	741	709	32	8	12	8	0	0	1	2	1	0	0	297	346	53	0	0	1	5	5	2	0	1.95	4.78	6.74	6	1	0	0				
35006004700	10	7	3	0	1	0	0	0	0	1	1	0	0	1	1	1	0	0	0	1	3	0	0	2.79	1.35	4.15	0	0	0	0				
35006004800	224	76	148	16	44	46	4	0	5	15	17	1	0	3	9	2	0	0	4	18	32	8	0	64.78	99.89	164.67	7	1	0	0				
35006004900	345	331	14	1	6	5	0	0	0	0	2	0	0	76	158	48	1	0	3	14	24	7	0	3.21	7.13	10.35	8	1	0	0				
35006005000	129	95	34	1	9	16	4	0	0	2	2	0	0	15	30	11	0	0	2	12	20	5	0	15.3	33.43	48.73	2	0	0	0				
35006005100	928	890	38	0	5	19	8	0	0	1	4	1	0	65	359	286	16	0	1	17	79	57	10	19.64	15.28	34.91	25	5	1	1				
35006005200	828	801	27	1	6	13	2	0	1	1	3	0	0	124	340	135	3	0	9	50	104	34	2	11.76	10.12	21.87	18	3	1	1				
35006005300	227	188	39	3	10	14	2	0	1	3	5	1	0	33	83	31	1	0	2	10	21	7	0	9.39	10.79	20.18	9	1	0	0				
35006005400	274	207	67	9	19	24	3	0	1	2	7	2	0	33	77	26	1	0	3	18	37	11	1	13.62	18.68	32.3	5	1	0	0				
35006005500	259	234	25	2	7	11	2	0	0	1	2	0	0	51	124	44	1	0	1	3	8	2	0	6.95	6.1	13.05	4	1	0	0				
35006005600	346	330	16	1	6	6	1	0	1	1	0	0	0	78	176	56	1	0	1	5	10	3	0	3.37	3.22	6.59	8	1	0	0				
35006005700	334	315	19	2	4	5	1	0	1	2	3	1	0	84	179	50	1	0	0	1	0	0	0	0.97	0.84	1.81	1	0	0	0				
35006005800	762	732	30	4	9	9	1	0	1	2	3	1	0	197	402	105	2	0	0	6	14	6	0	18.54	9.04	27.58	17	3	1	1				
35006010000	365	326	39	5	12	16	3	0	0	1	1	1	0	59	160	59	2	0	2	10	24	9	1	5	4.38	9.38	3	0	0	0				
35006010100	496	430	66	4	12	15	1	0	9	12	11	2	0	105	239	75	1	0	0	2	6	2	0	2.65	13.25	15.9	4	1	0	0				
35006010200	496	476	20	3	5	6	1	0	1	2	1	1	0	103	261	94	2	0	1	3	9	3	0	2.										

[B] Loss estimations of fire stations and the USAR station in the Ottawa study region.

M 6.0										
Fire Station ID	Damage					Functionality (%)		Injuries		
Generic	None	Slight	Moderate	Extensive	Complete	Day1	Day3	No Strategies	Strategies	
Station 1	0.615	0.281	0.103	0.001	0	61.4	62	3	1	
Station 2	0.754	0.226	0.02	0	0	75.3	75.8	3	1	
Station 3	0.058	0.277	0.543	0.119	0.004	5.7	6.4	10	10	
Station 4	0.642	0.329	0.029	0	0	64.2	64.9	3	1	
Station 5	0.493	0.364	0.136	0.007	0	49.3	50.1	3	1	
Station 6	0.902	0.095	0.003	0	0	90.2	90.4	2	1	
Station 7	0.953	0.044	0.003	0	0	95.2	95.3	3	1	
Station 8	0.954	0.046	0.001	0	0	95.3	95.4	3	1	
Station 9	0.819	0.151	0.03	0	0	81.8	82.1	3	1	
USAR Station	0.69	0.2	0.096	0.014	0.0004	68.71	69.15	13	5	
M 7.25										
Station 1	0.211	0.357	0.404	0.028	0	21.1	21.9	5	5	
Station 2	0.487	0.417	0.095	0.001	0	48.7	49.6	3	1	
Station 3	0.001	0.024	0.301	0.528	0.146	0.1	0.1	10	10	
Station 4	0.296	0.549	0.152	0.003	0	29.5	30.8	4	3	
Station 5	0.091	0.326	0.472	0.106	0.006	9	9.8	10	10	
Station 6	0.516	0.429	0.055	0	0	51.6	52.5	3	1	
Station 7	0.587	0.313	0.098	0.002	0	58.7	59.4	3	1	
Station 8	0.503	0.442	0.054	0	0	50.3	51.3	3	1	
Station 9	0.339	0.372	0.279	0.011	0	33.8	34.7	3	2	
USAR Station	0.34	0.36	0.21	0.075	0.02	33.64	34.45	13	5	

[C] Loss estimations of paramedic posts in the Ottawa study region.

Paramedic Post ID	M 6.0									
	Generic	Damage				Functionality (%)		Injuries		
	None	Slight	Moderate	Extensive	Complete	Day1	Day3	No Strategies	Strategies	
Post 1	0.693	0.217	0.089	0.001	0	69.3	69.8	0	0	
Post 2	0.831	0.155	0.014	0	0	83.1	83.4	0	0	
Post 3	0.791	0.179	0.029	0	0	79.1	79.5	0	0	
Post 4	0.754	0.226	0.02	0	0	75.3	75.8	0	0	
Post 5	0.779	0.215	0.006	0	0	77.8	78.3	2	1	
Post 6	0.779	0.205	0.016	0	0	77.9	78.3	2	1	
Post 7	0.885	0.113	0.002	0	0	88.4	88.7	2	1	
Post 8	0.737	0.256	0.007	0	0	73.6	74.2	2	1	
Post 9	0.478	0.43	0.091	0.001	0	47.8	48.7	2	1	
M 7.25										
Post 1	0.148	0.252	0.52	0.077	0.002	14.8	15.3	1	1	
Post 2	0.488	0.405	0.106	0.001	0	48.7	49.7	0	0	
Post 3	0.345	0.396	0.247	0.011	0	34.4	35.3	1	0	
Post 4	0.441	0.441	0.116	0.001	0	44.1	45.1	0	0	
Post 5	0.376	0.551	0.072	0	0	37.6	38.8	2	1	
Post 6	0.365	0.486	0.148	0.001	0	36.5	37.6	2	1	
Post 7	0.45	0.5	0.05	0	0	45	46.1	2	1	
Post 8	0.222	0.634	0.143	0.001	0	22.1	23.6	3	2	
Post 9	0.118	0.461	0.4	0.021	0	11.7	12.8	3	3	

[D] Loss estimations of medical care facilities in the Ottawa study region.

M 6.0							
Facility ID	Damage					Functionality (%)	
Generic	None	Slight	Moderate	Extensive	Complete	Day1	Day2
Facility 1	0.737	0.256	0.007	0	0	73.6	74.2
Facility 2	0.779	0.205	0.016	0	0	77.9	78.3
Facility 3	0.779	0.215	0.006	0	0	77.8	78.3
Facility 4	0.478	0.43	0.091	0.001	0	47.8	48.7
Facility 5	0.766	0.216	0.017	0	0	76.6	77.1
Facility 6	0.718	0.208	0.071	0.003	0	71.8	72.2
Facility 7	0.315	0.497	0.18	0.008	0	31.5	32.6
Facility 8	0.885	0.113	0.002	0	0	88.4	88.7
M 7.25							
Facility 1	0.222	0.634	0.143	0.001	0	22.1	23.6
Facility 2	0.365	0.486	0.148	0.001	0	36.5	37.6
Facility 3	0.376	0.551	0.072	0	0	37.6	38.8
Facility 4	0.118	0.461	0.4	0.021	0	11.7	12.8
Facility 5	0.237	0.512	0.249	0.002	0	23.6	24.8
Facility 6	0.167	0.32	0.423	0.087	0.003	16.7	17.4
Facility 7	0.037	0.308	0.551	0.1	0.004	3.7	4.4
Facility 8	0.45	0.5	0.05	0	0	45	46.1

[E] Loss estimations of shelters in the Ottawa study region.

Shelter ID	M 6.0					Functionality (%)	
	Generic	None	Slight	Moderate	Extensive	Complete	Day01
Shelter 1	0.3041	0.5266	0.1657	0.0034	0	30.4	31.6
Shelter 2	0.4472	0.3827	0.1606	0.0092	0.0002	44.7	45.5
Shelter 3	0.4412	0.2878	0.2546	0.016	0.0001	44.1	44.7
Shelter 4	0.7216	0.23	0.0476	0.0005	0	72.1	72.6
Shelter 5	0.1614	0.4851	0.3277	0.025	0.0005	16.1	17.2
Shelter 6	0.7914	0.1664	0.0413	0.0006	0	79.1	79.5
Shelter 7	0.8687	0.1248	0.0064	0	0	86.8	87.1
Shelter 8	0.6793	0.2579	0.0608	0.0018	0	67.9	68.5
Shelter 9	0.6367	0.2349	0.1244	0.0037	0	63.6	64.2
Shelter 10	0.1797	0.3979	0.3688	0.0516	0.0017	17.9	18.8
<b>M 7.25</b>							
Shelter 1	0.088	0.467	0.416	0.028	0	8.7	9.8
Shelter 2	0.091	0.326	0.472	0.106	0.006	9	9.8
Shelter 3	0.042	0.103	0.52	0.318	0.018	4.1	4.3
Shelter 4	0.2	0.376	0.389	0.035	0.001	19.9	20.8
Shelter 5	0.009	0.149	0.606	0.219	0.016	0.8	1.2
Shelter 6	0.21	0.342	0.41	0.037	0.001	21	21.8
Shelter 7	0.562	0.371	0.066	0	0	56.1	57
Shelter 8	0.169	0.393	0.381	0.056	0.002	16.8	17.7
Shelter 9	0.081	0.158	0.545	0.209	0.007	8	8.4
Shelter 10	0.026	0.186	0.528	0.235	0.025	2.5	3

Appendix 4.3: Results from the disaster SDSS. Note that all critical facilities are not uniquely identified as it is not the purpose of this research to individually evaluate facilities but rather to evaluate a community's post-earthquake emergency response.

[A] Results showing the distribution of segment passability in the Ottawa study region.

Segment Passability				
Scenario	Most Likely	Likely	May Be	Not Likely
M6.0	3264	6784	235	0
M7.25	2895	6959	425	4

[B] Results for fire services in the Ottawa study region.

Fire Station ID		M 6.0 Fire Coverage			Expected Delays	
Generic	Responding Units	Fires	Unattended Fires	# in Conflagration Zones	No	Yes
Station 1	1	0	0	0	0	0
Station 2	2	6	0	6	6	0
Station 3	1	1	0	1	1	0
Station 4	0	2	2	2	2	0
Station 5	2	2	4	2	2	0
Station 6	2	2	0	2	2	0
Station 7	1	4	3	4	4	0
Station 8	2	0	0	0	0	0
Station 9	2	3	1	3	3	0
M 7.25						
Station 1	0	2	2	2	2	0
Station 2	1	7	6	5	7	0
Station 3	0	3	3	3	3	0
Station 4	0	0	0	0	0	0
Station 5	1	7	6	7	7	0
Station 6	1	3	2	3	3	0
Station 7	0	7	7	7	7	0
Station 8	1	2	1	2	2	0
Station 9	1	3	2	3	3	0

[C] Results for emergency medical services - paramedic services in the Ottawa study region

<b>M 6.0</b>	
<b>Paramedic Post ID</b>	<b>Coverage</b>
<b>Generic</b>	<b>Deployable Trucks</b>
Post 1	0
Post 2	1
Post 3	1
Post 4	1
Post 5	2
Post 6	2
Post 7	2
Post 8	NA
Post 9	0
<b>M 7.25</b>	
Post 1	0
Post 2	0
Post 3	0
Post 4	0
Post 5	0
Post 6	0
Post 7	0
Post 8	NA
Post 9	0

[D] Results for search and rescue operations in the Ottawa study region.

	Hot Zones		LSAR Coverage		Deployable Trucks	USAR Coverage	
	LSAR	USAR	Police 1	Police 2		Delays	Critical Exposure
M6.0	1	0	Under Control	Under Control	3	No Expected Delays	Survivable
M7.25	27	3	Under Control	Unmanaged Volunteers	2	No Expected Delays	Survivable

[E] Results for emergency medical services – medical care facilities in the Ottawa study region.

Facility ID	Damage			Incoming Injuries			M6.0				
	Generic	Threat Level	Accessibility	Situation	Minor	Serious	Life-Threatening	Transfers	Evacuation	Evacuation Facility	Capacity of Evacuation Facility to treat Evacuees
Facility 1		2	Accessible	Resources Like Available	Under Control	Under Control	Under Control	0	0		
Facility 2		1	Accessible	Resources Like Available	Under Control	Under Control	Under Control	0	0		
Facility 3		1	Accessible	Resources Like Available	Under Control	Under Control	Under Control	0	0		
Facility 4		4	Accessible	Resources Like Available	Under Control	Under Control	At Capacity	0	135	Facility 3	Under Capacity
Facility 5		1	Relatively Accessible	Resources Like Available	Under Control	Under Control	At Capacity	0	0		
Facility 6		2	Accessible	Resources Like Available	Under Control	Under Control	At Capacity	0	0		
Facility 7		4	Relatively Accessible	Resources Like Available	Under Control	Under Control	At Capacity	0	35.5	Facility 6	Under Capacity
Facility 8		0	Accessible	Resources Like Available	Under Control	Under Control	Under Control	0	0		
<b>M 7.25</b>											
Facility 1		4	Accessible	Resources Like Available	Under Control	Under Control	Under Control	0	107.5		Assess
Facility 2		4	Relatively Accessible	Resources Like Available	Under Control	Under Control	Under Control	1	59.5		Assess
Facility 3		4	Accessible	Resources Like Available	Under Control	Under Control	Under Control	0	61.5		Assess
Facility 4		4	Accessible	Resources Like Available	Under Control	Over Capacity	Over Capacity	3	135		Assess
Facility 5		4	Relatively Accessible	Resources Like Available	Under Control	Under Control	At Capacity	0	71.5		Assess
Facility 6		4	Accessible	Resources Like Available	Under Control	Over Capacity	At Capacity	11	85		Assess
Facility 7		4	Accessible	Resources Like Available	Under Control	Over Capacity	Over Capacity	21	34.5		Assess
Facility 8		4	Relatively Accessible	Resources Like Available	Under Control	Under Control	Under Control	0	43.5		Assess

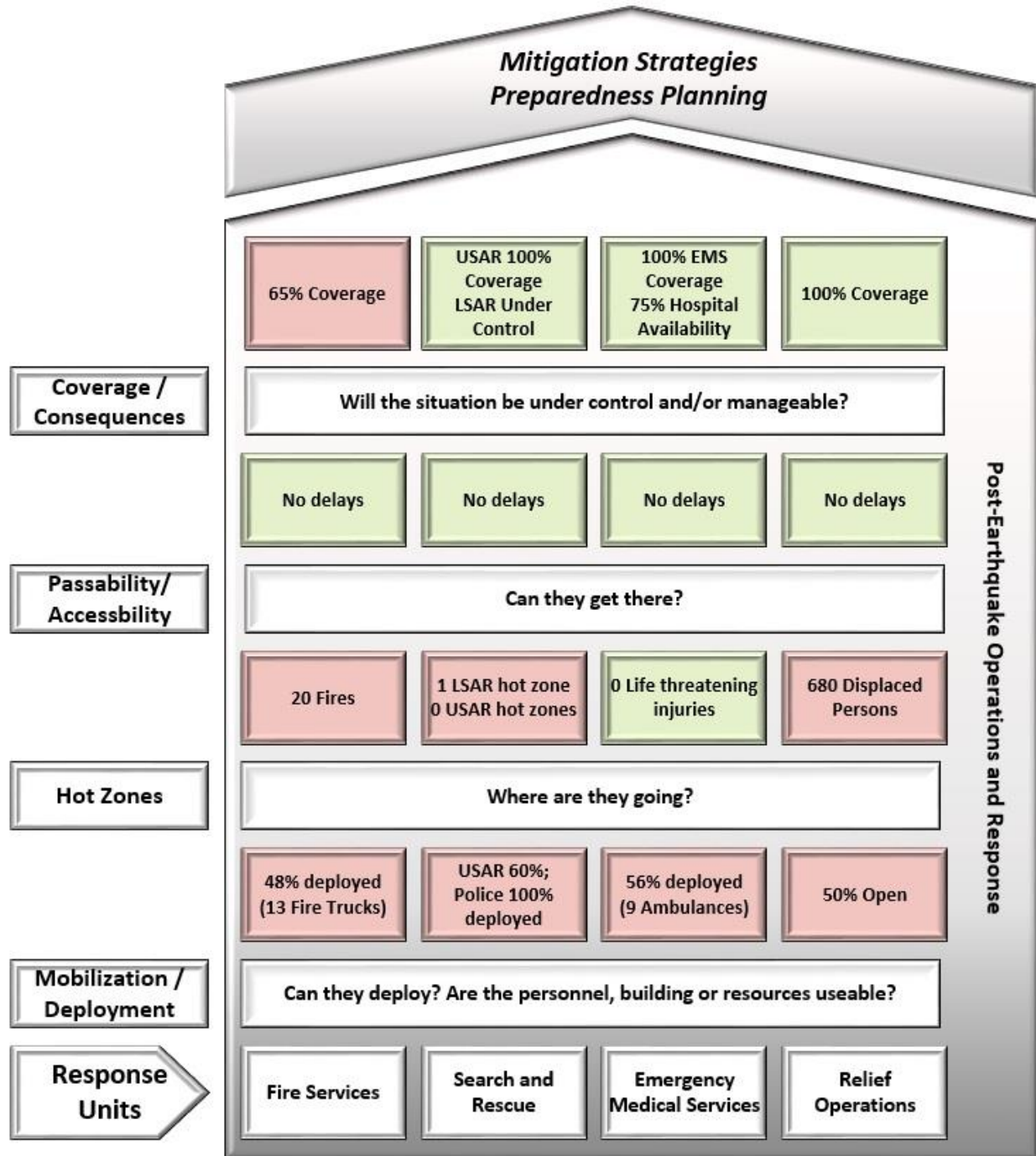
[F] Results for relief operations in the Ottawa study region.

M 6.0		
Shelters	Status	Capacity
Shelter 1	Closed	
Shelter 2	Closed	
Shelter 3	Closed	
Shelter 4	Open	Under Capacity
Shelter 5	Closed	
Shelter 6	Open	Under Capacity
Shelter 7	Open	Under Capacity
Shelter 8	Open	Under Capacity
Shelter 9	Open	Under Capacity
Shelter 10	Closed	

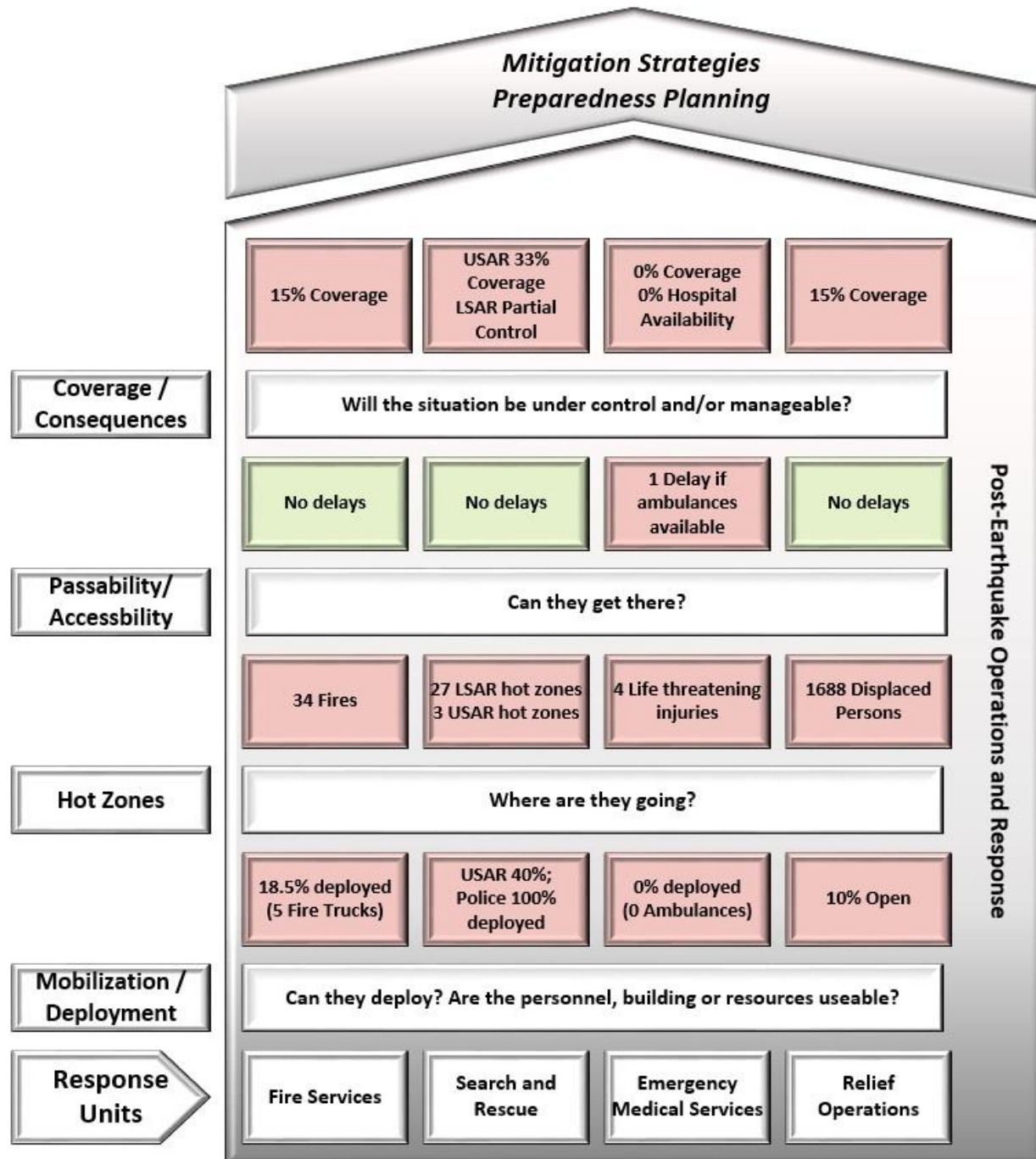
  

M 7.25		
Shelters	Status	Capacity
Shelter 1	Closed	
Shelter 2	Closed	
Shelter 3	Closed	
Shelter 4	Closed	
Shelter 5	Closed	
Shelter 6	Closed	
Shelter 7	Open	Over Capacity
Shelter 8	Closed	
Shelter 9	Closed	
Shelter 10	Closed	

Appendix 4.4: An overview of the operational readiness of emergency services for the Ottawa study region for a [A] M6.0 scenario.



[B] M7.25 scenario.



Appendix 4.5: Three examples of pre-scripted messages from the Southern California Catastrophic Earthquake Response Plan (California Emergency Management Agency et al., 2010).

<p><b>"First Steps At Home</b> - This is a special safety message from the California Emergency Management Agency.</p> <p>A strong earthquake has hit our area. If you're at home, these are the first safety steps to take:</p> <p>Check on the location and status of your family members.</p> <p>Use a fire extinguisher to put out small fires. Never use water on electrical or gas fires. If the fire can't be controlled quickly, evacuate the building right away.</p> <p>Check for gas leaks. If you smell or hear gas, open the windows before moving everyone outside.</p> <p>Look and listen for any signs of possible collapse by inspecting your home's foundation, walls and chimney.</p> <p>And stay tuned to this station for more information from the California Emergency Management Agency."</p>	<p><b>"Second Steps At Home</b> - This is a special safety message from the California Emergency Management Agency.</p> <p>If you're in a safe place right now, stay there! The earthquake danger may not be over yet... and strong aftershocks are possible.</p> <p>If you're at home and there's no immediate sign of collapse, fire or gas leaks, it's time to take a closer look at your utility connections.</p> <p>Turn off any appliance that was on when the earthquake hit and check it for damage.</p> <p>Check your water heater. If the earthquake caused it to fall over it may have broken a gas, electric or water line.</p> <p>If your utilities appear damaged, turn them off at the main meter.</p> <p>And stay tuned to this station for more information from the California Emergency Management Agency."</p>	<p><b>"Check List – Do's</b> - This is a special safety message from the California Emergency Management Agency.</p> <p>If the earthquake has damaged your neighborhood, here are some things you should remember to do:</p> <p>Stay calm and in touch with the people around you. Stay off the telephone. Put on sturdy shoes. Store water in a bathtub or large container and sterilize water that wasn't bottled before using it.</p> <p>Turn off leaking gas and damaged electric utilities at the meters.</p> <p>Clean up broken glass, medicines, and flammable liquids.</p> <p>And remember, every hour or so, to take a few moments to rest and to think about what you're going to do next.</p> <p>And stay tuned to this station for more information from the California Emergency Management Agency."</p>
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## General guidelines for post-earthquake emergency response planning

### Mitigation

- Unreinforced masonry (URM) building types are the most vulnerable to earthquake damage. URM structural systems, that is, the 'skeleton' of the building, are the most vulnerable to partial and complete building failure. URM non-structural elements, such as brick veneers, cornices, parapets, and chimneys are also most vulnerable to failure. Both types of URM failure can lead to indoor and outdoor casualties, as well as road blockages. Therefore, preference retrofit programs should prioritize URM buildings.
- Non-structural / operational and functional component (OFC) retrofit programs should be encouraged throughout the community. Occupancy classes with more inventory (retail, warehouses, and libraries) tend to generate the most number of casualties in addition to economic losses. However, the relative importance of OFC retrofits vary between occupancies. For example, burst water pipes, power outages, or non-functional HVAC systems can render a modern medical care facility unusable. Conversely, the fall of URM elements can cause road blockages and obstruct emergency vehicles. Additionally, unfastened / unanchored building content can also fall and cause injury in any occupancy class.
- Earthquake awareness, preparedness, and safety campaigns are simple and cost-effective options for any community. Although the types of campaigns can vary, educating school children much like fire safety activities, can be most beneficial. This establishes a long-term and sustainable strategy within a community as those children will grow up and retain those safety skills.
- Land use planning is another long-term mitigation strategy that can decrease earthquake risk. For example, preserving green space in urban regions will not only promote environmental conservation, but will also act as natural firebreaks in the event of post-

earthquake conflagrations. Another example is the use of geological maps (e.g. seismic microzonation) that are available. These maps denote potential areas of liquefaction and landslides, both of which have been observed in eastern Canada. Either hazard can damage and obstruct transportation networks and hinder the mobilization and movement of relief supplies. Soft sediments can also amplify incoming seismic waves, creating more losses. These areas can be targeted for further geotechnical testing or regulated to limit certain land uses / zoning, both of which can reduce exposure in those areas.

## Preparedness and planning

### *Fire services*

- Fire stations are not immune to damage, nor are fire fighters immune to injuries. Older fire halls, especially with URM elements, are vulnerable to damage. Fire trucks can be damaged by falling or overturning OFCs and vehicle bay doors can become misaligned and jammed. In all cases, fire fighters should undergo mandatory earthquake safety training. An uninjured fire fighter has the potential to save multiple lives and reduce physical and economic losses.
- Large earthquakes have a strong likelihood of generating spontaneous fires across a community. There are some occupancy classes that are traditionally more prone to post-earthquake fires. These numbers will likely overwhelm community fire services. Mutual aid pacts should be considered to help deal with these fires. Neighbouring fire brigades whether professional or volunteer should be engaged; other fire crews such as those used to fight forest fires should also be considered in these pacts.
- Unattended fires or lack of fire suppression can lead to conflagrations. These types of large fires are more common in densely packed community blocks of timber-framed buildings where no open areas are wider than 100 m.

- Fire services need to prepare and plan for potential damage to water trunk lines which will create low pressure and/or no water at fire hydrants. Investing in drafting capabilities and mapping alternative water sources are beneficial. Natural waterbodies and swimming pools have been used with success in previous earthquakes. Although alternative water sources may not provide enough water to suppress all fires, it does have the potential to suppress an average house fire. Mutual aid pacts should also be explored for water supplies via tenders, bladders, etc. Water bombers and water drops can also be beneficial for large fires.
- Investing in redundant communication systems for fire services is worthwhile. The ability to deploy units to priority locations has great benefits. For example, a key building may house irreplaceable documents or artwork, or be occupied by school children, or be densely populated.
- Pre-scripted messages can deliver targeted information to the affected population. In some case studies, there have been a second wave of fires after the restoration of power, and/or the attempt to use damaged furnaces and fireplaces. This is a high probability threat in Canada due the long cold season. Arguably, these fires can be prevented. It would be beneficial to prepare a message on the prevention of these fires. See Chapter 4 Appendix 4.5 for an example of pre-scripted messages in the Southern California Catastrophic Earthquake Response Plan.

### ***Search and Rescue Operations***

- Non-structural failures can occur in a M6.0 earthquake and potentially cause a few partial or complete collapses of URM buildings. A critical threshold exists between a M6.0 and M7.25 earthquake whereupon large reinforced concrete (R/C) building failures can occur with increased magnitude. For the most part, simple tools can be used for SAR operations on collapsed timber-framed and masonry buildings. However, collapses of concrete, steel, reinforced masonry buildings, or very large timber-framed buildings

require specialized equipment and skills. With the failure of a large building, the request of the national USAR team(s) should be made quickly as it may take many hours to mobilize and deploy.

- Emergent groups and convergent volunteerism are common after an earthquake. These volunteers can help or hinder operations. It is beneficial to incorporate this phenomenon into an emergency plan. Law enforcement officers are the natural choice to coordinate and direct these volunteers. However, police services often have other responsibilities and they too, can become overwhelmed. Therefore, other qualified persons need to be identified to perform this task. Additionally, plans should include the coordination of donated goods which can include everything from construction equipment to food to money. Training volunteers and/or volunteer groups have also proven to be beneficial to enhance post-earthquake response capacity.
- In Canada, cold weather is a major concern for entrapped survivors. Children are more susceptible to hypothermia than adults, and night time earthquakes lead to quicker exposure, in part due to light clothing usually worn in bed. Though there are critical exposure periods; these should not necessarily be used as cut-off times but rather as an important factor alongside access to food, water, or warmth (i.e. blankets, extra clothing).

### ***Emergency Medical Services***

- Injuries are a consequence of damaging earthquake events. Although most are minor, some are serious, and few are fatal and life-threatening. Any failure of a large occupied building will likely result in numerous injuries. It should be expected that many injured persons will arrive at a medical care facilities by private-vehicle and with minimal pre-hospital care, as it is likely that paramedic services will be overwhelmed. Based on North American case studies, falling is the primary mechanism of earthquake injury. Although these types of injuries are typically minor, some can be life-threatening. Many fall injuries

are preventable, and the overall risk can be decreased with earthquake safety campaigns.

- Life-threatening injuries including serious orthopedic, and survivable head / spinal injuries are more likely to occur during a daytime earthquake in buildings that do not collapse. Intra-trunk and crush injuries are more common in night time earthquakes and in buildings that do collapse. When planning for a large earthquake, medical care facility plans should include contingencies for alternative OR suites and resources needed to treat these injuries. Notably, specialists and procedures are (1) orthopedic surgeons and OR suites dedicated to fixation, debridement, and closed reductions along with their related supplies and pharmaceuticals, and (2) nephrologists, dialysis machines, and pharmaceuticals to treat crush syndrome.
- It is not uncommon for full hospital evacuations to be issued due to the loss of power (and backup systems), burst water pipes and failed HVAC systems. It would be beneficial to plan for full evacuations in all seasons. The evacuation of patients does not necessarily require specialized equipment, as previous experience demonstrates, but basic hospital resources such as wheelchairs, blankets, backboards, and mattresses are sufficient. Plans should also include the systematic evacuation of supplies, food, pharmaceuticals and equipment. Off-site / outdoor caches with generators, maintained fuel supplies, shelters, basic supplies, and means of warmth or shade are warranted.
- Deploying medical teams whether basic or advanced first aid to familiar and publicized locations will reduce the number of injured persons seeking treatment at medical care facilities. This will reduce the overall strain on the hospital system as well as help hospitals provide better medical treatment to those with serious and life-threatening injuries. Trained volunteers and community groups are also ideal candidates to render first aid in the field.

### ***Relief operations***

- There is a strong likelihood that shelters will be required for earthquakes M6.0 and greater. Neighbourhoods that are vulnerable to damage are the most likely areas requiring sheltering. However, this is not always the case as research indicates that some neighbourhoods have residents with social networks and have the ability to stay with family, friends, or neighbours. Even individuals whose homes have sustained minimal damage, can be anxious about aftershocks or being alone, or ordered to evacuate because they reside in a cordoned off area will require shelter.
- Many pre-designated shelters may be damaged during an earthquake and may not be usable. A list of pre-scouted secondary locations would be beneficial to maximize a community's potential to effectively respond.

### ***Convergent volunteerism***

- Altruism is an inherent behaviour in humans following earthquakes. This should be harnessed. A community-based approach to mitigation, preparedness and response fosters a shared vision and community resilience. Community Emergency Response Teams (CERT) can be a beneficial asset to emergency managers. These are volunteers who are trained by the community fire brigade, and have a developed knowledge, skill sets, and understanding of the protocols for mobilization, deployment and on-site activities. These types of groups should be pre-registered and trained at the community, provincial or national levels. For example, in Germany, the Federal Agency for Technical Relief (THW) is a highly specialized team of volunteers that is national in scope which can provide technical aid and services to support response and relief activities. Training volunteer groups and providing supplies (donated by local individuals, organizations, and businesses) can enhance a community's operational readiness. Examples of tasks delivered by volunteers to relieve emergency response units are the provision of first aid, the direction of traffic, the coordination of convergent volunteers and the management of donated goods.

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