SOCIAL DISRUPTION FOLLOWING AN EARTHQUAKE IN METRO VANCOUVER: A SPATIAL ASSESSMENT OF SOCIAL VULNERABILITY TO EARTHQUAKES IN METRO VANCOUVER, BRITISH COLUMBIA

By

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List of Figures

List of Tables

EXECUTIVE SUMMARY

This study assesses the potential social disruption from a major earthquake striking the Metro Vancouver region. The Metro Vancouver region has experienced substantial population growth over the last thirty years, and this is anticipated to continue into the coming decades. Regional population growth has in the past, and is anticipated to continue to be concentrated in suburban communities. Many of these communities are located on soils considered susceptible to soil amplification and liquefaction in an earthquake. The significant threat of a large seismic event occurring in Metro Vancouver has the potential to cause substantial economic and social losses.

Loss estimation studies for Metro Vancouver are out-of-date and limited in number and scope. Very little research has been conducted in assessing the level of social disruption that would follow in an earthquake. This study provides both a methodology and an estimate of the number casualties and displaced households in the region following an earthquake. Modelling was based on a hypothetical magnitude 7.3 seismic event occurring at 4 am with an epicentre located in the Straight of Georgia.

Results from the Casualty Model indicate that there would be approximately 25 serious injuries and 24 deaths in Metro Vancouver. The majority of these casualties were predicted to be concentrated in older settlements in Metro Vancouver such as Vancouver, Burnaby and New Westminster. In specific, the City of Vancouver accounts for 64% of all serious injuries and 33% of all deaths. The high concentration of casualties in the City of Vancouver is expected as the municipality has the highest population and oldest and largest concentrations of pre-1973 vintage building built in Metro Vancouver. Model results indicate that 81% of all serious injuries and 98% of all deaths would occur in unreinforced masonry buildings (URM).

Results from the Displaced Population Model indicate that 19% of all households in the Vancouver Census Metropolitan Area or 144,507 households would be displaced from their homes, of which 84,004 households would seek public shelter and 60,503 households would seek alternative shelter. The numbers of displaced households are concentrated in the urban core communities of Vancouver, Surrey and Burnaby, which account for 67% of all displaced households. Model results are highly influenced by assumptions made for the duration of water and power outages.

Model results indicate that building type and vintage are important factors in determining levels of social disruption. Areas of high concentrations of URM buildings are areas where significant building damage can be anticipated. Therefore, the combination of a large population, soft soil profile and old buildings seems to yield the highest rates of social disruption.

With significant population growth anticipated in the Metro Vancouver region, the need to incorporate disaster resiliency into regional planning is substantial. Regional trends indicate that in coming decades, there will be a growing population in areas considered to be vulnerable, significantly higher elderly populations, and lower reliance on and therefore access to vehicles. Based on these trends, it would be anticipated that the risk of social disruption from seismic events would increase. However, the risk of social disruption in the region may decline. The combination of better building codes, phasing out of older vintage buildings, and a more reliable power and water system, at least at the regional level, would likely be the key drivers for reducing social vulnerability.

Terms of Reference

This project uses established loss estimation models as the basis for developing both a Casualty and Displaced Population Model for the Metro Vancouver region in British Columbia. The most current and comprehensive models available were used in developing the models. The focus of this report is on earthquakes and the factors that influence levels of social disruption. Analysis was primarily conducted at the census tract level and then aggregated to larger Areas of Analysis and the municipal level. This project does not take into account most secondary hazardous events caused by a seismic event such as conflagration, inundation, landslides or aftershocks. The model does take into account soil amplification in assessing building damage for both the Casualty and Displaced Population Model and liquefaction in determining water and power availability in the Displaced Population Model. Further, the model does not take into account non-structural building damage, such as content shifts, in determining the number of casualties.

The scope of the analysis is limited to the Metro Vancouver region (Greater Vancouver Regional District) for the year 2006. Analysis is conducted for a single scenario earthquake event, and loss assessment is limited to two types of social impacts: casualties (deaths and serious injuries), and displaced households. The latter considers the demand for publicly-provided emergency shelter as well as for alternative shelter.

1. INTRODUCTION

1.1 Problem and research question(s)

Research connecting regional urban planning to regional disaster resilience in Metro Vancouver is contextualized into three broad problem contexts, including:

- Rapid regional population growth is occurring in areas considered to have additional vulnerability factors related to a seismic event.
- Very little academic literature exists that outlines what the potential social impacts of a large seismic event would be in Metro Vancouver.
- Limited incorporation of natural hazards into urban planning at both the regional and municipal levels.

Based on the identified problem contexts, this study investigates: "What level of social disruption, measured as the number of casualties and displaced households, would follow in a large seismic event in Metro Vancouver?"

1.1.1 Problem context

The Metro Vancouver Region (MVR) has experienced substantial population growth over the last 30 years. Between the periods of 1991 to 2006, the population in MVR increased from 1.6 million to 2.2 million (Metro Vancouver, 2009). Much of this population growth has been accommodated in suburban communities such as Surrey and Richmond. The regional population is projected to increase from 2.2 million in 2006 to 2.7 million in 2021 and 3.3 million in 2041 (Ibid). A substantial proportion of this growth is expected to be accommodated in suburban municipalities.

Numerous cities in Metro Vancouver, such as Richmond, are situated on soils classified as being susceptible to seismic amplification and liquefaction (See **Section 2.2.3**). These hazards potentially exacerbate damage to urban systems and can inflate social disruption levels in large seismic events.

Nine moderate- to large-sized earthquakes have occurred in South-western British Columbia in the last 130 years (Rogers, 1998). Onur and Seeman (2004) concluded that the probability of a structurally damaging earthquake (ground shaking levels of MMI VII or greater) due to crustal or sub-crustal earthquakes in Greater Vancouver is 2.5% over the next 10 years, 12% over 50 years, and 22% over 100 years. Therefore, the likelihood of a large seismic event occurring in the Metro Vancouver region, within a short period of time, is substantial. Understanding the social disruption risk posed to society is critical and should be addressed through regional planning policy.

Municipal and regional planning policy has promoted urban development patterns which follow the principles of sustainability. Core planning principles that have shaped the spatial pattern of urban development in the Metro Vancouver region include creating (Metro Vancouver, 2009):

- Compact, high density communities
- Mixed use, complete communities
- Sustainable regional and local transportation infrastructure system
- Protection of natural assets of the region.

While these planning principles are important components in achieving a sustainable region, Metro Vancouver regional plans have neglected disaster resiliency as part of the larger sustainability agenda. Disaster resiliency is commonly defined as the capacity of a community, either regional or local, to anticipate, prepare for, respond to, and recover quickly from impacts of a disaster (Mayunga, 2007).

The region is currently drafting a plan entitled *Metro Vancouver 2040: Shaping our Future* which projects and sets the foundation for future population growth in the region. The proposed plan addresses disaster resiliency through creating a policy in which Metro Vancouver would evaluate regional context statements to ensure land use decisions adequately consider risks from natural hazards and climate change (Metro Vancouver, 2009).

While the inclusion of disaster resiliency into the regional sustainability planning framework is progressive, there are critical gaps relating to resilient communities in the proposed plan that need to be addressed. Most importantly, the plan does not set guidelines indicating what level of risk is acceptable and also does not provide a clear understanding of what the current risk is to natural hazards in the region. Furthermore, the plan does not explicitly identify seismic risk as a natural hazard in which risk should be minimized through land use decisions.

Few studies have investigated the potential level of disruption caused by an earthquake in the region. Only out-of-date and limited-scope studies have been conducted in assessing various aspects of seismic risk and potential disruption in Metro Vancouver. More specifically, there have been no studies that have focused on the social impacts of a large seismic event in Metro Vancouver. On a broader level, few models have been developed to assess the social impacts of earthquakes. HAZUS, the most widely used loss estimation modelling program, is only available for the U.S. and has limitations in data and methodology (See **Section 2.1.2**).Therefore, there is a need to develop more context-specific, comprehensive model(s) that address the underlying components of social disruption caused by seismic events.

1.1.2 Goals and research questions

At the broadest level, this paper examines the relationship between regional sustainability planning and disaster resiliency. The primary objective of this investigation is to understand the potential social disruption that would follow a large seismic event in the region. More specifically, the primary research question addresses "What level of social disruption, measured as the number of casualties and displaced households, would follow a large seismic event in Metro Vancouver?"

This report provides a method of understanding the current level of social vulnerability to natural hazards and provides the necessary background data upon which regional disaster resiliency policies can be based upon. The results of this research inquiry should be used in assisting decision makers in understanding what the implications are of regional land use decision making and the potential benefits of incorporating hazard identification and mitigation plans with regional growth strategies. Based on this primary research question, the following secondary research questions were developed:

- How can levels of social disruption be assessed?
- Are there any significant intra-regional variations in the anticipated amount of social disruption?
- Which areas within Metro Vancouver would be most affected?

- What is the relationship between long range urban planning and the level of anticipated social disruption?

The cumulative results from these research inquiries will provide for a comprehensive understanding of the current social dimensions of risk relating to a seismic event in Metro Vancouver.

1.2 Scope

This investigation focuses on the Metro Vancouver Region, which is composed of 21 municipalities (See **Appendix 1**). The focus of this research investigation is to examine the implication of a large seismic event on social disruption levels in the Metro Vancouver area. Disruption to urban systems is complex, and a comprehensive examination of disruption of various urban systems is better suited for a more extensive study.

The majority of secondary hazards triggered by a seismic event, such as inundation, conflagration and landslides, are not taken into account in the Casualty and Displaced Population Models. Only liquefaction, soil amplification and landslides are factored into the models. Liquefaction and landslides are used in the Displaced Population Model to assess power and water availability. Soil amplification is used in both the Casualty and Displaced Population Models to determine building damage severity. Other secondary hazards, triggered by a seismic event, have the potential to exacerbate disruption in the region. It is beyond the scope of this research investigation to examine each hazard independently, or as part of the overall hazard risk in the region, in determining the amount of social disruption.

Levels of disruption do not remain constant after a natural disaster and change over time. In order to develop an understanding of what the early impacts would be after a seismic event, the models will be limited to disruption levels four days after the scenario event.

1.3 Approach

In order to account for the potential spatial variability in social impacts of a seismic event, Metro Vancouver was disaggregated into small smaller spatial units referred to here as Areas of Analysis (AOA) (See **Appendix 2**). These spatial units were assigned based on areas that were identified as having distinctly different soil composition from adjacent areas and which had considerable urban development. Soil composition was used as a primary determinant of zone boundaries as each soil type responds differently to seismic waves and may result in variable damage levels (see **Section 2.2.3**). The boundaries of the analysis zones were delineated within municipal boundaries to increase the ability to provide results that were specific to municipalities. Furthermore, subdividing the region into AOA's allows for a more accurate analysis since regional seismic variability can be taken into account.

The Casualty Model was developed using the HAZUS model framework, but incorporating regional building stocks and building damage models by Ventura et al. (2005). The Displaced Population Model was developed using methodology developed by Chang et al (2008). HAZUS is a widely used risk assessment methodology for analyzing potential losses from floods, hurricane winds and earthquakes (see **Section 2.1.2**). The Displaced Population Model developed by Chang et al (2008) uses a wide range of factors such as age, income, tenure, building damage and water and power outage duration to determine the number of households that will be displaced (see **Section 5.1**). Both the HAZUS and shelter models provide a framework upon which custom models can be developed to suit the available data and context-specific needs of the research.

1.4 Significance

This study addresses three aspects in understanding how social disruption can be measured quantitatively and the anticipated magnitude of social disruption that may follow in a large seismic event. First, the study adapts existing best practices in loss estimation modelling to providing a geographically specific assessment of levels of social disruption following an earthquake. Second, the study provides a quantitative estimation of the degree of social disruption that may occur following a seismic event in Metro Vancouver. Such a regionally scaled study has not been conducted for Metro Vancouver. Finally, a spatial analysis of the model outputs will provide an understanding of which areas of the region are most vulnerable to social disruption and which appear to be the most resilient.

Model results will be useful to decision makers at all levels of government. Specifically, the results will be usefully for urban planning professionals and council in developing mid- to long-range urban development plans which incorporate natural hazards. Basing regional development patterns on a wider range of factors, such as risk to natural hazards, may lead to not only reduced impacts on society but also increased robustness of urban systems in which these systems are more resilient to exogenous shocks and rebound faster to normal functionality.

The results will be useful for disaster management organizations in developing emergency management plans. Understanding the potential magnitude and spatial variability of social disruption that would follow in an earthquake is invaluable information for disaster management personal. This information may allow for the development of emergency plans that allocate resources more efficiently to areas modelled to have the most disruption, which may then lead to faster recovery.

2. BACKGROUND

2.1 Literature Review

2.1.1 Overview

The development of loss estimation models to assess the vulnerability of communities and regions to natural hazards has been limited in scope, using static modeling approaches and largely confined to engineering methods. Outputs from existing models have focused on the performance of physical infrastructural components of urban systems in terms of their associated damage, economic impacts and mortality/morbidity rates. Moreover, limited research has been conducted in which a holistic, systematic approach is used to examine the impacts of urban infrastructural disruption and damage to physical property on social systems (Simpson et al, 2005). The spatial analysis of social risk and vulnerability to hazardous events is an expanding area of research (Fox, 2008).

2.1.2 Social Loss Estimation Models

Models that estimate shelter demand and the number of casualties after a seismic event have been limited. The most commonly used model to estimate social losses from an earthquake is the Hazards United States Multi-Hazards (HAZUS-MH) model. HAZUS-MH is a methodology and software system used to estimate losses from earthquakes, floods and high winds. HAZUS uses geographical information system software to calculate and map hazards, damage and loss estimates. Loss estimates are based on current scientific and engineering knowledge of earthquake engineering.

In 2003, the U.S. Federal Emergency Management Agency (FEMA) introduced the earthquake loss estimation model in HAZUS. The model has the ability to estimate damage to residential, commercial, industrial buildings, essential facilities, transportation and utility lifelines. The model also has the ability to estimate debris quantities, shelter needs, fires, casualties and direct and indirect economic losses. HAZUS-MH predicts shelter use and casualties within its social impacts module and provides estimates for shelter requirements, displaced households and casualties.

While HAZUS-MH provides a useful methodology for estimating shelter demand and casualties, there are several limitations. A major limitation of the model is that the unit of analysis is the census tract rather than the household. Therefore, the model, at the Level 1 analysis, cannot differentiate between households within the census tract. Instead, HAZUS assumes a uniform distribution of people across all building types and damage levels (HAZUS-MH allows the modeling of site-specific impacts by assembling building stock inventories through the Advanced Engineering Building Module or the User Defined Building Module). The model also does not take into account the proximity of households to shelter locations or the effects of accessibility such as car ownership. Another limitation is that the model algorithms take into account each demographic attribute related to shelter demand, such as income and age, independently and therefore omits correlations between these factors. At a broader level, the casualty and shelter demand model do not take into account secondary events triggered by a seismic event, such as conflagration and inundation. The model also does not take into account non-structural building damage induced casualties. Therefore, HAZUS outputs only provide a partial understanding of what the potential social impacts may be following a seismic event. Further, according to Olshansky et al (2000), HAZUS is not well designed for capturing land use changes as the model is based on structural behaviour rather than planning land-use categories.

HAZUS has been applied in various countries, both in unmodified and modified versions. In 1998, the National Council of Taiwan initiated a project entitled HAZ-Taiwan to research seismic hazard analysis, structural damage assessment and socio-economic loss estimations (Yeh et al, 2006). The end product was a Taiwan Earthquake Loss Estimation System (TELES) which integrated various datasets and a range of analyses to meet the three objectives set out by HAZ-Taiwan (Ibid). TELES software utilizes a similar approach in analysis procedures as the HAZUS model but also has many model modifications (Ibid).

Major modifications include a change in analysis models, parameter values and software architecture to reflect the unique environment and engineering practice in Taiwan (Yeh et al, 2006). One of the largest additions TELES has contributed to the advancement of loss estimation has been the ability to automatically determine the disaster scale and the associated distribution early after an earthquake (Ibid). HAZUS does not have the necessary model capabilities to estimate early seismic loss estimation (Ibid). The TELES model, as shown in Figure 1, is divided into four sub models, including physical hazard, direct physical damages, indirect physical damages and socio-economic losses.

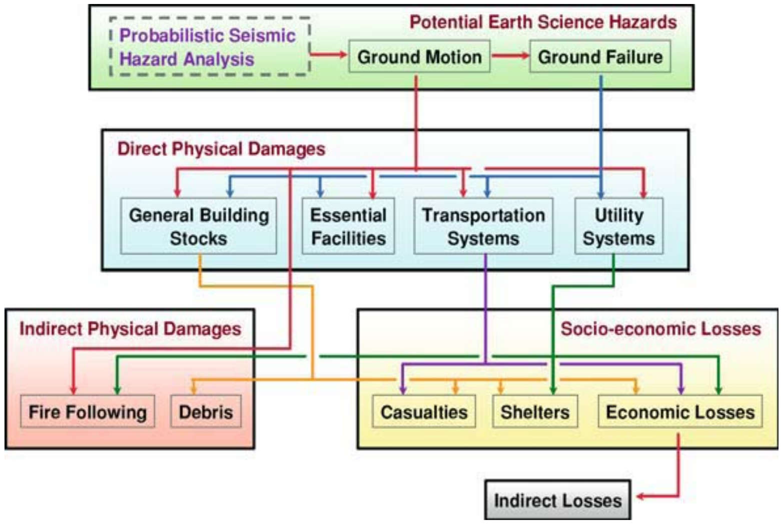


Figure 1: TELES Framework

Source: Yeh et al, 2006

Similar to HAZUS and TELES, the National Hazards Electronic Map and Assessment Tools Information System (NHEMATIS) developed by Emergency Preparedness Canada, provides a loss estimation model for hazardous events in Canadian cities (Webb, 2000). NHEMATIS is a software tool that enables the user to conduct multi-layer risk and vulnerability analysis of regions and municipalities through the use and integration of an expert system rule base, geographic information system, relational databases and quantitative models. Assessments can be performed for earthquakes, floods, tornadoes and landslides. Moreover, NHEMATIS takes into account a range of factors such as building classes, topography, location and soil type to predict damage to critical infrastructure, buildings and injuries. The NHEMATIS model algorithms have been migrated to EmerGeo where they are currently being used in GIS based software.

Pathways-DM is another model framework developed in Canada by Natural Resources Canada which is designed to assist local and regional authorities in analyzing natural hazard threat and risk reduction measures. Pathways is an knowledge integration and decision support system that translates earth science data into a format that is compatible with planning and decision support frameworks (Journeay et al, 2009; Journeay et al, 2010). The model has three main capacities including: 1) Integrating and visualizing existing natural and social data for a given region through the use of interoperable semantic web and data mining technologies 2) To use this dataset(s) in an integrated assessment modeling tools to examine likely future scenarios for a given area 3) Monitor progress towards the identified planning goals using sustainability indicators and decision-support tools. Pathways-DM has been implemented in Squamish, British Columbia, were the community is facing challenges with balancing development and hazard mitigation to threats such as floods, earthquakes and landslides (Ibid).

Recent work by Chang et al. (2008) provides a new approach to estimating public shelter demand and also addresses many of the key limitations within the shelter demand model of HAZUS. Specifically, this shelter demand model allows to take into account correlations between various household-level attributes such as income, mobility and housing tenure. The model also uses the household as the unit of analysis rather than the census tract. This allows for a more realistic model as decision-making about public shelter use is done at the household level.

The primary variables used in the model to determine shelter use include building damage, power and water outage and characteristics of the household. The model is structured by a series of questions. The outcome of each decision determines the process direction within the model.

2.1.3 Social Components of Risk

Socio-economic and demographical factors are influential in determining whether or not a household seeks shelter following a disaster. Socio-economic status, income, housing tenure and age have been related to decision-making relating to shelter use (Mileti et al, 1999). Specifically, research has indicated that households with low socio-economic status are more likely to utilize public shelters (Mileti et al, 1999 and Yelvington, 1997). Similarly, higher income families are less likely to stay at public shelters (Forthergil et al, 2004). Housing tenure also contributes to households deciding whether or not to leave. Rental housing is generally not maintained as well as owner housing and performs more poorly in an earthquake (Tierney et al, 2001). Therefore renters with lower incomes have a higher propensity to seek public shelter than house owners with high income. Age is also a contributing factor in the decision to seek public shelter or not. In specific, households with young and/or elderly members are more likely to choose to evacuate their home in the event of a disaster (Comerio, 1997).

Literature also suggests that the number and severity of injuries resulting from seismic events are in part related to the demographic profile of the impacted population. While numerous researchers have suggested that children, women and the elderly are at increased risk for injury and death (Shoaf et al, 2002; Mahue-Giangreco et al, 2001; Peek-Asa et al, 2003), the reported casualties among these groups are inconsistent (Shoaf et al, 2002). For-example, Shoaf et al. (2002) indicate that women had higher rates of injury in two southern California earthquakes but not in the Loma Prieta (northern California) earthquake. Furthermore, Shoaf et al. (2002) notes that in the Loma Prieta earthquake, older individuals were more at risk than other sub-populations; in the Northridge earthquake, younger individuals were more at risk; in the Whittier Narrows earthquake, age did not matter. Therefore, socio-economic or demographical profiles cannot be directly correlated with probability levels of becoming a casualty in an earthquake.

One explanation for this inconsistency in reported casualties amongst these sub-populations is due to cultural factors such as who sleeps where in the residence (Shoaf et al., 2002). Tanida (1996) indicates that in the Kobe earthquake, over half of all fatalities were people over the age of 60. One reason given for this statistic is that elderly individuals in Japan tend to live on the ground floor of dwellings and younger individuals live on upper floors (Ibid). Furthermore, the collapse of two-storey structures tends to result in higher mortality on the ground floor (Ibid). Therefore, elderly people were more vulnerable than other sub-population groups to becoming a casualty.

Another explanation for this inconsistency is the time of day the earthquake strikes (Shoaf et al., 2002). According to Shoaf et al. (2002), those who were indoors in all major past California earthquakes were more likely to be injured. Moreover, older individuals had a higher chance being home in the afternoon while other age groups were elsewhere, such as at work or school. Therefore, if a seismic event occurs during the day, there is a higher probability that the percentage of all casualties will be weighted more heavily toward the senior demographic (Ibid).

Given the inconsistency in findings relating to the relationship between casualties and demographical characteristics, researchers have not accounted for demographical factors in estimating casualties. Another primary reason why researchers have not accounted for demographical factors in modeling casualties is that the majority of related studies have not controlled for seismic or building confounders (Peek-Asa et al, 2003).

2.2 Metro Vancouver Overview

2.2.1 General Regional Population Trends

Metro Vancouver has experienced rapid population growth over the past 30 years and is one of the fastest growing regions in North America. In 1971, the region had a population of 1,082,187. This increased by 83.6% to 1,986,965 in 2001. Only 11.7% of this growth was in the City of Vancouver (Tomalty, 2002). In addition, the metropolitan core, consisting of Vancouver, Burnaby and New Westminster, only accounted for 19.7% of this growth during this time period. Over 80% of the growth occurred in the areas outside the core, mainly in the suburban municipalities of Surrey, Richmond, Delta, Coquitlam, and the Township of Langley (GVRD, 1999). More recently, the rate of regional population growth has decreased, but the overall population is still increasing significantly. Between 1996 and 2001, the region experienced a population growth of 8.5%, and in 1999, the population reached two million (GVRD, 1999). As of 2006, the regional population was 2,100,000 and is expected to reach 3.4 million by 2040 (Metro Vancouver, 2009).

As indicated in **Section 2.2.3**, the Metro Vancouver region is vulnerable to significant seismic activity. The significant projected population growth in the region may result in an increasing population vulnerable to social disruption from a seismic event. This vulnerability may be further exacerbated by the proportion of population growth that is concentrated in municipalities with soil profiles susceptible to additional hazards (see **Section 2.2.3**).

2.2.2 Trends in Seismic Codes

Significant progress has been made since the first seismic design provisions were incorporated into the National Building Code of Canada (NBCC) in 1953 (Finn, 1997). The first seismic provisions incorporated into the NBCC were referenced to a seismic zoning map that divided Canada into 4 seismic zones based on estimated damage potential of earthquakes (Finn, 1997). The zones ranged from 0 which indicated no potential damage to 3 which indicated major potential damage (Ibid). British Columbia is located in zone 3. Earthquake engineering progressed considerably since 1953, and by 1970 the first probabilistic hazard map was created, based on statistical studies of seismicity in Canada, and incorporated into the 1970 NBCC.

The next major revision to the seismic codes occurred in 1985 when two refined seismic hazard maps were developed. The maps were constructed to assess accelerations and velocities, respectively, to better represent the structural response to various frequencies (Finn, 1997). The seismic hazard maps constructed in 1985 were further refined in the 1999 edition of the NBCC with the addition of ground motions with a probability of exceedence of 2% in 50 years (Adams et al, 1999 as cited in Finn, 1997). The seismic design codes were also updated in 2005. The 2005 standards use a uniform hazard response spectrum that ensures an equal probability of exceedence at each period of structural response (Ibid). Further, in the Vancouver region, the seismic design is not controlled by the subduction earthquake (Ibid).

The procedures used to determine seismic design loads on buildings have also evolved. Specifically, the base shear design controls, which depend on the intensity of shaking, the period of the building, the structural form and the construction material, have changed since the 1950's.

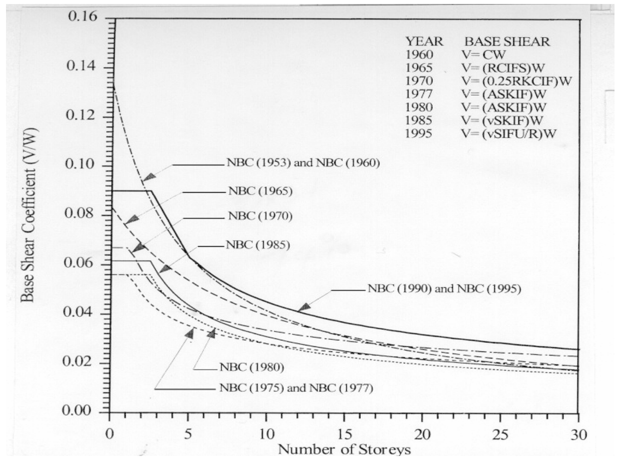


Figure 2: Variation of NBBC Base Shear Coefficient from 1960 -1995

(Source: Finn, 1997)

As indicated in Figure 2, since 1953 there have been considerable advances in the code provisions in the higher seismic demand attributed to long period buildings. For short period buildings, the demand has followed a decreasing trend since 1953 but has increased in the most recent code (NBCC 2005).

The 2006 NBCC introduced new seismic requirements based on a 1:2475 design earthquake, up from a 1:475 design earthquake. Each municipality adheres to the most current seismic provisions outlined in the NBCC and does not go beyond these requirements (Robertson, 2000).

The Metro Vancouver region is composed of buildings of various vintages and associated building codes. Various clusters of significantly older vintage buildings remain around some of the earliest settlements in the region such as Downtown New Westminster and the Downtown Eastside in Vancouver. For older buildings, that were not designed to the current building code, seismic upgrading is only required by each municipality when there is a renovation exceeding 70% of the assessed value of the property (exceeding twice the assessed value in the City of Vancouver); a major addition; or a major change in occupancy (Robertson, 2000). Therefore, a potentially significant inventory of vulnerable buildings exists in areas of Metro Vancouver.

2.2.3 Seismicity and Ground Failure Risk Factors

The Metro Vancouver Region is located in a seismically active region known as the Cascadia subduction zone, which is capable of producing catastrophic earthquakes. Nine moderate- to large-magnitude 6-7 earthquakes have occurred in Southwest British Columbia in the last 130 years (Rogers, 1998). Furthermore, magnitude 8 to 9 earthquakes occurred in the Pacific Northwest on average once every 500 years over the last several thousand years (Clague, 2001). A study conducted by Onur and Seeman (2004) outlined the probabilities of various MMI scale crustal or subcrustal earthquakes occurring for 10, 50 and 100 year recurrence intervals on firm ground. Onur and Seeman (2004) concluded that the probability of structurally damaging ground shaking (MMI VII or greater) due to crustal or subcrustal earthquakes in Greater Vancouver is 2.5% over the next 10 years, 12% over 50 years, and 22% over 100 years. Onur and Seeman (2004) also determined that the probability of a non-structurally damaging earthquake occurring (MMI VI) in the next 50 years is 35%. Therefore, there is significant risk to infrastructure and social systems in Metro Vancouver associated with an earthquake. The

Metro Vancouver Region is also susceptible to secondary hazards such as landslides, soil liquefaction and seismic amplification triggered by a seismic event which further increases the overall risk of disruption.

Ground motion amplification is of particular importance when assessing hazard risk in the region. Ground surface response of loose sediments to seismic shaking is substantially different than that of firm ground such as bedrock (Clague et al, 1998). Specifically, wave velocities in loose sediments are substantially higher than that found in young alluvial and deltaic sediment (Ibid). Thick Holocene sediments, as seen in **Appendix 3**, are particularly prone to ground motion amplification and are commonly found in the delta plain of the Fraser River (Ibid). Amplification modeling studies in the Fraser Delta suggests that low amplitude, long-period seismic waves would be amplified by the local soil characteristics (Harris et al., 1998). Most destructive, high-amplitude, short-period waves would be amplified along the margins of the delta adjacent to the Fraser River. Communities particularly susceptible to amplification include Richmond, Delta, and Pitt Meadows.

Liquefaction can also increase the magnitude of damage to infrastructure and disruption to social systems in the region. Liquefaction is a process by which saturated, non-cohesive sediments transform from solid to liquid (Thevanayagam et al, 2002). Areas particularly vulnerable to liquefaction, as shown in **Appendix 4**, have been identified by Watts et al. (1992) and are primarily located on the Fraser River floodplain, landfill sites and shorelines (Ibid). Communities located within these areas include Richmond, Delta, and portions of the majority of the remaining municipality in the region. Studies have assessed how the sediments at these locations would respond to seismic shaking (Monahan et al., 2000). These studies concluded that soils susceptible to liquefaction are highest at shallow depths beneath the delta (Ibid).

The occurrence of liquefaction can cause considerable disruption to transportation and other essential infrastructure services. According to Bird et al. (2004), liquefaction can cause damage to road pavement, bridges or railway tracks due to settlement or lateral spreading. Finally, liquefaction has the potential to cause serious damage to lifelines. According to Schiff et al. (2000), as cited in Bird et al. (2004), ground deformations caused by liquefaction are the main cause of pipeline damage in earthquakes. In the Greater Vancouver area, this is of particular concern as numerous lifelines such as gas, water, and sewer mains cross the Fraser River and are susceptible to liquefaction and lateral shifts.

Landslides are another type of ground failure that is commonly triggered by seismic activity. According to Bird et al. (2004), catastrophic landslides that claim lives are rare in seismic events, but disruptive failures of roads, rail and river embankments are very common and occurred in 46% of the 50 most recent and destructive earthquakes, with five cases of major routes, such as the Santa Monica freeway, being blocked by landslides.

Landslides in the region would likely vary in magnitude and the associated impacts which could range from damaged or destroyed buildings, bridges, buried roads and rail to injuries and deaths. According to Keefer (1984), as cited in (Clague, 2001), small magnitude slides can be triggered by smaller earthquakes in the range of magnitude 4 to 5. Similarly large earthquakes generally trigger large magnitude landslides (Clague, 2002). According to Mathews (1979), as cited in Clague (2002) the magnitude 7.3 Vancouver Island earthquake, which occurred in 1946, triggered more than 300, primarily small magnitude, slides over an area of 20,000km^2. This event, according to Clague (2002), provides some insight as to the extent of damage caused by an earthquake of similar magnitude in the Vancouver region. Clague (1996) further notes that the main highways, rail lines and energy lines as shown in **Appendix 5**, in the

Greater Vancouver area pass through valleys and canyons susceptible to landslides, which would likely be blocked in the event of a strong earthquake.

Inundation is another secondary event that can occur after a seismic event. Inundation, the process by which a body of water overflows onto normally dry land, can occur in two particular areas in the region. The first source of inundation risk is the Cleveland and Seymour dams which supply most of the drinking water to the Greater Vancouver area. A breach of either dam would cause potentially catastrophic inundation of lower-lying areas and subsequent loss. These dams, however, are not considered to pose an inundation threat to the surrounding municipalities as they are considered to have high seismic resistance (Nemetz, 1992).

A more serious inundation threat is posed by the failure of levees/dykes which are susceptible to liquefaction, overtopping and other breaches. The most vulnerable areas susceptible to inundation are the low-lying areas of the Fraser River which are protected by an extensive dyke system. Of particular concern is the municipality of Richmond. According to the Ministry of the Environment, cited in Nemetz (1992), the worst case scenario would be a breach in the Richmond levees system due to liquefaction which would result in a rapid flooding of most of Richmond if the earthquake coincides with high tide. Should such an event occur, the total building replacement cost, independent of liquefaction damage, in Richmond could range from $621 million to $1.1 billion (1992 dollars). Other communities subject to major inundation include New Westminster, Delta, (Port) Coquitlam and Pitt Meadows.

Bird et al. (2004) provide a breakdown of the most common geological risk factors that cause damage to various infrastructures. In assessing damage caused to utilities, shaking and liquefaction play a substantial role in both earthquakes with moderate and significant damage to utilities. For building damage, there is a distinct difference in the primary and secondary causes of damage from earthquakes. Primary damage to buildings caused by earthquakes is overwhelmingly related to the seismic shaking itself. For secondary causes of damage, liquefaction is the largest factor followed closely by landslides.

2.2.4 Summary

Metro Vancouver has experienced significant population growth over the last couple of decades. Regional population growth has been uneven, with most of the growth being absorbed in suburban municipalities such as Surrey, Richmond and Coquitlam. The regional population is anticipated to increase significantly from 2.1 million in 2006 to 3.4 million by 2040.

The Metro Vancouver region is vulnerable to significant seismic activity and numerous secondary hazards such as soil amplification and liquefaction. An increasing population, particularly in areas susceptible to secondary hazards, may exacerbate damage to infrastructure and increase levels of social disruption. While significant progress has been made in seismic design standards, a significant proportion of the building inventory in Metro Vancouver is of older vintage and at risk of significant damage. Therefore, given the vulnerability of Metro Vancouver to seismic events, secondary hazards and damage to older vintage buildings, significant social disruption may be expected following an earthquake.

2.3 Earthquake Loss Estimation Studies for Metro Vancouver

2.3.1 Munich Reinsurance of Canada Earthquake Loss Estimation

Earthquake loss estimation studies for Metro Vancouver have been extremely limited in number and scope. Of the studies that have estimated losses for the Greater Vancouver region, all have focused on economic impacts with limited, crude estimates of morbidity and mortality, and limited assessments of social impacts. Furthermore, the outputs of these studies have focused on impact measured in dollars rather than on the amount of disruption. One of the central studies for loss estimation in the region is the Munich Reinsurance report by Nemetz (1992). This study examined the economic impacts of a magnitude 6.5 earthquake on the Lower Mainland. The results indicated that an earthquake of such magnitude would result in $14.3 to $ 32.1 billion dollars (1992 dollars) in economic impact. **Appendix 6** and **7** includes the framework of the model used to conduct the earthquake loss estimation.

Two methodologies are used to determine losses. The first method uses aggregate square footage data multiplied by the replacement cost (per square footage) to derive the total replacement cost (Nemetz, 1992). The second methodology examines every structure within a pre-determined geographical area and uses this data to extrapolate loss estimates for the entire region. This method was applied to the commercial area of Downtown Vancouver and the residential area of the West end of Downtown Vancouver. Both geographical areas combined represented approximately 2,100 complete and occupied structures. The outcome of two earthquake scenarios, a design earthquake (MMI= X in Delta/Richmond and MMI VII-VIII for rest of the region) and a mega-thrust subduction earthquake (MMI= X for all region), indicate that total losses can range from $13 to 26 billion and $51 to 97 billion respectively (1992 dollars).

While this study provides critical insight into the potential losses of a large to catastrophic earthquake and a structured methodology of assessing these losses, it is out-of-date and limited in scope. The region has experienced substantial growth since this study was conducted. Furthermore, the region has become far more socially and economically complex with a higher degree of interconnectivity and interdependency making the earlier estimations out-of-date.

2.3.2 Ventura Building Damage Model

Studies conducted by Ventura et al. (2005) and Onur et al. (2005) provide more up-to-date research on loss estimations in the region. In Ventura et al. (2005), a building classification system and damage probability functions were developed for buildings in British Columbia. Buildings were divided into 31 classes based on their material, lateral load bearing system, height, use and age. These building classes were then used to develop a Damage Probability Matrix (DPM). The DPM primary function is to describe the probability of a building being in a certain damage level, such as light to moderate, given the ground shaking intensity. The final step of the study was to fit a probability distribution function to the discrete probability values for each intensity level (Ibid). The outcomes of this study allow for conducting regional damage and loss estimation in the Vancouver region.

The Ventura et al. (2005) study informed the research conducted by Onur et al. (2005) on assessing the regional seismic risk of the Vancouver and Victoria region. In conducting the risk assessment, Onur et al. (2005) used a seismic source zones for a probability level of 10% chance of exceedance in 50 years to determine ground shaking intensity. Modified Mercalli Intensity based damage matrices were used to estimate the amount of damage for different structural and non-structural components of buildings. The damage analysis was conducted on a city block level in Downtown Vancouver and included 20,000 structures. Information in the GIS based database of structures included: street address, primary use, construction material, lateral load bearing system, age, number of stories, shape, and footprint area for each building.

The outcomes of the research indicate that the historic areas in the study area, which are mainly comprised of unreinforced masonry buildings, had damage levels of 10% to 30% of the replacement cost for a MMI VIII event. The majority of the city was in a lower damage level percentile of 5% to 10% for the same MMI seismic event (Ibid). Onur et al. (2005) indicates that areas that experience the highest amount of damage may not relate to the highest level of economic losses. The historical areas of the study area had the highest amount of damage but the highest economic losses were in areas of low damage estimation such as the downtown core.

Another study by Onur et al. (2004) examined the effects of a recent change in the probability level used for the NBCC. Prior to the 2005 NBCC update, the probability level used as a seismic standard was a 10% chance of being exceeded in 50 years. In 2005, the probability level was reduced to 2% in 50 years. According to Onur et al. (2004), changing the probability level from 10% to 2% in 50 years increases the expected MMI levels from VIII to IX in Vancouver. Results indicate that damage would increase from 20-30% for MMI VIII to over 30% of the replacement cost for MMI IX in the old parts of the city (unreinforced masonry buildings), 5%-10% damage (MMI VIII) to 10%-15% (MMI IX) for residential neighbourhoods and 10%-20% (MMI VIII) to 20%-30% (MMI IX) for Downtown Vancouver (concentration of high-rises). Moreover, the loss per block for residential neighbourhoods for a MMI VIII event is expected to be less than $500,000 and greater than that amount for a MMI IX event. A limitation of this, along with other studies conducted in the region, is that they do not capture the impacts of secondary events such as liquefaction or fires into the loss estimation model. In summary, this loss estimation study indicated that larger events in the region would have lower probabilities of occurrence but higher potential for damaging effects.

2.3.3 Scawthorn Loss Estimation Due to Fire Following Earthquake Model

Scawthorn et al. (2001) provided an assessment of risk due to fire following a large earthquake in the Greater Vancouver area. The geographical unit of analysis in the study was the first three characters of postal codes which translated into approximately 80 zones of analysis (postal “forward sortation areas”). The study was based on the following scenarios:

- A 9.0 mega thrust earthquake in the Cascadian Subduction zone.
- Three earthquake scenarios ranging from 7.5 to 7.8 magnitude at various locations in the Strait of Georgia
- A magnitude 6.5 seismic event situated in the geographical center of the region in the municipality of New Westminster.

Scawthorn et al. (2001) indicates that most of the structures in the region, 58% of building stock value and 65% by total floor area, are wood structures. While wood-framed structures perform better in seismic events, they are extremely vulnerable to fire. High-rise buildings are also vulnerable to fire outbreaks as of the 1,200 high-rise buildings (7 stores or higher) in the region only 20% are sprinklered and almost none have on-site water supply.

The methodology used in the analysis treats each postal code in the study area as having uniform shaking intensity, building inventory and other characteristics within that postal code for calculation purposes. Several assumptions were used in the model including:

- Disruption of water supply at Burrard crossings will significantly affect fire-fighting capabilities.
- Coquitlam water supply is more robust but cannot feed all municipalities by itself.
- The Downtown Core is protected by highly reliable downtown fire suppression system.
- Alternative water supplies will play a significant role.
- There will be no mutual support for firefighting services in the region.
- Fire department resources will initially be totally devoted to fire suppression.

For each of the five scenarios, the number of initial fires was estimated and fire response times were also estimated by accounting for transportation, communications, water supply and other related factors. The analysis used Hamada equations, based on Japanese experiences in twentieth century conflagrations, to determine the growth and spread of conflagrations in the region. Based on the assumptions made above, each municipality's water supply reliability was categorized based on source and transmission aspects. This information was then used to develop water serviceability index for each service area. Loss was estimated as the monetary amount corresponding to this final burnt area.

The analysis revealed that most of the damage caused by conflagration for most scenarios was concentrated in the City of Vancouver and Richmond for most seismic scenarios. These estimations do not account for shaking damage. Table 1 provides an overview of the findings of the study.

Table 1 Scenario Events, Fires and Losses

(Loss in C$millions, % of total value at risk)

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

Source: Scawthorn et al. (2001)

For the magnitude 7.8 (1909) epicentre event, the greatest losses occurred in Vancouver with about $545 million followed by Richmond with $402 million. For the magnitude 7.5 (1975/1997) epicentre event, the greatest losses occurred in Vancouver with $1,489 million dollars in damage followed by Richmond with $744 million. Results for the magnitude 9 Cascadia subduction scenario indicates that the greatest losses would also be in Vancouver at

$2,680 million followed by Richmond $1,242 million. For the magnitude 7.5 (Georgia Strait) event, the greatest losses were in Vancouver at $1,352 million followed by Richmond at $917 million. Finally, results for the magnitude 9.5 (beneath New Westminster) event, losses were highest in Vancouver at $6,546 million followed by Richmond at $1,082 million.

2.3.4 Summary

Loss estimation studies for the Metro Vancouver region have been limited in scope and out-of-date. One of the central studies for loss estimation in the region is the Munich Re-insurance report (Nemetz, 1992). This report, while out-of-date, provides insight into the substantial amount of damage that can be expected following a large seismic event in the region. Subsequent studies conducted have provided new insight into loss estimation in the region. The models developed in this report will address a critical gap in the work by Nemetz by addressing the social dimensions of disruption following an earthquake.

Loss estimation relating to conflagration following an earthquake in the region provided by Scawthorn et al. (2001) provides a methodology and estimation of losses. While the model provides useful insight into economic losses due to conflagration, no methodology is readily available to link a conflagration model and results to Casualty/Displaced Population Models. Therefore, by not taking into account conflagration, along with other secondary hazards following a seismic event, models predicting social disruption may underestimate the overall level of social disruption.

Research conducted by Ventura et al. (2005) provides useful data on the damage probability of each building classification in British Columbia. Damage probabilities developed by Ventura et al. (2005) are a useful substation for the generic HAZUS building damage probability values given in calculating number of casualties and displaced in a seismic event. The Ventura et al. (2005) study also informed the research conducted by Onur et al (2005) on assessing the regional seismic risk of the Vancouver and Victoria region. The outcomes of the research indicate that the historic areas in the study area, which are mainly comprised of un-reinforced masonry buildings, had the highest amount of damage. The model findings provide a useful means of assessing whether the building damage outputs from the Casualty and Displaced Population Model are reasonable. The social disruption models developed in this report extend the study area from the City of Vancouver to the Metro Vancouver regional level and extend on the building damage/loss estimation provided to casualties and displaced populations.

3. 0 Earthquake Scenario.

3.1 Earthquake Scenario Overview

To account for intra-regional variability in shaking intensity Metro Vancouver was disaggregated into 28 smaller units of analysis known as Area of Analysis (AOA) (See **Appendix 2**). These spatial units were assigned based on areas that were identified as having considerable urban development and distinctly different soil composition from adjacent areas. AOA sizes were delineated based on municipal jurisdictional boundaries to ensure that model results could be specific to individual municipalities as it is at the municipal level where initial disaster relief is coordinated.

The scenario selected was based on a magnitude 7.3 seismic event with an epicentre located in the Strait of Georgia (located between Vancouver and Vancouver Island). The scenario was developed by the Analyzing Infrastructures for Disaster-Resilient Communities research group at UBC (www.chs.ubc.ca/dprc_koa), in collaboration with the BC Provincial Emergency Program. The diverse regional soil profile would result in a non-uniform ground motion distribution across the Metro Vancouver region. Therefore, as indicated in Figure 3, both the Casualty and Displaced Population Models account for intra-regional variations in ground shaking. Site specific ground motion is estimated in terms of MMI from a range of less than VI to VIII depending on the proximity of to the epicentre and predominant soil type.

While the region is susceptible to a wide range of secondary hazard events, the model only accounts for liquefaction in the Displaced Population Model in determining water and power infrastructure performance. Liquefaction was not used in assessing residential building damage as there was no basis available at the time of the study for assessing liquefaction impacts to buildings (The Ventura damage model does not take into account liquefaction).

Secondary hazards, outlined in this report, can exacerbate the magnitude of social disruption. The inclusion of secondary events would require more complex modelling than that presented in this analysis. Understanding the potential social disruption caused by a seismic event is the first step in understanding what the vulnerabilities are to Metro Vancouver residents to various natural hazards.

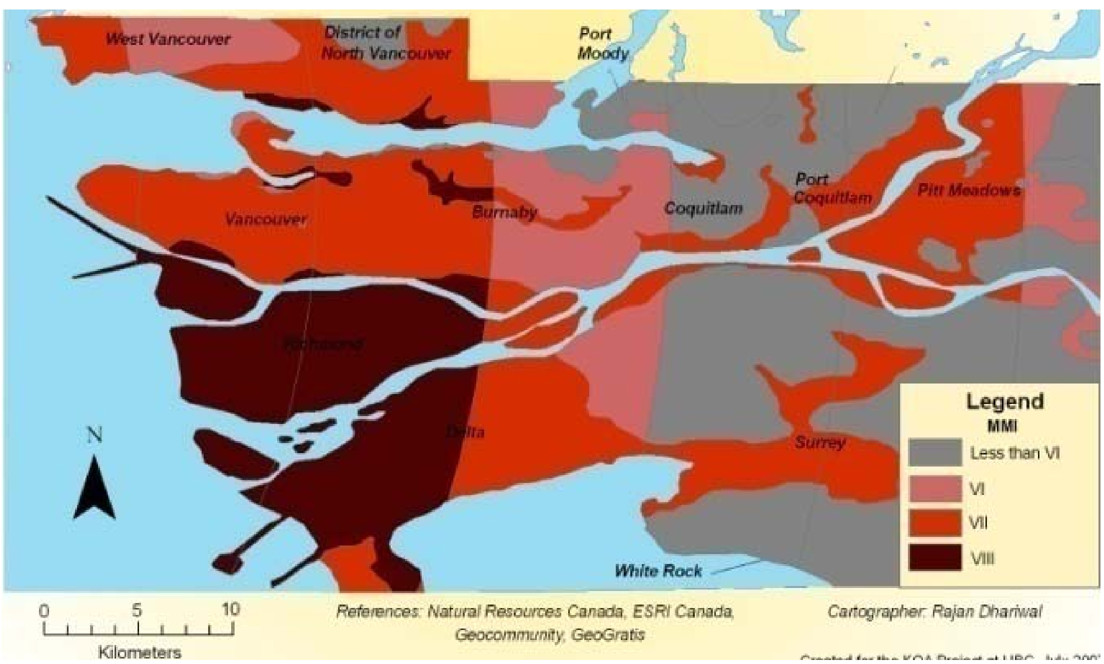


Figure 3: Earthquake Scenario Estimates of Ground Motion

(Source: Analyzing Infrastructures for Disaster-Resilient Communities project, 2007)

The time of day an earthquake occurs plays a critical role in determining the magnitude of social impacts. In specific, an event that occurs during mid-day is considerably more complex to model as people are distributed across a wider range of building types and across multiple transportation infrastructures. With more people being dispersed in a wider range of buildings and infrastructure, each having their own probabilities of damage and levels, it becomes inherently more complex to model social disruption. To simplify the model, the scenario is based on a seismic event that occurs on a weekday, during early morning hours when it is assumed that the entire population are in residential buildings. One limitation of this scenario attribute is that it does not account for population in critical buildings, such as hospitals, that may be susceptible to extensive damage and casualties.

Finally, the physical vulnerability of buildings, including the level of structural resistance to ground shaking, as prescribed in the NBCC, impacts the magnitude of social disruption following an earthquake. The NBCC is adopted by all Metro Vancouver municipalities and is updated when available. Within the NBCC there are seismic provisions which municipalities within this region must follow. These minimum standards may be exceeded by municipalities in areas with increased seismic hazardous conditions. It is assumed that municipalities follow the same seismic code provisions in the NBCC: that is, there is no variation in seismic code provisions across Metro Vancouver municipalities. This assumption is supported by a study conducted by Robertson (2000) which indicates that each municipality adheres to the most current seismic provisions outlined in the NBCC and does not go beyond these requirements. Furthermore, conformance to the NBCC is applied only to new buildings and those that have been altered in the development permitting process. It is up to the individual municipality to ensure compliance of building codes.

4.0 Residential Casualties Model

4.1 Methodology

4.1.1 Overview

The methodology used in this casualty model is adapted from HAZUS. The residential casualty model estimates the number of casualties, both serious injuries and deaths, which would follow after a seismic event in Metro Vancouver for each analysis areas and structure type. In specific, the model accounts for the number of buildings, by type, and population by AOA. The model also uses damage probability values for each residential structure type and shaking intensity to determine the amount of damage anticipated for the corresponding building type. The model takes into account intra-regional shaking intensity variability at the AOA level.

HAZUS casualty rates are used in determining the number of casualties in Metro Vancouver. HAZUS building damage probability values are not used in this model as the values are not specific to the building codes and design standards for British Columbia. The model goes beyond the generic values provided in the HAZUS model and instead uses damage probability values developed by Ventura et al (2005) that are specific to British Columbia.

A detailed flow diagram outlining the model framework is provided in Figure 4.The output of the model includes the number of serious injuries and deaths at the regional and individual AOA level. Results at the AOA level were also aggregated to the municipal level in order to understand the level of distribution at this scale.

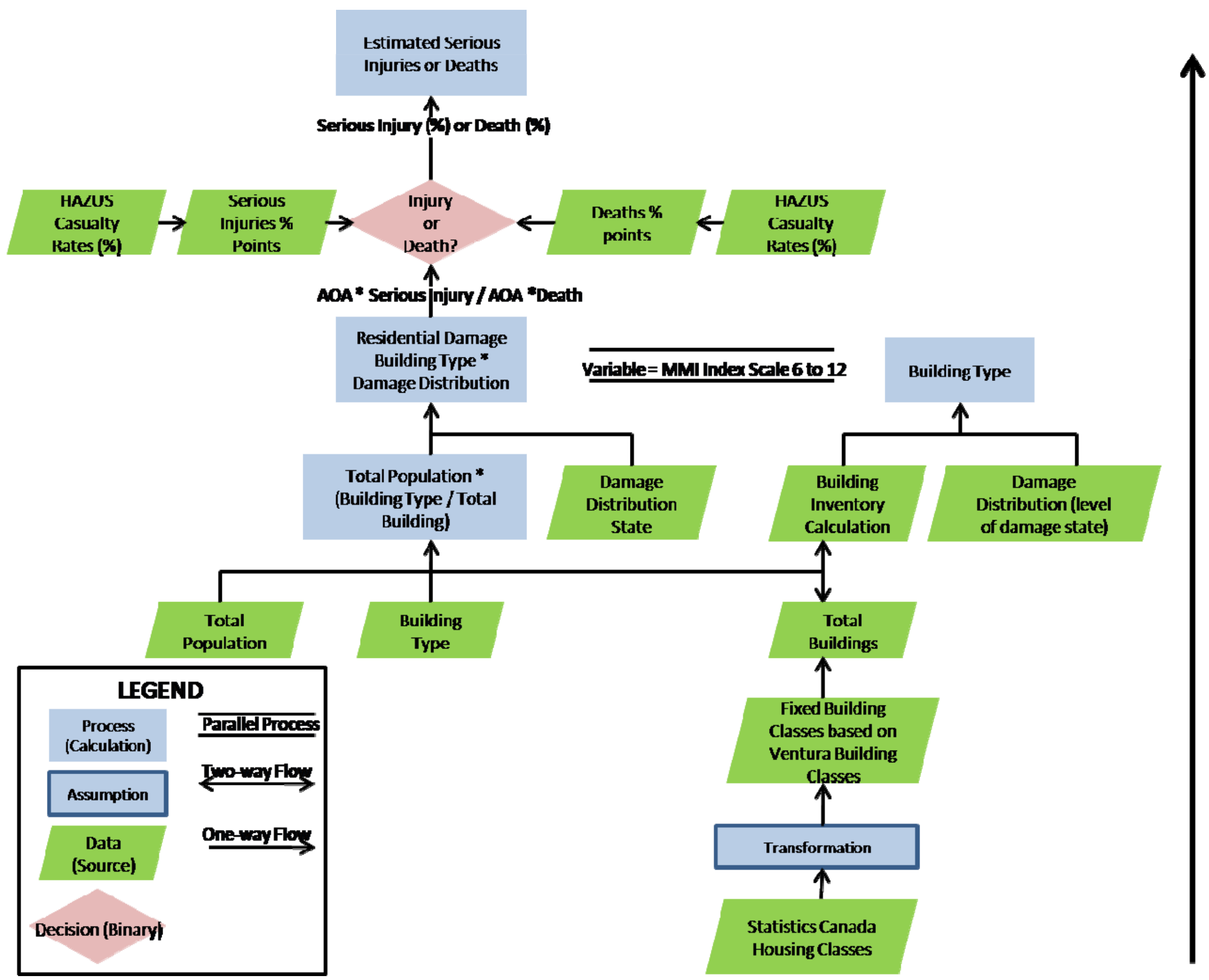


Figure 4: Residential Casualty Model Diagram

(Source: Gregorian, 2009)

4.1.2 Building Class and Population Inventory

Data on building inventory by structural type and total population by census tract was obtained using 2006 Census Data from Statistics Canada. In specific, census data on the total number of occupied private dwellings by structural type and total population for each census tract was obtained and grouped by AOA. Structural building types used in this analysis include: single-detached house, semi-detached house, row house, apartment duplex, apartment buildings (5 or more storeys), apartment buildings (fewer than 5 storeys) and mobile dwelling. These housing categories were aggregated to form new categories including single family (single detached), multi-family townhouse (semi-detached, townhouse, apartment duplex, other single attached house), low-rise multi-family (apartments fewer than 5 stories), multi-family high-rise (more than five stories) and mobile home. These new categories were formed based on the data input requirements of the building damage sub-model. Table 2 provides a summary of the total number of buildings by structural type for each municipality in Metro Vancouver.

Table 2: Total Number of Buildings by Structural Type and Municipality

Municipality	AOA	Total Occupied Private Dwellings	2006			Pre-1973	Post-1973	2006	
			Single-family	MF twhse	MF low-rise	MF low-rise	MF low-rise	MF hi-rise	Mobile home
City of Vancouver	(1-3)	253,680	48,795	55,300	88,140	72,805	15,335	61,325	130
UBC	4	4,410	395	775	2,290	255	2,035	950	-
City of North Vancouver	5	24,720	4,805	5,335	9,650	6,170	3,480	4,950	10
District of North Vancouver	6	27,250	15,680	7,195	3,205	950	2,255	1,150	10
West Vancouver	7	18,090	10,395	2,230	1,425	3,020	1,595	3,955	65
Richmond	(8-10)	60,750	24,735	16,985	15,070	1,895	13,175	3,780	225
Delta	(11-12)	33,835	21,720	6,615	4,830	765	4,065	405	240
White Rock	13	9,535	2,685	1,785	4,260	1,185	3,075	785	5
Surrey	(14-17)	131,225	56,845	42,035	28,060	2,175	25,885	2,610	1,700
New Westminster	(18-19)	24,645	4,915	4,145	9,710	7,720	1,990	5,845	50
Burnaby	(20-21)	78,020	21,290	21,085	21,060	11,295	9,765	14,625	30
Port Moody	22	10,130	3,845	3,720	2,245	575	1,670	310	5
Coquitlam	(23-24)	41,260	19,245	9,675	10,160	2,325	7,835	1,800	370
Port Coquitlam	25	18,715	8,725	6,155	3,795	505	3,290	-	45
Maple Ridge	26	25,010	15,305	5,615	3,145	660	2,485	685	230
Pitt Meadows	27	5,820	3,070	1,735	975	20	955	5	50
Langely	28	44,185	23,035	10,715	8,300	435	7,865	5	2,085

Upon data acquisition and organization, the percentage of population in each AOA by building class was calculated. The first step was to use 1971 census data on housing structural type counts to infer the number of pre and post 1973 low-rise multi-family units. To determine the number of pre-1973 multi-family low-rise units, the total number of owned dwelling apartments and rented dwelling apartments in 1971 were aggregated. Current low-rise multi-family units were determined by subtracting the total number of low-rise multi-family units in 2006 by the number calculated for pre-1973 housing stock. This division was necessary to reflect the period (1973) in which significant seismic codes were introduced (Finn, 1997).

The housing structural type data was then inferred into building classes that coincide with those used in the Ventura (2005) building damage model. Four Ventura building classes used in the analysis include Wood Light Frame Residential (WLFR), Wood Light Frame Low Rise Residential (WLFLR), Unreinforced Masonry Bearing Wall Low Rise (URMLR), Concrete Frame with Walls High Rise (CFCWHR), and Mobile Home (MH). These categories were populated using the following aggregations and calculations:

- WLFR (Single family units + multi-family townhouse)
- WLFLR ((90%*pre-1973 multi-family low-rise) + post-1973 multi-family low-rise))
- URMLR (10%*pre-1973 multi-family low-rise)
- CFCWHR (Multi-family high-rise)
- MH (Mobile home)

The population of each AOA was then distributed to the corresponding individual Ventura building class by taking the total population in the AOA and multiplying it by the percentage of total building stock for each building class in the AOA. Categorization was conducted at the AOA rather than the census tract level at the time of model development due to a lack of information found pertaining to the population by building class at the census tract level. A subsequent investigation revealed that data is available at the census tract level. Future model refinements should use this dataset in order to more accurately account for inter-AOA housing structural type variability.

A series of assumptions were made in this model. One such assumption was that all single-detached family houses and multi-family townhouses were in the wood light frame residential class. It was also assumed 10% of all multi-family low-rise that were constructed before 1973 were of unreinforced masonry bearing wall low rise construction and 90% were wood light frame low rise residential. All medium to high rise residential buildings were assumed to be of concrete frame with concrete walls construction. These assumptions were made as the census data, used to obtain information on building inventory, did not have data on structural building type.

The percentage used for determining the URMLR (un-reinforced masonry) building inventory was provided in a study by Ventura et al. (2005). This percentage was evenly applied to each AOA in the region. The application of a uniform percentage across all AOA's to determine the URML building inventory has limitations. Instead of a uniform inventory of URML buildings across the Metro Vancouver Region, a more variable inventory exists in which there are clusters of older building stock. Portions of Downtown Eastside of Vancouver and Downtown New Westminster are primary examples of areas that have a significantly higher proportion of overall building stock that is of pre-1973 vintage. More recently developed suburban municipalities, such as Surrey and Langley, are anticipated to have limited pre-1973 vintage building inventory. Therefore, applying a uniform percentage for URML buildings across all AOA's will add inaccuracy in calculating casualty rates. An attempt was made to determine AOA-specific URML percentages (including field checks of building inventories and consultation with municipal government staff). Due to a lack of data available at the municipal level regarding the URML building inventory and retrofits, no refinement of the URML percentage was applied in the model.

Finally, an assumption was made as to the population allocation to the various building classes for each census tract. The distributional method used to allocate the population does not fully reflect the actual population distribution in the various building classes and instead provides an approximate estimation. The population allocation results indicate that most of the population are within the WLFR building class (single-detached housing) which is in-line with actual population distributions outlined in Metro Vancouver statistics. Therefore, the allocation method used provides a reasonable estimation of population in each building class.

4.1.3 Damage Distribution by Damage State

In order to determine the number of casualties that would follow after a seismic event, it is necessary to determine the percentage of population in each building class in each building damage state. The output of this sub-model will provide the necessary data needed in the HAZUS casualty rate model. The first step in calculating the percentage of population in each building class, in each building damage state, was to develop lognormal fragility curve parameter tables for each Ventura building class used in the casualty model. Each table provides lognormal fragility curve parameters for the following damage states: slight, light, moderate, heavy, major and destroyed. Specific values for each damage state and building class were obtained from previous work by Ventura et al. (2005) which provide the parameters and form of the fragility curves from which it was possible to recreate the actual fragility curves. Table 3 provides an example of the lognormal fragility curve parameters for URML buildings, where A and B represent the mean and standard deviation, respectively, of in (MMI).

Table 3: Lognormal Fragility Curve Parameters for URML Buildings

	SLIGHT		LIGHT		MODERATE		HEAVY		MAJOR		DESTROYED	
Bl. Class	A	B	A	B	A	B	A	B	A	B	A	B
1-URMLR	1.610	0.140	1.820	0.072	2.000	0.120	2.200	0.130	2.360	0.120	2.810	0.330

(modelled after Ventura et al, 2005)

The parameter tables were then used in developing a table assessing the probability of damage greater or equal to the damage state for each given MMI value and building class. Values were derived for each damage state and MMI values ranging from 6 to 12. Table 4 provides an example of the probability table for URML buildings.

Table 4: Probability of Damage Greater or Equal to Damage State, Given MMI for URML Buildings

Bl. Class	**1-URMLR**						
DS \ MMI	6	7	8	9	10	11	12
SLIGHT	0.9029	0.9918	0.9996	1.0000	1.0000	1.0000	1.0000
LIGHT	0.3474	0.9598	0.9998	1.0000	1.0000	1.0000	1.0000
MOD	0.0413	0.3261	0.7460	0.9499	0.9942	0.9995	1.0000
HEAVY	0.0008	0.0253	0.1769	0.4915	0.7850	0.9360	0.9858
MAJOR	0.0000	0.0003	0.0097	0.0875	0.3162	0.6239	0.8510
DESTR	0.0010	0.0044	0.0134	0.0317	0.0621	0.1059	0.1623

These probability values were then used to construct the damage distribution by damage state for each MMI. The “none” damage state was included in this portion of the model to provide a more complete range of damage states. The value for “none” damage state was derived by subtracting from one, the probability of having or exceeding “slight” damage. For example, for MMI=6, the likelihood of being in the “none” damage state for URMLR buildings would be 0.0971 (=1 -0.9029). For the remaining damage states, the corresponding MMI/damage state value in the previous table was subtracted from the sum of all proceeding damage state values in that MMI level to derive a value. This procedure was repeated for the remaining damage states and MMI values for each building class. Table 5 provides an example of the damage distribution by damage state for URML buildings.

Table 5: Damage Distribution by Damage State, Given MMI for URML

Bl. Class	**1-URMLR**						
DS \MMI	6	7	8	9	10	11	12
NONE	0.097	0.008	0.000	0.000	0.000	0.000	0.000
SLIGHT	0.555	0.032	0.000	0.000	0.000	0.000	0.000
LIGHT	0.306	0.634	0.254	0.050	0.006	0.000	0.000
MOD	0.040	0.301	0.569	0.458	0.209	0.064	0.014
HEAVY	0.000	0.021	0.163	0.404	0.469	0.312	0.135
MAJOR	0.000	0.000	0.000	0.056	0.254	0.518	0.689
DESTR	0.001	0.004	0.013	0.032	0.062	0.106	0.162
CHECK	100%	100%	100%	100%	100%	100%	100%

The total population in each AOA / building class was multiplied by the corresponding building class damage state distribution for the MMI value anticipated to be experienced in that AOA. Regional shaking intensity variability was taken into account using the shaking intensity map provided in Section 3.1. This provided the percentage of population in each AOA in each building class in each building damage state category.

4.1.4 Number of Deaths and Serious Injuries

The final step was to calculate the number of deaths and serious injuries for each AOA by developing an algorithm which transforms the population in each building class and damage state to expected number of serious injuries and deaths using HAZUS values. To use the HAZUS casualty values, it was necessary to map the Ventura damage states onto the HAZUS categories as there are differences in the classification. The category changes are as follows:

- Ventura (Light) to HAZUS Slight
- Ventura (Heavy and Major) to HAZUS Extensive for both
- Ventura (Destroyed) to HAZUS Complete

Tables were used that relate Central Damage States (CDS) to a rate of injury for each of the severity classes. Categorical Damage States (CDS) were used rather than Central Damage Factors (CDF), which is used by HAZUS, as the Ventura fragility curves used in this report provide results in CDS not CDF. The HAZUS casualty rates for both serious injuries and deaths for each building class and damage state are provided in Table 6.

The next step was to use the HAZUS casualty rates to estimate the number of deaths for each AOA. The total number of anticipated deaths was determined by multiplying the total population in each building type and HAZUS damage state by the corresponding HAZUS death rate.

Table 6: HAZUS Casualty Rate (%): Collapse Rates Incorporated) by Building Type and Damage State (after HAZUS Technical Manual)

Bldg type	Damage	Serious Injury (Severity 2 and 3)	Death (Severity 4)
WLFR	Slight	0	0
WLFLR	Slight	0	0
URML	Slight	0	0
CFCWHR	Slight	0	0
MH	Slight	0	0
WLFR	Moderate	0.0003	0
WLFLR	Moderate	0.00025	0
URML	Moderate	0.00041	0.00001
CFCWHR	Moderate	0.0003	0
MH	Moderate	0.0003	0
WLFR	Extensive	0.00101	0.00001
WLFLR	Extensive	0.00101	0.00001
URML	Extensive	0.00202	0.00002
CFCWHR	Extensive	0.00101	0.00001
MH	Extensive	0.00101	0.00001
WLFR	Complete (no collapse)	0.0101	0.0001
WLFLR	Complete (no collapse)	0.0101	0.0001
URML	Complete (no collapse)	0.0101	0.0001
CFCWHR	Complete (no collapse)	0.0202	0.0002
MH	Complete (no collapse)	0.0101	0.0001
WLFR	Complete (collapse)	0.23	0.05
WLFLR	Complete (collapse)	0.25	0.1
URML	Complete (collapse)	0.25	0.1
CFCWHR	Complete (collapse)	0.25	0.1
MH	Complete (collapse)	0.23	0.05

A similar process was used for calculating the total number of serious injuries. The HAZUS model has three classes of injury severity. Only the second and third levels were included for this study. Severity two refers to injuries requiring medical care and medical technology such as x-rays or surgery, but is not life-threatening. Severity three refers to life-threatening injuries. Both severity levels were combined in the calculation of serious injuries. Severity one injures, which are minor and include things like minor cuts and sprains, were not included in the model. A large seismic event would most likely result in a significant number of individuals within this category. It is only injuries at severity levels two and three that are anticipated to pose significant disruption and strain on the healthcare system. To obtain the number of serious injuries, the population of each AOA/building class/damage state was multiplied by the corresponding rate in the HAZUS table.

4.2 Casualty Model Results and Benchmarking

4.2.1 Results

Model results indicate that the scenario magnitude 7.3 seismic event at 4am would result in 17 cases of serious injury and 13 deaths in Metro Vancouver. The initial casualty estimates were rounded up to the integer values for each AOA. As indicated by Table 7, the final casualty estimation, after rounding the values, is 25 serious injuries and 24 deaths. The majority of these casualties are concentrated in older settlements in Metro Vancouver such as Vancouver, Burnaby and New Westminster. In specific, the City of Vancouver accounts for 64% of all serious injuries and 33% of all deaths. The high concentration of casualties in the City of Vancouver is expected as the municipality has the highest population and oldest and largest concentrations of pre-1973 vintage building built in Metro Vancouver.

Many of these older municipalities, as a result of heritage building retention planning initiatives, have a larger inventory of older buildings, such as un-reinforced masonry, than new municipalities such as Langley. Model results indicate that 81% of all serious injuries and 98% of all deaths would occur in un-reinforced masonry buildings (URML). The remaining serious injuries are anticipated to occur in wood light frame buildings (WLFR) (15%) and concrete high-rises (CFCWHR) (4%). The remaining deaths are anticipated to occur in wood light frame buildings (WLFR) (2%).

Table 7: Number of Casualties by Municipality[1]

Municipality	AOA	Predominant MMI	Serious Injuries	% of Total Serious	Deaths	% of Total Deaths
Vancouver	(1-3)	VII	16	64%	8	33%
UBC	4	VII	0	0%	0	0%
City of North Vancouver	5	VII	1	4%	1	4%
District of North Vancouver	6	VII	1	4%	1	4%
West Vancouver	7	VI	1	4%	1	4%
Richmond	(8-10)	VIII	2	8%	2	8%
Delta	(11-12)	VIII	1	4%	1	4%
White Rock	13	VI	0	0%	0	0%
Surrey	(14-17)	VI	0	0%	1	4%
New Westminster	(18-19)	VI	1	4%	2	8%
Burnaby	(20-21)	VI	2	8%	4	17%
Port Moody	22	VII	0	0%	1	4%
Coquitlam	(23-24)	VI	0	0%	1	4%
Port Coquitlam	25	VII	0	0%	1	4%
Maple Ridge	26	VI	0	0%	0	0%
Pitt Meadows	27	VII	0	0%	0	0%
Langely	28	VI	0	0%	0	0%
TOTAL			**25**	**100%**	**24**	**100%**

*Initial casualty estimates are rounded up to integers values. For-example, 0.1 is referred to as 1 casualty.

[1] Both census tract 206 and 207 were unintentionally omitted from the dataset. These two census tracts combined represent Downtown New Westminster. Combined, the population of these tracts was 4,287 in 2006. Upon an extensive field investigation it was determined that almost all of the population in these tracts live in either mid-rise (3-4 storey apartments) or high-rises. Many of these residential buildings have a young vintage. A significant concentration of historical buildings exists in these tracts. However, the buildings, generally considered to have high risk of damage in an earthquake, are used almost exclusively for commercial uses. Therefore, the omission of these tracts would most likely not result in a statistically significant increase in casualties. Populations of several census tracts in AOA 3 were also inadvertently omitted due to aggregation error. This omission was not caught in time for correction in this report; however, the consequent underestimation of losses may be significant and should be addressed in subsequent research.

Another key finding is that the majority of casualties did not occur in municipalities with soft soils. The casualty model takes into account soil amplification by adjusting the MMI values accordingly for each AOA. AOA's with soft soil profiles were assigned higher MMI values and are expected to have higher building damage and casualties than areas of firm soil. Only 16% of serious injuries and 25% of deaths occurred in municipalities located on soft soils. Therefore, soil profiles susceptible to liquefaction and soil amplification alone do not result in high casualty rates. Instead, the combination of two or more factors, such as soft soils and the abundance of unreinforced masonry buildings, may result in high casualty rates.

In addition to the casualties caused by structural damage to residential structures, the inclusion of internal building content shifts and collapses would potentially result in a greater number of casualties. Further, the inclusion of vulnerable critical structures, such as St. Paul's Hospital in Vancouver, would increase the casualty rate as these structures are anticipated to experience significant damage following a seismic event.

As indicated in Figure 5, the number of serious injuries is spatially concentrated in the urban core communities of Vancouver, Burnaby and Richmond. More generally, all the serious injuries are anticipated in the western portion of Metro Vancouver.

Figure 5: Number of Anticipated Serious Injuries by Municipality

The number of serious injuries generally aligns with the MMI map presented in Figure 3, which indicates a decreasing intensity towards the eastern portion of Metro Vancouver. This indicates that the combination of vulnerable municipal residential building inventory and high seismic intensity experienced at a location, together represent a reasonable predictor of casualties.

As indicated in Figure 6, the number of deaths is spatially concentrated in the urban core communities of Vancouver, Burnaby, New Westminster and Richmond. The number of deaths, while concentrated in a few municipalities, is more spread out than that of serious injuries. The relationship between earthquake intensity, building damage and number of casualties is also apparent in the location of the anticipated deaths.

Figure 6: Number of Anticipated Deaths by Municipality

4.2.2 Benchmarking

Establishing a benchmark for the Casualty Model is difficult, in that the South Coast region has not experienced a major earthquake in over half a century. On average, a damaging earthquake occurs somewhere in the region about every twenty years. The largest earthquake this century was a magnitude 7.3 event in 1946 centered beneath central Vancouver Island. Since no major damage, casualties or injuries occurred in the Greater Vancouver area from these larger seismic events, developing a benchmark based on these events is not feasible. As a result, a benchmark needed to be developed based on another seismic event that has occurred in recent times in North America. A review of large seismic events in North America reveals that the Northridge (NR) earthquake is the only event that may be of use in developing a benchmark for Greater Vancouver. Benchmarking was conducted to obtain an order-of-magnitude verification of the Casualty Model results. A detailed benchmarking analysis should be conducted in future refinements of the study to provide for a more accurate comparison of model results.

A series of seismic events and regional characteristics were used in determining the feasibility of using NR as a benchmark. The 6.7 magnitude NR earthquake occurred on Monday, January 17, 1994 at 4:31 A.M in the San Fernando Valley about 31 km northwest of downtown Los Angeles near NR (Peek-Asa et al, 1998). As indicated by Figure 7, the predominant shaking intensity for the NR earthquake in Los Angeles County was VI to VII MMI which is similar to that of the scenario Metro Vancouver seismic event.

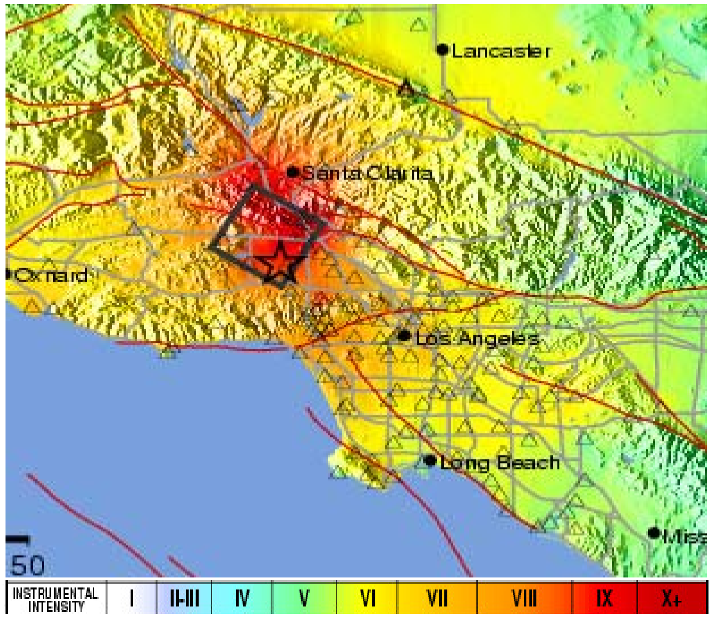


Figure 7 Shaking Intensity for Los Angeles County (Northridge Earthquake)

Source (United States Geological Survey, 2009)

The initial event characteristics align with the scenario used in this study as the event occurred during the same time of day, had similar magnitude and occurred within a similar geographical proximity to a major urban center. The NR earthquake is one of the only seismic events in North America that has occurred in recent times that has been large enough, in terms of shaking intensity, to cause substantial damage, and one for which there is sufficient data. Parallels could also be drawn between the two regions in terms of the housing building composition. Both regions are primarily composed of light frame wood, single-detached dwelling units. Therefore the overall building performance in both regions is assumed to be similar. There are, however, differences between the building codes that may affect the benchmark assessment. Due to the frequency of seismic activity in California, building codes have higher seismic standards there than in Greater Vancouver, and it would therefore be expected that Los Angeles would have a lower casualty rate. Based on these factors, the NR event was deemed to be the most appropriate benchmark.

Assessing the characteristics of injuries and deaths is important in developing a benchmark. The NR event had approximately 33 fatalities directly related to the seismic event (Tierney, 1994). Of the 33 fatalities, 22 were caused by residential structural damage (Peek-Asa, 1998). The residential casualty model yielded a result of 24 deaths. Given that the population in the affected area of NR is substantial larger, it was necessary to scale the value down to more accurately reflect the population in Metro Vancouver. To facilitate this, the NR death rate was determined by dividing the number of deaths attributed to earthquake (22) by the 1990 population in Los Angeles County of 8,863,164 (Peek-Asa et al, 1998). The death rate for the NR earthquake was 0.00000248. This rate was then multiplied by the Greater Vancouver population (Vancouver CMA 2,116,581 in 2006). The result yielded a benchmark of 5 deaths which is considerably lower than the 24 estimated to occur in Metro Vancouver. The difference between the benchmark and the model results may be accounted for in the higher number of unreinforced masonry buildings in Vancouver than Los Angeles. Therefore, the model results, based on the benchmark value, provide a reasonable estimate of deaths following a seismic event in Metro Vancouver.

HAZUS methodology is a reasonable predictor of number and severity of earthquake related injuries. There is no standardized methodology, however, for determining the total number of actual casualties following an earthquake. The number of injuries reported varies according to the type of injuries captured, the time frame used after the event and the locations analyzed. Therefore, there is generally a discrepancy between HAZUS casualty assessments and what is reported after an earthquake. Specifically, there are definitional differences between what is considered "serious injuries" between HAZUS and various studies. Both severity level 2 (injuries requiring hospitalization but are not life-threatening) and severity level 3 (life threatening) were combined in defining "serious injuries" in this report. HAZUS does not take into account non-structural building damage (i.e. content shifts) induced casualties and only accounts for structural building damage related injuries. Further, casualties not attributable to immediate physical impact such as heart attacks are excluded from HAZUS. However, various reports estimating serious injuries from the NR earthquake provide totals which include serious injuries related to non-structural building components, motor vehicle accidents and other outdoor casualties.

The most commonly cited source for casualty estimation, and the one used in this report, is the Peek-Asa et al (1998) report. This report estimates the number of serious injuries occurring from the NR event at 138 individuals (Ibid). Injuries were defined as earthquake-related if the injury was due to consequences of earthquake activity. The majority of the injuries in the NR event were caused by non-structural objects followed by the earthquake force and behaviour (Shoaf, 2002). Structural object accounted for few serious injuries (ibid). Injuries caused by structural failure (hit/trapped by building parts) accounted for only 12 of the estimated 138 serious injuries (Peek-Asa et al, 1998).

To ensure continuity between HAZUS and the Peek-Asa (1998) report, only serious injuries, those requiring hospitalization and those that were caused by structural failure were considered in the development of the benchmark. The benchmark for serious injuries was calculated to be 3 for Greater Vancouver. The benchmark rate was calculated by dividing the total number of serious injuries (12) by the 1990 Los-Angeles County population (8,863,164). The injury rate for the NR earthquake was 0.00000135. This rate was then multiplied by the total population in Metro Vancouver.

While the Metro Vancouver model serious injury total of 25 is considerably higher than the benchmark of 3, there are various factors that may account for the considerable difference between the benchmark and model results. One such factor is the prevalence of older buildings, many of which are masonry, in the Metro Vancouver core. This factor alone can account for the considerable difference between the benchmark and model result. Another factor that may account for this difference is the relationship between local shaking intensity and building class / vintage. A concentration of older, more vulnerable building, located in an area of significant shaking may yield a higher number of casualties than if the same area had a lower level of shaking and more resilient building stock. The number of estimated serious injuries may actually be higher in the scenario event if vulnerable critical facilities and infrastructure are taken into account. Critical structures, such as hospitals, have large numbers of individuals within them and would potentially result in numerous casualties if significant damage is sustained. Other aspects unaccounted for in the model, such as internal building content movement, would also potentially increase the number of casualties.

Taking into account the NR benchmark, the overall results of the casualty model yielded a reasonable set of values. Casualty modeling is not a precise science and a margin of error should be anticipated in model results. Given the limited sampling range for potential benchmarks, the calculated value reflects the best attainable benchmark for determining order-of-magnitude.

5.0 Displaced Population Model

5.1 Overview

The most commonly used model for forecasting public shelter demand is the HAZUS-MH model which predicts shelter use within the social impacts module and provides estimates for the number of households displaced in a seismic event. While the model provides for a reasonable estimate of public shelter needs, there are a series of limitations that reduce the overall effectiveness of the model outputs. Three major limitations of the HAZUS model, according to Chang et al. (2008), are as follows:

- The use of the census tract as the unit of analysis does not allow for the differentiation between households within a census tract.
- The model does not account for the locations of households relative to shelter locations.
- Mobility variables such as car ownership are not accounted for in HAZUS.

Recent research by Chang et al. (2008) provides a more comprehensive shelter model which builds upon HAZUS-MH. One of the key distinguishing model features is the use of the household as the unit of analysis. According to Chang et al (2008), using the household as the unit of analysis allows for a more accurate reflection of decision-making and shelter use. The model framework is provided in Figure 8. The model is based on a series of decisions that result in the household remaining at home, seeking public shelter or seeking alternative shelter. As indicated in Figure 7, the first sequence of events is the occurrence of an earthquake. Water / power availability, building damage and demographic characteristics of the household are assessed in determining whether the household will seek public or alternative shelter. The outcome of each decision in the model determines the direction within the overall model. The model developed and used for this analysis follows a similar model framework developed by (Chang et al, 2008). A detailed assessment of the data acquisition methodology used is provided in the proceeding sections. Variables used in the shelter model are defined in **Appendix 8**.

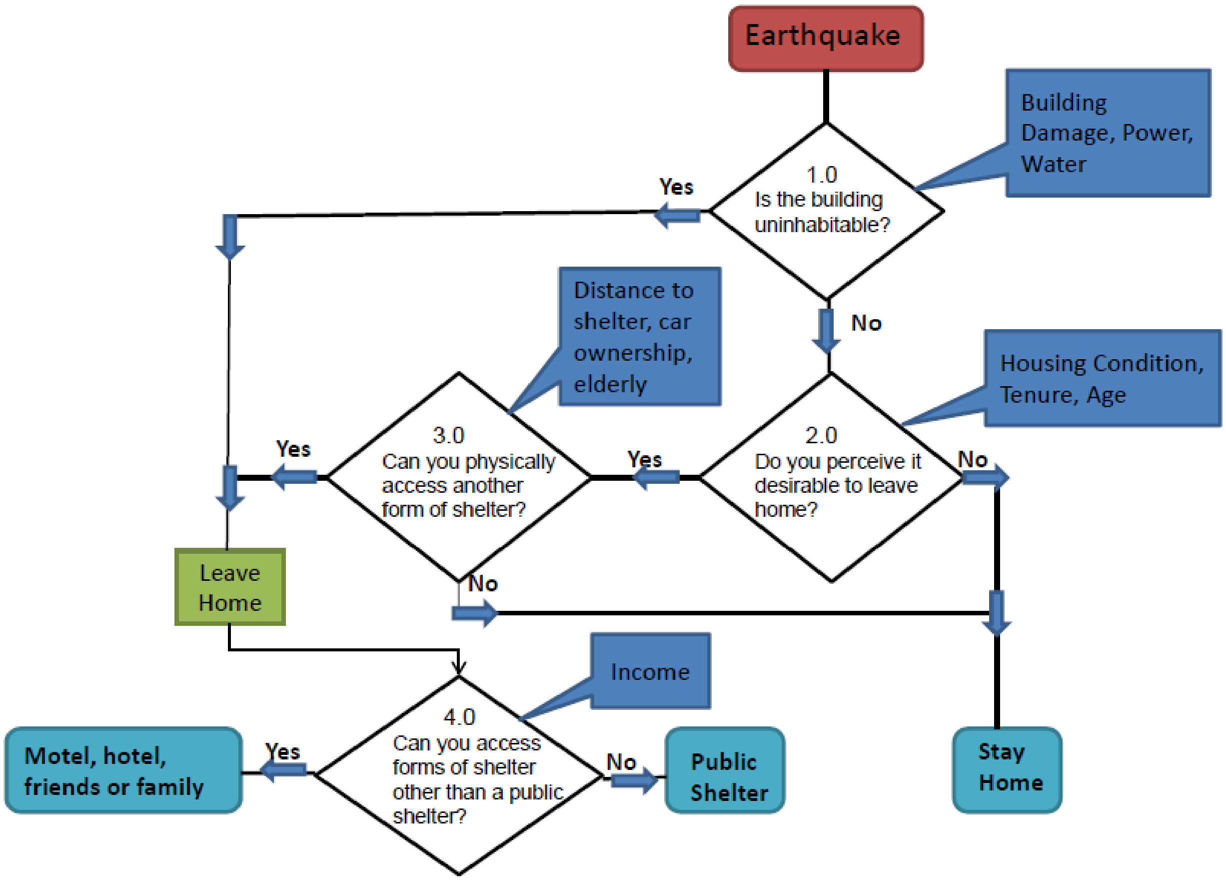


Figure 8: Displaced Population Model Flow Diagram

Source: Chang et al. (2008)

5.2 Data Collection

5.2.1 Overview

The household unit was used in the model as the unit of analysis since residential building damage impacts all members of the household equally and decisions made in the event of a disaster are made at the household level. Census data on households are available at all spatial scales including Census Metropolitan Area (CMA), at the highest level, to micro data which represents individual households. While micro data is available for the majority of the variables outlined in the Chang et al (2008) model, it is not suitable for use in the Displaced Population Model as it is aggregated at the CMA level. The aggregation of the micro data at a CMA level does not allow for an inter-regional analysis. Therefore, data was acquired using both census tract and special tabulation data at the census tract level, allowing for an intra-regional analysis.

The following data was used in the development of the Displaced Population Model:

- Household type (family household / non-family household)
- Household income

- Presence of elderly (65 years and older) in household
- Presence of children (18 years and younger) in household
- Census tract location of household
- Household tenure (renter or owner)
- Access to vehicle
- Building damage
- Water and power availability

Variables used in the model developed by (Chang et al, 2008) that were not used here include: Hispanic ethnicity, neighbourhood condition, and weather. While these variables are of importance in determining whether or not a household will be displaced in a seismic event, there is no data available for these attributes. Furthermore, the relationship between ethnicity and shelter demand has not been investigated in the Metro Vancouver area.

According to Statistics Canada, in 2006 there were 760,000 households in the Vancouver Census Metropolitan Area. A 5% sample size (37,935 households) was used for the model dataset, as described below. Model results presented in **Section 5.4.1** are scaled to 100%. Each of the sample households was given a unique identification number with which various demographic characteristics were linked to the household.

5.2.2 Household Type and Income Assignment

Statistics Canada does not have one definition of family and instead includes multiple forms of families such as economic and census families and non-families. Both non-family and family households comprise all persons living in private households (see **Appendix 9**). Therefore, the first attribute that needed to be assigned to each of the 37,935 households was whether it was a family household or a non-family household. The second attribute was the household income level.

Household type and income were assigned probabilistically, so that the overall profile of the 5% sample matched that of the entire population of households. A probability table was created that indicated the percent distribution of Vancouver CMA households among household type (family- or non-family) and income categories (11 income brackets). Each household in the sample was assigned a random number (0.0~1.0). The random number was used to look up a corresponding household type and income category in the probability table.

5.2.3 Elderly Population Assignment to Households

Using a similar procedure, each household was then assigned a Yes/No value to indicate the presence of an elderly person in the household. Data on number of individuals in the household that are 65 years of age and over was obtained through a special, CMA-level, census tabulation on the total number of elderly persons per household income group. Data was available separately for family- and non-family households. Probability tables were created from this data. The tables indicated the likelihood of no elderly persons in the household, depending on household type and income bracket. The assignment of elderly individuals to the household was done by looking up the probability tables using a random number generated for the household. If the random number were higher than the corresponding income group/elderly probability value, then an elderly person was assigned to the household.

5.2.4 Household Location (Census Tract) Assignment

The location, in terms of census tract, of each household was inferred based on household income previously assigned to each household sample. The assignment of household location was done randomly by matching a random number generated for each household with a probability table that was developed. The logic used for census tract assignment was that if X% of Vancouver CMA's low-income families live in census tract Y, then a low-income family in the sample should have an X% chance of being located in census tract Y.

Family households were arranged according to their respective income groups. Separate probability tables were created for each income groups. Random numbers generated for each household were then matched with the probability values for the corresponding income group to assign the associated census tract to the household.

For non-family households, the same methodology was used as for family household census tract allocation. Due to differences in census data reporting, census tract assignment was not based on household income and was instead based on household living arrangements. Probability values were developed by taking the total number of persons in non-family households in each census tract and dividing that value by the total number of persons in non-family households in the CMA.

5.2.5 Presence of Children Assignment to Households

Each household was assigned a "yes" or "no" value to indicate the presence of children, under the age of 18, in the household. This was assigned based on census tract. The assignment of children to the household was done randomly by matching the random number generated for the household with a probability table that was developed. If the random number assigned to the household were less than or equal to the probability value generated for that corresponding census tract, then a "yes" value was assigned for presence of children.

According to Statistics Canada, over 99% of children in the Vancouver CMA area are in family households. Therefore, for the purposes of this analysis, no children were assigned to non-family households. This represents only a minor inaccuracy in the overall assignment process.

5.2.6 Tenure Assignment to Households

Household tenure (rent or own) was assigned based on the census tract to which the household belongs. The assignment of tenure was done randomly by matching a random number generated for the household with a probability table that was developed. If the random number assigned to the household were less than or equal to the probability value, then the household was assigned an "owner" status; otherwise, they were assigned "renter" status. The same method was used for non-family tenure allocation.

5.2.7 Distance to Shelter and Car Access

One of the predictive variables for shelter use is the household's distance to the nearest shelter. The distance to shelter is defined in this model as the distance from the centroid of the census tract within which the household is located to the shelter that is closest to this point. Due to a lack of available data on emergency municipal shelter locations, community centres were assumed to be the primary shelter locations. The exception to this was for the City of Surrey where public schools are designated as the primary shelter locations in the event of a disaster

(Surrey School District, 2010). Using geographic information systems, the location of each shelter was mapped in relation to census tracts.

A 1 km buffer was delineated around each shelter to determine which census tracts were within walking distance to it. This distance was based on walkability indices research conducted by Frank et al. (2004) which used a 1km buffer to indicate a walkable distance (10-20 minutes) from a household's residence. Figure 9 represents the census tracts that are considered to be within walking distance to a public shelter. Census tracts represented in this map as having access to a public shelter meet at least one of two conditions. The two conditions are as follows:

- Condition 1: The census tract contains a shelter location
- Condition 2: The census tract is within 1 km of a shelter location

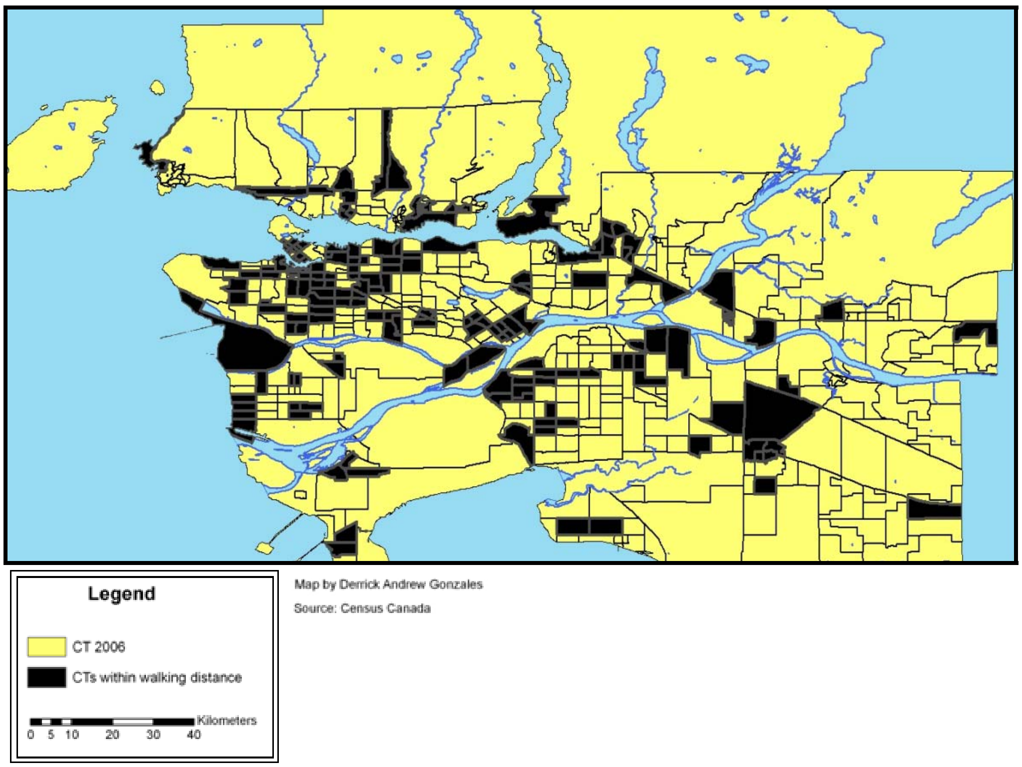


Figure 9: Census Tracts within Walkable Distance of Public Shelter

Car access assignment followed a similar assignment to that of tenure, which was based on census tract level data. The assignment of car ownership was done randomly by matching the random number generated for the household with a probability table that was developed. Probability values were developed for each census tract by calculating the percentage of total commuters that has access to a vehicle. Those who have access to a vehicle were determined for the purposes of this analysis to be commuters who have access to a vehicle, are passengers in a vehicle or own a motorcycle. Those who do not have access to a vehicle are those who commute to work by transit, taxi, walking or biking. If the random number assigned to the household were less than or equal to the probability value, then the household was assigned a "car access" value of "yes."

5.2.8 Building Damage

Building damage data on the number of people per damage state for each AOA was obtained from the residential casualty model. The assignment of building damage state for each household residence was done randomly by matching the random number generated for the household with a probability table that was developed. This method potentially presents a significant source of error as in reality level of income and building damage are correlated (Chang et al, 2008).

5.2.9 Power and Water Data

Both power and water availability are important factors in determining whether or not a household leaves home and seeks alternative shelter. The data used for the model are reported as the number of days needed to restore power and electricity. The subsequent sections provide a system overview, vulnerability identification and system performance estimate for both the electric power and water systems in Metro Vancouver. Both water and power availability data used for the Displaced Population Model were based on a series of assumptions, as vulnerability and post-event performance information pertaining to these infrastructural systems was not available at the time of the study.

5.2.10 Power model

5.2.10.1 System Overview

A conventional electric power system can be generalized into broad categories of: power generation, transmission, and distribution to the end user. Power generally flows from a power generating source through a series of high voltage transmission lines to a substation where voltage is transformed from high to low or reverse using transformers. Power flows from these substations through a series of distribution lines to the end-user.

The Greater Vancouver power system, as seen in Figure 10, is organized in a similar manner with the exception of power generation. While hydro and thermal power generation do exist in limited sites in Greater Vancouver, the majority of the regional power supply originates outside the region. The majority of the power is transmitted into Metro Vancouver by a single high voltage, 500 Kilovolt, transmission line which traverses through the Fraser Canyon located east of the Lower Mainland. From this line, the system generally branches out into a series of lower voltage transmission lines which are interconnected by a series of substations. From these substations and transmission lines, power flows through a series of municipal level power distribution networks to the end consumer. Most of the distribution and transmission network is located above ground with few areas in the urban core (Vancouver, Burnaby and New Westminster) having part of their high voltage power supply underground.

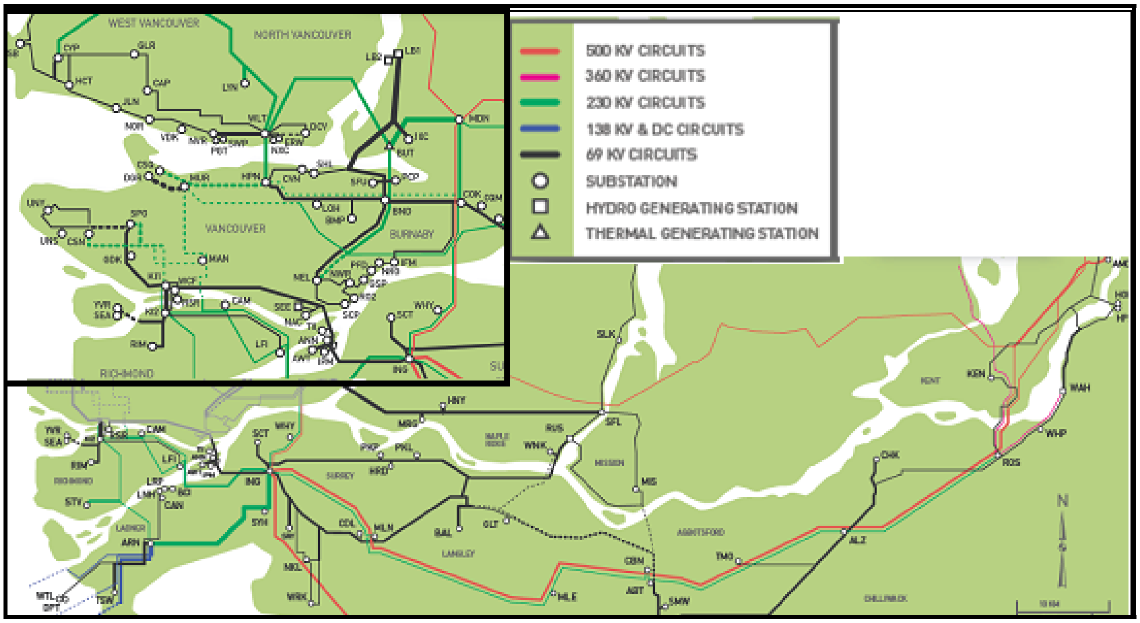


Figure 10: Metro Vancouver and Fraser Valley Power System

(Source: British Columbia Transmission Corporation, 2009)

5.2.10.2 Vulnerability Identification

Power systems and their associated components are not immune from service disruptions and, depending on the location, face a series of geological hazards that have the potential to compromise the entire or part of the system. Metro Vancouver is subject to a series of natural hazards and secondary effects including seismic events, landslides, inundation, soil liquefaction and soil amplification. Each of these hazards poses a considerable risk to the normal functioning of the power system.

Past earthquakes have demonstrated that power infrastructure can be extremely vulnerable to damage and also provide for a means of assessing what the potential disruption may be to the Metro Vancouver power grid. The Chi-Chi, Taiwan earthquake provides for a good illustration of the potential spatial and temporal impacts associated with a power system failure that may ensue following a seismic event. The Chi-Chi earthquake, registered at 7.6 magnitude, resulted in significant physical damage to both infrastructural systems, property and resulted in numerous casualties (Moh et al, 1999). The Chi-Chi earthquake also demonstrated that damage to high-voltage transmission lines causing widespread power disruption is possible following a seismic event (Schiff et al, 2000). The earthquake caused a transmission tower carrying 2 of 4 critical power lines to collapse (Ibid). The earthquake also destroyed the Chunglaio substation, leaving the northern and central portion of Taiwan without power (Ibid). As shown in Table 8, a significant number of transmission towers of varying voltage and associated infrastructure were structurally damaged.

Table 8: Summary of Damage to the Transmission System in Chi-Chi Earthquake

Item	Quantity	Description
Substation Buildings	14	Wall cracked
345 kV Tower	1	Collapsed
345 kV Towers	6	Leaning
345 kV Towers	124	Distorted
345 kV Towers	227	Foundations Sunk/Crack
345 kV Towers	4	Foundations Displaced
345 kV Lines	28	Damaged
161 kV Towers	10	Collapsed
161 kV Towers	7	Leaning
161 kV Towers	42	Distorted
161 kV Towers	143	Foundations Sunk/Crack
161 kV Towers	3	Foundations Displaced
161 kV Lines	30	Damage
69 kV Towers	4	Collapsed
345 kV CCPT	53	Porcelain Housing Broken
345 kV Surge Arresters	46	Porcelain Housing Broken
345 kV Support Insulators	3	Broken
345 kV Gas Insulated Lines	334m	Distorted
345 kV Gas Insulated Switchgear	28 sets	Foundations Sunk
345 kV Bus	4	Damaged

(Source: Schiff et al, 2000)

Many of the towers failed due to their location in mountainous geography with steep, rugged slopes susceptible to ground failure. As a result, the north section of the entire island lost complete power for over a week and power resumed gradually over several weeks following the earthquake (Moh et al, 1999). Other research has indicated that the main vulnerability for transmission lines is foundation failures triggered by landslides and slope failure for distribution poles (Scawthorn et al, 2002).

Given that the Lower Mainland is located within a high seismic zone and has substantial amount of land susceptible to liquefaction and amplification (See **Section 2.2.2 Seismicity and Ground Failure Risk Factors**), the risk to power infrastructure damage and associated power outages is significant. Overlaying the power transmission system over the geologic (soils) profile of the Lower Mainland reveals that the main high voltage transmission lines that supply the majority of power to the Lower Mainland are located on soils susceptible to liquefaction and amplification and go through the Fraser Canyon, which is highly susceptible to landslides. These high voltage transmission lines pass through steep mountain slopes susceptible to landslides triggered by a seismic event. According to Clague (1996) and Natural Resources Canada (2009a) portions of the transmission line that pass through the steep-sided mountain valleys in the Fraser Canyon would be either damaged or destroyed by landslides initiated by a large earthquake. Upon exiting the Fraser Canyon into the Lower Mainland, the main transmission line crosses rivers and soft soils which increase the vulnerability of these lines to damage.

Once this power is transferred to the distribution network and supplied to municipalities, the overall vulnerability of this portion of the system varies across the region. No publicly available documents are available outlining the vulnerability of the power system across the region. Therefore, a series of assumptions were made as to determining which area of Metro Vancouver would have power failure. It was assumed that areas susceptible to soil liquefaction such as Richmond, Delta and parts of municipalities that are adjacent to the Fraser River have higher susceptibility of damage occurring to their power systems. Furthermore, areas with the heaviest damage to physical infrastructure are areas where there may be greatest damage to the power system.

5.2.10.3 System Performance

Estimating how infrastructural systems as complex as power systems perform in large seismic events without a recent historical seismic event to reference upon is problematic. The lack of documentation, outlining how the system is anticipated to perform after a seismic event, limits the ability to predict power system performance.

System performance estimates for the purposes of determining whether or not households have power were conducted using a variety of sources and assumptions. According to the Munich-Reinsurance Company (1992), power restoration after a major seismic event, at both the municipal and regional level, is estimated to be within 36 to 72 hours. Furthermore, literature suggests that out of all the major utilities, power can be restored the fastest and within 8 to 48 hours (Ibid). However, the Chi-Chi earthquake indicates that if extensive damage is sustained during a seismic event, restoration time will take considerably longer.

The shelter model requires information on whether or not there is power within 2 days of the event, and if not, whether the outage is more than 4 days. Given the vulnerabilities identified to various geological hazards, it was assumed that:

- Power will not be available for non-critical facilities and residential dwellings during the first 72 hours. This assumption was made because the main high voltage power transmission lines through the Fraser Canyon will be compromised in certain vulnerable points and will take substantial time to access and repair damaged sections of the lines.
- The entire system will need to be shut down deliberately to do inspections the first 24hrs.
- Essential facilities such as hospitals, which have backup power generators, will have power during the first 72 hours.

After three days, it was assumed that highest-level priority customers such as hospitals, government buildings and airports and areas less vulnerable to liquefaction and amplification such as Vancouver will have power. Isolated pockets of power outages were assumed to occur in cities vulnerable to liquefaction and soil amplification. Municipalities that are more susceptible to liquefaction and amplification were assumed to have more damage to the power grid and will take longer to resume normal functionality. Table 9 provides indicates the assumed power outage duration for each AOA.

Table 9: Power Outage for Each Area of Analysis

Area of Analysis	Power out less than 2 days?**	Power out more than 4 days?*
Vancouver	No	No
South Vancouver	No	No
Downtown Vancouver	No	No
University Endownment	No	No
City of North Vancouver	No	No
District of North Vancouver	No	No
West Vancouver	No	No
Richmond	No	Yes
YVR	No	Yes
Mitchelle Island (North Richmond)	No	Yes
Tawwassen (Delta)	No	Yes
Delta	No	Yes
White Rock	No	No
South Surrey	No	No
Central Surrey	No	Yes
North Surrey	No	No
Surrey (Sea-Port)	No	Yes
Quay/Queensborough (New Westminster)	No	Yes
Big Bend (Burnaby)	No	Yes
Burnaby	No	No
Port Moody	No	No
South Coquitlam	No	No
Coquitlam	No	No
Port Coquitlam	No	Yes
Maple Ridge	No	No
Pitt Meadows	No	Yes
Township of Langley	No	No
City of Langley	No	No

*If more than 50% (approx) of land is in liquifaction zone then YES, else NO
** assumes at least one day the system will be shut down for inspection and at least another day to patch the municipal grid (downed poles/wires)

5.2.10.4 Model Limitations

Power networks are complex infrastructural systems that have various redundancies and interdependencies. Estimating power outages without readily available quantitative and/or qualitative assessments of the vulnerability of the various sections of the system was problematic. Furthermore, information on seismic retrofits was also not available, which adds even more uncertainty to modelling power restoration times. Past earthquakes have demonstrated that restoration times can be fairly quick, such as in the Loma Prieta earthquake, or take a considerable amount of time if the damage is extensive, such as in the Chi-Chi earthquake. Therefore, estimating power outage duration based on past seismic events provides some insight into what may be expected in the earthquake scenario for Metro Vancouver, but much further research is needed.

5.2.11 Water Model

5.2.11.1 System Overview

A conventional water system can be generalized into eight broad categories from source to tap, including water source, filtration and chlorination, transmission through regional pipes, pumping station and secondary chlorination, storage of some water and distribution through a series of smaller pipes through individual municipalities to consumers. The Metro Vancouver water system, as seen in **Appendix 10**, is administered at both the regional and municipal level. At the regional level, Metro Vancouver Water District (MVWD) provides for the regional water supply through the use of three dams and associated reservoirs located in the northern portion of the region. Each dam provides water for specific geographical areas of the region.

Water to the municipality, however, can be redirected from another dam if the dam that regularly supplies drinking water is temporarily unavailable. Water is then transferred through large underground pipes to filtration/chlorination facilities which disinfect the water. From these facilities, water is primarily transferred through gravity-induced flows, to individual municipalities through a series of large pipes. Water pumps are used in strategic locations to ensure that water pressure is maintained. These transmission pipes must often cross multiple bodies of water to reach their final destination. Regional water pipes to the southern Municipality of Delta, for example, must cross three bodies of water. River crossings, as is described in the following section, add an element of risk to water systems due to possible breaches due to scouring, lateral ground shifts and liquefaction. From these transmission pipes, water flows either to municipal or regionally-operated reservoirs, to secondary filtration systems or straight to the end consumer. Secondary reservoirs, for the purposes of the shelter model, are assumed to be a critical source of water supply in the event that water supply from the region is not possible. From either the reservoirs or the regional transmission system, the water is then transferred to the municipal distribution system, which uses smaller pipes to feed the water to end-users.

5.2.11.2 Vulnerability Identification

Similar to other infrastructural systems, geological hazards such as seismic events, liquefaction, lateral soil movement, and landslides have the potential to significantly compromise the normal functioning of a water system. The main areas of vulnerability in Metro Vancouver are in areas where pipes cross bodies of water due to high liquefaction potential. As seen in **Appendix 10**, the MVWD primary transmission lines from both the Seymour and Capilano reservoirs cross the Burrard Inlet. Soils in areas adjacent to the inlet, where the pipes cross, are considered to be areas susceptible to liquefaction. Previous earthquake studies have indicated that for both transmission and distribution pipes, damage tends to be concentrated in areas of soil transition and in areas of soft soil susceptible to liquefaction (Eidinger et al, 1999). Pipelines in firm soil have lower damage rates during seismic events (Ibid). Furthermore, the highest vulnerability pipelines tend to be old, poorly maintained, cast iron pipes (along with other types) (American Water Works Association, 1994).

These trends can be verified in relatively recent seismic events in Northridge, Loma Prieta and Kobe. In the Loma Prieta earthquake, numerous breaks in the domestic water supply network serving the San Francisco marina district, built on artificial fill, were widespread (Eidinger et al, 1999). Similarly in Kobe, primarily build on alluvial soils and artificial fill, the city experienced between 1,500 to 2,000 breaks in the water distribution system which took two months to repair (Ibid). Similarly, transmission water pipeline damage in the Northridge earthquake took between 2 and 67 days to repair (Ibid). While damage to water systems can be extensive, areas prone to seismic activity generally have baseline performance targets in mind when designing or replacing old water mains. According to Eidinger et al (1999), baseline performance goals for maximum earthquakes (large earthquakes with a 475 year recurrence interval) have a target of having potable water for domestic use at central locations for pickup within 3 days and minimum service to 70% of customers within 10 days.

5.2.11.3 System Performance

At the regional level, MVWD has been proactive in retrofitting aging water infrastructure and ensuring there is enough redundancy in the regional transmission system to provide water after a large seismic event. In specific, water supplies at the three dams in the region have all been seismically upgraded to standards that would allow these facilities to remain operational after a large seismic event (Archibald, 2007). Water transmission seismic upgrades have also been actively conducted on many of the major transmission lines across the region (Ibid). For-example, the transmission line and pumping stations along a land-based link from Coquitlam to Downtown has been seismically upgraded to ensure secure water supply to Vancouver.

Numerous points of the transmission system remain vulnerable to seismic activity. Most vulnerable to failure are the transmission pipelines that cross water bodies. According to Archibald (2007), the Burrard Inlet and Fraser River crossings could easily be compromised in seismic event. Furthermore, given that most of these lines are underwater and underground they would be hard to repair (Ibid). In 1997, the Port Mann crossing (Fraser River) was compromised and took 2 months to temporarily fix and was not permanently fixed until almost a year later. During this event, water was redirected from other transmission lines and from the Coquitlam Dam, but meeting the needs of municipalities south of the Fraser River such as Surrey and Delta proved to be extremely difficult, and severe water restrictions were put in place. This incident then provides insight into what may be expected in this portion of the region in the event of a large earthquake.

Liquefaction was a primary factor in determining system performance for both the transmission and distribution components for each AOA. It was assumed that municipalities that are closest to the water reservoirs and do not have transmission lines crossing rivers to service them will have water service within two days of the seismic event. Other municipalities were assumed not to have water service within two days. However, there were a few exceptions to this with Downtown Vancouver, University of British Columbia lands, and the City of Langley all considered having enough reservoir capacity for the first few days before transmission lines are repaired or, in the case of Downtown Vancouver, have hardened and redundant lines to service them.

According to Archibald (2007), many southern river crossings would be expected to be broken but given that there is considerable redundancy, 75% of the service targets are expected to be met within 3 to 5 days. However, according to Frank Huber, Division Manager of Engineering Services at Metro Vancouver, the Fraser River crossing, constructed in 1974, would fail in a moderate to major tremor (Journal of Commerce, 2009). Furthermore, the Burrard Inlet crossing was built in 1940 and would not be expected to survive even a minor tremor. According to Archibald, it is anticipated that disruptions to the remaining portions of the water transmission system would be minor and within 3 to 5 days service to municipalities would be resumed. Municipalities susceptible to soil liquefaction are anticipated to take longer to restore and it is expected that by 2 weeks the majority of water flowing to municipalities would be restored.

At the municipal level it is expected that there will be more breaches in the water distribution system than to the transmission system. Older municipalities such as Vancouver, Burnaby and New Westminster and even more suburban municipalities such as Surrey, Richmond and Delta have distribution systems that are largely composed of old piping material such as cast iron, are segmented and not restrained at the joints. These distribution systems are assumed to experience severe and extended outages lasting more than a week (Archibald, 2007). With many municipal distribution systems down, municipal and regional water reservoir tanks may have to be relied on for potable drinking water. Based on past the performance of water systems in past earthquakes in other regions, Metro Vancouver Engineering expertise and studies that have been done identifying vulnerable points in the transmission system, each municipality was assigned a “Yes” or “No” value as to whether or not the area had water after two days or after 4 or more days.

Based on the vulnerability of the municipal distribution system, it was assumed that municipalities that did not have water after two days would not have it within four days. This assumption was made on the premise that multiple breaches in the distribution system would take extended periods of time to fix. Water availability assumptions for each AOA after the scenario seismic event in Metro Vancouver are provided in Table 10.

Table 10: Water Availability in Metro Vancouver after a Seismic Event

Area of Analysis	Water Access 2 days?	Water Access 4 days?
Vancouver	no	no
South Vancouver	no	no
Downtown Vancouver	Yes	Yes
University Endownment	Yes	Yes
City of North Vancouver	Yes	Yes
District of North Vancouver	Yes	Yes
West Vancouver	Yes	Yes
Richmond	no	no
YVR	no	no
Mitchelle Island (North Richmond)	no	no
Tawwassen (Delta)	no	no
Delta	no	no
White Rock	no	no
South Surrey	no	no
Central Surrey	no	no
North Surrey	no	no
Surrey (Sea-Port)	no	no
Quay/Queensborough (New Westminster)	no	no
Big Bend (Burnaby)	no	no
Burnaby	no	no
Port Moody	Yes	Yes
South Coquitlam	Yes	Yes
Coquitlam	Yes	Yes
Port Coquitlam	Yes	Yes
Maple Ridge	No	No
Pitt Meadows	No	No
Township of Langley	No	No
City of Langley	Yes	No

5.2.11.4 Model Limitations

Estimating water disruption at the municipal scale in one of the largest water districts in North America is problematic in that there is no uniformity in terms of age of pipes, construction methods or material used. The diverse soils profile and associated geological risks in the region, coupled with a lack of accessible municipal data on distribution pipeline vulnerability, further complicates the assignment of municipal water availability. Another limitation is with the assumption made that multiple breaches in the distribution system means no water access for municipalities. In actuality, municipalities with multiple breaches in the distribution system would have pockets of outages at the intra-municipal level rather than city-wide outages. However, without a detailed inventory of vintage and construction type of municipal water systems, an intra-municipal outage forecast could not be conducted.

5.3 Shelter (Displacement) Model Methodology

5.3.1 Overview

As described earlier in **Section 5.1**, the shelter model consists of a linear set of decisions in which the importance of each decision is determined by its placement in the sequence of decisions. Building damage (housing condition) is the most influential variable and is given the most weight in determining the number of displaced households.

Income is the only variable used to determine whether or not a displaced household will seek public shelter or alternative shelters. Studies have shown that income is a strong indicator of accessibility to alternative options of shelter (Morrow, 1999; Tierney et al, 2001).

The outcome of each decision within the model is calculated based on a series of variables. The outcome of each decision is either "yes" or "no". The following discussion describes the inputs and outputs of each decision and how each "yes" or "no" outcome is determined. The model algorithms and structure are based closely on those developed in Chang et al (2008).

5.3.2 Decision 1: Is the building uninhabitable?

The input variables for this decision are building damage (BD), Power (P), and Water (W). The combination of these three variables is referred to in the model as housing condition (HC). The likelihood of the household dwelling being uninhabitable is represented by low, medium or high values for the (HC) variable. The following conditions are applied in the model:

- Housing condition (HC) is "very low" if building damage (BD) is complete (BDC)
- Housing condition (HC) is "low" if one of the following conditions is satisfied:
    - Building damage (BD) is extensive (BDE)
    - Water (W) is out of service for more than 4 days
    - Power (P) is out of service for more than 4 days
    - Building damage (BD) is moderate (BDM) and both water (W) and power (P) are out of services for more than 4 days.
- Housing condition (HC) is "high" if building damage (BD) is negligible (BDN) and both water (W) and power (P) are out of service for no more than 2 days.
- HC = "mod" otherwise.

The outcome of Decision 1 ("Is the building uninhabitable?") is "yes" if housing condition (HC) is "very low". The outcome is "no" if housing condition HC is low, moderate, or high. If the outcome is "yes", that household is assumed to "leave home", and is considered a displaced household. If the outcome is "no", the household is modeled to consider decision 2, "do you perceive it desirable to leave home?"

5.3.3 Decision 2: Do you perceive it desirable to leave home?

The variables considered in this decision include housing condition (HC), tenure (T), and age (A). The decision outcomes "yes" or "no" were determined by combinations of the input variables.

The outcome of decision 2 is "yes" if one of the following combinations is satisfied:

- Housing condition (HC) is "low", and tenure (T) is "rent"
- Housing condition is "low", tenure is "rent" and at least one member of the household is less than 18 years of age or more than 65 years of age

The outcome of Decision 2 is "no" otherwise. If the outcome of the decision is "no", the household is not considered a displaced household. If on the other hand the outcome is "yes", the household was modeled to consider decision 3, "Can you physically access another form of shelter?"

5.3.4 Decision 3: Can you physically access another form of shelter?

The variables considered in this decision include distance to shelter (D), car ownership (C) and elderly (E). The outcome of the decision is "yes" if one of the following is satisfied:

- The household owns a car (C=yes)
- The household is within a census tract that contains the shelter location (used to determine access to shelter by walking)
- Households are in a census tract for which the centroid is within 1 km of a shelter location

The outcome of the decision was "no" otherwise, and the household is assumed to stay home. If the outcome of the decision was "yes" the household is assumed to leave home. The latter two bullet points capture households which do not have a car and are within walking distance to a shelter. A distance of 1 km was chosen based on research conducted by Frank et al (2004) examining walkable neighbourhoods.

The total number of displaced households was determined by summing the number of households displaced at each of the three decision steps. The displaced households continue on to the final decision, which determines whether or not the household will seek public shelter.

5.3.5 Decision 4: Can you access forms of shelter other than public?

Households with moderate to high income are assumed to access alternative shelter to public shelter. The outcome of this decision is "yes" if income (I) is moderate or high. The outcome of this decision is "no" if income is "low". Households with a "no" decision are modeled as seeking public shelter. Low household income is defined as $0 to $40,000; medium income is defined as $40,000 to $90,000; and high income is defined as $90,000 and above.

5.4 Displaced Population Model Results and Benchmarking

5.4.1 Results

Model results indicate that following a large seismic event in Metro Vancouver, there would be a substantial amount of displaced households seeking either public or alternative shelter. Overall, the model indicates there would be 144,507 households displaced, of which 84,004 would seek public shelter and 60,503 would seek other shelter. The number of displaced households represents 19% of the total number of households in the Vancouver CMA. Furthermore, with 58% of the displaced households seeking public shelter, there is a greater demand for public shelter than alternative shelter locations.

As indicated in Table 11, municipalities which account for the highest proportion of the total regional displaced households are as follows:

- City of Vancouver: 52,800 displaced households (37%)
- Surrey: 23,140 displaced households (16%)
- Burnaby: 19,580 displaced households (14%)
- Langley: 11,280 displaced households (8%)
- Richmond: 10,600 displaced households (7%)

This indicates that there is a significant variation and concentration of the number of displaced households in Metro Vancouver. The three largest municipalities in the region combined (Vancouver, Surrey and Burnaby) account for 67% of all displaced households in the region. The remaining fourteen Metro Vancouver municipalities analyzed in the model only account for 33% of the total displaced households. This indicates that the greatest need for social assistance after a large seismic event in Metro Vancouver will be in the urban core municipalities.

Table 11: Public and Alternative Shelter Demand by Municipality and AOA[2]

		Seeking Public Shelter	Seeking Other Shelter			
Municipality	**AOA**	**Number of Households Displaced**	**Number of Households Displaced**	**% of Regional Total Displaced Households**	**Total Households Displaced**	**% of Municipal Populatio**
City of Vancouver	1	29,100	19,800		48,900	
South Vancouver	2	2,220	1,640		3,860	
Downtown Vancouver	3	20	20		40	
City of Vancouver	**(1-3)**	**31,340**	**21,460**	**37%**	**52,800**	**20.4%**
University of British Columbia	4	0	0		0	
City of North Vancouver	**5**	**20**	**0**	**0%**	**20**	**0.1%**
District of North Vancouver	**6**	**20**	**20**	**0%**	**40**	**0.1%**
West Vancouver	**7**	**240**	**80**	**0%**	**320**	**1.9%**
Richmond	8	4880	4140		9020	
Richmond (Vancouver Airport)	9	60	60		120	
Mitchelle Island/North Richmond	10	680	240		920	
Richmond	**(8-10)**	**5,620**	**4,440**	**7%**	**10,060**	**16.3%**
Delta (Tawwassan)	11	840	500		1340	
Delta	12	2560	2140		4700	
Delta	**(11-12)**	**3,400**	**2,640**	**4%**	**6,040**	**18.2%**
White Rock	**13**	**1,204**	**923**	**1%**	**2,127**	**22.4%**
Surrey (South)	14	900	800		1,700	
Surrey (Central)	15	980	940		1,920	
Surrey (North)	16	10,480	8,640		19,120	
Surrey (Seaport)	17	220	180		400	
Surrey	**(14-17)**	**12,580**	**10,560**	**16%**	**23,140**	**17.7%**
Downtown New Westminster /Queensborough	18	540	360		900	
New Westminster	19	4,620	3,440		8,060	
New Westminster	**(18-19)**	**5,160**	**3,800**	**6%**	**8,960**	**32.6%**
Burnaby (Bigbend)	20	140	240		380	
Burnaby	21	11,720	7,480		19,200	
Burnaby	**(20-21)**	**11,860**	**7,720**	**14%**	**19,580**	**25.4%**
Port Moody	**22**	**0**	**0**	**0%**	**0**	**0.0%**
Coquitlam (South)	23	0	0		0	
Coquitlam	24	0	0		0	
Coquitlam	**(23-24)**	**0**	**0**	**0%**	**0**	**0.0%**
Port Coquitlam	**25**	**1,180**	**820**	**1%**	**2,000**	**10.7%**
Maple Ridge	**26**	**3,020**	**2,140**	**4%**	**5,160**	**20.5%**
Pitt Meadows	**27**	**1,640**	**1,340**	**2%**	**2,980**	**51.7%**
Langley	**28**	**6,720**	**4,560**	**8%**	**11,280**	**27.2%**
Total		**84,004**	**60,503**	**100%**	**144,507**	**18.0%**

[2] Both census tract 206 and 207 were unintentionally omitted from the dataset. These two census tracts combined represent Downtown New Westminster. Combined, the population of these tracts was 4,287 in 2006. Upon an extensive field investigation it was determined that almost all of the population in these tracts live in either mid-rise (3-4 storey apartments) or high-rises. Many of these residential buildings have a young vintage. A significant concentration of historical buildings exists in these tracts. However, the buildings, generally considered to have high risk of damage in an earthquake, are used almost exclusively for commercial uses. Therefore, the omission of these tracts would most likely not result in a statistically significant increase in casualties. Populations of several census tracts in AOA 3 were also inadvertently omitted due to aggregation error. This omission was not caught in time for correction in this report; however, the consequent underestimation of losses may be significant and should be addressed in subsequent research.

As indicated in Figure 11, the spatial distribution of total displaced households is concentrated in the urban core areas of Vancouver, Burnaby, New Westminster, Richmond and North Surrey. Overall number of displaced households were moderate in southern AOA's and lowest in AOA's in northern portions of Metro Vancouver.

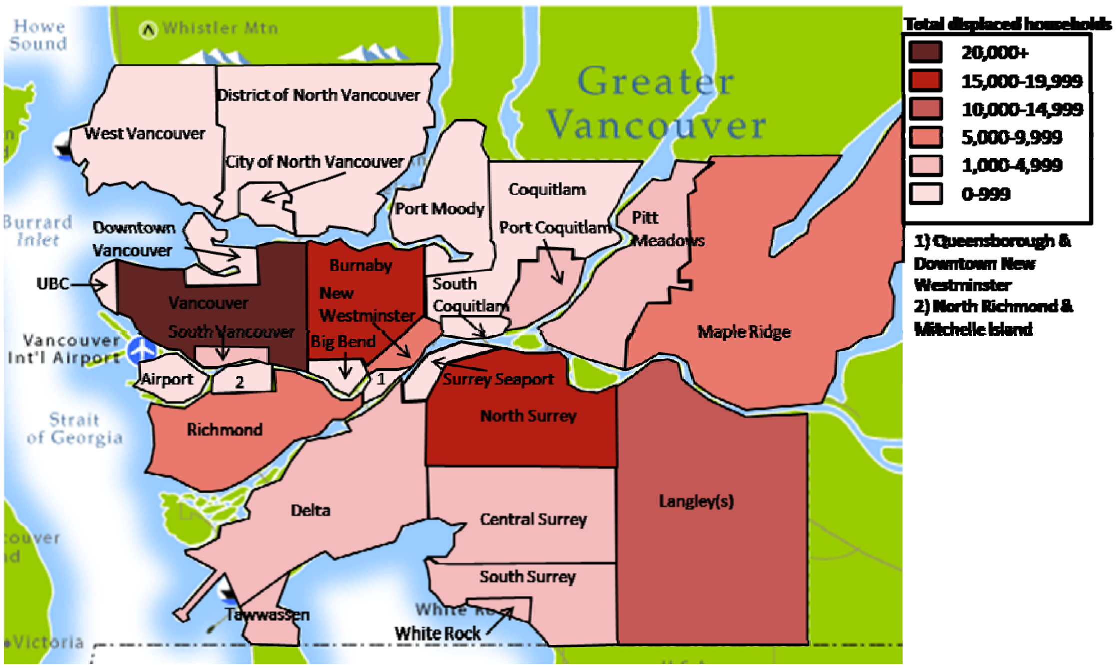


Figure 11: Total Displaced Households in Metro Vancouver AOA's

The total number of households displaced was also transformed into total number of individuals displaced for each municipality. Statistics on average household size in 2006 for each of the Greater Vancouver municipalities were obtained from Metro Vancouver Planning Department. Average household sizes were then multiplied by the total displaced households to determine the percentage of municipal population that is anticipated to be displaced. Based on this analysis the following municipalities had the highest percentage of municipal population displaced after the secenario sesimic event:

- Pitt Meadows (51.7%)
- New Westminster (32.6%)
- Langely (27.2%)
- White Rock (22.4%)
- City of Vancouver and Maple Ridge (20.4% and 20.5% respectively)

As indicated in Figure 12, the spatial distribution of the percentage of population displaced by municipality, with the exception of Pitt Meadows, is highest in the urban core of Vancouver, Burnaby and New Westminster. Overall number of displaced households were moderate in southern AOA's and lowest in AOA's in northern portions of Metro Vancouver. Model results indicate that Pitt Meadows has the highest percentage of municipal population displaced. The percentage displaced for Pitt Meadows is substantially higher than that of surrounding communities. Based on similar population characteristics, soil profile and infrastructural condition to surrounding communities, the total number of displaced individuals in Pitt Meadows should be inline with surrounding AOA's.

Figure 12: Percentage of Population Displaced by Municipality

The Displaced Population Model results also indicate that AOA's on soft soil, susceptible to greater damage to infrastructure and housing than on firm soils, account for only 27,200 households or 18.8% of total displaced households. The majority (81.2%) of displaced households originated in AOA's with firm soil conditions which theoretically were susceptible to fewer secondary hazard events.

Displaced Population Model results indicated that there are three distinct relationships. First, both the public and alternative shelter demand was highest in the urban core. In specific, shelter demand was highest in Vancouver, Burnaby and North Surrey. The results generally indicated that municipalities with the highest population have the highest shelter demand. The relationship between municipal population and shelter demand was also apparent for AOA's with the lowest shelter demand.

Shelter demand was lowest in AOA's in close proximity or adjacent to water supplies such as West and North Vancouver, Coquitlam, Port Moody and Port Coquitlam. The results indicated that the potable water availability plays an important role in the decision to leave home. The significance of water and power accessibility in determining shelter demand was also prevalent in the Northridge shelter demand study (Chang et al, 2008).

Municipalities located on soft soil profiles were initially hypothesized as having more potential for disruption than areas on firm soil. Soft soils, as previously indicated, are related to soil amplification and soil liquefaction which both increase the chances of damage to property and infrastructural systems. The Displaced Population Model accounted for these conditions in both the damage to residential buildings and in water and power accessibility. Model results indicated that AOA's with soft soil conditions, such as Richmond and Delta, do not have the highest number of displaced households.

As indicated in the model results, the percentage of population displaced in the municipality of Pitt Meadows is 41-60%. This result is not consistent with results for adjacent municipalities such as Maple Ridge and Langley which both are anticipated to have no power and water after the scenario event, just like Pitt Meadows, but have a lower overall displacement rate. The higher proportion of households displaced in Pitt Meadows is a result of the disproportionately higher number of households that were randomly assigned to Pitt Meadows in the 5% sample. For-example, the Pitt Meadows AOA, with a 2006 population of 15,560, was randomly assigned 910 households in the 5% sample. In comparison, the White Rock AOA, with a 2006 population of 18,020, was only assigned 385 households. Therefore, Pitt Meadows, in relation to its population and similar populations of other AOA's was assigned a higher proportion of the sample households. Future model refinements should account for this error.

5.4.2 Benchmarking

Establishing a benchmark for the Displaced Population Model is limiting in that the South Coast region has not experienced a major earthquake in over half a century. A review of large seismic events in North America reveals that the North Ridge (NR) earthquake is the only event that may be of use in developing a benchmark for Greater Vancouver. The rationale for selection Northridge Ridge as the seismic event to benchmark upon is provided in **Section 4.2.2**.

The Displaced Population Model simulation developed by Chang et al (2008) for the Northridge Earthquake of 1994 estimates that of the 3,126,279 households in Los Angeles, 25,472 households will leave their home and 14,983 will seek public shelter (0.48% of total number of households in Los Angeles County). The actual number of households seeking public shelter at the Red Cross after the Northridge event is estimated to be at 11,000 households (EQE International, 1997).

Model results for the Metro Vancouver simulation indicate that there would be 144,507 households displaced, of which 84,004 would seek public shelter and 60,503 would seek other shelter. The number of displaced households represents 19% of the total number of households in the Vancouver CMA, or approximately 11% of the total number of households in Greater Vancouver (758,715), which is substantially higher than the 0.48% of households in Los Angeles County that were predicted to seek public shelter.

The substantial difference in the percentage of households seeking public shelter between the Northridge and Metro Vancouver event is apparent in the difference in the number of household with a "high" housing condition. According to Chang et al (2008) 73.7% of households in the Northridge model were categorized as having a "high" housing condition. Further, all power was restored within 24hrs and water between 0 to 7 days. The Greater Vancouver model had no households in the "high" housing condition category. Approximately 0.01% of the sample households were categorized as "very low", 72% as "low", and 27% as "moderate". The primary reason why no household were in the "high" category was due to the extended period of time utility service was estimated to be disrupted and the high number of buildings categorized as having at least slight damage. In order for a household to be categorized as "high" housing condition, both power and water cannot be out of service for more than two days and building damage is negligible. In the Greater Vancouver scenario water and power were modelled to be out for more than two days. Further, 93% of the sample size was in buildings with slight damage and only 5% of households were in buildings classified as having negligible damage.

With the majority of households within the “low” to “moderate” category it is reasonable to expect a substantially higher percentage of households being displaced in the Greater Vancouver event. The Verdugo Earthquake simulation, conducted by Chang et al (2008) estimated that 11% of the total number of households in Los Angeles would leave home and 6.7% will seek shelter. The primary reason for the higher displacement rate is due to more extensive building damage and longer utility (power and water) outages than the Northridge earthquake simulation. Therefore, these two factors significantly impacted the predicted number of households displaced.

5.5 Model Limitation

While the Displaced Population Model provides insight into what degree of social distribution may occur following an earthquake, there was a significant degree of uncertainty pertaining to the spatial distribution of displacement numbers and the magnitude of the numbers.

The scenario event attributes had a major role in determining the overall magnitude of number of households displaced. In specific, the favourable weather conditions used in the model did not play a role in determining overall displacement numbers. Modelling based on inclement weather may result in more displaced households.

The spatial extent and duration of water and power outage was based on limited publically available documentation. Therefore, this component of the model may have serious limitations in outage duration and spatial extent. Conducting more precise modelling based on detailed data could result in significant shifts in the overall displacement numbers.

Model limitations are also present in the assignment of households to specific census tracts and various socio-economic and demographical attributes. Household assignment to a census tract was randomly assigned based on income attributes of the household. Therefore, intra-regional variations in displacement values may be inaccurate. Similarly, random assignment for the socio-economic and demographical attributes of the household could also potentially impact overall displacement values. While this methodology inherently adds a significant degree of uncertainty to the model results, it represents the only complete methodology to determine potential public and alternative shelter demand.

6.0 Implications for Regional Growth Management

6.1 Introduction

Metro Vancouver has had an established history of managing growth at a regional level to promote sustainable development. The main mechanism for coordinating growth regionally in the current Liveable Region Strategic Plan (LRSP) is the Growth Concentration Area (GCA). The GCA is designed to restrict growth outside a planning boundary (refer to Figure 12) and provides a recommended growth target for municipalities within the GCA. In specific, the LRSP recommends that 68.4% of growth be within the GCA by 2021(Metro Vancouver, 2009: liveable region strategic plan 2005 update). As of 2006, 64% of the population was within the GCA (Metro Vancouver, 2009).

The Casualty and Displaced Population Model results indicate that 71% of households that would be displaced are from AOA’s within the GCA and 29% outside of this boundary. Furthermore, 76% of the serious injuries and 71% of the projected deaths occur in the GCA. The higher magnitude of social disruption projected in the GCA is, in part, a function of the higher proportion of the regional population located within this area. Therefore, it can be hypothesized that if population growth were to occur at a faster pace outside the GCA, especially in areas susceptible to soil liquefaction and amplification, where infrastructure and building damage would be higher, there would be a higher proportion of casualties outside the GCA than within it. The following sections outline the key regional trends that can be expected to influence the casualty and displacement rates. It is also speculated, based on these trends, how social disruption levels may change according to these urban changes.

6.2 Urban Planning/Engineering Trends

6.2.1 Regional Planning Policy

Based on the 2006 population of Metro Vancouver, the model results indicate that the highest social impacts will occur in the municipalities with the highest population such as Vancouver, Surrey (northern portion) and Burnaby. AOA's located on soft soils, such as Richmond and Queensborough/Downtown New Westminster had lower overall household displacement and casualty rates due to a smaller population than the larger municipalities. Therefore, the growth rate, total population of a municipality, soil profile and building vintage could potentially increase the magnitude of social disruption. Therefore, growth management planning trends are examined in speculating where potential shifts and increases in overall numbers in social impacts may occur in the future.

Disaster resiliency, as part of the sustainability concept, has largely been neglected in previous regional planning in Metro Vancouver. The LRSP does not explicitly address disaster resiliency. While the LRSP does not provide disaster management policies, it has, in part, reduced the risk to individuals living in Metro Vancouver by discouraging growth outside the GCA. Areas outside the GCA boundary, as indicated in Figure 12, include a substantial amount of land with a soil profile susceptible to secondary hazards from a seismic event.

Metro Vancouver is currently undergoing a re-visioning of its current regional growth strategy (LRSP) and has drafted a plan entitled *Metro Vancouver 2040: Shaping Our Future*. A primary goal identified in the draft plan is to develop resilient communities in which risk from natural hazards are minimized (Metro Vancouver, 2009).While the plan does not provide concrete benchmarks or goals it is a first step in providing a vision of sustainability that includes minimizing risk to natural hazards. Therefore, to reduce the risk of social disruption from a natural hazard in Metro Vancouver, it is necessary to develop a series of benchmarks, goals and policies that provide realistic strategies for reducing risk to natural hazards in the region.

6.2.2 Population Growth

The draft regional plan provides a new set of urban growth containment boundaries which includes lands considered to be high risk for soil amplification and liquefaction. A comparison of Figure 13 and Figure 14 indicates that the current LRSP growth boundaries are situated on considerable firmer soils than that of the proposed growth boundaries. For both Figure 13 and 14, red indicates land with a high susceptibility to soil liquefaction and yellow indicates land with a low susceptibility. In specific, the proposed boundaries include a large proportion of the City of Richmond and numerous areas around water bodies considered to be at higher risk of liquefaction and soil amplification. The majority of the new areas identified in the growth boundary already have an established population; future growth will potentially exacerbate social disruption levels.

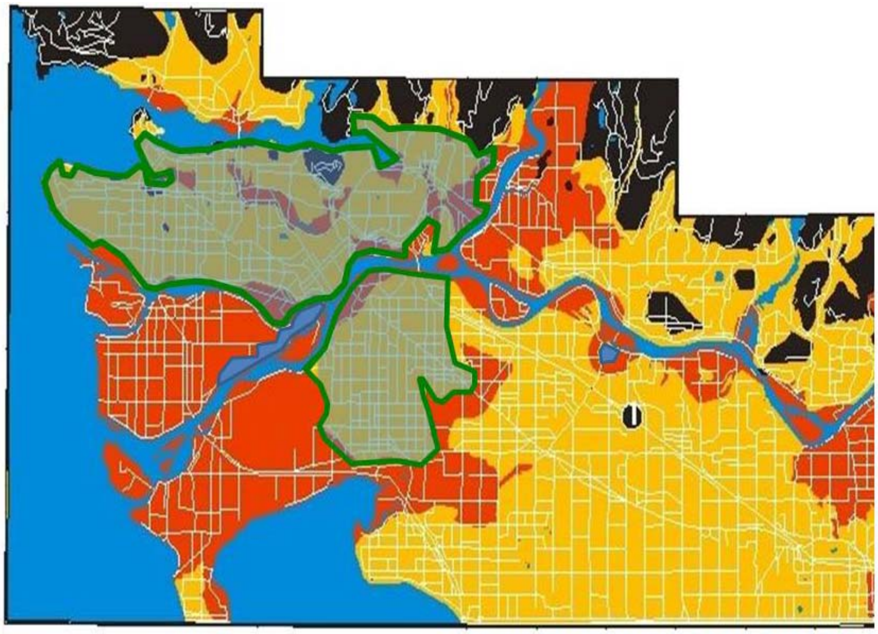


Figure 13 Existing LRSP Regional Growth Boundaries

(Base Map Source: Natural Resources Canada, 2009b)

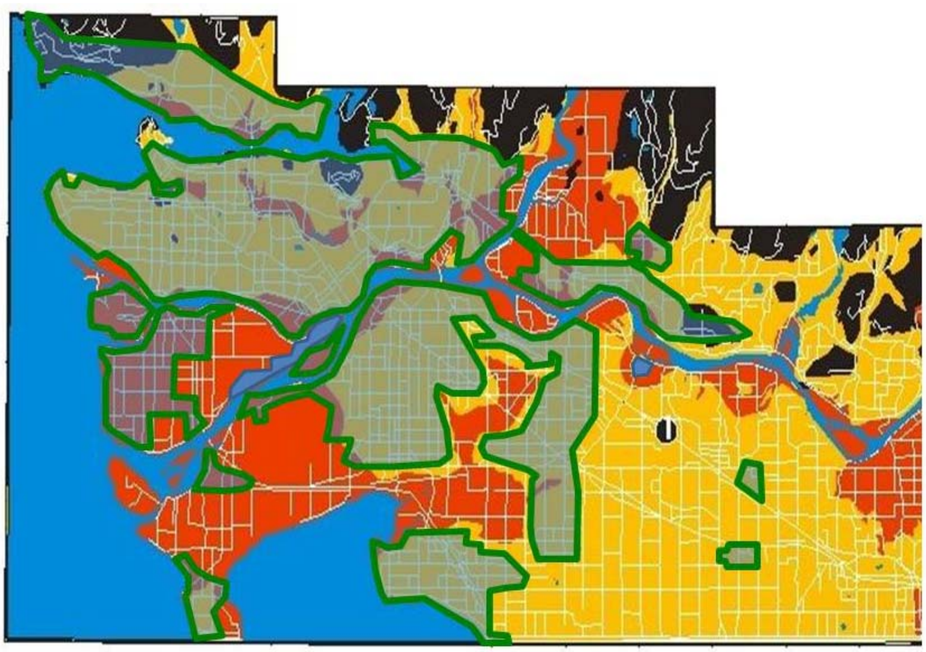


Figure 14 Proposed Regional Growth Boundaries

(Base map source: Natural Resources Canada, 2009b)

This proposed growth concentration boundary is designed to accommodate the substantial population growth anticipated in Metro Vancouver. Population growth in the region is expected to increase from approximately 2.2 million in 2006 to 3.3 million in 2041 (Translink, 2009). Regional population growth, as indicated in Figure 15, is expected to have an uneven spatial distribution. Much of the growth is anticipated to occur outside of the initial GCA identified in the LRSP.

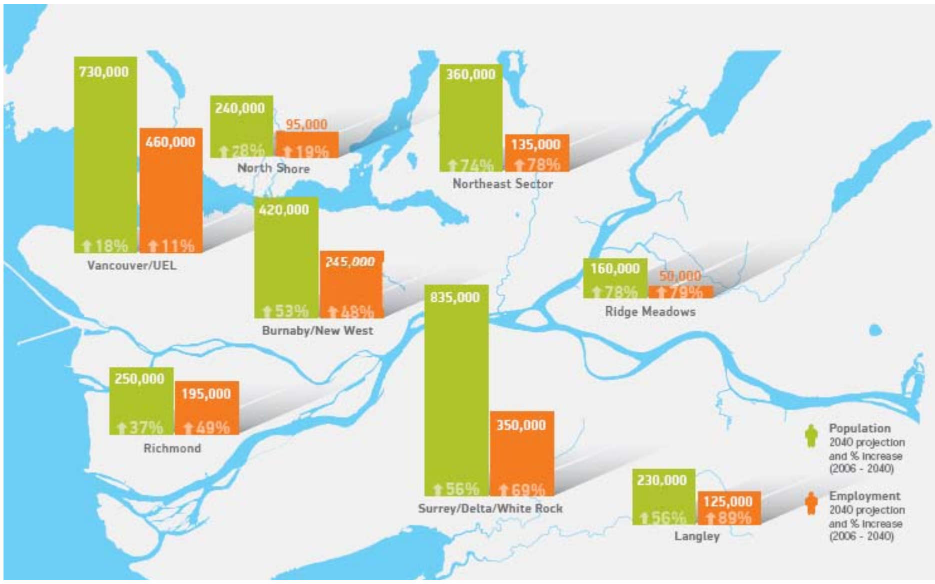


Figure 15: Population and Employment Growth Projections to 2040

(Source: Translink 2040 Plan (2009))

Furthermore, areas considered to have additional hazard risks, such as liquefaction, are projected to have substantial population growth. Areas considered having a large proportion of the land mass on soft soils and significant population growth between 2006 and 2040 include:

- Richmond (37% increase in population)
- Northeast Sector (Port Coquitlam and Coquitlam) (74%)
- Ridge Meadows (Maple Ridge and Pitt Meadows) (78%)
- South Sector (Surrey/Delta/White Rock) (56%)

Significant population increases in vulnerable areas, assuming all other regional trends remain static, would result in potentially larger social disruption in an earthquake. While population growth is a significant factor in projecting future social disruption patterns, it is only one of many other factors that need to be factored in concurrently with the other factors. The following sections outline the key demographic and infrastructural/engineering trends in the region which may exacerbate or reduce the magnitude of future social disruption in an earthquake.

6.3 Regional Infrastructure

Both water and electric power access to households after a seismic event significantly contributes to determining the housing condition and whether or not the household will seek alternative shelter. Long term power and water outage was modelled to be concentrated in municipalities with significant liquefaction risk and in areas requiring a river crossing.

The water infrastructural system in Metro Vancouver has been identified as having two major vulnerable points, including the Fraser River and the Burrard Inlet crossings. The existing Fraser River pipeline crossing was built in 1974 and would fail during a moderate or major earthquake. The Burrard Inlet crossing was constructed in the 1940’s and would not survive a minor earthquake.

As part of a larger seismic infrastructural program, Metro Vancouver is currently in the process of replacing both older sections of the regional water supply and both identified crossing. Both tunnels will be constructed to withstand a magnitude seven earthquake in the Metro Vancouver region and are anticipated to be completed between 2013 and 2020. Municipalities reliant on these pipeline crossings will have a more secure water source upon construction completion. The provision of water to the municipalities from the regional system does not guarantee water access. The phasing out of old water pipelines and replacing them with newer more resilient pipes at the municipal distribution level will be critical in ensuring water access to households.

As previously identified in this report, the regional power infrastructure has considerable vulnerabilities which may impair both short and long term power availability for Metro Vancouver. The two largest sources of vulnerability are the Fraser Canyon, where the single power supply line is vulnerable to landslides and damage, and in areas of soft soil conditions. There are preliminary plans to twin the existing 500 kilovolt transmission line to provide additional capacity for the growing Metro Vancouver Region. The line would be situated in the same corridor as the existing line and would provide redundancy to the power system which currently has very limited redundancy. While the line would add much needed redundancy, the proposed line is in the early design phase and potentially may not be realized.

Therefore, based on planned infrastructural projects, Metro Vancouver may have a more reliable water transmission and distribution system within the next decade and a power system that is largely unchanged in vulnerability. Based on these improvements, housing condition may improve after a large seismic event in the region which may lead to less displaced households.

6.3.1 Housing

The level of structural damage to a building is, in part, related to the vintage, dwelling type and building code standard. Building damage is a primary indicator of casualty and displacement rates and has a significant role in shaping future levels of social impact to an earthquake in the region.

Unreinforced Masonry (URM) buildings were the source of most casualties and displaced households in the models. Phasing out or structurally reinforcing URM buildings will potentially reduce the overall social impacts following an earthquake. Masonry buildings are concentrated in the older portions of the region including Downtown Vancouver, Downtown New Westminster and the City of North Vancouver. The number of casualties and displaced households in these areas of the region would decrease if there is a significant reduction or seismic upgrading of URM buildings.

Improved building design and seismic codes could also offset potential increases in social disruption in a future seismic event. Significant improvements to seismic building codes have occurred over the last forty years. As building science improves and further revisions are made to the seismic building code provisions, buildings will become more resilient to seismic hazards. The trend towards, more resilient buildings will result in less structural damage to these buildings and fewer casualties and displaced households.

A trend towards higher density built forms will impact the housing composition in Metro Vancouver, which will further impact the amount of building damage that will occur following a seismic event. The housing composition in Metro Vancouver in 2006 was approximately 61% ground-oriented units (including: single detached, row housing, secondary suites and mobile units) and 39% apartments (including: apartments less than and greater than 5 storeys) (Metro Vancouver, 2040 plan)

With geographical limits to urban expansion and a growing population, urban densification will result in a gradual transition towards a more even mix between ground-oriented and apartment units. Projections conducted by Metro Vancouver (2009), indicate that by 2041 the housing composition in Metro Vancouver may shift to 55% ground-oriented units and 45% apartment units.

In a study examining the performance of wood frame construction in seven major earthquakes over the past 40 years revealed that wood-frame buildings can resist severe shaking with a low risk of injuries or structural damage (Canadian Wood Council, 2010). Further, in the 1994 Northridge earthquake, single family dwellings experienced minimal structural damage to elements that are important to the safety of occupants (Ibid). Therefore, the shift towards higher density forms of housing, which are not wood-frame based, may result in higher overall building damage and more individuals becoming casualties and / or higher number of displaced households.

6.3.2 Personal Transportation

Transportation is a critical component to the shelter model in that it determines whether or not a household is able to access a shelter. Those with a vehicle were assumed to have access to a shelter, while those without a vehicle and living beyond a 1 km distance to the nearest shelter were assumed to have no access to a shelter.

The level of auto-dependency varies considerably across the region with high density, mixed-use neighbourhoods, having lower dependency rates than suburban subdivisions. In areas of high-density living, public transit accounts for a higher proportion of transportation needs. Therefore, the trend in reduced auto-dependency is an important factor affecting the level of access to shelters in Metro Vancouver.

Auto-dependency has been steadily increasing in Metro Vancouver with the number of registered vehicles rising by 16% from 2001 to 2007 (Translink, 2009). Approximately 77% of all resident trips in the region occur by auto (driver or passenger), 11% transit, 11% walking and 2% biking in 2004. Auto-dependency has increased the fastest in low-density suburban communities with the number of registered vehicles increasing the fastest between 2001-2007 in: Surrey (31%), Port Moody (27%) and Langley (27%) (Ibid). Vehicle ownership has increased at a substantially slower rate in urbanized areas such as Vancouver (9%), Richmond (9%), and Burnaby/New Westminster (12%).

With both the Transport and Metro Vancouver 2040 plan requiring new growth to be concentrated in the expanded growth boundary it can be expected that vehicle ownership and auto-dependency will decrease substantially in the coming decades. This trend will be most prevalent in urban areas where the Transport 2040 plan makes provisions for substantial public transit investments.

With auto-dependency and auto-ownership anticipated to decrease substantially in urban areas and stabilize in suburban areas it is assumed that households will rely more on public transit to seek public and alternative shelter in a seismic event. Should auto-dependency and auto-ownership decrease and transit investment not keep pace with population growth, one could expect a substantial increase in the number of households who do not have access to alternative shelters after a seismic event. Alternatively, the increase in population density will warrant the development of new community centres and therefore access to a wider population.

6.4 Socio-Demographical Trends

6.4.1 Aging Population

Both the number of children under the age of eighteen and the number of seniors over the age of sixty-five influence the propensity of a household to seek alternative shelter in a seismic event. While both age groups play an influential role in determining whether or not a household perceives it desirable to leave home, the number of seniors has an added role in determining whether or not a household can access a shelter. Given the significant role the elderly population has in determining shelter demand it is essential to understand the aging trends in the region.

According to the Urban Futures Institute (2006), the proportion of the regional population that is 65+ is expected to substantially increase from 13% in 2006 to over 25% by 2044. Relative changes in the regional population aged 65+ and 0-19 years of age is anticipated to change by +207% and +37% respectively between 2005 and 2045 (Ibid).

The rate at which the proportion of the population that is 65 years of age and older is expected to increase is projected to be spatially uneven across municipalities in the region. According to Urban Futures (2006), the greatest projected change in the proportion of the municipal population which is 65+ is in Pitt Meadows/Maple Ridge (351%), Port Moody/Port Coquitlam/Coquitlam (Tri-Cities) area (352%) and Surrey/White Rock (241%) and lowest in West Vancouver/North Vancouver/Delta (127%) and Vancouver (148%). Similarly, the greatest projected change in the proportion of the municipal population which is 0-19 years of age is Maple Ridge/Pitt Meadows (84%), Surrey/White Rock/Tri-Cities (56%) and lowest in Delta (-3%), West Vancouver/North Vancouver (3%) and Vancouver (6%).

Given the projected increases in the number of seniors, and assuming other variables described are held constant, a significant increase may occur in the number of households that perceive it to be desirable to leave after an earthquake. This trend may also reduce the number of households with senior members who can access an alternative shelter.

7.0 CONCLUSION

The Metro Vancouver region has experienced substantial population growth over the last thirty years and is anticipated to continue into the coming decades. Regional population growth has in the past, and is anticipated to continue into the future, to be concentrated in suburban communities. Many of these communities are located on soil profiles susceptible to soil amplification and liquefaction. The significant threat of a large seismic event occurring in Metro Vancouver has, as indicated in this and previous studies, the potential to cause substantial economic and social losses. Loss estimation studies for Metro Vancouver are out-of-date, limited in number and in scope. The Munich-Reinsurance report (1992), the premier loss estimation study for Metro Vancouver, indicates that a large seismic event in the region would be devastating to physical infrastructure and the economy. Loss estimation modeling for Metro Vancouver also indicates that damage to residential buildings would be substantial (Ventura et al, 2005 and Onur et al, 2005) and numerous fires would follow in an earthquake (Scawthorn, 2001).

While the loss estimation studies conducted for Metro Vancouver provide significant insight into the economic cost of an earthquake, limited research has been conducted in assessing the level of social disruption that would follow a large seismic event. This study provides both a methodology and an estimate of the number casualties and displaced households in the region.

Modelling was based on a magnitude 7.3 seismic event at 4am with an epicentre located along the Straight of Georgia. Results from the casualty model indicate that there would be approximately 25 serious injuries and 24 deaths in Metro Vancouver. The majority of these casualties were predicted to be concentrated in older settlements in Metro Vancouver such as Vancouver, Burnaby and New Westminster. In specific, the City of Vancouver accounts for 64% of all serious injuries and 33% of all deaths. The high concentration of casualties in the City of Vancouver is expected as the municipality has the highest population and oldest and largest concentrations of pre-1973 vintage building built in Metro Vancouver. Model results indicate that 81% of all serious injuries and 98% of all deaths occurred in un-reinforced masonry buildings (URML).

Results from the Displaced Population Model indicate that 19% of all households in the Vancouver CMA or 144,507 households would be displaced of which 84,004 would seek public shelter rand 60,503 would seek alternative shelter. The numbers of displaced households are concentrated in the urban core communities of Vancouver, Surrey and Burnaby which account for 67% of all displaced households.

The initial thesis of the study was that municipalities susceptible to soil liquefaction and amplification would experience a greater degree of social disruption, both casualties and number of displaced households, than municipalities on firm soil. Model results, however, indicate that building type and vintage is a more important factor in determining social disruption. Areas of high concentrations of URML buildings are areas where significant building damage can be anticipated. Therefore, the combination of a large population, soft soil profile and older vintage buildings seems to yield the highest rates of social disruption.

With the population anticipated to increase significantly in the Metro Vancouver Region, the need to incorporate disaster resiliency into regional planning is substantial. Regional trends that influence the social disruption models indicate that there will be a growing population in vulnerable areas of the region, significantly higher elderly population and lower reliance on personal vehicles. Based on these trends it would be anticipated that social disruption would increase. However, even with these trends in the region, the risk of social disruption in the region may decline. The combination of better building codes, phasing out of older vintage buildings, and a more reliable power and water system, at least at the regional level, would likely be the key drivers for reducing social vulnerability.

8.0 RECOMMENDATIONS

This study estimated the amount and distribution of social disruption following an earthquake in the Metro Vancouver area based on current populations and land use arrangements. It was hypothesized that as the population increases in areas considered to have a soft soil profile, susceptible to soil amplification and liquefaction, the overall vulnerability would increase and be higher than cities located on firm ground. Model results indicate that the most significant factor influencing levels of social disruption is the vintage and building type in conjunction with the soil profile for casualties and displaced households rather than just soil profile. Access to water and power are also very important factors influencing magnitude of displaced households.

A base model, such as the one developed in this report, allows for the testing of other hypotheses regarding the relationship between growth, development, and disaster resilience. One such related hypothesis that should be tested is as follows: Growth management through redevelopment of built-up urban areas (compact development) reduces the magnitude of social disruption following an earthquake. This hypothesis is based on the premise that as older, more vulnerable buildings, are replaced by newer building stock, with higher seismic design standards, less damage and social disruption will occur. This hypothesis should be tested using various growth management scenarios currently being explored by Metro Vancouver. Both a sprawl and compact growth scenario could be the bases for conducting such research.

Patterns of social disruption are likely to change with anticipated growth and development in the Metro Vancouver area. Therefore, the models should be re-run using the outputs of the growth scenarios. The modelling should be conducted for short, mid and build-out populations to provide for a better understanding of how patterns of social disruption and associated vulnerability will change over time. It will also provide for a better understanding of how various proposed growth management strategies would influence the magnitude and location of social disruption following an earthquake in the region. It would be useful for planners to explore alternative land use scenarios in light of potential disaster impacts through using models such as the one described in this project as a standard practise when conducting growth management policy review.

There are several model refinements that should be incorporated in future revisions. One such refinement is in the number of secondary hazards that are accounted for in the model. Future model refinements should include sub-models that assess how secondary events such as conflagration and inundation impact overall levels of social disruption.

The social dimension of disruption provides only a partial assessment of the overall disruption experienced after a natural hazard event. A separate economic disruption model should be developed to assess the impact and earthquake would have on the regional economy. This model should be integrated with the social disruption model to provide for one comprehensive model to assess the overall disruption anticipated following an earthquake.

The magnitude of social disruption may change depending on the time of day the scenario event takes place. The model should be re-run using a daytime scenario. This scenario would provide an estimate of the magnitude and location of social disruption that would follow during business hours. This scenario would account for population in a wider range of building structures, such as commercial buildings, and would also allow for the inclusion of workforce and commuter populations. This analysis would also provide for an interesting subsequent analysis comparing night and daytime differences in social disruption levels and locations.

Finally, the assumptions made regarding the percentage of pre-1973 buildings that are multi-family low rise (unreinforced masonry bearing wall and wood light frame) should be tested for accuracy. Assessor data, where available, should be substituted for this assumption to determine whether or not the initial model outputs are accurate.

REFERENCES

Adams, J., Weichert, D., Halchuk, S. (1999) Lowering the Probability level – Fourth Generation Seismic Hazard Results for Canada at the 2% in 50 Year Probability Level. Proceedings, Eighth Canadian Conference on Earthquake Engineering, Vancouver.

American Water Works Association (1994). Minimizing Earthquake Damage: A Guide for Water Utilities

Archibald, P. (2007). Interview transcript from Interview with Paul Archibald of Metro Vancouver Water Services. School of Community and Regional Planning, University of British Columbia.

Bird, J.F., Bommer, J.J. (2004) Earthquake Losses Due to Ground Failure. Engineering Geology. 75 (2): 147-179.

British Columbia Transmission Corporation (2009). Greater Vancouver and Fraser Valley Transmission Line Maps. Retrieved from: http://www.bctc.com/transmission_system/maps/ Accessed on Feb 10, 2009

Canadian Wood Council (2010). Wood-Frame Housing: A Canadian Marvel. Retrieved from: http://www.cwc.ca/NR/rdonlyres/A230989E-6B19-4468-BB96-F7B97C74AC87/0/BP_4housinge.pdf on Feb 15, 2010.

Chang, S, Pasion, C, Tatebe, K, Ahmad, R (2008). *Linking Lifeline Infrastructure Performance and Community Disaster Resilience: Models and Multi-Stakeholder Processes*. Technical Report (MCEER-08-0004).

Clague, J. (1996) Paleoseismology and Seismic Hazards, South-western British Columbia. Geological Survey of Canada, Bulletin No. 494: pg 88.

Clague, J., Luternauer, J.L, and Mosher, D.C.(1998) Geology and Natural Hazards of the Fraser River Delta, British Columbia. Geological Survey of Canada, Bulletin 525: pg 270

Clague, J. (2001) Tsunamis. In: Brooks, G.R. (ED), A Synthesis of Geological Hazards in Canada, Geological Survey of Canada, 548: 27-42.

Clague, J. (2002) *The Earthquake Threat in South-western British Columbia: A Geologic Perspective*. Natural Hazards: 26: 7-34.

Comerio, M. (1997) Housing Issues after Disasters. Journal of Contingencies and Crisis Management, 5 (3): 166-178.

Eidinger, J and Avila, E. (1999) *Guidelines for The Seismic Evaluation and Upgrade of Water Transmission Facilities*. Technical council on lifeline earthquake engineering, Monograph No 15, January 1999.

Finn, L. (1997) Earthquake Engineering in Canada; A selective Overview. Geotechnical New, September 1997.

Forthergill, A, Peek, L.A. (2004). Poverty and Disasters in the United States: A review of Recent Sociological Findings. Natural Hazards: 32: 89-110

Fox, J (2008). Vulnerable Populations: A Spatial Assessment of Social Vulnerability to Earthquakes in Vancouver, B.C (Masters Report). School of Community and Regional Planning, University of British Columbia.

Frank, L.D., Andresen, M.A., & Schmid, T.L.(2004). Obesity relationships with community design, physical activity, and time spent in cars. American Journal of Preventative Medicine, 27 (2): 87-96.

Gilbert, R. (2009) Vancouver Digs Deep to Reduce Earthquake Risks. Retrieved from the Journal of Commerce: http://www.joconl.com/article/id33524?search_term=earthquake . Accessed on October 29, 2009.

GVRD (Greater Vancouver Regional District) (1999). GVRD Trends: Population Dynamics in the Region. Working Paper Series. Policy and Planning Department.

Harris, J.B., Hunter, J.A., Luternauer, J.L, Finn, W.L. (1998). Site Amplification Modelling of the Fraser Delta, British Columbia. In: Geology and Natural Hazards of the Fraser River Delta, British Columbia. Survey of Canada, Bulletin No. 525: 211-216.

Journeay, M., Talwar, S., Hastings, N. and Brodaric, B. (2010)Pathways-DR: A framework for integrated risk assessment and disaster resilience planning in Canada; GSC Open File Report (in review).

Journeay, M. and Talwar, S. (2009): Disaster Risk Management and Land Use Planning - A Case Study. 6th Annual CRHNet Symposium, Edmonton, Alberta, Canada.

Keefer, D.K. (1984) Landslides Caused by Earthquakes. Bulletin of the Geological Society of America. 95: 406-421.

Mahue-Giangreco M, Mack W, Seligson H, Bourque LB. (2001) Risk factors associated with moderate and serious injuries attributable to the 1994 Northridge Earthquake, Los Angeles, California. *Annals of Epidemiology*. 11:347-357

Mathews, W.H. (1979) Landslides of Central Vancouver Island and the 1946 Earthquake, Seismol, Society. Amer, Bull, 69: pg. 445-450.

Mayunga, J (2007). Understanding and Applying the Concept of Community Disaster Resilience: A Capital-based Approach. Retrieved from: http://www.ehs.unu.edu/file.php?id=349 on Dec 10, 2009.

Metro Vancouver Water District (2009) Metro Vancouver Water Transmission System Overview Map. Retrieved from: http://yourwatermatters.com/uncategorized/metro-vancouver-water-source-and-supply-map/ Accessed on: March 29, 2009.

Metro Vancouver (2009) Metro Vancouver 2040 Plan. Retrieved from: http://www.metrovancouver.org/planning/development/LRSPreview/LRSPDocs/DraftRGSNovember2009.PDF Accessed on Dec 1, 2009.

Mileti, D. S. (1999) Disasters by Design: A Reassessment of Natural Hazards in the United States. Washington, D.C. : Joseph Henry Press.

Moh, Z. C, Hwang, R. (1999) Chi Chi Earthquake of Taiwan. Retrieved from: hhttp://www.maa.com.tw/common/publications/2000/200-037.pdf Accessed on March 15, 2009.
Morrow, B. H. (1999). *Identifying and Mapping Community Vulnerability*. Disasters, 23 (1) (March): 1-18.

Monahan, P.A., Levson, V.M., Henderson, P. And Sy, A. (2000) Relative Liquefaction Hazard Map of Greater Victoria, British Columbia Geological Survey, Ministry of Energy and Mines.

Munich Reinsurance (1992). A Study of the Economic Impact of a Severe Earthquake in the Lower Mainland of British Columbia.

Natural Resources Canada. (2009a) Retrieved from: http://geoscape.nrcan.gc.ca/vancouver/mountain_e.php Accessed on Nov 20, 2008.

Natural Resources Canada (2009b) Liquefaction Map for Lower Mainland, B.C. Retrieved from: http://gsc.nrcan.gc.ca/urbgeo/geomapvan/geomap8_e.php Accessed on Dec 10, 2008.

Nemetz, P (1992). Earthquake: Economic Impact Study. A study of the Economic Impact of a Severe Earthquake in the Lower Mainland of British Columbia. Munich Reinsurance of Candada.

Olshansky, R.,Wu, Y. (2000) Earthquake Risk Analysis for Los Angeles County Under Present and Planned Land Uses. Environment and Planning: Planning and Design, 28: 419-432.

Onur, T, Ventura, C.E., Finn, W.D. (2004). Effect of Earthquake Probability Level on Loss Estimations. 13th World Conference on Earthquake Engineering, Vancouver, B.C., Canada. Paper No. 2608.

Onur, T and Seemann, M.R. (2004) Probabilities of significant earthquake shaking in communities across British Columbia: Implications for Emergency Management. 13th World Conference on Earthquake Engineering. Paper No. 1065.

Onur, T., Ventura, C.E. and Finn, W.D.L., (2005) Regional Seismic Risk in British Columbia - Damage and Loss Distribution in Victoria and Vancouver. Canadian Journal of Civil Engineering. 32 (2): 361-371.

Peek-Asa, C, Ramirez, M, Seligson, H, Shoaf, K. (2003) Seismic, Structural, and Individual Factors Associated with Earthquake Related Injury. Injury Prevention, March: 9 (1): 62-66.

Peek-Asa, C, Kraus, J.F., Bourque, L.B., Vimalachandra, D.,Yu, J.,Abrams, J., (1998) Fatal and Hospitalized Injuries Resulting from the 1994 Northridge Earthquake, *International Journal of Epidemiology*; 27: 459-465.

Robertson, J. (2000). Administrative Report (April 18, 2000). City of Vancouver. File Number: 3601/2603

Rogers, G.C (1998). Earthquakes and earthquake hazard in the Vancouver area. In Geology and Natural Hazards of the Fraser River Delta, British Columbia. Geological Survey of Canada Bulletin 525, 17-25

Scawthorn, C, and Chen, W.F. (2002) Earthquake Engineering Handbook. CRC Press, Boca Raton.

Scawthorn, C, Eidinger, J, Schiff, A. (2001) Fire Following Earthquake. Technical Council on Lifeline Earthquake Engineering. Monography No. 36.

Schiff, A and Tang, A (2000) Chi-Chi, Taiwan, Earthquake of September 21, 1999 Lifeline performance.

Shoaf, K. (2002) Injuries as a Result of California Earthquakes in the Past Decade. Volume 22, Issue 3, pg: 218 – 235.

Simpson, D. W, Rockaway, T. Coomes, P., Hollowman, C. (2005) *Framing a new approach to critical infrastructure modelling and extreme events*. International Journal of Critical Infrastructure Volume 1, Nos 2/3.

Statistics Canada (2009) Number of Households in Metro Vancouver and Household Attributes. Accessed on March 4, 2008.

Surrey School District. (2010) Use of Schools For Reception Centres and Emergency Shelters. Retrieved from: http://www.sd36.bc.ca/board/policies/5000/5208.2-emergencysocialservic.pdf on Feb 15, 2010.

Tanida, N (1996). What Happened to Elderly People in the Great Hanshin Earthquake. BMJ, 313: 1133-1135.

Thevanayagam, S., Kanagalingam, T., Shenthan, T (2002) Contact Density – Confining Stress – Energy to Liquefaction. Retrieved from: http://www.civil.columbia.edu/em2002/proceedings/papers/428.pdf on January 10, 2010.

Tierney, K. (1994) Social Impacts and Emergency Response. University of Delaware Disaster Research Center. Article No. 279

Tierney, K., Lindell, M. L., and Perry, R. W. (2001). *Facing the Unexpected. Disaster Preparedness and Response in the United States*. Washington, D.C.: Joseph Henry Press.

Tomalty, R. (2002) Growth Management in the Vancouver Region. The Assessment and Planning Project, B.C. Case Report No. 4. Retrieved from: http://ersserver.uwaterloo.ca/research/asmtplan/pdfs/BC_4.pdf on January 10, 2009.

Translink (2009).Transport 2040 Plan. Retrieved from: http://www.translink.ca/~/media/Documents/Plans%20and%20Projects/Transport%202040/Transport%202040.ashx on March 28, 2009.

United States Geological Survey (2009). Shake Intensity Map for Los Angeles County, Northridge Earthquake. Retrieved from: http://earthquake.usgs.gov/eqcenter/shakemap/sc/shake/Northridge/ on January 10, 2010.

Ventura, C.E., Finn, W.D.L., Onur, T., Blanquera, A and Rezai, M. (2005) Regional Seismic Risk in British Columbia-Classification of Buildings. Canadian Journal of Civil Engineering, Vol. 32, No.2, April 2005, pp: 372-387.

Watts, B.D., Seyers, W.D., Stewart, R.A. (1992). Liquefaction susceptibility of Greater Vancouver Area Soils. Geotechnique and Natural Hazards, Vancouver Geotechnical Society and Canadian Geotechnical Society, Geo-hazards Symposium Volume,Pg.145-157.

Webb, T. (2000) Adapting the NHEMATIS Approach for use in a Raster Based Modeling Tool for Emergency Preparedness Canada; Emergency Preparedness Canada, 52.

Yelvington, K. (1997) Coping in a Temporary Way: The Tent Cities, in Peacock, W.G., Morrow, B.H., Gladwin, H, Hurricane Andrew: Ethnicicity, Gender, and the Sociology of Disasters, International Hurricane Center, Laboratory for Social and Behavioral Research, Miami, Fl, pg. 92-115.

Yeh, C, Loh, C, Tsai, K (2006) Overview of Taiwan Earthquake Loss Estimation System. Natural Hazards, 37: 23-37.

Urban Futures (2006). Spatial Projections of Population, Housing and Employment in the Southwest Metropolitan Region, 2005 to 2045. Retrieved from: http://www.urbanfutures.com/reports/Report%2067.pdf on March 20, 2009.

APPENDIX 1 METRO VANCOUVER MUNICIPALITIES

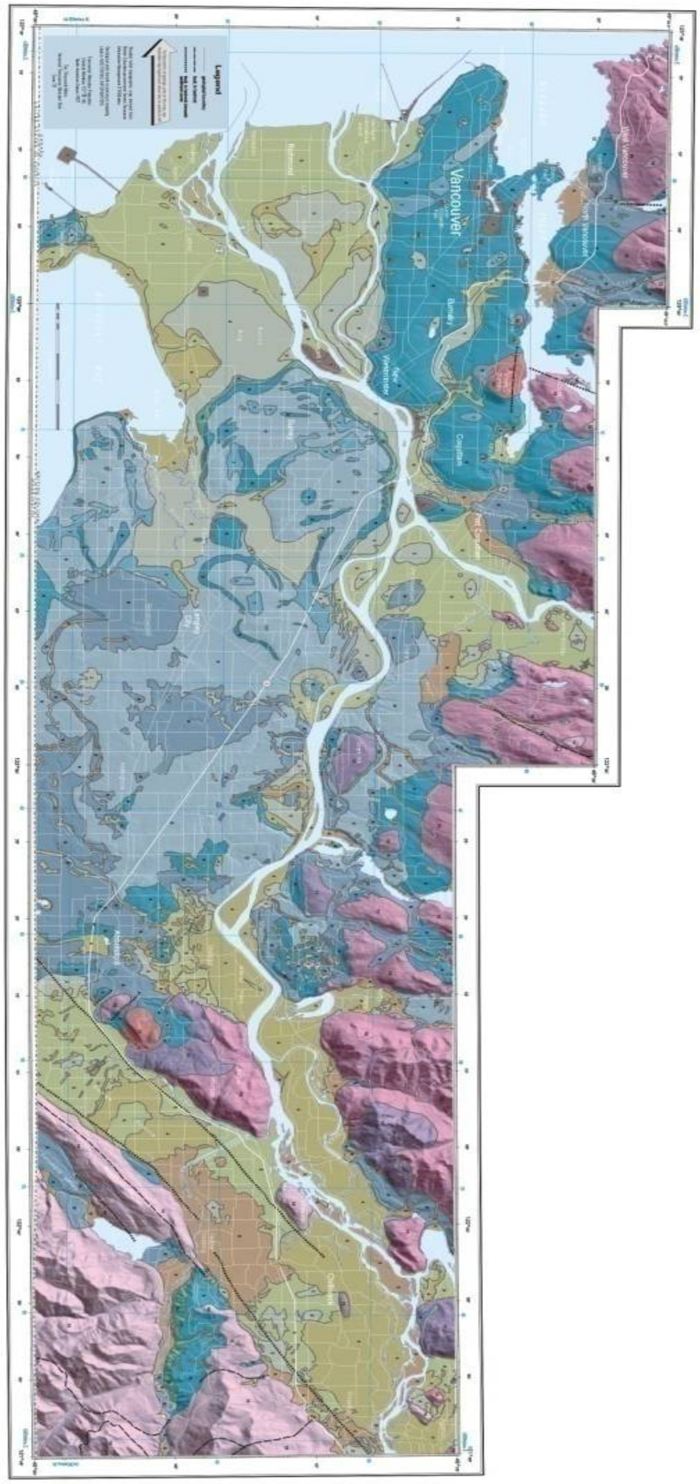
Source: www.cbc.ca/bc/features/civicvote2008/

APPENDIX 2 AREA OF ANALYSIS (AOA)

1) Queensborough & Downtown New Westminster

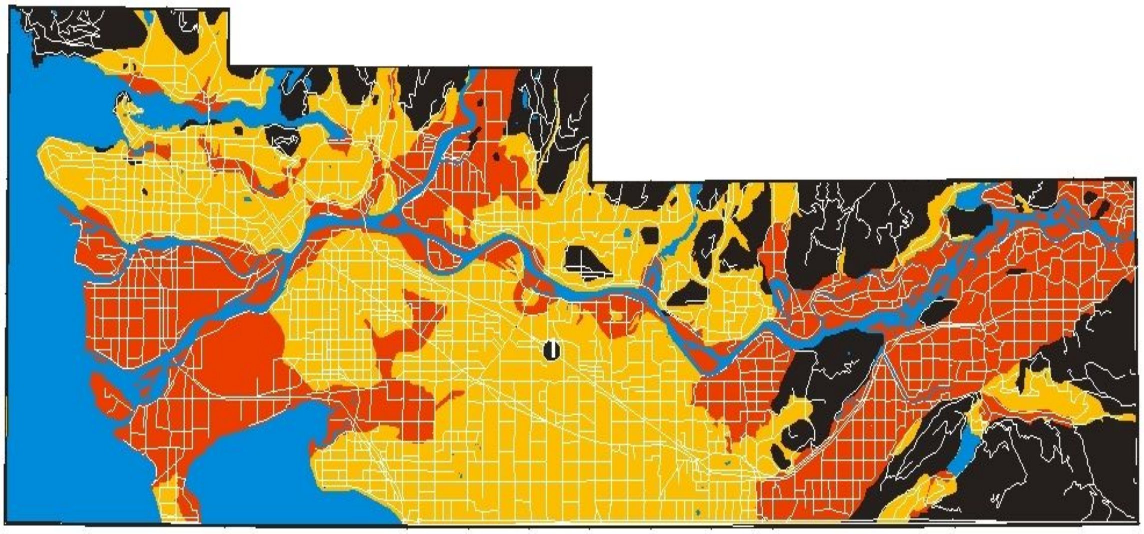
2) North Richmond & Mitchelle Island

APPENDIX 3 SOILS PROFILE OF LOWER MAINLAND OF VANCOUVER



Source: http://gsc.nrcan.gc.ca/urbgeo/geomapvan/geomap2_e.php

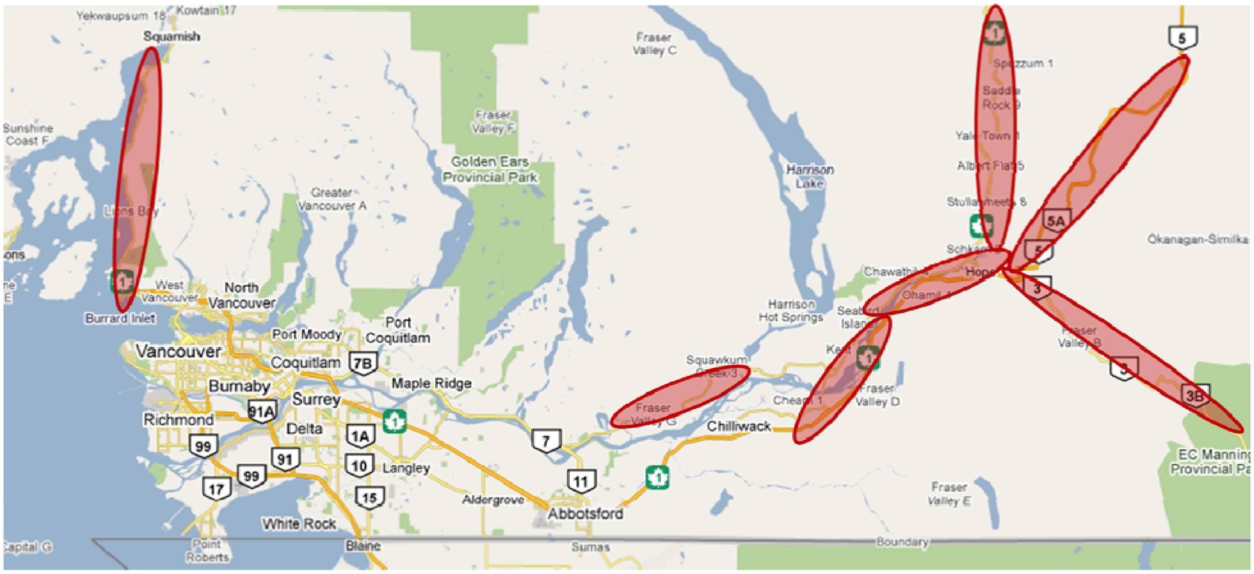
APPENDIX 4 SOIL LIQUEFACTION MAP



(Red indicates high susceptibility, Yellow indicates moderate to low susceptibility, and black indicates no risk)

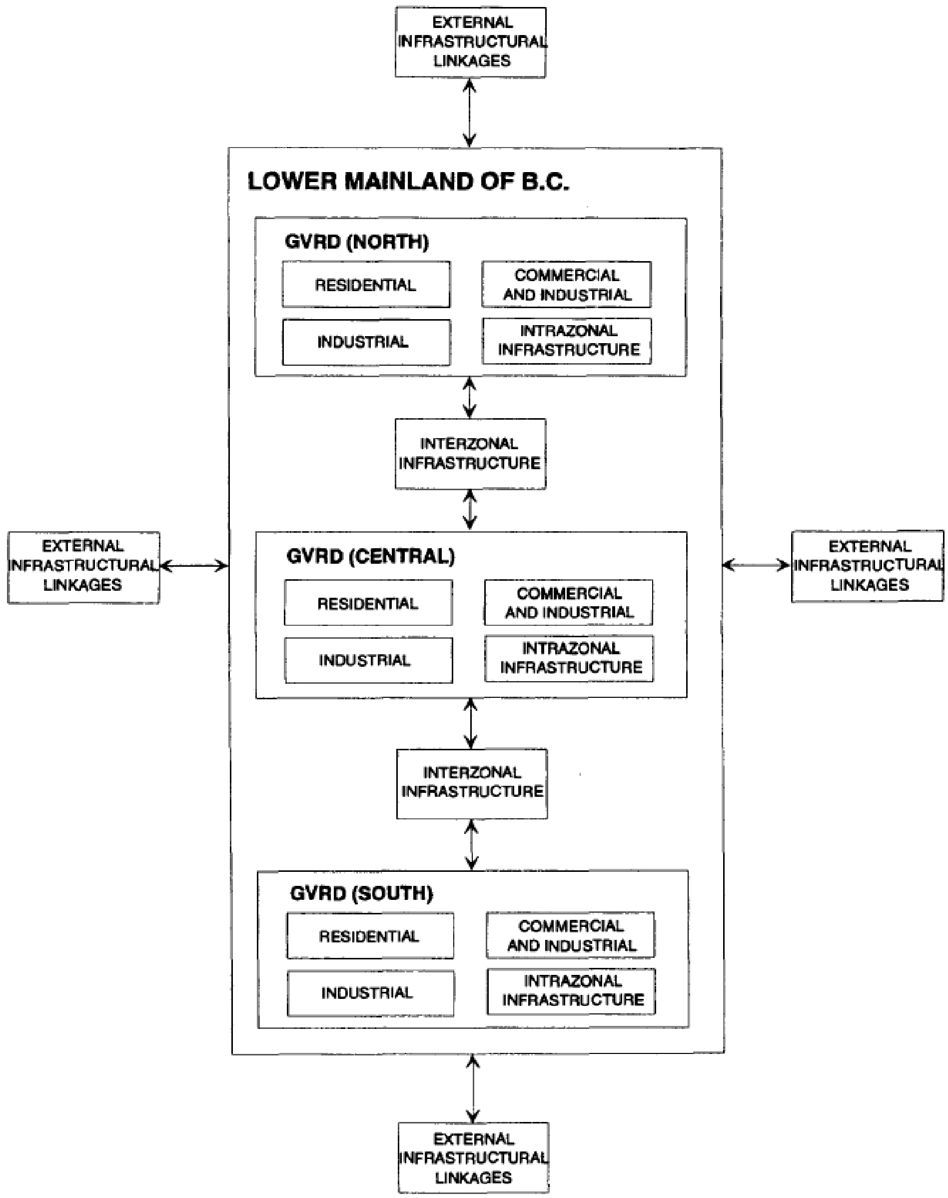
Source: http://gsc.nrcan.gc.ca/urbgeo/geomapvan/geomap8_e.php

APPENDIX 5 MAJOR TRANSPORTATION AND ENERGY LIFELINES VULNERABILITY DUE TO LANDSLIDES TRIGGERED BY AN EARTHQUAKE (HIGHLIGHTED SECTIONS)



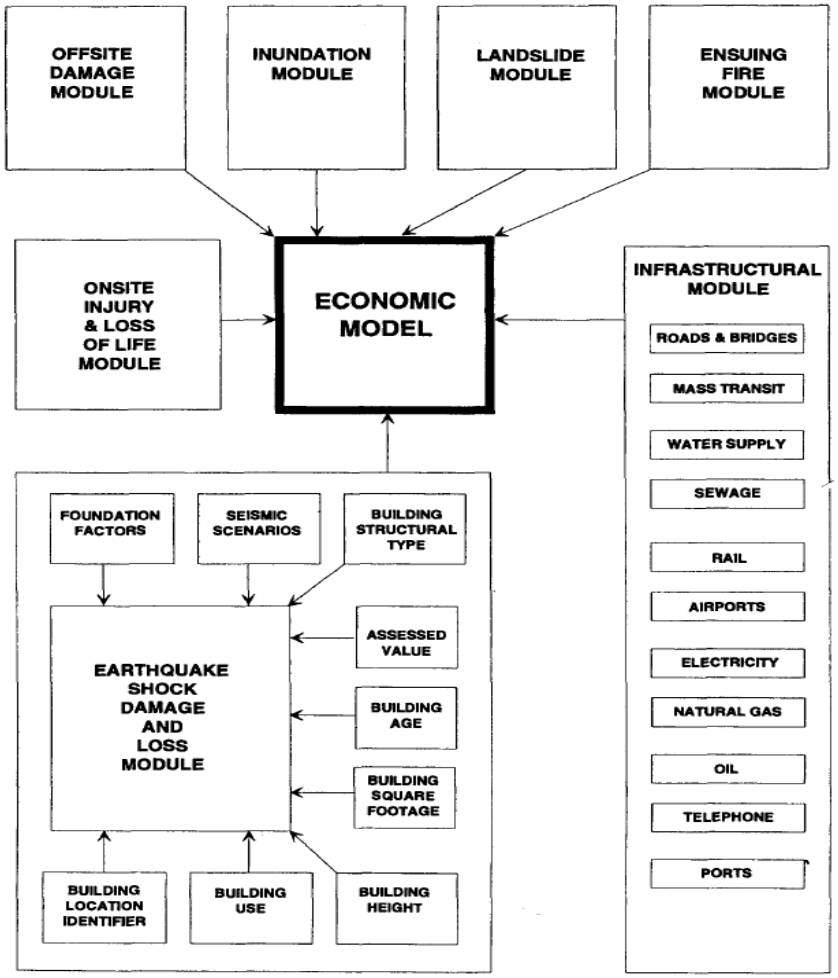
Source: “After (Clague, 1996)”

APPENDIX 6 LOSS ESTIMATION MODEL FRAMEWORK INPUTS



Source: Nemetz, 1992

APPENDIX 7 LOSS ESTIMATION MODEL FRAMEWORK



Source: Nemetz, 1992

APPENDIX 8 DEFINITION OF DISPLACED POPULATION MODEL VARIABLES

Building damage: Building damage is defined as the probability of damage to a structure of a certain type of use, within ranges of damage, i.e., none or extensive.

Water: Water outage is defined as the number of days a household's home is without potable water prior to water restoration.

Power: Power outage is defined as the number of days a households home is without electrical power prior to restoration of electricity.

Car Ownership: Defined as whether or not a household owns a car. A car provides a household with a means to get to different forms of shelter.

Tenure: Defined as whether a household rents of owns their home.

Distance: Distance is defined as the walkable distance to a shelter. In the model distance is approximated by the distance between the centroid of the census tract in which the household resides and the location of the shelter closest to this point. Within the model 1 km is considered a walkable distance.

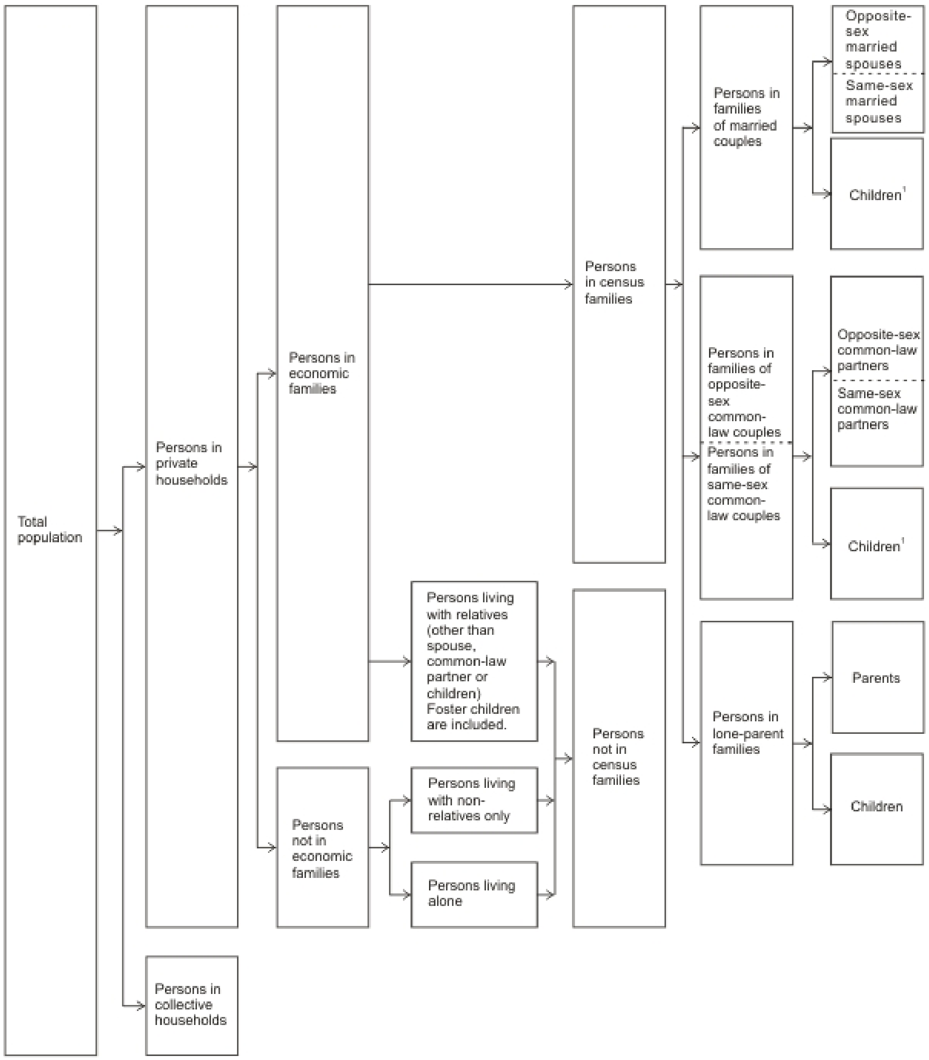
Income: Household income is assigned to levels of high, medium or low income based on the distribution of income is in Metro Vancouver. Lower household income is defined as $0 to $40,000; medium income is defined as 40-90,000; and high income is defined as $90,000 and above.

Age: This variable is assigned "yes" if at least one household member is less than 18 years of age or greater than 65 year of age. The variable is assigned no otherwise.

Elderly: This variable is assigned "yes" if at least one member of the household is 65 years or older.

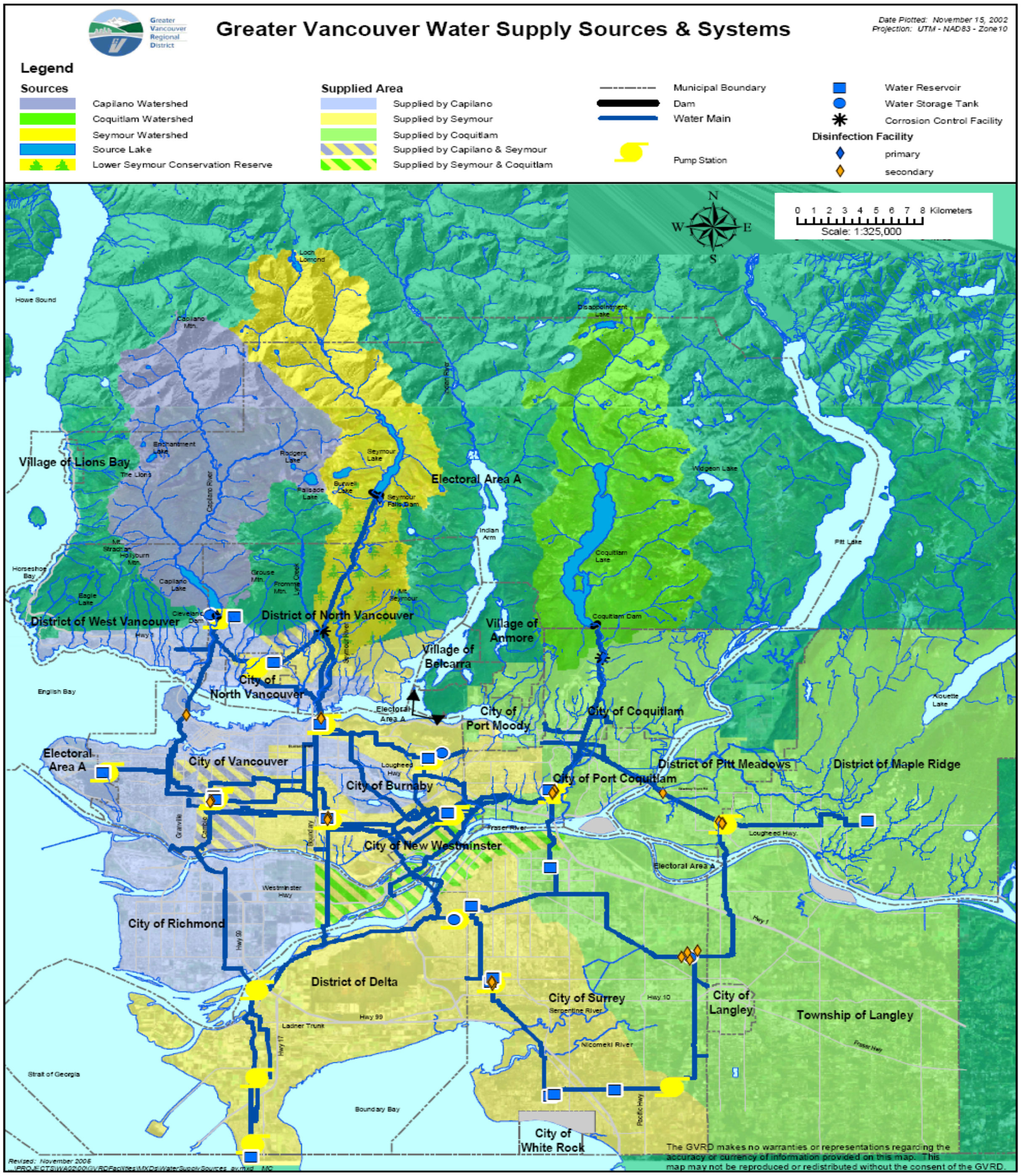
Source: Chang et al, 2008

APPENDIX 9 BREAKDOWN OF FAMILY IN CENSUS



Source: Statistics Canada, 2009

APPENDIX 10 METRO VANCOUVER WATER TRANSMISSION SYSTEM



Source: Metro Vancouver, 2009