SHAPING A DISASTER RESILIENT REGION: THE ROLE OF LAND USE PLANNING IN MITIGATING SEISMIC RISK IN METRO VANCOUVER, 2041

by

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EXECUTIVE SUMMARY

The aim of this master's project is to understand how land use affects disaster resiliency in Metro Vancouver. Located in one of the highest seismic zones in Canada, the likelihood of a structurally damaging crustal or subcrustal earthquake occurring in Metro Vancouver is estimated to be 2.5 percent over the next 10 years, 12 percent over 50 years, and 22 percent over 100 years (Onur and Seemann, 2004). With the region expected to grow significantly over the next 35 years, the probability of a large seismic event occurring in Metro Vancouver is significant and poses a real threat to residents.

Using the population and dwelling unit projections provided by Metro Vancouver's Regional Growth Strategy, *Metro Vancouver 2040 – Shaping Our Future*, this research explores the seismic risk consequences of four land use and density scenarios:

1. *Status Quo Growth* - growth follows current development and new population will be distributed to all currently settled areas in a variety of building types proportionally to current population;
2. *Compact Growth* - new population will only locate to current and anticipated high density areas in multi-family building structures;
3. *Sprawled Growth* - new population will only locate to current low-density areas in single detached dwellings and a limited number of multi-family low-rise structures; and,
4. *Safe Growth* – new population will not be allowed to locate in MMI VIII areas (i.e. areas with high shaking intensity in the earthquake scenario considered); growth will only be distributed to areas with a MMI level of VII or lower in primarily wood frame buildings.

Specifically, the research question is, "*How might future earthquake casualties in Metro Vancouver vary depending on land use and density?*" This question is investigated in the context of a hypothetical magnitude 7.3 subcrustal earthquake in 2041 with the epicentre under the Strait of Georgia. Estimates of deaths and serious injuries were calculated using a casualty model adapted from the United States Federal Emergency Management Agency's (FEMA) loss estimation model, HAZUS-MH. To ensure the model is applicable to Metro Vancouver, building damage was estimated based on a model by Ventura et al. (2005) that reflects the building practices and standards of British Columbia.

While all four scenarios provide insight into the potential number of casualties resulting from land use development, the Safe Growth scenario is the only scenario to use a sustainable hazard mitigation approach. The concept of 'sustainable hazard mitigation' helps link the "wise management of natural resources with local economic and social resiliency, viewing hazard mitigation as an integral part of a much larger context" (Mileti, 1999, p.2). Therefore, in managing growth and development through land use, local and regional governments can work to "shift existing development and steer new development to areas that are relatively hazard free" (Burby, 1999, p.10).

Results indicate that the earthquake event would produce relatively similar numbers of deaths and serious injuries in all four scenarios, although the Safe Growth scenario would result in the fewest casualties at 14 deaths and 31 serious injuries. The other three

scenarios showed the same number of deaths at 16, but varied in terms of serious injuries at 34 for Status Quo Growth, 36 for Sprawled Growth, and 37 for Compact Growth. All deaths in the region are attributed to unreinforced masonry structures, which are known to be more vulnerable to ground shaking than other structural types (Ventura et al., 2005).

For the Safe Growth scenario, in addition to the reduction in casualties, the model also estimates a significant decrease in the number of people living in significantly damaged dwellings. This indicates that land use planning could be effective at reducing risk in Metro Vancouver. Yet, while shifting new development from less hazardous areas is effective at reducing risk, the loss in development revenue for local municipalities would likely result in negligible adoption of this approach in practice. In order to create a more disaster-resilient region, especially in light of climate change, a truly regional governance structure should be explored.

One of Metro Vancouver's key goals is to create a compact urban area. While this has sustainability benefits, this research indicates that compact growth may exacerbate seismic risk in the region. The findings in the Compact Growth scenario are quite contrary to the existing literature that supports compact growth as a risk mitigation measure. However, most of this research has been on land use planning and floods, which may be more responsive to direct land use interventions (e.g. limiting development on flood plains) (Burby, 1998). Seismic risk, on the other hand, involves a multitude of factors, ranging from the built environment to geological conditions and prevailing social systems and institutions. Therefore, this type of hazard risk may be harder to control with land use planning because of the possible convergence of multiple vulnerabilities to exacerbate damage and disruption.

Overall, this research provides a much needed methodology and estimate of earthquake casualties in the Metro Vancouver region. By being proactive in understanding future seismic risk, this research can provide a sound basis for decision-making in the region regarding the placement, form and density of development that best protects the residents of Metro Vancouver in the likely event of an earthquake.

TERMS AND DEFINITIONS

To promote the common understanding of disaster risk reduction concepts and to assist the risk reduction efforts of authorities, practitioners and the public, the disaster and risk management community uses terminology in a very specific fashion (UNISDR, 2009). This report adheres to these conventions and the terms and definitions referred to in this report are provided below.

Disaster: a serious disruption of the functioning of a community or a society involving widespread human, material, economic or environmental losses and impacts, which exceeds the ability of the affected community or society to cope using its own resources

Disaster risk: a function of the characteristics and the frequency of hazards experienced in a specific location, the nature of the elements at risk and their inherent degree of vulnerability or resilience

Disaster risk management: the systematic process of using administrative directives, organizations, and operational skills and capacities to implement strategies, policies and improved coping capacities in order to lessen the adverse impacts of hazards and the possibility of disaster

Emergency management: the organization and management of resources and responsibilities for addressing all aspects of emergencies, in particular preparedness, response and initial recovery steps

Mitigation: any structural (physical) or non-structural (e.g. land use planning, public education) measure undertaken to minimize the adverse impact of potential natural hazard events

Natural hazard: a natural process or phenomenon (e.g. earthquake, landslide, tsunami, windstorm, wave or surge, flood or drought) that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage

Resilience: the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions

Risk: the combination of the probability of an event and its negative consequences (*risk = hazard x vulnerability*)

Vulnerability: the characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of hazard

Source: UNISDR, 2009 and Benson and Twigg, 2007

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1.0 INTRODUCTION

1.1 Overview

As urban regions become more complex and interconnected, the potential for significant damage and disruption from natural hazards is dramatically increasing. To protect against economic, social and human losses, risk reduction strategies such as early warning and education, relief and insurance, and structural protection have been widely utilized (Burby, 1999). While these strategies do help to a certain extent, there is growing consensus that a more proactive and sustainable approach is needed to successfully mitigate risk. Therefore, the concept of 'sustainable hazard mitigation' helps link the "wise management of natural resources with local economic and social resiliency, viewing hazard mitigation as an integral part of a much larger context" (Mileti, 1999, p.2).

One promising sustainable hazard mitigation approach is land use planning. In managing growth and development through land use, local and regional governments can work to "shift existing development and steer new development to areas that are relatively hazard free" (Burby, 1999, p.10). In addition, land use planning can influence the design and construction of the built environment to account for area-specific vulnerabilities (Burby, 1999). By fully understanding the hazards, vulnerabilities, and limits to a place, urban planners can help to foster the development of both sustainable and disaster-resilient communities.

The aim of this master's project is to understand how land use affects disaster resiliency in Metro Vancouver, a region highly susceptible to seismic activity. Using the region's population and dwelling unit projections for 2041, this research investigates how future earthquake casualties in Metro Vancouver might vary depending on land use and density. The earthquake scenario is a hypothetical magnitude 7.3 earthquake occurring in 2041.

By understanding the relationship between land use, density and seismic risk, this research can provide valuable insight to planners and decision makers about the effectiveness of using land use planning to facilitate disaster resiliency. This is especially important in the context of a growing region, such as Metro Vancouver, to ensure that economic, social and human losses are minimized in the likely event of an earthquake.

1.2 Research Context

Metro Vancouver, a highly populated metropolitan region in southwestern British Columbia, is located in one of the highest seismic zones in Canada (Onur and Seemann, 2004) (Figure 1). This area has experienced nine earthquakes with a magnitude of 6 or 7 in the past 130 years (Rogers, 1998). More recently, a magnitude 6.4 earthquake with an epicentre 300 kilometres west of Vancouver occurred on September 9, 2011 and was felt in many parts of the region (Natural Resources Canada, 2011).

The likelihood of a large seismic event occurring in the region is significant and poses a real threat to residents. According to Onur and Seemann (2004), the likelihood of a structurally damaging[1] crustal or subcrustal earthquake occurring in Metro Vancouver is 2.5 percent over the next 10 years, 12 percent over 50 years, and 22 percent over 100 years. In addition, numerous municipalities in the region are situated on soils that are susceptible to seismic amplification and liquefaction, which could potentially exacerbate damage and disruption in large seismic events (Cassidy and Rogers, 2004).

According to the 2006 Census of Canada, Metro Vancouver is home to an estimated 2.1 million people (Statistics Canada, 2006). Based on the region's new Regional Growth Strategy (RGS), *Metro Vancouver 2040 - Shaping our Future*, this area is expected to increase to 3.4 million people by 2041 (Appendix A). To accommodate this growth, over 570,000 dwelling units are projected for the next 35 years (Metro Vancouver, 2011a). This represents a substantial increase in both population and housing units in the region. Depending on how the region develops and whether sustainable hazard mitigation is considered, many residents, existing and new, could be exposed to considerable risk in the event of an earthquake.

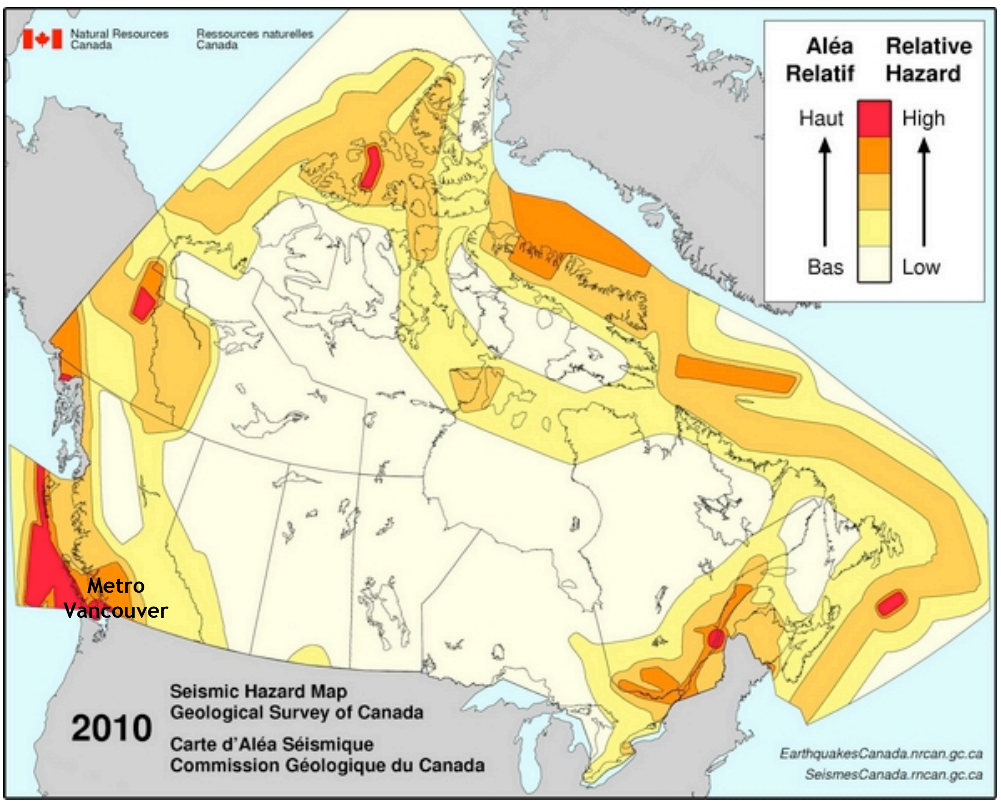

Figure 1: Relative Seismic Hazard in Canada
Source: Natural Resources Canada, 2011 (used with permission)

[1] Onur and Seemann (2004) determined the threshold for structural damage to be ground shaking levels of VII or greater on the Modified Mercalli Intensity (MMI) scale. Other significant levels of ground shaking intensity include MMI V (a widely-felt earthquake event) and MMI VI (threshold for non-structural damage) (Onur and Seemann, 2004).

1.3 Aims and Research Question

The primary aim of this research is to understand how land use and density affects disaster resiliency in a seismically active region. Using the case study of Metro Vancouver, this project utilizes the region's population and dwelling unit projections for 2041 to explore the social consequences of four land use and density scenarios:

1. *Status Quo Growth* - growth follows current development and new population will be distributed to all currently settled areas in a variety of building types proportionally to current population;
2. *Compact Growth* - new population will only locate to current and anticipated high density areas in multi-family building structures;
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Specifically, the research question is, *"How might future earthquake casualties in Metro Vancouver vary depending on land use and density?"* This question is investigated in the context of a hypothetical magnitude 7.3 earthquake occurring in 2041.

This project further aims to educate planners and decision makers about the importance of incorporating hazard information and risk mitigation in land use plans and policies. In particular, this research provides a viable methodology for assessing different land use and density scenarios in the attempt to better understand the consequences of developing in areas susceptible to earthquakes. This methodology could serve as a powerful tool for all levels of government in encouraging development that respects the natural environment and reduces vulnerabilities that exacerbate seismic risk.

1.4 Scope and Approach

A strong seismic event can cause significant losses, as well as extensive disruption, in a large metropolitan region. Furthermore, damage can be exacerbated by secondary hazards triggered by the initial seismic event. While it would be of great interest and importance to explore the interconnections between seismic hazard, vulnerability and level of disruption in Metro Vancouver, the complexity of this research is beyond the scope of this project. The context of this study is limited to human casualties (deaths and serious injuries) resulting from the initial earthquake event. The secondary hazard of soil amplification is also considered, but only as a determinant of physical building damage.

The modeling framework used for this project is a casualty model adapted from the loss estimation model, HAZUS-MH. HAZUS-MH is a well-established methodology for estimating the physical, economic, and social impacts of earthquakes, floods, and hurricanes in the United States (FEMA, 2011). To ensure the model is applicable to the Metro Vancouver region, building damage was estimated with building damage probabilities specific to British Columbia to account for regional building practices (Ventura et al., 2005).

This research is the continuation of a larger study on seismic risk in Metro Vancouver. The modeling approach used in this project is adopted from retrospective analyses already conducted for the region for the years 1971 and 2006 (Chang et al., forthcoming). The results from this study will help develop a fuller picture of how risk has changed, and is continuing to change, in Metro Vancouver.

The unit of analysis in this model is an Area of Analysis (AOA). These spatial units correspond generally to municipalities. In some cases, municipalities were divided into two or more AOAs that are comprised of census tract aggregations of relatively homogeneous soil types and urban development. Using this methodology, Metro Vancouver was divided into 32 AOAs. Overall, these smaller spatial units allow for a more precise and accurate analysis of seismic risk and how it varies within the region.

1.5 Significance

This research provides valuable insight into the feasibility of land use planning in mitigating seismic risk in Metro Vancouver. This is important because while the disaster management community often recommends land use planning for risk reduction, few authorities have fully applied this approach in practice. In addition, the exploratory nature of this research provides insight into the impacts of land use and density before development actually occurs. This knowledge can inform where development should occur in the region, now and into the future, to ensure lives are protected in a region highly susceptible to seismic events.

This research further provides a methodology that not only estimates earthquake casualties, but can also help local authorities, policymakers and the general public 'visualize' different development scenarios. This visualization can help generate community discussions about the tradeoffs of developing in hazard prone areas, and through the process, improve preparedness though public awareness.

2.0 BACKGROUND

2.1 Metro Vancouver Overview

Metro Vancouver, officially named the Greater Vancouver Regional District (GVRD), is comprised of 22 municipalities, one electoral area, and one treaty First Nation (Metro Vancouver, 2011c) (Figure 2). The region has a land area of 2,877 square kilometres and is the most populated regional district in British Columbia, with a population density of 735.6 people per square kilometre in 2006 (Statistics Canada, 2006).

Figure 2: Member Municipalities of Metro Vancouver
Source: UBC Transportation Planning, 2011 (used with permission)

2.1.1 Governance Structure

As the regional authority, Metro Vancouver fulfills three interconnected roles - political forum, policy, and services (Metro Vancouver, 2011c) (Appendix C). In its policy role, Metro Vancouver develops and uses an integrated system of plans to manage and administer resources and services that are best dealt with at a regional level (Metro Vancouver, 2011c). Both growth management and regional emergency management are part of the organization's planning and regulatory responsibilities.

Member municipalities have control in the management of the region through the Metro Vancouver Board. Directors of the Board are members of a municipal, electoral area, or First Nation council who have been appointed by their respective councils on a 'representation by population' basis (Metro Vancouver, 2011c). Directors are allowed one vote for every 20,000 people in their area, up to a total of five votes. In addition, the Board uses a consensus-based decision-making model whereby full agreement among representatives must be reached for actions to pass (Tomalty, 2002).

Since 2002, Metro Vancouver has formally put the concept of sustainability at the centre of its operating and planning philosophy (Metro Vancouver, 2011c). Known as the Sustainable Region Initiative, a comprehensive sustainability framework was later adopted in 2008 to ensure sustainability principles are reflected in all of the organization's activities (Metro Vancouver, 2011c). This process lead to the development of three sustainability principles to inform decision-making:

1. Protect and enhance the natural environment;

2. Provide for ongoing prosperity; and
3. Build community capacity and social cohesion (Metro Vancouver, 2011c).

2.1.2 Population Growth

Metro Vancouver is one of the fastest growing metropolitan regions in Canada (Metro Vancouver, 2007). Between 2001 and 2006, Metro Vancouver's population increased from 1,986,965 to 2,116,581, representing a growth rate of 6.5 percent (Statistics Canada, 2006). This rate is slightly lower than the 8.5 percent from the preceding five years (1996 to 2001), but is still higher than both the provincial and national growth rates at 5.3 and 5.4 percent, respectively (Metro Vancouver, 2007).

In terms of absolute population growth between 2001 and 2006, Surrey led all municipalities with 47,151 additional residents, followed by Vancouver (32,370), Richmond (10,115), and Burnaby (8,845) (Metro Vancouver, 2007). However, in terms of growth rate, population growth in suburban municipalities, such as Anmore, Surrey, and Port Moody, is quickly outpacing the traditional core cities of Vancouver, Burnaby and New Westminster (Metro Vancouver, 2007) (Figure 3).

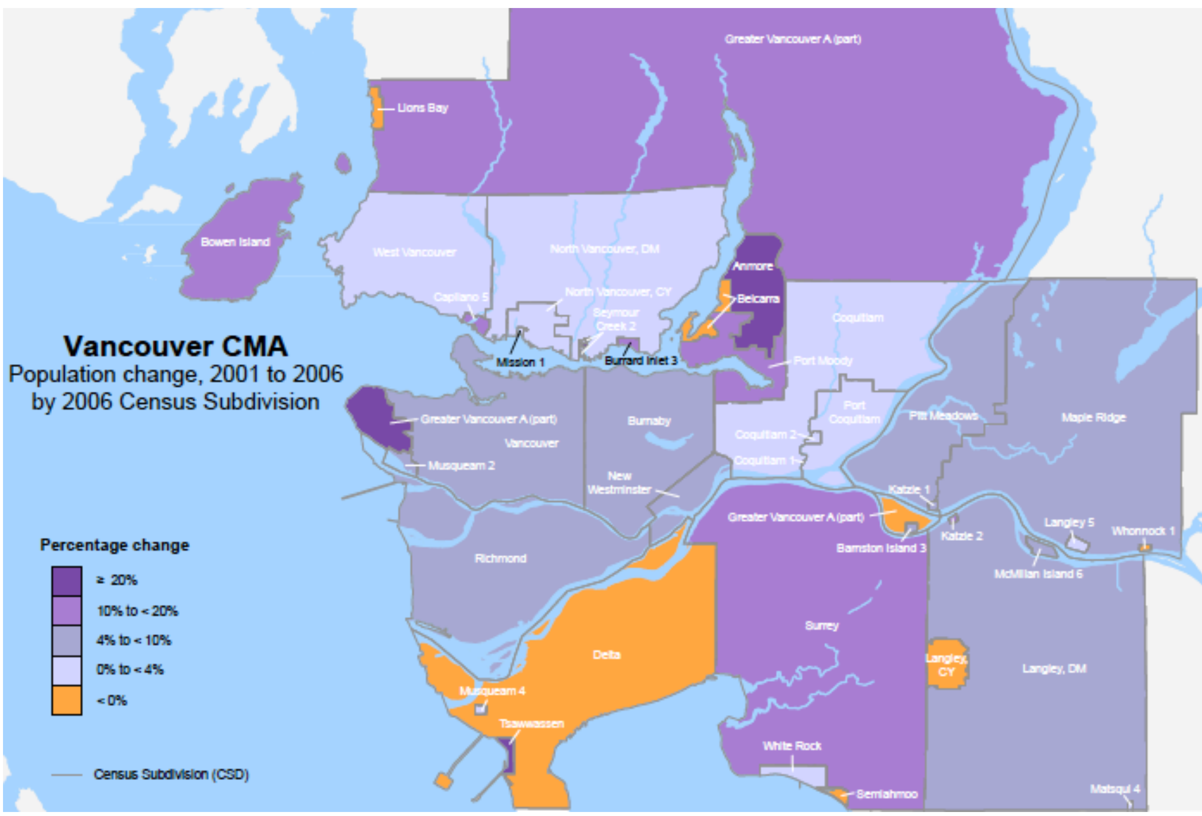

Figure 3: Population Change between 2001 and 2006 by Census Tract
Source: Statistics Canada, 2007 (used with permission)

While population growth is shifting towards the suburban municipalities, the majority of residents still lived within the Growth Concentration Area in 2006 (Figure 4). In fact, the population within this area increased by 65,110 over the 2001 to 2006 census period, accounting for 64 percent of the region's total population (Metro Vancouver, 2007). The share of dwelling units also increased in the Growth Concentration Area from 66 percent of the region's total between 1996 and 2001 to 67 percent between 2001 and 2006 (Metro Vancouver, 2007).

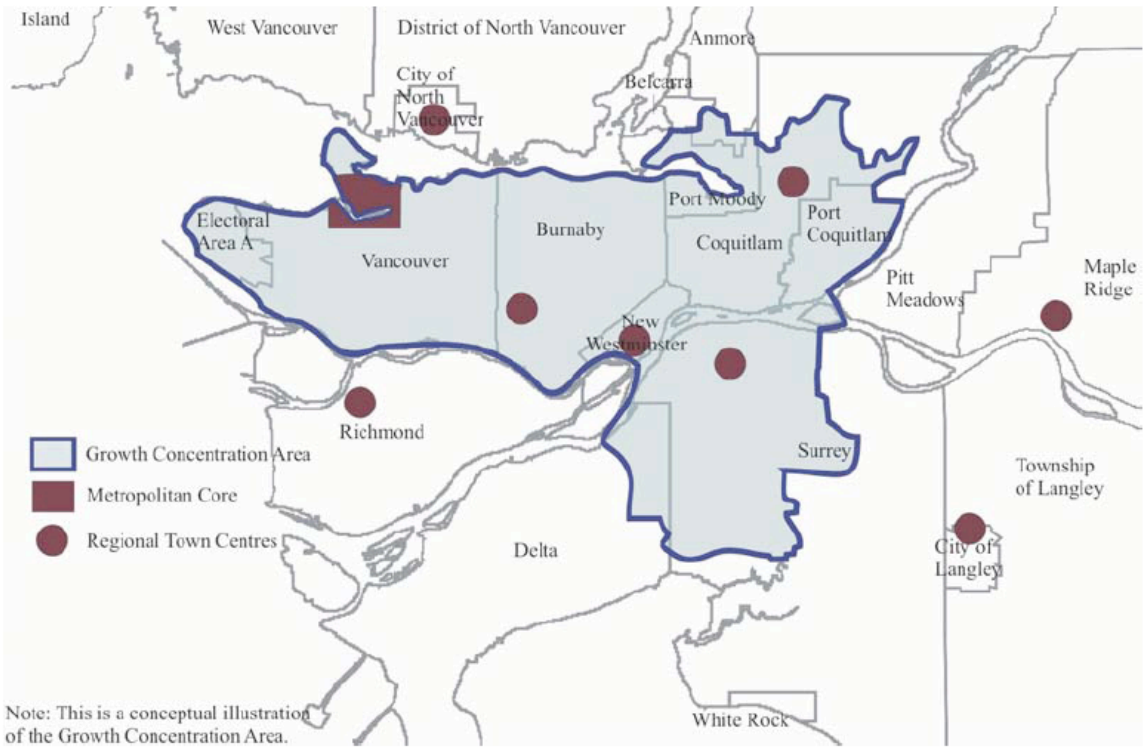

Figure 4: Growth Concentration Area and Regional Town Centres, 2006
Source: Metro Vancouver, 2007 (used with permission)

Based on the population projections provided by the current Regional Growth Strategy, Metro Vancouver is expected to reach 3.4 million residents by 2041 (Metro Vancouver, 2011a) (Appendix A). The municipalities projected to receive the highest population growth in the next 35 years include Surrey (324,000), Vancouver (131,900), the Township of Langley (113,300) and Coquitlam (108,900) (Appendix D). To accommodate this growth, dwelling units are also expected to increase from approximately 848,000 units[2] in 2006 to 1,422,000 units in 2041 (Metro Vancouver, 2011a).

[2] The number of dwelling units in 2006 is different between the Regional Growth Strategy (848,000) and Statistics Canada (817,035). The higher number reported by the regional plan could be due to the inclusion of the Census undercount.

2.1.3 Building Stock

To accommodate Metro Vancouver's high growth rate, the regional building stock has seen a noticeable shift in the quantity and density of buildings. Between 1991 and 2006, the region increased from 609,380 to 817,035 dwellings for an increase of 238,650 units (Metro Vancouver, 2011b). Most of this increase has been in the form of apartments, which now accounts for the largest share of all dwelling types in the region (Metro Vancouver, 2011b) (Figure 5). Single detached dwellings, which have been the predominant dwelling type in the past, have experienced the most significant decrease, accounting for only 35 percent of building stock in 2006 (Metro Vancouver, 2011b).

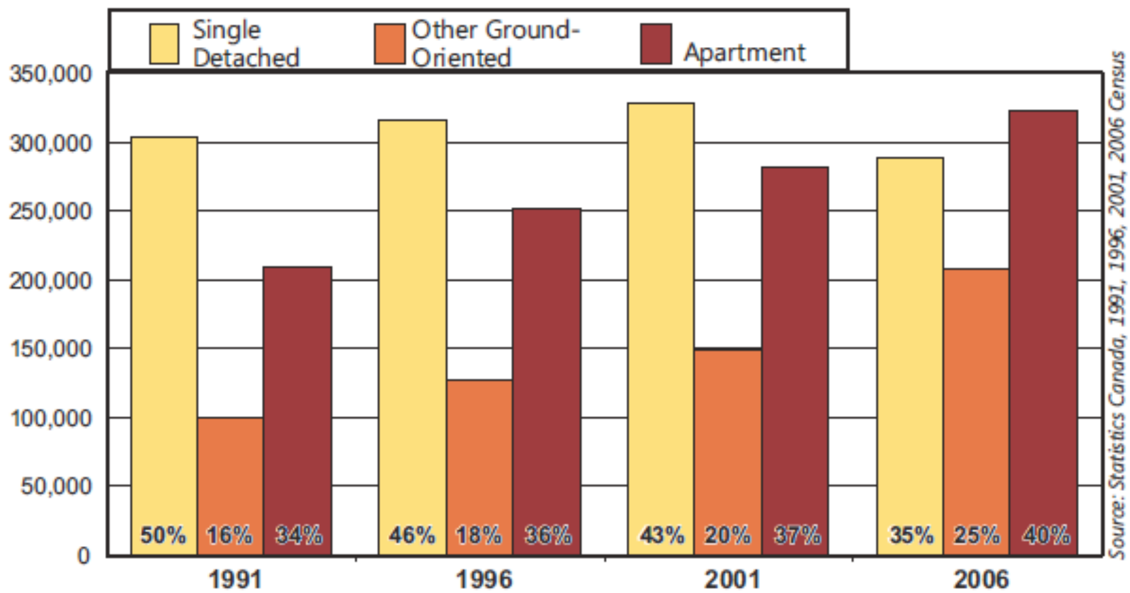

Figure 5: Regional Dwelling Inventory by Structural Type, 1991 to 2006
Source: Metro Vancouver, 2011b (used with permission)

The growth rate for dwelling units varies significantly depending on the municipality. Between 1991 and 2006, the municipalities south of the Fraser River, including Surrey and the Township of Langley, had a growth rate between 22 to 25 percent, well above the regional growth rate at 18 percent (Metro Vancouver, 2011b). In contrast, the North Shore municipalities of the City of North Vancouver, the District of North Vancouver and West Vancouver only had a growth rate of 8 percent during this same period (Metro Vancouver, 2011b). Overall, the spatial distribution of the built environment is changing considerably, especially in suburban municipalities that are experiencing high growth.

Another important consideration in regards to the building stock and seismic risk is the building vintage. Vintage is a key concern because modifications to building codes and construction practices have led to variations across building vintages in structural type, design, and vulnerability characteristics (Chang et al., forthcoming). In British Columbia, buildings constructed prior to the 1970s have limited structural resistance to earthquake effects (Ventura et al., 2005). This represents a significant source of vulnerability in the region since there were 515,870 dwelling units constructed before 1970 in 2006, or almost one-third of housing units in Metro Vancouver (Statistics Canada, 2006).

2.1.4 The British Columbia Building Code

In British Columbia, the building code "is a provincial regulation for new construction and building alterations, establishing minimum standards for safety, health, accessibility, fire and structural protection and protection from water and sewer damage" (BC Ministry of Housing, 2010). While these standards mainly govern the design and construction of new buildings, the code does require that if an "existing building is altered, rehabilitated, renovated or repaired, or there is a change in occupancy, the level of life safety and building performance shall not be decreased below a level that already exists" (BC Ministry of Housing, 2006). However, the building code cannot "enforce the retrospective application of new requirements to existing buildings or existing portions of relocated buildings, unless specifically required by local regulations or bylaws (BC Ministry of Housing, 2006). Therefore, older buildings built to lower structural standards are highly vulnerable to seismic impacts.

The BC Building Code does contain seismic provisions to aid the design and construction of buildings to be as "earthquake-proof as possible" (Natural Resources Canada, 2008). However, these guidelines are only minimum standards. "They are meant to prevent structural collapse during major earthquakes and thereby protect human life. The provisions, may not, however, prevent serious damage to individual structures" (Natural Resources Canada, 2008).

While building codes are effective at mitigating risk, there are limitations. For instance, building codes often create a false sense of security among authorities and citizens. This is particularly dangerous if this false sense of security becomes a justification for increasing development in known hazard areas (Nelson & French, 2002). This predicament, termed the "Safe Development Paradox," explains how attempts to make hazardous areas safer for development are in fact making them targets for catastrophe because of well-intentioned, but short-sighted, government policies (Burby, 2006). Another limitation of building codes is that while these standards are developed on sound scientific research, they are only designed to reduce the probability of loss from disasters up to certain extents. Disasters that exceed these limits can result in catastrophic outcomes to both lives and property (Nelson & French, 2002).

2.1.5 Growth Management and the Regional Growth Strategy

Metro Vancouver is often recognized as a jurisdiction with highly progressive growth management plans and policies. Since the region's first growth management strategy, the *Livable Region Plan*, in 1975, the organization has continued to have an enduring planning vision of creating a livable and sustainable region (Tomalty, 2002). Even today, through multiple iterations of the plan, the core ideas of creating a more compact urban region, improving transit and reducing car use, concentrating growth in the metropolitan core and regional town centres, and establishing a regional green system remain important objectives (Tomalty, 2002).

The Local Government Act provides all regional districts in British Columbia the statutory authority to manage growth with a regional growth strategy. According to the Act, "the purpose of a regional growth strategy is to promote human settlement that is socially, economically and environmentally healthy and that makes efficient use of public facilities and services, land and other resources" (BC Laws, 2011) (Appendix E). Included in a list of considerations for the regional growth strategy is "settlement patterns that minimize risk associated with natural hazards" (BC Laws, 2011).

The Local Government Act also strengthens regional planning institutions by requiring municipalities to respect the regional plan (Tomalty, 2002). While municipal governments remain responsible for planning and land use decisions (Government of British Columbia, 2011), the Act requires municipalities to prepare a Regional Context Statement (RCS) outlining how its Official Community Plan (OCP) complies with the growth strategy. In cases where the OCP is not consistent with the regional plan, the RCS must indicate how the plan will be brought into conformance with the strategy (BC Laws, 2011).

The relationship between the region and its member municipalities is 'horizontal' rather than 'vertical' (Tomalty, 2002). A regional district needs all member municipalities to agree to the regional strategy before the plan may be adopted. In turn, municipalities are required to include the regional plan in their own planning documents (Tomalty, 2002). This process of mutual agreement helps ensure the regional plan has a high degree of support among member municipalities.

Metro Vancouver's current Regional Growth Strategy, *Metro Vancouver 2040 – Shaping Our Future*, was adopted on July 29, 2011 (Metro Vancouver, 2011). This plan focuses on land use policies to guide the future development of the region and support the efficient provision of transportation, regional infrastructure and community services (Metro Vancouver, 2011). *Metro Vancouver 2040* is structured around five key goals:

- GOAL 1 - Create a Compact Urban Area
- GOAL 2 – Support a Sustainable Economy
- GOAL 3 – Protect the Environment and Respond to Climate Change Impacts
- GOAL 4 – Develop Complete Communities
- GOAL 5 – Support Sustainable Transportation Choices (Appendix F)

Each goal further has strategies and policies that detail how these goals will be achieved and the actions expected of Metro Vancouver, member municipalities and other levels of government (Metro Vancouver, 2011c).

Another important component of the regional plan are land use designations. Aimed at guiding future land use decisions, one of the most important designations in the RGS is the Urban Containment Boundary, which limits where urban development can occur in the region (Figure 6). To ensure growth is contained within the Boundary, Metro Vancouver restricts extension of regional sewage services into areas outside of these boundaries[3] (Metro Vancouver, 2011a).

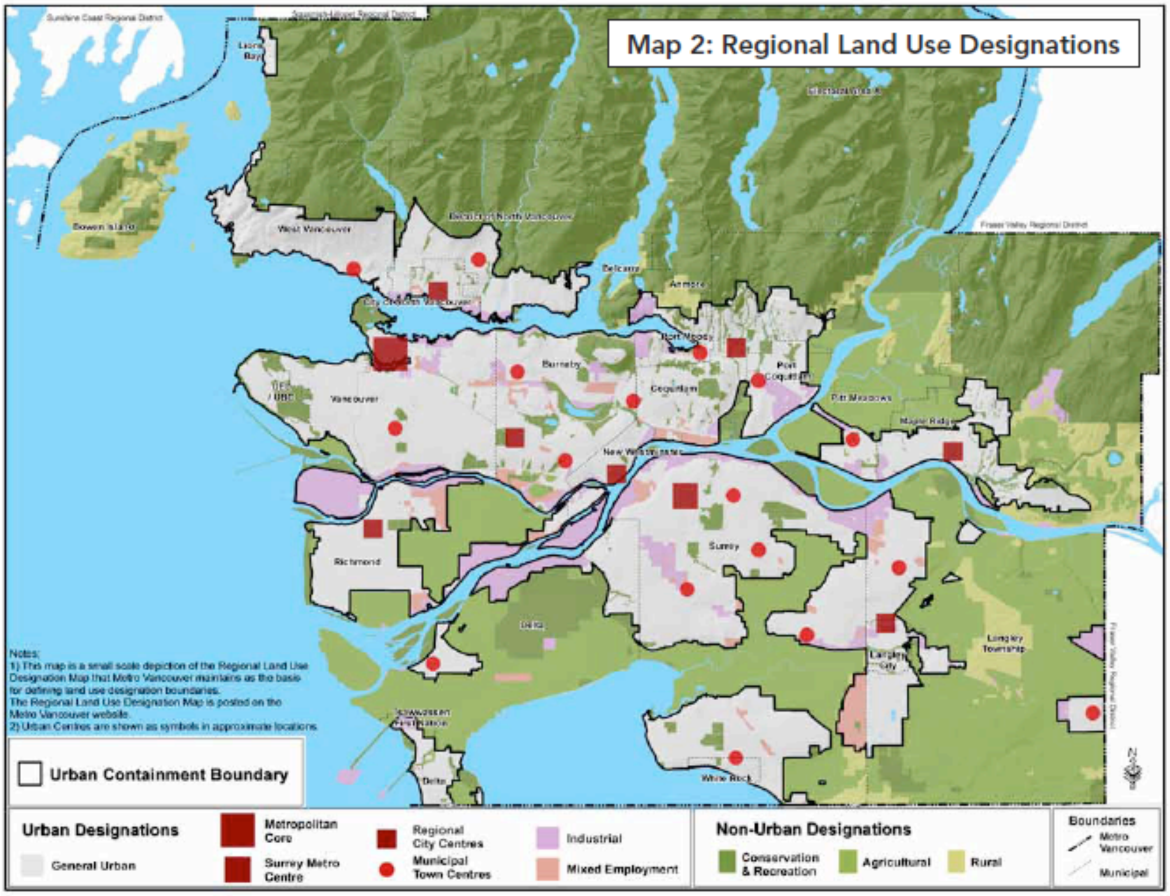

Figure 6: Urban Containment Boundary and Regional Land Use Designations in Metro Vancouver
Source: Metro Vancouver, 2011a (used with permission)

The current RGS recognizes natural hazards to be a significant challenge to creating a livable and sustainable region:

> The major natural hazard risks facing the Metro Vancouver region include earthquakes, floods, and slope instability. Many of these are exacerbated by the global threat of climate change. The challenge is to prepare for and mitigate regional natural hazards and reduce the greenhouse gas emissions which can increase many of these risks, not only through mitigation strategies, but also through land use and transportation patterns generally (Metro Vancouver, 2011a, p.6).

[3] Exceptions to this policy include: to address a public health issue, protect the region's natural assets or service agriculture or agri-industry (Metro Vancouver, 2011a)

The inclusion of a sustainable hazard mitigation ideology in the RGS is very progressive since disaster resiliency has seldom been considered in regional land use plans. Yet, while actions have been outlined for Metro Vancouver and other levels of government (Appendix G), how this strategy is translated into practice remains to be seen.

2.1.6 Regional Seismic Hazard

Metro Vancouver is highly susceptible to seismic activity due to its proximity to the Cascadia Subduction Zone. At this Zone, the Juan de Fuca plate is being forced beneath the North America plate, producing three distinct types of earthquakes: shallow (crustal) earthquakes within the North America plate, deep (subcrustal) earthquakes within the Juan de Fuca plate, and “megathrust” earthquakes at the interface of the two plates (Onur and Seemann, 2004) (Figure 7).

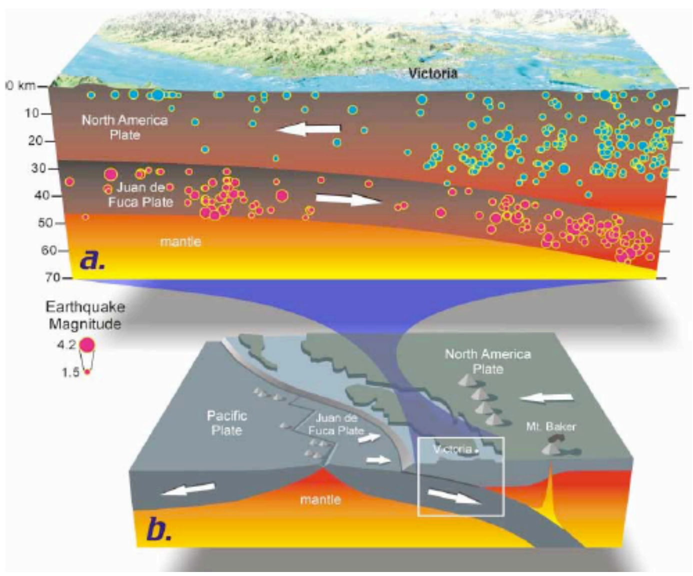

Figure 7: Cascadia Subduction Zone
Blue circles indicate crustal earthquakes and red circles indicate subcrustal earthquakes
Source: Onur and Seemann, 2004

Seismic activity in southwestern British Columbia is predominantly crustal and subcrustal. A large concentration of subcrustal earthquakes occurs beneath the Strait of Georgia, the waterway separating Vancouver Island from the coastal mainland, affecting major urban areas including Metro Vancouver (Onur and Seemann, 2004). In a study conducted by Onur and Seemann (2004), the authors determined that the likelihood of a crustal or subcrustal earthquake producing structurally damaging ground shaking (MMI VII or greater) is 2.5 percent over the next 10 years, 12 percent over 50 years, and 22 percent over 100 years. The same study found that the probability of a non-structurally damaging earthquake (MMI VI) is 35 percent in the next 50 years (Onur and Seemann, 2004).

Megathrust earthquakes, on the other hand, have much longer recurrence periods but produce significantly larger magnitude events. The last megathrust earthquake to occur at the Cascadia subduction interface was in the year 1700 and had an estimated magnitude of 9.0 (Onur and Seemann, 2004). Geological evidence indicates that large subduction earthquakes have occurred in this region every 300 to 800 years (Natural Resources Canada, 2011). Onur and Seemann (2004) estimate the probability of the next Cascadia subduction earthquake occurring in the next 50 years to be 11 percent.

Ground motion amplification refers to “the increase in the intensity of ground shaking that can occur due to local geological conditions, such as the presence of soft soils” (Monahan et al., 2000). This type of ground response is important when assessing seismic risk because “site conditions play a major role in establishing the damage potential of incoming seismic waves” (Finn and Wightman, 2003, p.272). For example, the response of loose sediments to seismic shaking is substantially different than that of firm ground because wave velocities in loose sediment are significantly higher than that found in young alluvial and deltaic sediment (Clague et al., 1998).

Soil conditions in Metro Vancouver are quite diverse (Appendix H). The City of Vancouver, for example, lies almost entirely on glacial till and is therefore not expected to experience significant amplification of ground shaking intensities (Onur et al., 2004). In contrast, the Fraser River delta is overlain with thick Holocene deltaic deposits, which are especially prone to ground amplification (Uthayakumar and Naesgaard, 2004). In a study conducted by Cassidy and Rogers (2004) on the variation in ground shaking in the Fraser River delta, the authors found that near the centre of the delta where soft soils were thickest, peak amplification of four to ten times that of bedrock was measured. However, when measured near the edge of the delta, amplification was up to 12 times relative to bedrock (Cassidy and Rogers, 2004). Therefore, the municipalities of Richmond and Delta are especially vulnerable to seismic acitivity.

2.2 Disaster and Risk Management Overview

2.2.1 “Unnatural” Disasters

It is increasingly recognized that while hazards are natural, the catastrophic economic, social and human losses that result from disaster events are not. Instead, these “unnatural” disasters expose the cumulative implications of many earlier decisions (Sanghi, 2010). Thus, while natural disasters are often described as random “Acts of God”, they are more often the consequences of systematic and deliberate actions (or inactions).

The misunderstanding with disasters begins with the idea that people can use technology to control nature (Alexander, 1999; Mileti, 1999). This technocratic attitude assumes that human ingenuity is sufficient to “overcome a particular hazard, either by modifying it or by making the environment safe” (Alexander, 1999, p.16). Yet, despite significant improvements in engineering and technology, the direct and indirect costs of hazard events have continued to rise. Furthermore, the more technologically complex our society becomes, the more diverse are the risks and impacts of disasters (Alexander, 1999). Therefore, human vulnerability is often the "result of ignorance not merely about the scope of natural disaster impacts but also about the limited degree to which a given technology is capable of mitigating them" (Alexander, 1999, p.16).

Another misconception is that disasters are unique and exceptional events (Alexander, 1999). Extreme hazard events have occurred consistently throughout human history. Yet, prolonged lulls between events often lead to complacency from individuals and governments about the need to prepare for hazards, as well as to reduce vulnerabilities (Alexander, 1999). This is reflected in the fact that most governments spend more money on post-disaster relief than on prevention (Sanghi, 2010). While prevention is often considered an expensive course of action for an "unpredictable" hazard, mitigation would likely cost less than the economic, social and human costs (direct and indirect) accrued from a disaster event (Sanghi, 2010).

2.2.2 Sustainable Hazard Mitigation

The disaster management community today is a multidisciplinary and interdisciplinary group of researchers and practitioners. The expansion in the breadth and knowledge in this field has helped to produce better understandings of the complexities between hazards, the natural environment, the built environment and human society. As a result, a shift is occurring where the traditional technocratic approach of controlling nature is being replaced with a more progressive vision of cooperating with nature (Burby, 1998).

The concept of sustainable hazard mitigation "links the wise management of natural resources with local economic and social resiliency, viewing hazard mitigation as an integral part of a much larger context" (Mileti, 1999, p.2). Nested in the principle of sustainability, sustainable hazard mitigation represents a fundamental shift in the character of how citizens, communities, governments, and businesses conduct themselves in relation to the natural environments they occupy (Mileti and Gailus, 2005). Rather than simply responding to natural hazards in an ad hoc way as they arise, this approach provides a holistic way of understanding the complex factors that contribute to disaster events (Mileti and Gailus, 2005).

Sustainable hazard mitigation further utilizes a global systems perspective to recognize that "disasters arise from the interactions among the earth's physical systems, its human systems, and its built infrastructure, rather than from discrete environmental events" (Mileti and Gailus, 2005, p.496). This perspective views human actions as the cause of disaster losses and shifts responsibility from nature to people.

This approach also minimizes the role of technology. While technology remains a useful tool, it is no longer regarded as the ultimate solution to natural hazards mitigation (Mileti and Gailus, 2005). Rather, the new perspective recognizes hazards to be dynamic and under the influence of both natural and anthropogenic factors. One particularly important influence today is climate change, which is drastically altering physical phenomena, including natural hazards (van Aalst, 2006; Helmer and Hilhorst, 2006) (Appendix I). Not only does climate change cause changes in known hazard risks, it also raises the level of uncertainty in the intensity and reoccurrence of hazard events (van Aalst, 2006). It is thus important that disaster risk reduction strategies be adaptable to the increasing risks associated with climate change.

This paradigm shift to sustainable hazard mitigation is gaining momentum. The seven recommendations for fostering sustainable hazard mitigation developed by Mileti (1999) has been a useful aid in this process:

1. Develop local 'sustainable hazard mitigation networks' in communities that would bring together various stakeholders to carry out plans for identifying and dealing with potential hazards;
2. Redesign government and policy framework so that policies and programs related to hazards and sustainability are integrated and consistent;
3. Conduct nationwide hazard and risk assessment to examine the interactions between the physical, social, and constructed systems that can affect the outcome of natural hazards;
4. Build national databases about mitigation efforts and losses from past and current disasters to determine the true cost of hazards and disasters;
5. Provide comprehensive, interdisciplinary education and training in hazard mitigation and preparedness for people involved with hazards management;
6. Think about issues related to natural hazards that may fall outside of one's traditional fields of study; and
7. Share the knowledge internationally and learn from other.

2.2.3 Land Use Planning as a Sustainable Hazard Mitigation Approach

> Disaster reduction policies and measures need to be implemented with a two-fold aim: to enable societies to be resilient to natural hazards while ensuring that development efforts do not increase the vulnerability to these hazards.
>
> \- U.N. Commission on Sustainable Development, 2001

A significant aspect of human vulnerability to natural hazards stems from where and how human development occurs (Mileti and Gailus, 2005). While both location and design are important considerations in creating disaster-resilient communities, the locational approach is far superior in reducing disaster losses because it limits development in hazardous area (Burby, 1998). Burby (1998) explains that in managing the location of development, local governments can work to shift existing development and steer new development to areas that are relatively hazard free. Furthermore, local governments have various regulatory and non-regulatory tools to enable this approach. For example, zoning is a land use regulation that can easily restrict development in hazardous areas, while locating development-inducing infrastructure only in areas that are relatively free of hazard is a good example of a non-regulatory strategy (Burby, 1998).

While the locational approach is powerful, it is certainly less popular with government authorities. This is due to the fact that the gains of risk reduction come at the cost of giving up the economic benefits of development (Burby, 1998). Yet, the consequence of not adopting this approach is serious since most losses from disasters have occurred where settlements have developed in known hazard areas (Godschalk, 2003). Regrettably, disasters have tended to occur in tandem with unsustainable development (Mileti and Gailus, 2005).

In contrast, the goal of the design approach is safe construction in hazardous areas (Burby, 1998). This type of land use allows economic gains to be realized, but at the cost of greater loss of natural values and susceptibility to greater damage when events exceed the design standards employed (Burby, 1998). Examples of regulatory design techniques include building codes and stand-alone ordinances that require structural compliance against hazards. Non-regulatory design techniques would consist of more voluntary measures, such as public information, training programs, and subsidies (Burby, 1998). A properly conducted planning process would allow communities to find the appropriate mix of these two land use approaches (Burby, 1998).

While using land use planning to mitigate risk is important in all locales, it may be especially critical in cities and larger metropolitan regions. This is because urban areas are at risk both from a wide range of hazards and from their own multiple vulnerabilities (Moor, 2001). As Moor (2001) notes, points of urban vulnerability are numerous and can range from infrastructure systems and buildings to telecommunications, transport, and energy supply lines.

This focus on urban risk has led to the idea of resilient cities. According to Godschalk (2003), a resilient city is a sustainable network of physical systems and human communities. Physical systems are the constructed and natural environmental components, such as roads, buildings, and infrastructure, as well as waterways, soils, and topography. Human systems, on the other hand, are the social and institutional components of the city and include all formal and informal, stable and ad hoc human associations that operate in an urban area (Godschalk, 2003). During a disaster, both systems must be able to survive and function under extreme stress. In addition, while hazard mitigation has primarily focused on making physical systems resistant to disaster forces, Godschalk (2003) argues that future mitigation must also focus on teaching the city's social communities and institutions to reduce risks and respond effectively to disasters.

Overall, land use planning is not only an effective risk mitigation strategy because of its ability to control the location and design of development, but also because it can convey hazard information to communities. For instance, land use plans are effective communications materials to explain the potential limitations of hazard-prone areas (Burby, 1998). Furthermore, in the process of creating these plans, local governments often engage residents. This process provides an effective forum for dialogue with stakeholders about hazards in the areas, as well as suitable mitigation strategies for the community. Overall, land use management and plans enhance prospects for a sustainable future – one in which citizens and their elected officials make informed choices about using hazardous areas in ways that will not jeopardize the long-term viability of their community (Burby, 1998).

3.0 EARTHQUAKE SCENARIO

3.1 Scenario Overview

The hypothetical earthquake scenario selected for this research is a magnitude 7.3 subcrustal earthquake with the epicentre under the Strait of Georgia, approximately 18 kilometres southeast of Gibsons, British Columbia (Figure 8). This scenario was developed by the *Analyzing Infrastructures for Disaster-Resilient Communities*[4] research team at the University of British Columbia, in collaboration with the British Columbia Provincial Emergency Program. This scenario is a strong, but realistic event for this region.

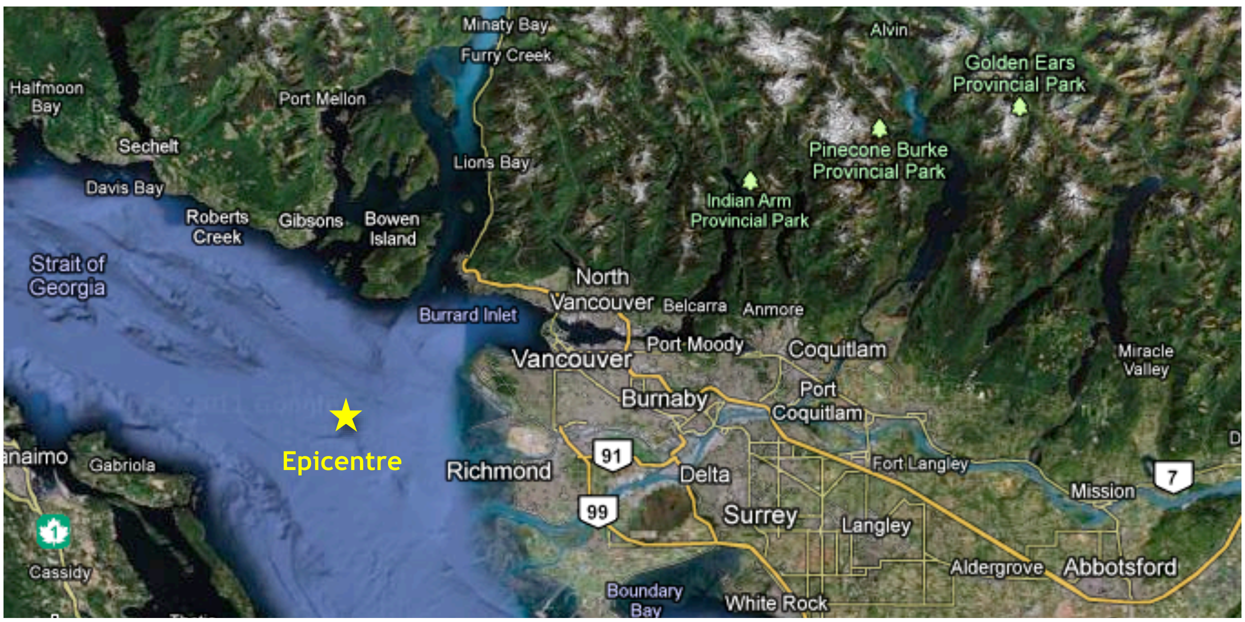

Figure 8: Earthquake Scenario in the Strait of Georgia, British Columbia
Source of base map: Google Maps, 2011

3.2 Scope

The level of damage and destruction caused by an earthquake is determined by the intersection of various temporal, physical and social factors. While these factors are important, they can also be highly complex to model. Therefore, in order to simplify the model, this earthquake scenario makes certain scoping assumptions, including the time of day, the presence of aftershocks and secondary hazards, and the structural type (Table 1).

[4] For more information about the Analyzing Infrastructures for Disaster-Resilient Communities at the University of British Columbia, please visit http://www.chs.ubc.ca/dprc_koa/index.html.

Table 1: Earthquake Scenario Scoping Assumptions

CONSIDERATION	SCOPE	EXPLANATION
Structural type	Residential buildings only	Focus of this research is on the population and dwelling unit projections provided by the region
Time of day	4am (weekday morning)	Model focuses on deaths and injuries associated with residential structures, therefore an earthquake event in the middle of the night may be the best time approximation for when the majority of people are at home
Ground failure (e.g. ground motion amplification, liquefaction, landslide) caused by initial event	Ground motion amplification only	Amplification of different soil types found in the region provide the spatial pattern of ground shaking that is used to calculate structural damage in the model
Aftershocks or secondary hazards caused by initial event	None	Only deaths and serious injuries caused by the initial earthquake event is considered in this research

4.0 RESIDENTIAL CASUALTY MODEL

4.1 Model Framework

A casualty model to estimate earthquake deaths and serious injuries was used for this analysis. Developed by Dr. Stephanie Chang and collaborators from the University of British Columbia, the basic model framework was adopted from the United States Federal Emergency Management Agency's (FEMA) loss estimation model, HAZUS-MH. HAZUS-MH is a well-established model for estimating potential losses from earthquakes, floods and hurricanes (FEMA, 2011), but is highly specific to the United States. Therefore, to ensure the model is applicable to Metro Vancouver, building damage was estimated based on a model by Ventura et al. (2005) that reflects the building practices and standards of British Columbia. The casualty model retains the HAZUS-MH casualty rates in determining deaths and serious injuries. Overall, the "model is comprised of three sequential submodels that respectively estimate building inventory, building damage (given ground shaking intensities), and human casualties” (Chang et al., forthcoming) (Figure 9).

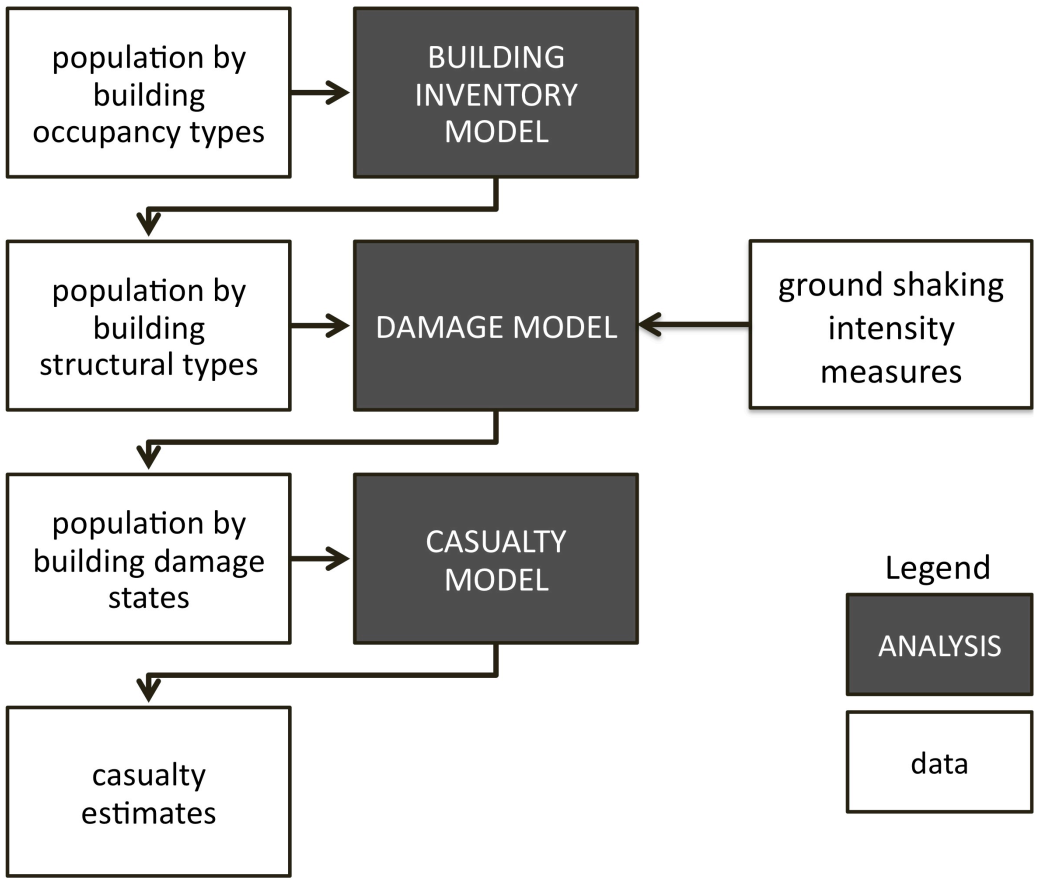

Figure 9: Conceptual Diagram of Casualty Model
Source: Chang et al., forthcoming

As noted earlier, the spatial unit of analysis in this model is an Area of Analysis (AOA). Aggregated from census tracts, AOAs were formed based on areas that had distinctly different soil compositions from adjacent areas and relatively homogeneous urban development. Soil typology was of particular importance in determining AOA boundaries due to the fact that soil types respond differently to seismic waves, resulting in varying levels of damage within the region (Gregorian, 2010). For this model, ground shaking is estimated in terms of MMI from a range of VI to VIII, depending on the proximity to the epicentre of the earthquake and predominant soil type (Figure 10) (Appendix J).

AOA boundaries were further delineated to match municipal boundaries. This correspondence ensures model results are provided at the municipal level, which is important given that “each municipality within Metro Vancouver is responsible for their own emergency management and response” (Metro Vancouver, 2011c). In total, the region is divided into 32 AOAs (Appendix B).

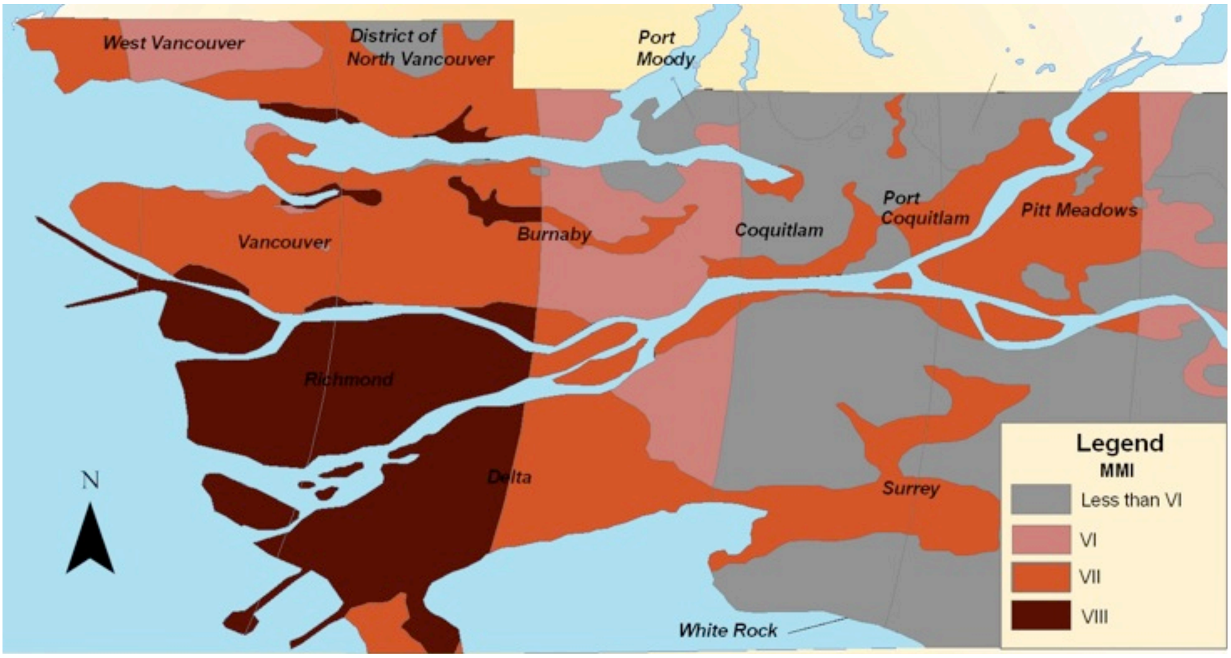

Figure 10: Estimated Ground Shaking in Metro Vancouver
Source: Chang et al., forthcoming

Overall, this model was designed to emphasize risk factors that are influenced by urban growth and change (Chang et al., forthcoming). Therefore, using this model, casualty estimates are determined for four different land use and density scenarios through changes to the building inventory, the distribution of population with respect to structural types and the location of buildings.

4.2 Methodology

4.2.1 Building Inventory Model

The first sub-model estimates the total building inventory in Metro Vancouver. In order to calculate this, both dwelling unit and population data were required. Since this analysis is for the year 2041, both variables had to account for existing and projected numbers. Therefore, existing dwelling units were ascertained for each census tract using the 2006 Census of Canada variable, "occupied private dwellings by structural type," in addition to the period of construction. Existing population was also provided by the 2006 census at the census tract level. Metro Vancouver's Regional Growth Strategy provided the 2041 projections for both variables (Appendix A).

Metro Vancouver's projections are presented at the municipal level, not by census tracts. Therefore, part of the task for creating each land use and density scenario was to allocate different dwelling unit and population estimates to each census tract. This process is explained in the next section on Model Scenarios.

The next step in this model was to transform the census structural types into five categories: Single Family, Multi-Family Townhouse, Apartment Buildings Under Five Storeys, Apartment Buildings Five Storeys and Above, and Mobile Home (Table 2). This step was executed using percentages informed by historical periods with distinct building practices (e.g. building codes had limited seismic provisions prior to the 1970s (Mitchell et al., 2010)), regional construction trends, anecdotal evidence, as well as certain assumptions. For example, the model assumes that of the total apartment buildings five storeys and above constructed prior to 1945, 97 percent were mid-rise (five to eight storeys) and three percent were high-rise. In contrast, for the period after 1945, the model assumes 90 percent of all apartments constructed in the region are high-rise apartments (Hutton, 2010). A detailed table of the percentages is provided in Appendix K.

Table 2: Model Building Types and Corresponding Census Structural Types

Building Type in Model	Corresponding Census Structural Type(s)
Single Family	Single-Detached House
Multi-Family Townhouse	Semi-Detached House; Row House, Apartment Duplex; and, Other Single-Attached House
Apartment Building <5 Storeys	Apartment Building that has Fewer than Five Storeys
Apartment Building 5+ Storeys	Apartment Building that has Five or More Storeys
Mobile Home	Movable Dwelling

Building types were subsequently manipulated to correspond to a structural classification scheme suitable for earthquake damage modeling. The classification scheme selected was Ventura et al.'s (2005) building classes because of their suitability to the model, as well as their relevance to British Columbia construction practices. Table 3 provides the list of building classes selected for analysis. A complete list of building classes in British Columbia is included in Appendix L.

Once all dwelling units were transformed into Ventura et al.'s (2005) building classes, the results from each census tract were aggregated into the larger spatial units of AOAs. The population of each AOA was then distributed to each building class by multiplying the total population in the AOA by the percentage that each building class represented as a total of the building stock in the AOA.

Table 3: Building Classes Utilized in Building Inventory Sub-Model

Building Class	Code
Wood Light Frame Residential	WLFR
Wood Post and Beam	WPB
Wood Light Frame Low Rise Residential	WLFLR
Unreinforced Masonry Bearing Wall Low Rise	URMLR
Unreinforced Masonry Bearing Wall Medium Rise	URMMR
Concrete Frame with Infill Walls	CFIW
Concrete Frame with Concrete Walls Low Rise	CFCWLR
Concrete Frame with Concrete Walls Medium Rise	CFCWMR
Concrete Frame with Concrete Walls High Rise	CFCWHR
Mobile Home	MH

4.2.2 Damage Model

The damage model estimates the level of physical damage caused by ground shaking in the region. These estimates were calculated by converting Ventura et al.'s (2005) building fragility equations from their lognormal form into damage probability matrices. These matrices are each specific to a building class and translate ground shaking intensity (measured by MMI) into the probability of experiencing different damage states (Chang et al., forthcoming). The seven damage states used in this model include: none, slight, light, moderate, heavy, major, and destroyed (Table 4).

Using the population by building class results from the building inventory model, each AOA was multiplied by the corresponding building class damage state based on the MMI value assigned to each AOA (Figure 8; Appendix B). The results for the seven Ventura et al. (2005) damage states were then aggregated into the HAZUS-MH damage states (none, slight, moderate, extensive, and complete) to allow for the final step of casualty estimation (Table 5).

Table 4: Damage States and Description

Damage state	Description
None	No damage
Slight	Limited localized minor damage not requiring repair
Light	Significant localized damage of some components generally not requiring repair
Moderate	Significant localized damage of many components warranting repair
Heavy	Extensive damage requiring major repairs
Major	Major widespread damage that may result in facility being demolished or repaired
Destroyed	Total destruction of the majority of the facility

Source: Ventura et al., 2005

Table 5: Ventura Damage States and Corresponding HAZUS-MH Damage States

Ventura Damage States	Corresponding HAZUS-MH Damage States
None	None
Slight and Light	Slight
Moderate	Moderate
Heavy and Major	Extensive
Destroyed	Complete

4.2.3 Casualty Model

The final step of the casualty model is to calculate the number of deaths and serious injuries for each AOA. Serious injuries in this model include "both life-threatening injuries and those non-life-threatening injuries that require medical care or medical technologies, such as x-rays or surgery" (Chang et al., forthcoming). Total casualties were estimated by multiplying the results from the damage model with casualty rates provided by HAZUS-MH. The casualty rates for deaths and serious injuries correspond to HAZUS-MH Severity Levels two, three and four. The final number of deaths and serious injuries were aggregated by building class and damage state for each AOA and summed over all AOAs to produce a projection of potential casualties in Metro Vancouver in 2041. Results are rounded to the closest integer.

4.3 Model Scenarios

In order to understand the effects of land use and density on seismic risk in Metro Vancouver in 2041, four scenarios were developed for analysis:

1. *Status Quo Growth* - growth follows current development and new population will be distributed to all currently settled areas in a variety of building types proportionally to current population;
2. *Compact Growth* - new population will only locate to current and anticipated high density areas in multi-family building structures;
3. *Sprawled Growth* - new population will only locate to current low-density areas in single detached dwellings and a limited number of multi-family low-rise structures; and,
4. *Safe Growth* – new population will not be allowed to locate in MMI VIII areas (i.e. areas with high shaking intensity in the earthquake scenario considered); growth will only be distributed to areas with a MMI level of VII or lower in primarily wood frame buildings.

The Status Quo Growth scenario presents a development trajectory where growth continues as it is currently occurring in each census tract and by each structural type. The Compact Growth and Sprawled Growth scenarios represent opposite ends of the land use spectrum. On one end, the Compact Growth scenario concentrates growth in census tracts that already are, or are expected to become, highly dense areas with predominantly larger-scale multi-family development. On the other end of the spectrum is the Sprawled Growth scenario, which allocates the new growth in low-density census tracts. The building types utilized in this scenario are single detached homes and developments with lower densities, such as duplexes and townhouses. The final scenario, Safe Growth, represents a sustainable hazard mitigation approach. In this case, no new growth is allowed in AOAs with a ground shaking level of MMI VIII, the highest MMI level estimated in Metro Vancouver for a M7.3 earthquake scenario. Instead, growth is distributed only to AOAs with ground shaking levels of MMI VII or lower. For the City of Richmond, which is classified entirely as MMI VIII, the projected growth is redistributed equally to AOAs with a MMI level of VI (the lowest MMI in the region).

All four scenarios utilize the dwelling unit and population projections provided by the Regional Growth Strategy (Appendix A). The difference between the 2041 estimates and the 2006 census figures represents the amount of growth expected in the region in the next 35 years. According to Metro Vancouver, the region is to grow by 1,192,120 people and 565,900 dwelling units during the 35-year period (Metro Vancouver, 2011a). The growth figures were then allocated according to the land use and density scenario. Once the allocation process was complete, each scenario was put into the casualty model to calculate the number of deaths and serious injuries that would result from a seismic event in 2041.

4.3.1 Scenario 1 – Status Quo Growth

The Status Quo Growth scenario depicts Metro Vancouver in 2041 to be very similar, in both land use and density distribution, to the region today. The only difference is the additional people and dwelling units that must be accommodated between now and 2041 (Appendix A). To ensure the development trajectory stays the same, this scenario utilizes the current percentages for each structural type in each census tract as the basis for allocating growth.

Since the Metro Vancouver growth projections are provided at the municipal level, the data has to first be manipulated and then redistributed to individual census tracts in order to facilitate the use of the casualty model. Therefore, the 2006 census values for total occupied dwelling units for each census tract was divided by the municipal total to obtain the percentage that each census tract represented in the municipality. This percentage was then multiplied by the projected growth in dwelling units for the municipality to determine how many units should be allocated to each census tract in 2041.

Once the number of dwelling units for each census tract was determined, it was then necessary to calculate the proportion of each building type in the census tract. This followed a similar process where the total occupied dwellings in each building type by census tract was divided by the total number in each building type to determine its percentage of the whole. This percentage was then multiplied by the established number of units for each census tract to determine the number of units to be allocated to each building type.

This process was completed for every census tract in Metro Vancouver, except for the census tract representing the municipality of Bowen Island, which is not a designated growth area in the current Regional Growth Strategy (Metro Vancouver, 2011a). The new units were later added to the existing 2006 census data to provide a complete dwelling unit and population total for 2041 (Appendix M). This information is subsequently incorporated into the casualty model to estimate the number of deaths and serious injuries resulting from this development scenario.

4.3.2 Scenario 2 – Compact Growth

The Compact Growth scenario provides a high-density vision of growth in Metro Vancouver. In this scenario, new development can only locate in a few core areas within each municipality. Furthermore, this growth will primarily be in the form of compact, higher-density developments. In this scenario, the percentage breakdown for new growth in each structural type is as follows:

- 0 percent single family dwellings;
- 10 percent townhouses;
- 30 percent apartments under five storeys;
- 60 percent apartments five storeys and above; and,
- 0 percent mobile homes.

A map of the census tracts selected for growth is provided in Figure 11. In total, only 149 out of 408 census tracts were selected for future development in this scenario.

Census tracts were chosen through consideration of two factors: current densities and anticipated densities. Current densities were calculated by first separating all dwellings in the region into two categories: lower density dwellings (e.g. single-detached house, semi-detached house, apartment duplex, other single-attached house and movable dwelling) and higher density dwellings (e.g. row houses, apartments fewer than five storeys and apartments with five or more storeys). Afterwards, both categories were divided by the total number of dwellings in Metro Vancouver. Census tracts that already had a high percentage of higher density dwellings (80 percent of higher) were then selected for this scenario.

Determining whether certain areas were anticipated for higher density development required the consideration of additional information. For instance, the Official Community Plans and land use maps for each municipality in Metro Vancouver were assessed to determine which areas are slated for future growth. In addition, factors such as town centre designations, transportation corridors, and comprehensive development areas were also considered in the selection of census tracts for this scenario (Figure 12). Overall, the Compact Growth scenario corresponds well to density trends seen in the region (Figure 13).

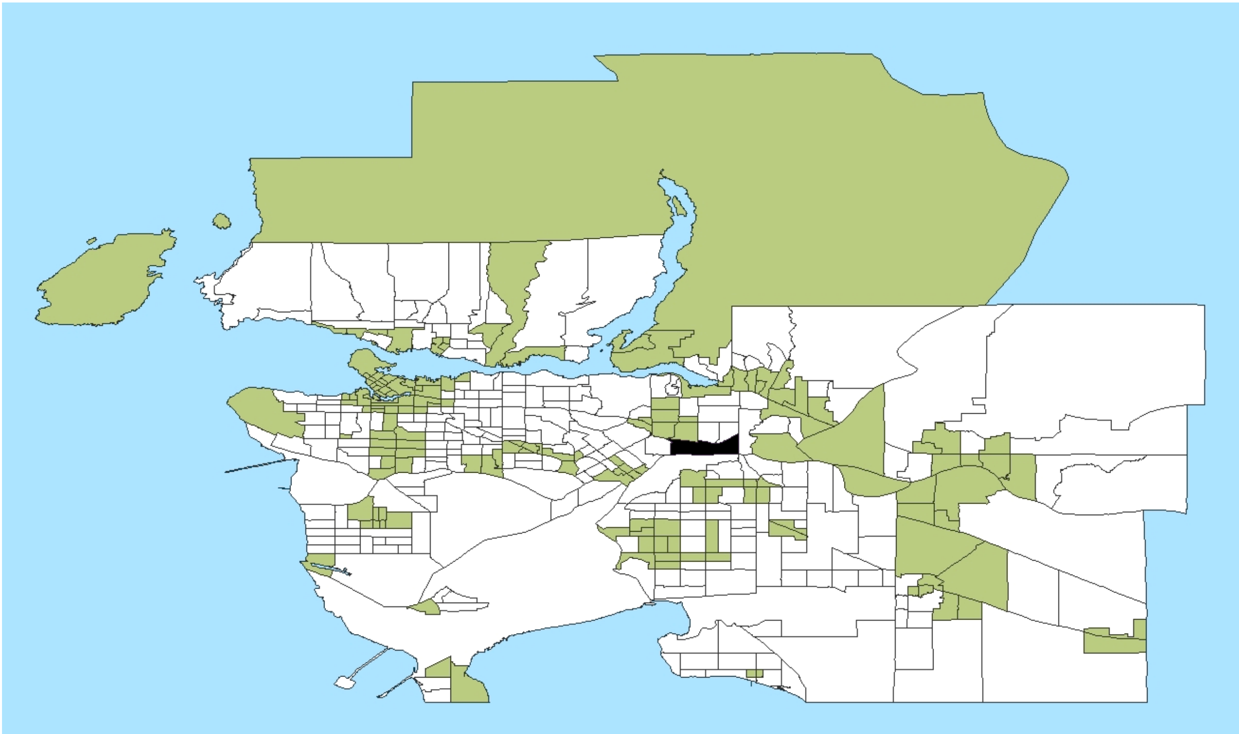

Figure 11: Map of Census Tracts Selected in Compact Growth Scenario
Shaded areas represent development areas; black area represents no data available
Source: Tse, 2011

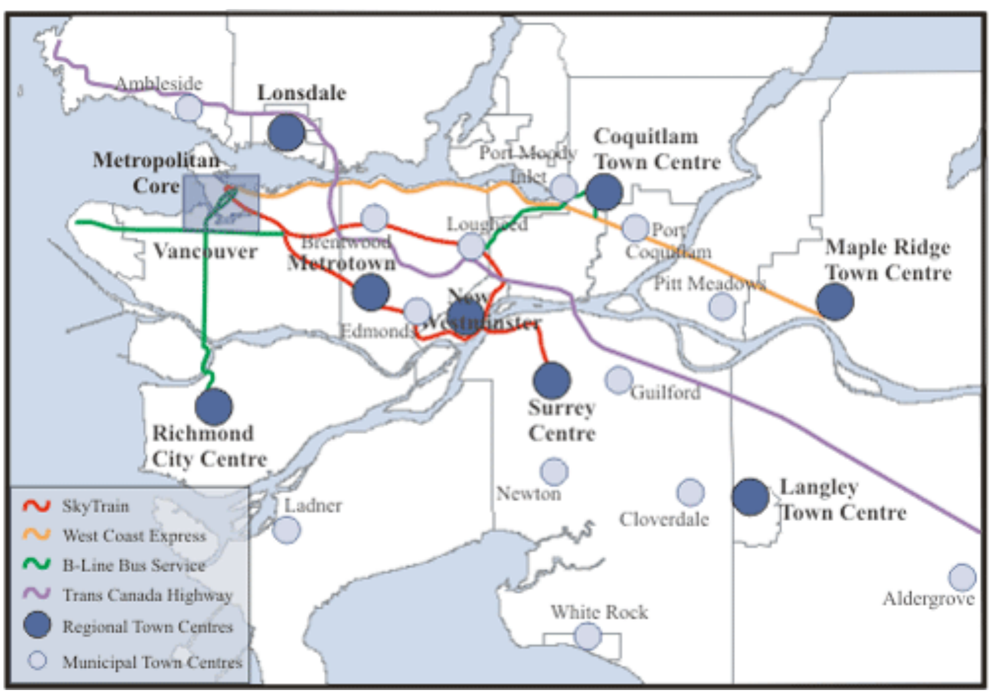

Figure 12: Town Centres and Transportation Corridors
Source: Metro Vancouver, 2011c (used with permission)

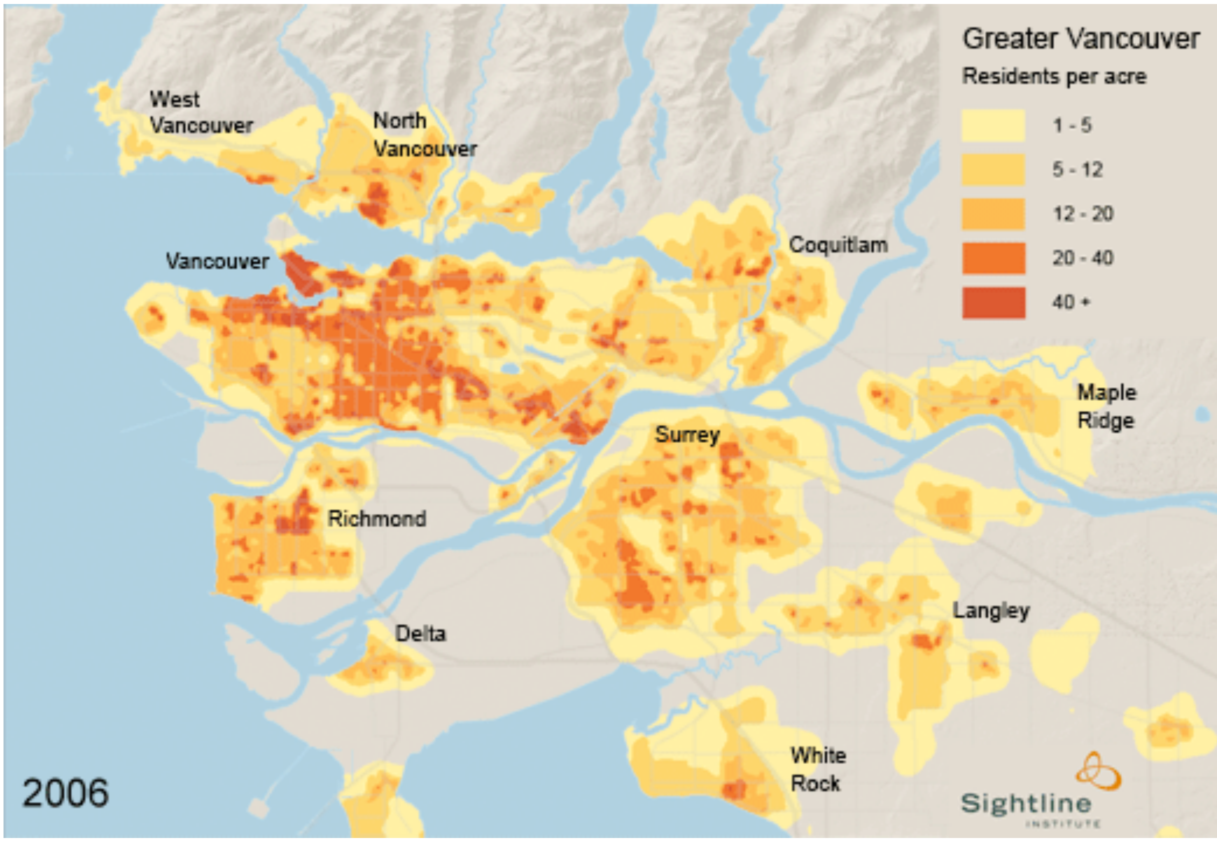

Figure 13: Metro Vancouver Density Map (Residents per Acre) in 2006
Source: Sightline Institute, 2008 (used with permission)

Once the census tracts were identified for this scenario, the tracts were summed for each municipality and divided by the new growth projected for each local area. Table 6 provides a summary of the census tracts selected for each municipality in this scenario. The complete dwelling unit and population totals are provided in Appendix N.

Table 6: Summary of Census Tracts by Municipality selected for Compact Growth Scenario

Municipality	AOA(s)	Dwelling Unit Growth Between 2006 to 2041	Number of 'Dense' Census Tracts	Number of Dwelling Units per Census Tract	Existing and Expected Dense Areas of Municipality
Vancouver	(1-3)	74,000	48	1,542	Downtown Vancouver; Coal Harbour; Olympic Village; Broadway Corridor; Cambie Street Corridor; River District (Fraser River)
Electoral Area A (UBC)	4	6,000	1	6,000	University Lands

City of North Vancouver	5	8,000	3	2,667	Lonsdale Regional Town Centre
District of North Vancouver	6	13,000	4	3,250	Lower Lynn, Lynn Valley, Maplewood Town Centres; Lower Capilano-Marine Village Centre
West Vancouver	7	3,000	2	1,500	Marine Drive/Ambleside
Richmond	(8-10)	51,000	8	6,375	City Centre; No. 3 Road Corridor
Delta	(11-12)	16,000	8	2,000	Ladner Municipal Town Centre; North Delta; Tsawwassen
White Rock	13	3,000	2	1,500	White Rock Municipal Town Centre
Surrey	(14-17)	146,000	18	8,111	Surrey City Centre; Guilford; Newton; Cloverdale
New Westminster	(18-19, 31)	19,000	6	3,167	New Westminster Downtown; Queensborough
Burnaby	(20-21)	68,000	10	6,800	Metrotown; Edmonds, Lougheed, Brentwood Town Centres
Port Moody	22	8,000	2	4,000	Port Moody Town Centre
Coquitlam	(23-24)	50,000	10	5,000	Coquitlam Town Centre; Northeast Coquitlam; Burquitlam and Lougheed Neighbourhoods
Port Coquitlam	25	19,000	5	3,800	Port Coquitlam Town Centre
Maple Ridge	26	25,000	7	3,571	Blaney, Forest and Horse Hamlets; River Village
Pitt Meadows	27	4,000	1	4,000	Pitt Meadows Town Centre
Township of Langley	28	46,000	10	4,600	Aldergrove, Walnut Grove, Willoughby
City of Langley	29	6,000	3	2,000	Langley Town Centre
Bowen Island	30	0	0	0	* No growth because not in Urban Growth Boundary *
Electoral Area (Anmore, Belcarra, Lions Bay)	32	900	1	900	Anmore, Belcarra and Lions Bay Town Centres
TOTAL		**565,900**	**149**		

4.3.3 Scenario 3 – Sprawled Growth

The third scenario analyzed is a Sprawled Growth scenario, where new development is distributed to all census tracts not selected in the Compact Growth Scenario. Two local areas, the University of British Columbia and Electoral Area, were included in both scenarios, although the nature of development changed accordingly. For the Sprawled Growth scenario, new growth was overwhelmingly accommodated in detached dwellings. A limited amount of growth was also distributed to lower density multi-family structures, such as townhouses.

Using this criterion, a total of 261 census tracts were chosen (Figure 14). The structural type percentages for new growth are as follows:

- 85 percent single family dwellings;
- 10 percent townhouses;
- 0 percent apartments under five storeys;
- 0 percent apartments five storeys and above; and,
- 5 percent mobile homes.

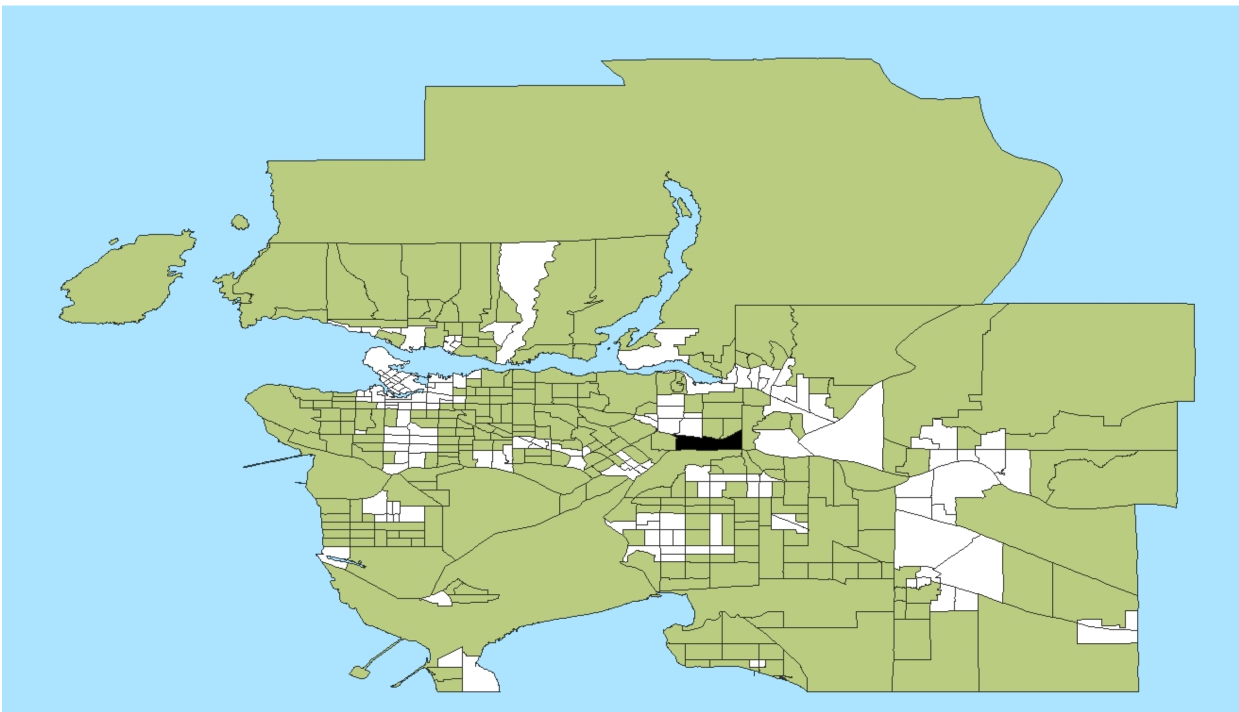

Figure 14: Map of Census Tracts Selected in Sprawled Growth Scenario
Shaded areas represent development areas; black area represents no data available
Source: Tse, 2011

Current densities were calculated using the same methodology as the Compact Growth scenario, although the focus was shifted to lower-density dwellings. Table 7 provides a summary of the total number of census tracts selected for each municipality in this scenario. The 2041 dwelling unit and population totals for this scenario is listed in Appendix O. While this scenario represents an unlikely growth situation because of the region's commitment to creating compact communities, this scenario provides insight into the implications of sprawled growth.

Table 7: Summary of Census Tracts by Municipality selected for Sprawled Growth Scenario

Municipality	AOA(s)	Dwelling Unit Growth Between 2006 to 2041	Number of 'Sprawled ' Census Tracts	Number of Dwelling Units per Census Tract
Vancouver	(1-3)	74,000	59	1,254
Electoral Area A (UBC)	4	6,000	1	6,000
City of North Vancouver	5	8,000	5	1,600
District of North Vancouver	6	13,000	13	1,000
West Vancouver	7	3,000	7	429
Richmond	(8-10)	51,000	25	2,040
Delta	(11-12)	16,000	11	1,455
White Rock	13	3,000	2	1,500
Surrey	(14-17)	146,000	60	2,433
New Westminster	(18-19, 31)	19,000	7	2,714
Burnaby	(20-21)	68,000	31	2,194
Port Moody	22	8,000	4	2,000
Coquitlam	(23-24)	50,000	12	4,167
Port Coquitlam	25	19,000	4	4,750
Maple Ridge	26	25,000	6	4,167
Pitt Meadows	27	4,000	2	2,000
Township of Langley	28	46,000	8	5,750
City of Langley	29	6,000	3	2,000
Bowen Island	30	0	0	0
Electoral Area (Anmore, Belcarra, Lions Bay)	32	900	1	900
TOTAL		**565,900**	**261**	

4.3.4 Scenario 4 – Safe Growth

The Safe Growth scenario provides a sustainable hazard mitigation example for analysis in this project. While the first three scenarios distributed growth to all areas of Metro Vancouver regardless of ground shaking intensity, this scenario prohibits new growth in AOAs with a MMI level of VIII, which is the highest MMI level estimated for the region for the scenario earthquake under study. By preventing new growth from occurring in highly vulnerable areas, this scenario uses land use planning to minimize the number of people exposed to seismic risk in the region.

A total of six AOAs have a MMI level of VIII in this study (AOA 2, 8, 9, 10, 12, and 20). Since no growth can be allocated to these particular AOAs, only 351 out of a total of 408 census tracts were chosen to accept growth in this scenario Figure 15). In the unique case of Richmond, which is located entirely in an area with a MMI level of VIII, the 51,000 dwelling units projected for the city was distributed evenly to all AOAs in the region with a MMI level of VI, the lowest MMI level in the region. Population projections for these restricted AOAs were also distributed evenly to other AOAs in the municipality, or in the case of Richmond, were re-allocated to AOAs with a MMI level of VI. Appendix P provides the complete dwelling unit and population totals for this scenario. Table 8 provides a summary of the number of units each AOA is to accommodate in this scenario.

The percentage breakdown for new growth in each structural type is:

- 40 percent single family dwellings;
- 30 percent townhouses;
- 30 percent apartments under five storeys;
- 0 percent apartments five storeys and above; and,
- 0 percent mobile homes.

Lower density, wood frame buildings were favoured in this scenario because of the ability of these structures to withstand significant ground shaking (Ventura et al., 2005). Overall, the first three growth scenarios present different land use patterns for regional growth, while the Safe Growth scenario provides a sustainable hazard mitigation approach that actually limits growth in highly vulnerable areas. The latter scenario is of particular interest because it provides much needed insight into the feasibility of using land use controls to mitigate seismic risk in the Metro Vancouver region.

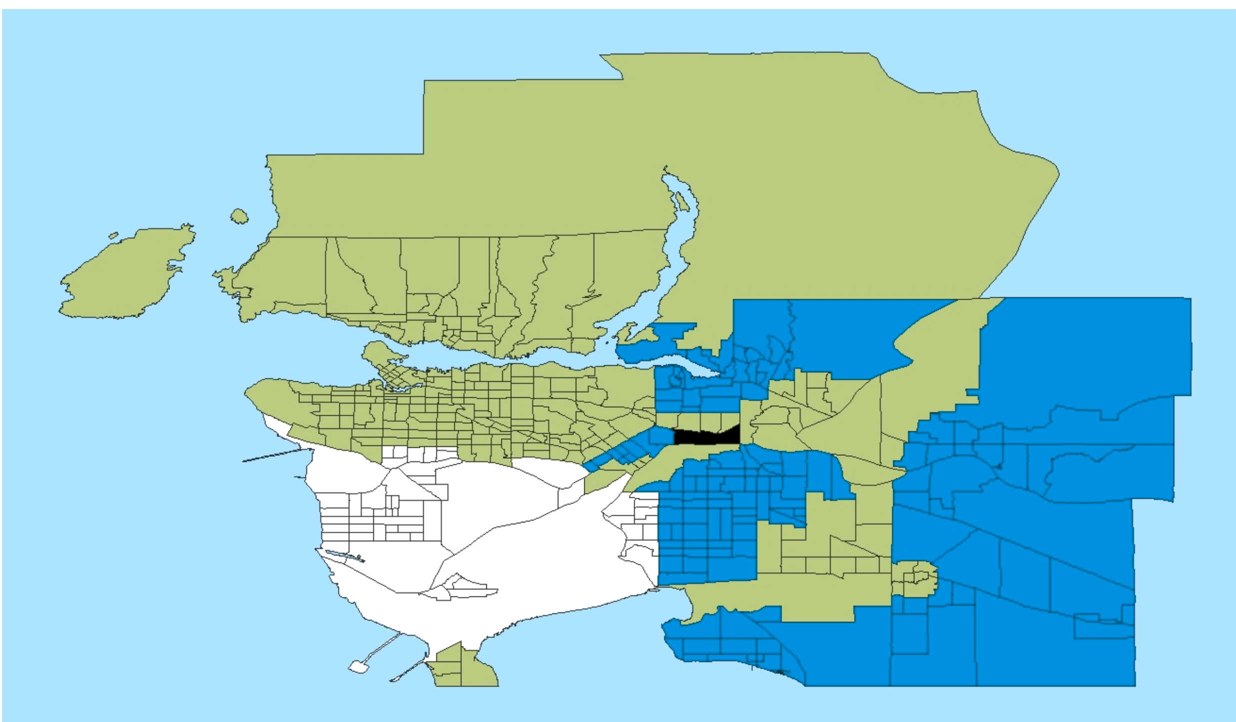

Figure 15: Map of Census Tracts Selected in Safe Growth Scenario
Lighter shaded areas represent development areas; darker shaded areas represent development areas allocated additional growth because of their lower MMI level; black area represents no data available
Source: Tse, 2011

Table 8: Summary of Census Tracts by Municipality selected for Safe Growth Scenario

Municipality	AOA	MMI	Dwelling Unit Growth Between 2006 to 2041	Number of 'Safe' Census Tracts	Number of Dwelling Units per Census Tract
Vancouver (Eastside and Westside)	1	VII	74,000	77	740
South Vancouver	2	VIII		0	0
Downtown Vancouver	3	VII		23	740
University of British Columbia	4	VII	6,000	1	6,000
City of North Vancouver	5	VII	8,000	8	1,000
District of North Vancouver	6	VII	13,000	16	813
District of West Vancouver	7	VII	3,000	9	333
Richmond	8	VIII	51,000*	0	0
Richmond (Airport)	9	VIII		0	0
Mitchell Island/North Richmond	10	VIII		0	0
Delta (Tsawwassen)	11	VII	16,000	4	4,000
Delta (Ladner and North Delta)	12	VIII		0	0
White Rock	13	VI	3,000	4	750 + 386*
Surrey (South)	14	VI	146,000	10	1,872 + 386*
Surrey (Central)	15	VII		12	1,872
Surrey (North)	16	VI		55	1,872 + 386*
Surrey (Seaport)	17	VII		1	1,872
New Westminster (Queensborough)	18	VII	19,000	2	1,462
New Westminster	19	VI		9	1,462 + 386*
Downtown New Westminster	31	VII		2	1,462
Burnaby (Big Bend)	20	VIII	68,000	0	0
Burnaby	21	VII		40	1,700
Port Moody	22	VI	8,000	6	1,333 + 386*
Coquitlam (South)	23	VII	50,000	5	2,273
Coquitlam (North)	24	VI		17	2,273 + 386*
Port Coquitlam	25	VII	19,000	9	2,111
Maple Ridge	26	VI	25,000	13	1,923 + 386*
Pitt Meadows	27	VII	4,000	3	1,333
Township of Langley	28	VI	46,000	18	2,556 + 386*
City of Langley	29	VII	6,000	6	1,000
Bowen Island	30	VII	0	0	0
Electoral Area (Anmore, Belcarra, Lions Bay)	32	VII	900	1	900
TOTAL			**565,900**	**351**	

** Population growth for Richmond divided equally between all AOAs with MMI VI*

5.0 RESULTS AND DISCUSSION

5.1 Results Summary

The results from the casualty model indicate that a hypothetical earthquake event in Metro Vancouver in 2041 would produce relatively similar numbers of deaths and serious injuries, although the Safe Growth scenario would result in the fewest casualties at 14 deaths and 31 serious injuries. The other three scenarios showed the same number of deaths at 16. In terms of serious injuries, the Status Quo Growth scenario resulted in a few more injuries than the Safe Growth scenario at 34, followed closely by the Sprawled Growth example at 36 and the Compact Growth case at 37. The casualty numbers for each scenario are presented at the regional level in Table 9 and by individual municipalities in Table 10.

Table 9: Summary Results by Growth Scenario for Metro Vancouver

	Status Quo Growth	Compact Growth	Sprawled Growth	Safe Growth
Total Population in 2041*	3,308,551	3,308,551	3,308,551	3,392,251
Population in MMI=VIII Areas	407,267	407,267	407,267	287,389
Population in Wood Frame Buildings	2,885,219 (87.2%)	2,238,101 (67.3%)	2,945,339 (89.0%)	3,071,200 (90.5%)
Population in Masonry Buildings	17,544 (0.1%)	17,488 (0.1%)	18,104 (0.1%)	17,672 (0.1%)
Population in Concrete Frame Buildings	377,341 (11.4%)	1,049,195 (31.7%)	262,944 (7.9%)	290,282 (8.6%)
Population in Significantly** Damaged Dwellings	35,909 (1.1%)	51,420 (1.5%)	41,313 (1.2%)	27,614 (0.1%)
Total Dwelling Units in 2041*	1,374,442	1,377,968	1,376,965	1,383,145
Number of Deaths	**16**	**16**	**16**	**14**
Fatality Rate (Deaths/1,000 People)	0.0048	0.0048	0.0048	0.0042
Number of Serious Injuries	**34**	**37**	**36**	**31**
Serious Injury Rate (Injuries/1,000 People)	0.0103	0.0112	0.0109	0.009

** Total population and dwelling units may not match Metro Vancouver projections due to the author's use of existing census data, rather than projections, as well as rounding*
*** Significantly damaged dwellings include "moderate," "extensive," and "complete" damage states*

Table 10: Summary Results by Growth Scenario for AOAs and Municipalities

			Growth Scenarios							
Municipality	**AOA**	**MMI**	**Status Quo Growth**		**Compact Growth**		**Sprawled Growth**		**Safe Growth**	
			Deaths	*Injuries*	*Deaths*	*Injuries*	*Deaths*	*Injuries*	*Deaths*	*Injuries*
Vancouver (Eastside and Westside)	1	**VII**	8	9	8	9	7	8	7	8
South Vancouver	2	**VIII**	2	3	2	3	2	3	1	2
Downtown Vancouver	3	**VII**	2	6	2	6	3	8	2	7
University of British Columbia	4	**VII**	0	0	0	0	0	0	0	0
City of North Vancouver	5	**VII**	1	1	1	1	1	1	1	1
District of North Vancouver	6	**VII**	0	1	0	1	0	1	0	1
District of West Vancouver	7	**VII**	0	0	0	0	0	0	0	0
Richmond	8	**VIII**	1	7	1	9	1	8	1	5

Richmond (Airport)	9	**VIII**	0	0	0	0	0	0	0	0
Mitchell Island/North Richmond	10	**VIII**	0	1	0	1	0	1	0	1
Delta (Tsawwassen)	11	**VII**	0	0	0	0	0	0	0	0
Delta (Ladner and North Delta)	12	**VIII**	0	3	0	4	0	3	0	3
White Rock	13	**VI**	0	0	0	0	0	0	0	0
Surrey (South)	14	**VI**	0	0	0	0	0	0	0	0
Surrey (Central)	15	**VII**	0	0	0	0	0	0	0	0
Surrey (North)	16	**VI**	0	0	0	0	0	0	0	0
Surrey (Seaport)	17	**VII**	0	0	0	0	0	0	0	0
New Westminster (Queensborough)	18	**VII**	0	0	0	0	0	0	0	0
New Westminster	19	**VI**	0	0	0	0	0	0	0	0
Burnaby (Big Bend)	20	**VIII**	0	0	0	0	0	0	0	0
Burnaby	21	**VII**	2	3	2	3	2	3	2	3
Port Moody	22	**VI**	0	0	0	0	0	0	0	0
Coquitlam (South)	23	**VII**	0	0	0	0	0	0	0	0
Coquitlam (North)	24	**VI**	0	0	0	0	0	0	0	0
Port Coquitlam	25	**VII**	0	0	0	0	0	0	0	0
Maple Ridge	26	**VI**	0	0	0	0	0	0	0	0
Pitt Meadows	27	**VII**	0	0	0	0	0	0	0	0
Township of Langley	28	**VI**	0	0	0	0	0	0	0	0
City of Langley	29	**VII**	0	0	0	0	0	0	0	0
Bowen Island	30	**VII**	0	0	0	0	0	0	0	0
Downtown New Westminster	31	**VII**	0	0	0	0	0	0	0	0
Electoral Area (Anmore, Belcarra, Lions Bay)	32	**VII**	0	0	0	0	0	0	0	0
TOTAL CASUALTIES			**16**	**34**	**16**	**37**	**16**	**36**	**14**	**31**

While the primary objective of this research is to estimate earthquake casualties, other factors also need to be considered to fully understand seismic risk in relation to land use. For example, it is interesting to note that by prohibiting new development from MMI VIII areas, in addition to allocating most growth to wood frame structures, the Safe Growth scenario resulted in substantially fewer people living in significantly damaged dwellings (27,407) than compared to the Status Quo Growth (35,909), Sprawled Growth (41,313), and Compact Growth (51,420) scenarios. The potential for greater risk from higher-density development is supported by research conducted by Berke et al. (2009). The authors found that high-density developments often place more people, residential and commercial buildings, and infrastructure at risk than conventional low-density development on an equivalent land unit exposed to hazards (Berke et al., 2009). While the potential risks associated with higher-density development are acknowledged, the authors do not advocate for sprawl. Instead, they argue for greater awareness and anticipation of local hazards, as well as more proactive mitigation in areas with higher densities.

When analyzing by AOA, it becomes clear that certain municipalities are particularly vulnerable. In particular, the City of Vancouver accounts for the majority of deaths and serious injuries in all four scenarios. The City of Burnaby is also projected to have two deaths and 3 serious injuries in all growth scenarios. Casualties in both cities can most probably be attributed to the fact that both are older municipalities with large concentrations of pre-1973 building vintages. The vulnerability of older building vintages to seismic shaking, especially unreinforced masonry buildings, cannot be ignored. As Table 11 illustrates, building class remains an important indicator of casualties in 2041, as the deaths in all four scenarios were attributed to unreinforced masonry. This is because unreinforced masonry "exhibits higher probabilities of being in higher damage states at all MMI levels compared with other building types" (Ventura et al., 2005).

Table 11: Deaths and Serious Injuries based on Building Class

	Growth Scenarios							
Building Class	**Status Quo Growth**		**Compact Growth**		**Sprawled Growth**		**Safe Growth**	
	Deaths	*Injuries*	*Deaths*	*Injuries*	*Deaths*	*Injuries*	*Deaths*	*Injuries*
Wood Light Frame Residential	0	8 (28%)	0	5 (16%)	0	9 (29%)	0	6 (24%)
Wood Post and Beam	0	0	0	0	0	0	0	0
Wood Light Frame Low Rise Residential	0	0	0	0	0	0	0	0
Unreinforced Masonry Bearing Wall Low Rise	16 (100%)	16 (55%)	16 (100%)	16 (52%)	16 (100%)	16 (52%)	14 (100%)	14 (56%)
Unreinforced Masonry Bearing Wall Medium Rise	0	4 (14%)	0	3 (10%)	0	5 (16%)	0	4 (16%)
Concrete Frame with Infill Walls	0	0	0	0	0	0	0	0
Concrete Frame with Concrete Walls Low Rise	0	0	0	0	0	0	0	0
Concrete Frame with Concrete Walls Medium Rise	0	1 (3%)	0	7 (23%)	0	0	0	1 (4%)
Concrete Frame with Concrete Walls High Rise	0	0	0	0	0	0	0	0
Mobile Home	0	0	0	0	0	1 (3%)	0	0
TOTAL CASUALTIES *	**16**	**29**	**16**	**31**	**16**	**31**	**14**	**25**

** Numbers of deaths and serious injuries may not match final totals due to rounding*
For final totals, numbers are rounded to closest zero after aggregated for each AOA)

While the Safe Growth scenario accounted for ground shaking levels, the other three scenarios did not. Therefore, looking at soil type and its influence on these three cases, the results indicate that most deaths did not occur in municipalities with soils more susceptible to ground shaking (indicated by a higher MMI value in the model). It was expected that soil amplification would influence deaths, but for each of the three scenarios only 19 percent of fatalities occurred in AOAs with the highest MMI value of VIII. This is reflected by the relatively minor difference in casualties between the sustainable hazard mitigation approach and the other more general land use scenarios. However, soil types did seem to correspond more with the incidence of serious injuries. For instance, the percentage of serious injuries that occurred in the highest MMI value for the Status Quo Growth, Compact Growth and Sprawled Growth scenarios were 41 percent, 46 percent and 42 percent, respectively. Overall, the presence of soils susceptible to amplification alone does not seem to cause significant damage. Rather, it is likely the combination of both vulnerable soils and building types that result in the highest casualty rates.

Understanding the dominant building class in each scenario further helps to explain the results. According to Ventura et al. (2005), fragility curves that lie further to the right of the graph and are flatter at higher intensities and damage states reflect relatively less observed damage at higher shaking levels. Therefore, comparing the Wood Light Frame Residential (WLFR) building type that predominates the Safe, Status Quo and Sprawled Growth scenarios to the Concrete Frame Concrete Wall High-Rise (CFCWHR) of the Compact Growth case, the differences between the fragility curves are noticeable (Figure 16).

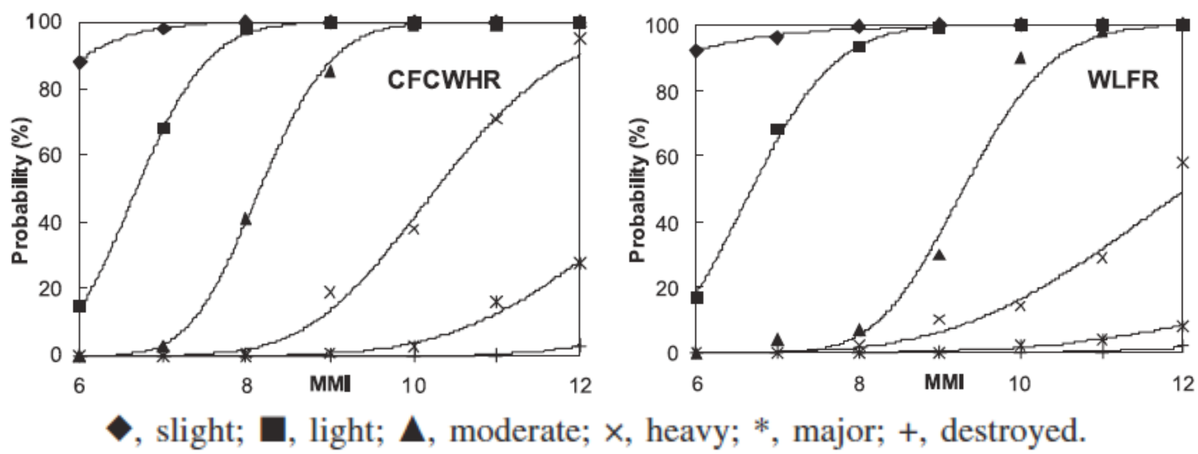

Figure 16: Comparison of Wood Frame and Concrete Frame Building Class Fragility Curves

Source: Ventura et al., 2005

5.2 Implications for Future Growth in Metro Vancouver

5.2.1 Land Use

This research is first and foremost an investigation into whether land use is an effective seismic risk mitigation tool in the Metro Vancouver region. Based on the results of the model, it appears that the Safe Growth scenario does result in fewer deaths and serious injuries. If comparing only the scenarios that did not use a sustainable hazard mitigation approach, the Status Quo Growth scenario, which allocated new growth according to the current development trajectory, seems most successful at mitigating seismic risk.

The success of the Safe Growth and Status Quo Growth scenarios is even more evident when a retrospective analysis of risk in the region is provided. Table 12 shows the results of research conducted on seismic risk in Metro Vancouver in 1971 and 2006. All three time periods, 1971, 2006 and 2041 were analyzed using the same methodology, thereby allowing an assessment to be made on how seismic risk has changed over time.

Table 12: Number of Deaths and Serious Injuries for 1971, 2006 and 2041

	1971	2006	2041 - Status Quo Growth	2041 - Safe Growth
Total Population*	1,080,035	2,116,431	3,308,551	3,392,251
Population in MMI=VIII Areas	122,585 (11.4%)	287,389 (13.6%)	407,267 (12.3%)	287,389 (8.7%)
Population in Wood Frame Buildings	972,304 (90.0%)	1,842,201 (87.0%)	2,885,219 (87.2%)	2,983,495 (90.4%)
Population in Masonry Buildings	30,611 (2.8%)	19,010 (0.9%)	17,544 (0.1%)	17,382 (0.1%)
Population in Concrete Frame Buildings	72,646 (6.7%)	240,610 (11.4%)	377,341 (11.4%)	286,459 (8.7%)
Population in Significantly** Damaged Dwellings	21,545 (2.0%)	32,078 (1.5%)	35,909 (1.1%)	27,407 (0.1%)
Total Dwelling Units*	256,235	802,675	1,374,442	1,383,145
Number of Deaths	**29**	**16**	**16**	**14**
Fatality Rate (Deaths/1,000 People)	0.0269	0.0076	0.0048	0.0042
Number of Serious Injuries	**43**	**34**	**34**	**31**
Serious Injury Rate (Injuries/1,000 People)	0.0398	0.0161	0.0103	0.009

** Total population and dwelling units for 2041 may not match Metro Vancouver projections due to the author's use of existing census data, rather than projections, as well as rounding*
*** Significantly damaged dwellings include "moderate," "extensive," and "complete" damage states*

The results in Table 12 show that seismic risk in Metro Vancouver has been decreasing since 1971. The number of deaths and serious injuries in 1971 went from 29 and 43, respectively, to 16 and 34 in 2041 for the Status Quo scenario and 14 and 31 for the Safe Growth scenario. Furthermore, the 2041 casualty numbers for the Status Quo Growth case, which are the same as 2006 numbers in absolute terms, are actually decreasing relative to population growth. This is indicated by the fatality and serious injury rates, which went from 0.0076 and 0.0161, respectively, in 2006 to 0.0048 and 0.0103 in 2041.
While the number of casualties has been decreasing since 1971, the number of people living in strong MMI shaking areas has increased, in absolute terms, for both the 2006 and the 2041 Status Quo scenarios. While this number is decreasing in relation to the entire population, there remains a large population of people living in vulnerable areas.

Conversely, the Safe Growth scenario in 2041 shows a substantial decrease in the number of people living in strong MMI shaking areas. This reduction was achieved by deliberately limiting new growth from known hazardous areas in the region (areas with a MMI level of

VIII). This research clearly shows that land use planning can help mitigate seismic risk in the region. However, whether this approach will be adopted in actual practice is questionable. Based on the current governance structure in the region, municipalities need to champion growth and development in their jurisdiction for revenue. This means that limiting development will not be a popular idea to municipalities unless a more regional approach to governance is explored.

5.2.2 Governance

While Metro Vancouver is the regional authority, its power to influence land use planning is limited. In this region, municipalities are in charge of all planning and land use decisions, including the location and design of development projects. Therefore, while the region may recognize the challenge of natural hazards in the area, how risk will be mitigated at the local scale remains up to individual municipalities.

In the context of global climate change and the need for a more sustainable and resilient future, other methods of governance are now being explored. One approach that could potentially aid disaster management is Ecosystem-Based Management (EBM). This method of governance integrates the "environment and development planning within a coherent management unit, defined in terms of biophysical and socioeconomic similarities (a bioregion)" (Slocombe, 1993).

Overall, EBM is a management approach that:

- Integrates ecological, social and economic goals and recognizes humans as key components of the ecosystem;
- Considers ecological- not just political – boundaries;
- Addresses the complexity of natural processes and social systems and uses an adaptive management approach in the face of resulting uncertainties;
- Engages multiple stakeholders in a collaborative process to define problems and find solutions;
- Incorporates understandings of ecosystem processes and how ecosystems respond to environment perturbations, and,
- Is concerned with the sustainability of both human and ecological systems (Ecosystem-Based Management Tools Network, 2010).

The adoption of a governance structure such as EBM could significantly alter the way risk is managed in Metro Vancouver. Viewing the region as a bioregion, rather than solely a political entity, growth could be managed in a way that is not constrained by municipal boundaries. In the case of disaster management, growth could be allocated to areas that are relatively hazard free, as opposed to the current method of distributing growth to all member municipalities with no consideration of local risk factors.

The impacts of climate change further pose a threat to Metro Vancouver as disruptions to natural systems, including natural hazards, are expected to increase in intensity and variability (van Aalst, 2006). Metro Vancouver's Regional Growth Strategy does take climate change and its impacts into account. However, whether the current governance system is effective in dealing with the challenges of climate change is unknown.

The municipalities most susceptible to seismic risk in the region, such as Richmond and Vancouver, are also likely areas to be affected by climate change impacts (e.g. sea level rise, flooding, etc.). Adopting a stronger hazards mitigation approach in the region can help complement climate change adaptation strategies. By identifying risks, reducing vulnerabilities and encouraging mitigation, disaster management activities can help to foster resilient communities that are more able to withstand and overcome disruptions to the natural, economic and social systems.

5.2.3 Building Technology

Understanding and utilizing sound building technologies can significantly reduce risk in Metro Vancouver. However, a particular vulnerability in the region is the older building stock that was constructed before seismic standards were incorporated into the provincial building code. This is particularly relevant to heritage buildings, which are often protected by planners and government officials because of their history and value to the community. In fact, the province acknowledges that "to apply present Building Code provisions to existing buildings is, in many cases, impractical and with heritage buildings may compromise historic appearances or authenticity" (BC Ministry of Housing 2006). Furthermore, while the building code advocates for the use of sprinklers in heritage buildings, there are no recommendations for seismic upgrades or retrofits. The valuing of authenticity over structural safety may be compromising disaster resiliency in the region.

To rectify this, government authorities need a firm action plan on older buildings, whether that is in the form of retrofits or demolition. This is an opportune time as many older buildings are now in need of repairs. Furthermore, while this topic is relevant to residential structures, it may be even more important for critical infrastructure buildings, such as hospitals, and public institutions, such as schools.

While building safety is an important part of reducing risk in Metro Vancouver, the over-reliance on building technologies can unknowingly exacerbate risk. This is especially true if other vulnerabilities, such as where development is located, are overlooked because of a strong belief on technological fixes.

5.2.4 Model Limitations

A series of assumptions were made in the development of the model and in the calculation of the growth scenarios that could potentially limit the applicability of this analysis. One potential limitation is the percentages used to transform the census structural types into Ventura et al. (2005) building types (Appendix K). While all percentages were chosen with support from existing literature and anecdotal evidence, there could potentially be errors in the percentages and in how the percentages were allocated to each structural category. This is especially true for older building vintages where information was very limited.

Another possible limitation is the separation between mid-rise apartments and high-rise apartments that was created for this analysis. Due to the fact that Statistics Canada only provides a general category of “apartments five storeys and above,” the separation between mid-rise (five to eight storeys) and high-rise apartments (eight storeys and above) was made to account for their very different construction methods. However, since there was no data available, anecdotal evidence had to be used to determine the prevalence of each building type. It was therefore decided that prior to 1945, approximately 97 percent of apartments over five storeys were mid-rises, while after 1945, only 10 percent of apartments over five storeys were mid-rise apartments (Hutton, 2010). Understanding the prevalence of older mid-rise apartments was important because of the common practice then of using unreinforced masonry, which is the most vulnerable building type in the region and exhibits higher probabilities of being damaged in a seismic event than other building classes (Ventura et al., 2005).

In addition, only current building practices and development regulations are considered in this analysis. Future changes to building codes, construction practices, land use, density and zoning may result in very different casualty estimations for the region. Demolition of existing buildings is also not taken into account. With the research results indicating that all estimated deaths in the region are to occur in unreinforced masonry structures, the removal of this building type from the region’s housing stock could significantly reduce seismic risk in Metro Vancouver.

6.0 RECOMMENDATIONS – PATH TO A DISASTER-RESILIENT REGION

This research estimated the number of deaths and serious injuries that would result from four growth scenarios in Metro Vancouver in 2041. While the Status Quo Growth scenario represents the existing development trajectory of the region, the Compact Growth and Sprawled Growth scenarios characterize the opposite ends of the development spectrum. The Safe Growth scenario, which serves as the sustainable hazard mitigation example, appears most effective at reducing the number of casualties, as well as at minimizing the population living in significantly damaged dwellings. Yet, better refinement to each growth scenario is needed; therefore, one recommendation would be to work directly with municipalities in Metro Vancouver to develop more probable scenarios of future growth.

One of the key goals of Metro Vancouver’s Regional Growth Strategy is to create a compact urban area. However, based on this analysis, the Compact Growth scenario resulted in the highest number of serious injuries and the highest number of people living in significantly damaged dwellings. Overall, this research does not suggest that this goal be disregarded, especially in light of the many sustainability benefits afforded by high-density development, including less disruption to the natural environment by concentrating growth and increased capacity for more active forms of transportation. However, better research on and understanding of the relationship between high-density development and seismic risk is needed to ensure the region is not exacerbating vulnerabilities and unknowingly putting residents in harm’s way.

In addition, this project primarily worked within the confines of Metro Vancouver's Regional Growth Strategy and utilized the population and dwelling unit projections, as well as the list of municipalities expecting growth, in the allocation process. A more complete investigation into the effectiveness of land use could use multiple scenarios to explore different combinations of AOA growth allocations, structural types and hazard levels. This would significantly refine the casualty estimates provided by the Safe Growth scenario and reveal greater insight into the impacts of land use planning in mitigating seismic risk in the region. This format would be more in line with the locational and design approaches advocated by Burby (1998) and would contribute to a better understanding of sustainable hazard mitigation in practice.

Another recommendation would be to utilize visualization, in conjunction with the model. By doing so, the scenarios would seem more 'real' and approachable. In addition, having more hands-on tools could help facilitate the move to a more participatory and engaging process for risk management, which can help increase public awareness and education about hazards and vulnerabilities.

In addition, further refinements to the model can also be made, especially in regards to resolving the assumptions and limitations of the current model. Furthermore, an expansion in scope, such as including all building structures and infrastructure, could significantly improve understandings of the potential social disruption caused by an earthquake event. Accounting for economic disruption would further round out this methodology. While this would undoubtedly make the model more complex, the results of the model would also be more applicable to real world situations.

7.0 CONCLUSIONS

The purpose of this research has been to develop a better understanding of how land use and density affects seismic risk in the growing region of Metro Vancouver. The casualty estimates calculated in this report do confirm that land use planning, as a sustainable hazard mitigation approach, is effective at reducing the number of deaths, serious injuries, and people living in significantly damaged dwellings. However, the reductions achieved by limiting development from more hazardous areas is only slightly better than the other three scenarios (Status Quo Growth, Compact Growth, and Sprawled Growth) in terms of number of deaths and serious injuries. Therefore, while shifting new development from less hazardous areas is effective at reducing risk, the loss in development revenue for local municipalities would probably result in negligible adoption of this technique in practice.

While the Safe Growth scenario proved superior in mitigating risk in Metro Vancouver, the other three scenarios represent more likely development situations in the region. This may be especially true for the Compact Growth scenario, which represents a development vision similar to Metro Vancouver's goal of creating a compact, urban region. Yet, this scenario resulted in the same number of deaths as the Status Quo and Sprawled scenarios at 16, and higher numbers for both serious injuries and people living in significantly damaged structures.

The results of the Compact Growth scenario are quite contrary to the existing literature on land use, compact growth, and risk mitigation. This is likely due to the fact that most of this research is focused on floods, which may be more responsive to direct land use interventions such as limiting development on flood plains (Burby, 1998). Seismic risk, on the other hand, involves a multitude of factors, ranging from the built environment to geological conditions and prevailing social systems and institutions. Therefore, this type of hazard risk may be harder to control with land use planning because of the possible convergence of multiple vulnerabilities to exacerbate damage and disruption.

Overall, this research provides a much needed methodology and estimate of earthquake casualties in the Metro Vancouver region. By being proactive in understanding future seismic risk, this research can provide a sound basis for decision-making in the region regarding the placement, form and density of development that best protects the residents of Metro Vancouver in the likely event of an earthquake.

8.0 REFERENCES

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9.0 APPENDIX

Appendix A: Population and Dwelling Unit Projections for Metro Vancouver

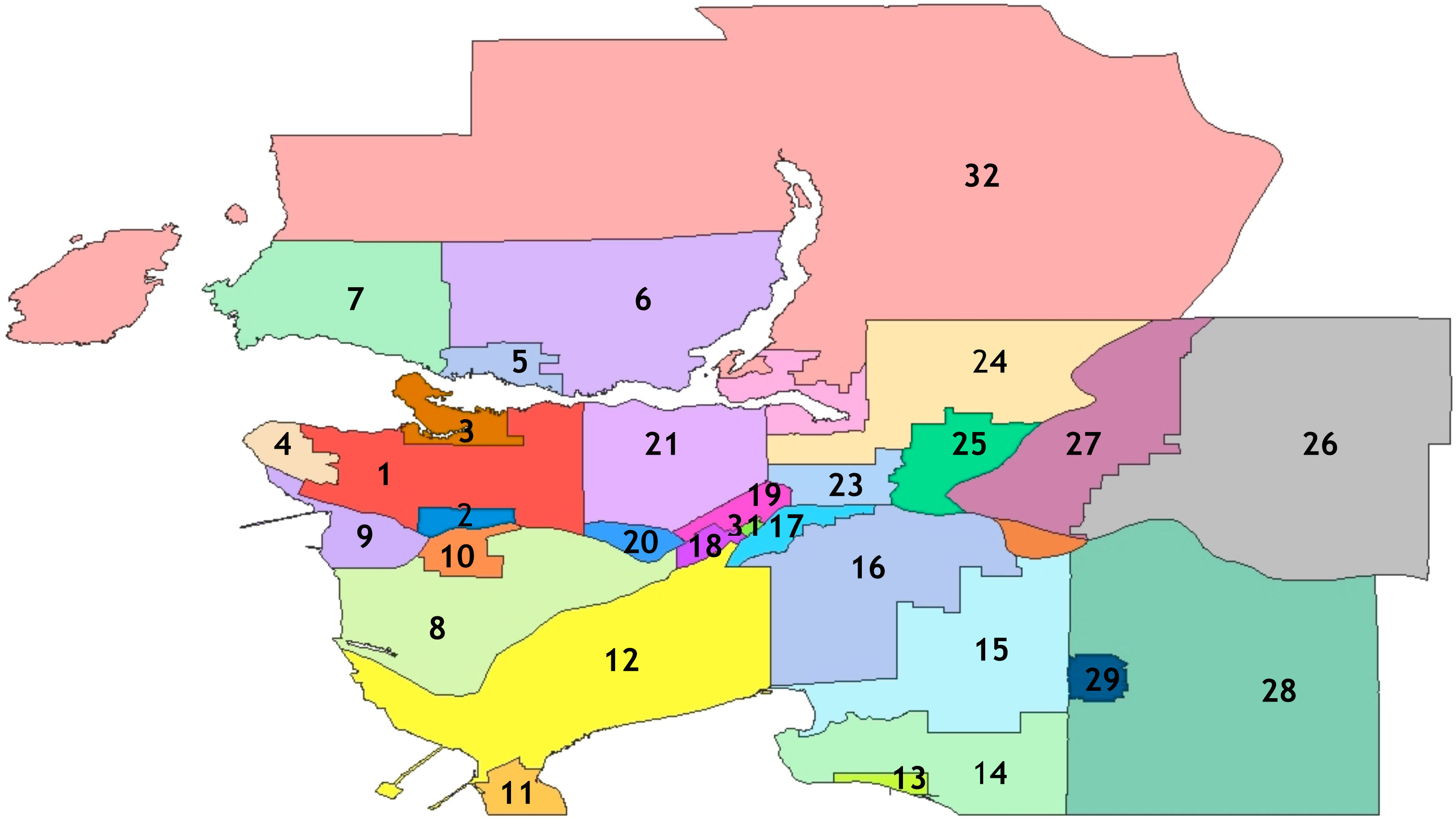
SUBREGION	TOTAL POPULATION				TOTAL DWELLING UNITS			
MUNICIPALITY	2006	2021	2031	2041	2006	2021	2031	2041
Metro Vancouver Total	**2,195,000**	**2,780,000**	**3,129,000**	**3,400,000**	**848,000**	**1,130,000**	**1,307,000**	**1,422,000**
Burnaby, New Westminster	271,000	357,000	406,000	447,000	109,150	152,100	178,600	196,300
Burnaby	210,500	277,000	314,000	345,000	81,110	115,000	136,000	149,300
New Westminster	60,500	80,000	92,000	102,000	28,040	37,100	42,600	47,000
Langley City, Langley Township	122,200	178,000	223,000	249,000	45,670	68,200	86,300	97,000
Langley City	24,900	32,000	35,000	38,000	11,160	14,500	16,000	17,100
Langley Township	97,300	146,000	188,000	211,000	34,510	53,700	70,300	79,900
Maple Ridge, Pitt Meadows	88,100	117,000	136,000	156,000	32,020	44,300	52,700	60,300
Maple Ridge	71,500	95,000	113,000	132,000	25,920	36,100	43,700	50,900
Pitt Meadows	16,600	22,000	23,000	24,000	6,100	8,200	9,000	9,400
Northeast Sector	205,400	286,600	337,500	364,400	73,690	110,770	136,830	150,000
Anmore	1,900	2,800	3,600	4,400	560	850	1,080	1,310
Belcarra	700	800	900	1,000	260	320	350	390
Coquitlam	119,600	176,000	213,000	224,000	42,960	67,700	86,700	94,100
Port Coquitlam	54,500	68,000	76,000	85,000	19,400	26,300	30,900	34,300
Port Moody	28,700	39,000	44,000	50,000	10,510	15,600	17,800	19,900
North Shore	181,300	206,600	224,900	244,000	72,370	84,340	93,340	100,490
North Vancouver City	47,500	56,000	62,000	68,000	22,360	25,600	28,000	30,200
North Vancouver District	87,000	98,000	105,000	114,000	31,260	37,500	41,500	45,000
West Vancouver	45,400	51,000	56,000	60,000	18,200	20,600	23,100	24,500
Lions Bay	1,400	1,600	1,900	2,000	550	640	740	790
Delta, Richmond, Tsawwassen	282,500	338,000	376,000	406,500	98,600	130,600	153,200	167,900
Delta	99,000	109,000	118,000	123,000	34,300	40,300	45,400	48,000
Richmond	182,700	225,000	252,000	275,000	64,000	88,400	104,900	115,500
Tsawwassen First Nation	800	4,000	6,000	8,500	300	1,900	2,900	4,400
Surrey, White Rock	431,900	601,000	693,000	767,000	146,480	222,900	268,000	298,600
Surrey	413,000	578,000	668,000	740,000	136,580	211,200	255,700	285,200
White Rock	18,900	23,000	25,000	27,000	9,900	11,700	12,300	13,400
Vancouver, Electoral Area A	612,800	697,000	734,000	770,000	269,600	317,500	338,700	353,700
Vancouver	601,200	673,000	705,000	740,000	264,500	306,700	325,400	339,500
Electoral Area A	11,600	24,000	29,000	30,000	5,100	10,800	13,300	14,200

Notes:

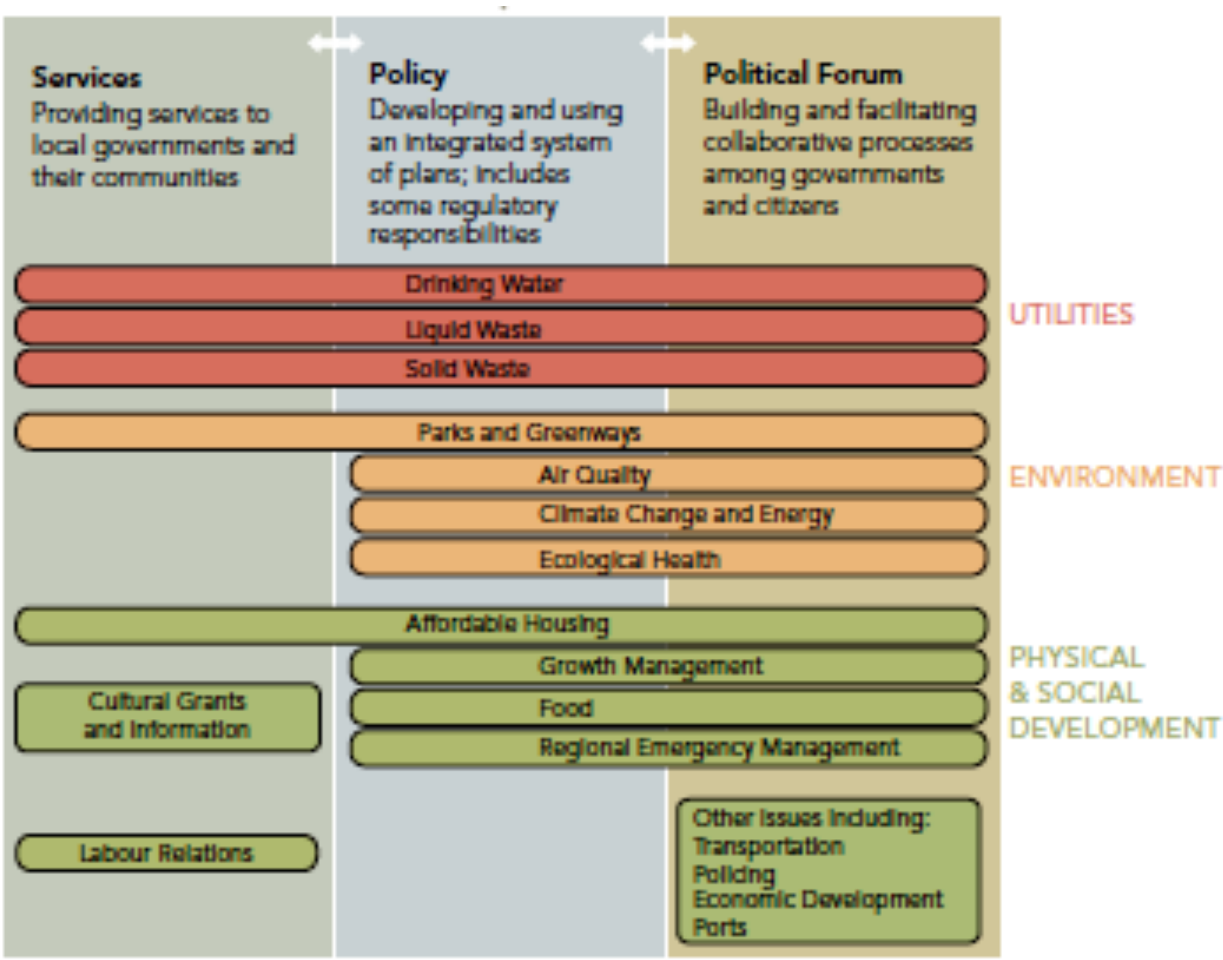
1. These projections are to assist in long range planning and are guidelines only.
2. Metro Vancouver growth projections are provided as guidance to member municipalities and regional agencies.
3. Figures for the year of 2006 are based on Census of Canada 2006 and include estimated Census undercount.
4. Population projections for Metro Vancouver are based on provincial and Regional District projections prepared by the Province of British Columbia (BC Stats PEOPLE 33, July 2008). Population, dwelling and employment projections for subregions and municipalities were prepared by Metro Vancouver in consultation with member municipalities.
5. All figures in this table are rounded and may include minor inconsistencies for summary totals.
6. All municipal totals include Indian Reserve or First Nation communities located within municipal boundaries, with the exception of Tsawwassen First Nation.

Source: Metro Vancouver, 2011a (used with permission)

Appendix B: Areas of Analysis (AOAs)



Appendix C: Roles of Metro Vancouver



Source: Metro Vancouver, 2011a (used with permission)

Appendix D: Population and Dwelling Unit Increases, 2006 to 2041

	Total Population			Total Dwellings		
Municipalities	**2006**	**2041**	**Growth***	**2006**	**2041**	**Growth***
Anmore	1,900	4,400	2,500	600	1,300	700
Belcarra	700	1,000	300	300	400	100
Burnaby	212,100	348,000	135,900	82,000	150,000	68,000
Coquitlam	120,100	229,000	108,900	43,000	93,000	50,000
Delta	102,100	130,000	27,900	35,000	51,000	16,000
Electoral Area A	11,300	23,000	11,700	5,000	11,000	6,000
Langley City	24,600	38,000	13,400	11,000	17,000	6,000
Langley Township	97,700	211,000	113,300	35,000	81,000	46,000
Lions Bay	1,400	1,520	120	500	600	100
Maple Ridge	72,900	134,000	61,100	26,000	51,000	25,000
New Westminster	61,800	105,000	43,200	29,000	48,000	19,000
North Vancouver City	47,900	68,000	20,100	23,000	31,000	8,000
North Vancouver District	88,100	115,000	26,900	32,000	45,000	13,000
Pitt Meadows	16,800	24,000	7,200	6,000	10,000	4,000
Port Coquitlam	55,200	95,000	39,800	20,000	39,000	19,000
Port Moody	28,800	48,000	19,200	11,000	19,000	8,000
Richmond	182,800	272,000	89,200	64,000	115,000	51,000
Surrey	415,000	739,000	324,000	137,000	283,000	146,000
Vancouver	607,100	739,000	131,900	267,000	341,000	74,000
West Vancouver	46,800	54,000	7,200	19,000	22,000	3,000
White Rock	19,700	28,000	8,300	10,000	13,000	3,000
Metro Vancouver	**2,214,800**	**3,406,920**	**1,192,120**	**856,400**	**1,422,300**	**565,900**

* Calculations performed by author

Source: Metro Vancouver, 2011a (used with permission)

Appendix E: Local Government Act – Part 25 – Regional Growth Strategies

849 Purpose of regional growth strategy

(1) The purpose of a regional growth strategy is to promote human settlement that is socially, economically and environmentally healthy and that makes efficient use of public facilities and services, land and other resources.

(2) Without limiting subsection (1), to the extent that a regional growth strategy deals with these matters, it should work towards but not be limited to the following:

(a) avoiding urban sprawl and ensuring that development takes place where adequate facilities exist or can be provided in a timely, economic and efficient manner;

(b) settlement patterns that minimize the use of automobiles and encourage walking, bicycling and the efficient use of public transit;

(c) the efficient movement of goods and people while making effective use of transportation and utility corridors;

(d) protecting environmentally sensitive areas;

(e) maintaining the integrity of a secure and productive resource base, including the agricultural land reserve;

(f) economic development that supports the unique character of communities;

(g) reducing and preventing air, land and water pollution;

(h) adequate, affordable and appropriate housing;

(i) adequate inventories of suitable land and resources for future settlement;

(j) protecting the quality and quantity of ground water and surface water;

(k) *settlement patterns that minimize the risks associated with natural hazards*;

(l) preserving, creating and linking urban and rural open space including parks and recreation areas;

(m) planning for energy supply and promoting efficient use, conservation and alternative forms of energy;

(n) good stewardship of land, sites and structures with cultural heritage value.

850 Content of regional growth strategy

(1) A board may adopt a regional growth strategy for the purpose of guiding decisions on growth, change and development within its regional district.

(2) A regional growth strategy must cover a period of at least 20 years from the time of its initiation and must include the following:

(a) a comprehensive statement on the future of the region, including the social, economic and environmental objectives of the board in relation to the regional district;

(b) population and employment projections for the period covered by the regional growth strategy;

(c) to the extent that these are regional matters, actions proposed for the regional district to provide for the needs of the projected population in relation to

(i) housing,

(ii) transportation,

(iii) regional district services,

(iv) parks and natural areas, and

(v) economic development;

(d) to the extent that these are regional matters, targets for the reduction of greenhouse gas emissions in the regional district, and policies and actions proposed for the regional district with respect to achieving those targets.

(3) In addition to the requirements of subsection (2), a regional growth strategy may deal with any other regional matter.
(4) A regional growth strategy may include any information, maps, illustrations or other material.

Source: BC Laws, 2011

Appendix F: Goals of Metro Vancouver 2040 – Shaping Our Future

GOAL 1

Create a Compact Urban Area

Metro Vancouver's growth is concentrated in compact communities with access to a range of housing choices, and close to employment, amenities and services. Compact transit-oriented development patterns help reduce greenhouse gas emissions and pollution, and support both the efficient use of land and an efficient transportation network.

GOAL 2

Support a Sustainable Economy

The land base and transportation systems required to nurture a healthy business sector are protected and supported. This includes supporting regional employment and economic growth. Industrial and agricultural land is protected and commerce flourishes in Urban Centres throughout the region.

GOAL 3

Protect the Environment and Respond to Climate Change Impacts

Metro Vancouver's vital ecosystems continue to provide the essentials of life – clean air, water and food. A connected network of habitats is maintained for a wide variety of wildlife and plant species. Protected natural areas provide residents and visitors with diverse recreational opportunities. Strategies also help Metro Vancouver and member municipalities meet their greenhouse gas emission targets, and prepare for, and mitigate risks from, climate change and natural hazards.

GOAL 4

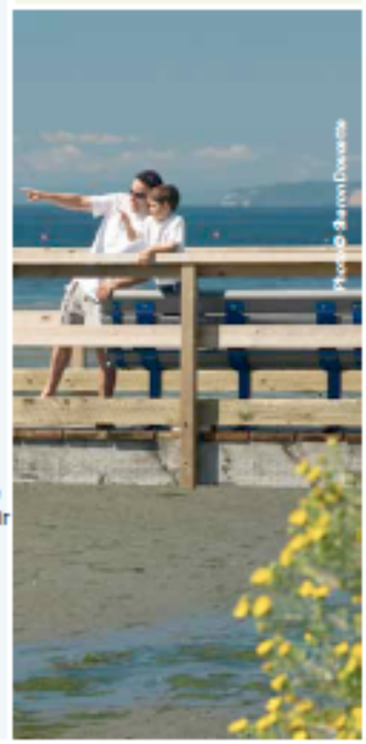
Develop Complete Communities

Metro Vancouver is a region of communities with a diverse range of housing choices suitable for residents at any stage of their lives. The distribution of employment and access to services and amenities builds complete communities throughout the region. Complete communities are designed to support walking, cycling and transit, and to foster healthy lifestyles.

GOAL 5

Support Sustainable Transportation Choices

Metro Vancouver's compact, transit-oriented urban form supports a range of sustainable transportation choices. This pattern of development expands the opportunities for transit, multiple-occupancy vehicles, cycling and walking, encourages active lifestyles, and reduces energy use, greenhouse gas emissions, household expenditure on transportation, and improves air quality. The region's road, transit, rail and waterway networks play a vital role in serving and shaping regional development, providing linkages among the region's communities and providing vital goods movement networks.



Source: Metro Vancouver, 2011a (used with permission)

Appendix G: Strategy for Managing Natural Hazard Risks in Metro Vancouver through Land Use and Transportation Infrastructure

STRATEGY 3.4

Encourage land use and transportation infrastructure that improve the ability to withstand climate change impacts and natural hazard risks

Metro Vancouver's role is to:

3.4.1 Incorporate climate change and natural hazard risk assessments into the planning and location of Metro Vancouver utilities, assets and operations.

3.4.2 Work with the federal government and the province, TransLink and municipalities to:

a) consider climate change impacts (e.g. sea level rise) and natural hazard risks (e.g. earthquake, flooding, erosion, subsidence, mudslides, interface fires) when extending utilities and transportation infrastructure that encourages land use development;

b) research and promote best practices in adaptation to climate change as it relates to land use planning.

3.4.3 Accept Regional Context Statements that encourage land use, transportation and utility infrastructure which improve the ability to withstand climate change impacts and natural hazard risks and that meet or work towards Actions 3.4.4 and 3.4.5.

The role of municipalities is to:

3.4.4 Adopt Regional Context Statements that include policies to encourage settlement patterns that minimize risks associated with climate change and natural hazards (e.g. earthquake, flooding, erosion, subsidence, mudslides, interface fires).

3.4.5 Consider incorporating climate change and natural hazard risk assessments into the planning and location of municipal utilities, assets and operations.

Actions Requested of Other Governments and Agencies

3.4.6 That the Integrated Partnership for Regional Emergency Management, in collaboration with the federal government and the province, and other agencies:

a) identify areas that are vulnerable from climate change and natural hazard risks, such as those listed in Actions 3.4.2 and 3.4.4;

b) coordinate priority actions to address the vulnerabilities identified, including implementation and funding strategies.

3.4.7 That the federal government and the province, in collaboration with the Integrated Partnership for Regional Emergency Management and other agencies:

a) provide financial assistance and timely data and information, such as flood hazard mapping, shoreline mapping, hydrological and hydraulic studies, to better enable local governments to fulfill their flood hazard management roles and responsibilities;

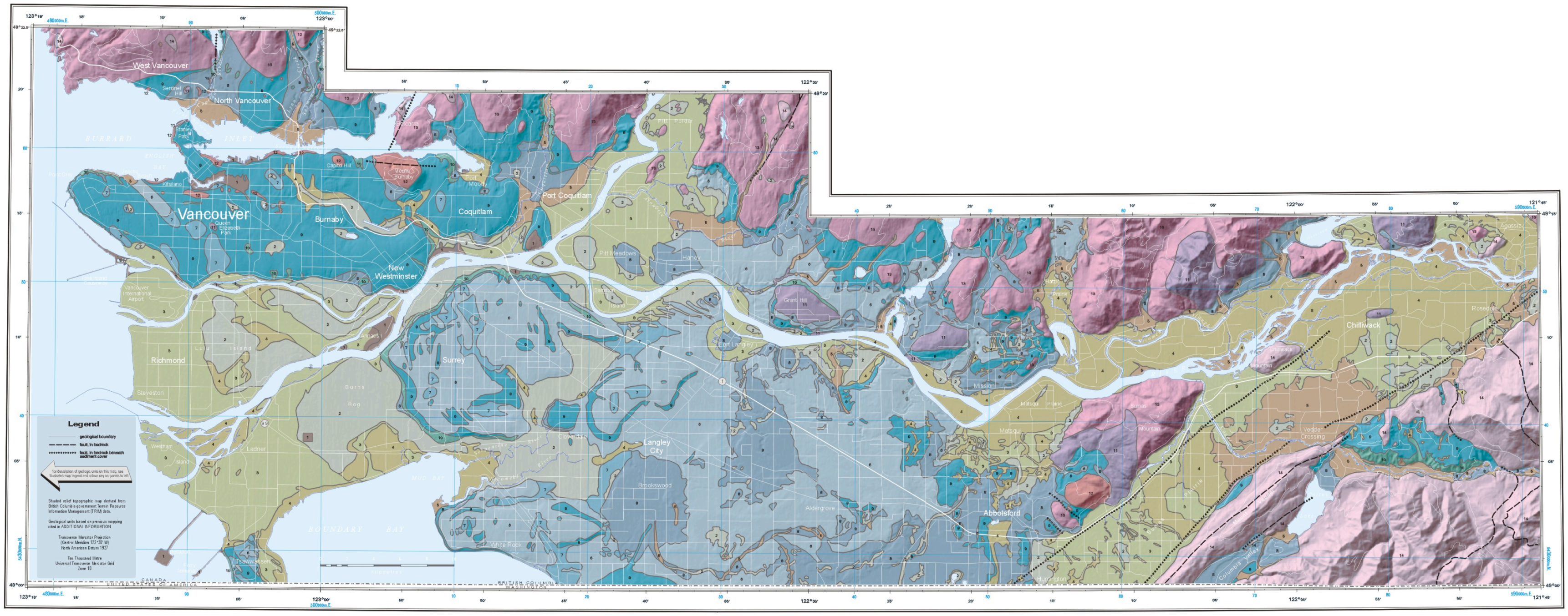
b) provide a coordination role to address flood hazard issues and management decisions;

c) implement appropriate preparatory actions to address the implications of long-term sea level rise on infrastructure planning, construction, and operations;

d) review and improve the effectiveness of existing provincial legislation and guidelines regarding flood hazard management by municipalities.

Source: Metro Vancouver, 2011a (used with permission)

Appendix H: Soil Map of Metro Vancouver



Modern Sediments

1 Landfill
2 Peat
3 Silt and clay
4 Sand and silt
5 Gravel and sand

Ice Age Sediments

6 Silt and clay
7 Sand
8 Gravel and sand
9 Till
10 Steepland sediments

Bedrock

11 Volcanic rock
12 Sandstone
13 Granitic rock
14 Foliated sedimentary and volcanic rock

Source: Geological Survey of Canada, 2011 (used with permission)

Appendix I: Examples of Projected Changes in Extreme Climate Phenomena, with Examples of Projected Impacts

Projected changes during the twenty-first century in extreme climate phenomena and their likelihood	Representative examples of projected impacts (all high confidence of occurrence in some areas)
Higher maximum temperatures; more hot days and heatwaves over nearly all land areas (very likely)	• Increased incidence of death and serious illness in older age groups and urban poor • Increased heat stress in livestock and wildlife • Shift in tourist destinations • Increased risk of damage to a number of crops • Increased electric cooling demand and reduced energy supply reliability
Higher (increasing) minimum temperatures; fewer cold days, frost days and cold waves across nearly all land areas (very likely)	• Decreased cold-related human morbidity and mortality • Decreased risk of damage to a number of crops, and increased risk to others • Extended range and activity of some pest and disease vectors • Reduced demand for heating energy
More intense precipitation events (very likely in many areas)	• Increased flood, landslide, avalanche and mudslide damage • Increased soil erosion • Increased flood runoff could increase recharge of some floodplain aquifers • Increased pressure on government and private flood insurance systems and disaster relief
Increased summer drying over most mid-latitude continental interiors and associated risk of drought (likely)	• Decreased crop yields • Increased damage to building foundations caused by ground shrinkage • Decreased water resource quantity and quality • Increased risk of forest fire
Increase in tropical cyclone peak wind intensities, and mean and peak precipitation intensities (likely over some areas)	• Increased risks to human life, risk of infectious disease epidemics and many other risks • Increased coastal erosion and damage to coastal buildings and infrastructure • Increased damage to coastal ecosystems, such as coral reefs and mangroves
Intensified droughts and floods associated with El Niño events in many different regions (likely) (see also under droughts and intense precipitation events)	• Decreased agricultural and rangeland productivity in drought- and flood-prone regions • Decreased hydro-power potential in drought-prone regions
Increased Asian summer monsoon precipitation variability (likely)	• Increase in flood and drought magnitude and damages in temperate and tropical Asia
Increased intensity of mid-latitude storms (little agreement between current models)	• Increased risks to human life and health • Increased property and infrastructure losses • Increased damage to coastal ecosystems

Source: van Aalst, 2006

Appendix J: Modified Mercalli Intensity (MMI) Scale for MMI VI and Higher and Description of Effects

MMI	Description of effects
VI	Felt by all, many frightened; some heavy furniture moved; a few instances of fallen plaster; damage slight
VII	Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built structures; some chimneys broken
VIII	Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures; fall of chimneys, factory stacks, columns, walls; heavy furniture overturned
IX	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb; damage great in substantial buildings, with partial collapse; buildings shifted off foundations
X	Some well-built wooden structures destroyed; most masonry and frame structures with foundations destroyed; rails bent
XI	Few, if any, masonry structures remain standing; bridges destroyed; rails bent greatly
XII	Damage total; lines of sight and level distorted; objects thrown into air

Source: Ventura et al., 2006

Appendix K: Building Inventory Model Percentages for Transforming Census Structural Types into Building Types

	Wood Frame			**Masonry**		**Concrete Frame**				**Mobile Home**
Census Structural Type and Vintage	WLFR	WPB	WLRLR	URMLR	URMMR	CFIW	CFCWLR	CFCWMR	CFCWHR	MH
Single- Detached House										
- 1946-1960	80%	20%								
- All other vintages	100%									
Other Dwellings										
- Semi-Detached House	100%									
- Row House	100%									
- Apartment, Duplex	100%									
Other Single-Attached House	100%									
Apartment <5 Storeys										
- Pre-1970			90%	10%						
- 1971-2006			90%				10%			
Apartment 5+ Storeys										
- Medium-Rise Pre-1945					40%	45%		15%		
- Medium-Rise Post-1945								100%		
- High Rise									100%	
Movable Dwelling										100%

Source: Chang et al., forthcoming

Appendix L: British Columbia Building Classes

Class No.	Class	Code
Wood		
1	Wood light frame residential	WLFR
2	Wood light frame low rise commercial–institutional	WLFCI
3	Wood light frame low rise residential	WLFLR
4	Wood post and beam	WPB
Steel		
5	Light metal frame	LMF
6	Steel moment frame low rise	SMFLR
7	Steel moment frame medium rise	SMFMR
8	Steel moment frame high rise	SMFHR
9	Steel braced frame low rise	SBFLR
10	Steel braced frame medium rise	SBFMR
11	Steel braced frame high rise	SBFHR
12	Steel frame with concrete walls low rise	SFCWLR
13	Steel frame with concrete walls medium rise	SFCWMR
14	Steel frame with concrete walls high rise	SFCWHR
15	Steel frame with concrete infill walls	SFCIW
16	Steel frame with masonry infill walls	SFMIW
Concrete		
17	Concrete frame with concrete walls low rise	CFCWLR
18	Concrete frame with concrete walls medium rise	CFCWMR
19	Concrete frame with concrete walls high rise	CFCWHR
20	Concrete moment frame low rise	CMFLR
21	Concrete moment frame medium rise	CMFMR
22	Concrete moment frame high rise	CMFHR
23	Concrete frame with infill walls	CFIW
Masonry		
24	Reinforced masonry shear wall low rise	RMLR
25	Reinforced masonry shear wall medium rise	RMMR
26	Unreinforced masonry bearing wall low rise	URMLR
27	Unreinforced masonry bearing wall medium rise	URMMR
Tilt up		
28	Tilt up	TU
Precast		
29	Precast concrete low rise	PCLR
30	Precast concrete medium rise	PCMR
Mobile		
31	Mobile homes	MH

Source: Ventura et al., 2005

Appendix M: Status Quo Growth Scenario 2041 – Building and Population Totals

AOA	Population by building type										TOTAL	
	Wood Frame			Masonry		Concrete Frame				Mobile		
	WLFR	WPB	WLFLR	URMLR	URMMR	CFIW	CFCWLR	CFCWMR	CRCWHR	MH	Dwellings	Population
1	285168	4456	164947	6053	231	260	12275	30929	972	157	207810	505447
2	24197	378	16317	748	0	0	1065	717	22	0	16327	43444
3	8068	11	44805	1680	2204	2479	3298	96550	3131	196	101670	162421
4	5860	74	10634	44	8	9	1137	4621	143	0	10398	22531
5	24978	482	25943	809	9	10	2074	11139	345	46	29255	65834
6	86743	2806	11714	221	10	11	1081	8034	249	73	43168	110942
7	34776	1366	3758	109	91	102	309	10785	340	187	20979	51823
8	154791	940	55198	327	18	20	5806	13619	422	713	101145	231854
9	1118	41	0	0	0	0	0	0	0	0	503	1159
10	25971	117	2310	5	0	0	251	1764	55	174	11259	30647
11	19954	166	5882	56	0	0	598	265	8	0	12321	26929
12	84888	639	9787	155	0	0	932	1023	32	918	37109	98373
13	12434	253	10970	170	0	0	1049	2113	65	0	12489	27055
14	88931	395	14647	43	0	0	1585	225	7	1298	48811	107132
15	82721	237	5328	38	0	0	554	0	0	111	33823	88989
16	360842	2032	118229	695	11	12	12442	13571	420	7597	189352	515852
17	5953	100	522	2	0	0	56	0	0	479	2979	7113
18	7003	41	5843	30	0	0	619	7565	234	102	8938	21436
19	26875	560	27228	810	91	102	2215	14490	454	38	32782	72863
20	1452	30	276	5	0	0	25	0	0	0	655	1789
21	178122	3224	82078	1577	140	158	7543	61926	1924	218	144298	336910
22	34832	260	9221	91	0	0	934	1333	41	0	17951	46712
23	41611	484	11461	115	0	0	1159	2106	65	1085	24264	58085
24	113696	744	38261	325	0	0	3927	7153	221	1073	66476	165399
25	72926	342	17166	84	0	0	1823	0	0	150	37282	92492
26	108411	879	15091	176	0	0	1500	3141	97	1000	49490	130295
27	18999	56	3267	12	0	0	351	0	0	138	9761	22823
28	178943	606	14098	35	0	0	1531	60	2	12277	79089	207552
29	16623	79	18243	181	0	0	1846	0	0	35	16497	37006
30	3211	47	70	0	0	0	8	0	0	26	1295	3362
31	231	6	3282	111	22	24	253	3414	107	0	4018	7450
32	6355	21	91	3	0	0	7	0	0	354	2247	6832
SUM	**2116681**	**21873**	**746665**	**14710**	**2834**	**3188**	**68252**	**296542**	**9358**	**28448**	**1374442**	**3308551**

** Totals might not fully match regional projections because calculations were performed using exact numbers from the 2006 Census of Canada, while Metro Vancouver uses rounded numbers*

Source: Statistics Canada, 2006 and Metro Vancouver, 2011a

Appendix N: Compact Growth Scenario 2041 – Building and Population Inventory

	Population by building type										TOTAL	
AOA	Wood Frame			Masonry		Concrete Frame				Mobile		
	WLFR	WPB	WLFLR	URMLR	URMMR	CFIW	CFCWLR	CFCWMR	CRCWHR	MH	Dwellings	Population
1	243240	4753	159989	6457	247	277	11320	76647	2387	130	194800	505447
2	18798	357	15088	707	0	0	969	7298	226	0	17265	43444
3	10604	10	44509	1496	1962	2208	3450	94981	3067	135	114168	162421
4	3737	74	8010	44	8	9	846	9508	295	0	10405	22531
5	19829	481	23714	807	9	10	1828	18549	574	34	29320	65834
6	63172	2800	17195	221	10	11	1690	25017	774	51	43260	110942
7	30353	1365	5221	109	91	102	471	13526	424	160	20995	51823
8	91214	895	58751	311	17	19	6217	71836	2223	371	106250	231854
9	1083	76	0	0	0	0	0	0	0	0	275	1159
10	25873	214	2310	10	0	0	247	1764	55	174	6150	30647
11	14317	166	6331	56	0	0	648	5250	162	0	12365	26929
12	60470	637	15198	155	0	0	1534	19164	593	622	37195	98373
13	10038	253	10090	170	0	0	951	5385	167	0	12500	27055
14	88492	835	14647	90	0	0	1537	225	7	1298	23105	107132
15	82458	500	5328	81	0	0	511	0	0	111	16010	88989
16	168362	1633	131273	558	8	10	14028	191177	5913	2890	235630	515852
17	5842	212	522	5	0	0	53	0	0	479	1410	7113
18	5157	43	5822	32	0	0	615	9413	291	64	8417	21436
19	20140	639	24732	924	103	116	1824	23622	737	25	28755	72863
20	1426	56	276	10	0	0	20	0	0	0	350	1789
21	108942	3207	86243	1568	140	157	8014	124659	3865	116	145100	336910
22	21335	259	10726	91	0	0	1101	12804	396	0	18030	46712
23	24231	560	13474	133	0	0	1364	17222	533	568	20970	58085
24	57835	706	41914	308	0	0	4349	58033	1795	460	70055	165399
25	40492	340	21121	84	0	0	2263	27274	844	74	37500	92492
26	60043	875	25186	175	0	0	2623	39669	1227	498	49750	130295
27	12143	56	4450	12	0	0	483	5430	168	82	9785	22823
28	86937	604	38399	35	0	0	4231	70016	2165	5163	79390	207552
29	11902	78	15247	180	0	0	1514	7820	242	22	16525	37006
30	3211	47	70	0	0	0	8	0	0	26	1295	3362
31	604	3	2356	51	10	11	210	4077	127	0	8693	7450
32	4078	21	793	3	0	0	85	1590	49	213	2250	6832
TOTAL	**1396360**	**22754**	**808986**	**14883**	**2605**	**2931**	**75004**	**941956**	**29304**	**13766**	**1377968**	**3308551**

** Totals might not fully match regional projections because calculations were performed using exact numbers from the 2006 Census of Canada, while Metro Vancouver uses rounded numbers*

Source: Statistics Canada, 2006 and Metro Vancouver, 2011a

Appendix O: Sprawled Growth Scenario 2041 – Building and Population Inventory

AOA	Population by building type										TOTAL	
	Wood Frame			Masonry		Concrete Frame				Mobile		
	WLFR	WPB	WLFLR	URMLR	URMMR	CFIW	CFCWLR	CFCWMR	CRCWHR	MH	Dwellings	Population
1	342781	4028	115446	5472	209	235	7355	21546	680	7694	229863	505447
2	28969	349	11681	691	0	0	606	513	16	617	17657	43444
3	8064	14	44805	2170	2846	3202	2808	95184	3131	196	78710	162421
4	14781	74	4502	44	8	9	456	1946	61	650	10405	22531
5	35097	481	18864	807	9	10	1289	8095	251	932	29320	65834
6	91182	2867	8388	226	10	11	706	5746	178	1628	42260	110942
7	36648	1365	3221	109	91	102	249	9216	291	531	20995	51823
8	182152	990	31751	344	19	21	3184	7816	243	5335	96050	231854
9	1099	9	0	0	0	0	0	0	0	51	2315	1159
10	27722	92	993	4	0	0	106	758	23	949	14310	30647
11	21348	182	4364	61	0	0	424	197	6	347	11274	26929
12	87618	619	6440	150	0	0	565	673	21	2286	38286	98373
13	15558	253	8337	170	0	0	756	1606	50	325	12500	27055
14	95305	406	7134	44	0	0	749	110	3	3380	47438	107132
15	83802	177	1887	29	0	0	181	0	0	2913	45210	88989
16	424468	2142	58982	732	11	13	5821	6758	210	16715	179663	515852
17	6421	78	192	2	0	0	19	0	0	401	3843	7113
18	11538	46	3852	34	0	0	394	4987	154	433	7964	21436
19	46065	517	14752	747	84	94	892	7777	246	1690	35541	72863
20	1662	8	38	1	0	0	3	0	0	77	2544	1789
21	241968	3256	44282	1593	142	160	3328	33269	1038	7875	142906	336910
22	38953	259	5130	91	0	0	479	741	23	1036	18030	46712
23	48564	500	5357	119	0	0	476	984	30	2054	23470	58085
24	137405	732	17022	320	0	0	1572	3182	98	5068	67555	165399
25	80325	340	8469	84	0	0	857	0	0	2417	37500	92492
26	115697	875	7507	175	0	0	659	1562	48	3771	49750	130295
27	20073	56	1931	12	0	0	203	0	0	548	9785	22823
28	189158	604	5929	35	0	0	624	25	1	11176	79390	207552
29	23323	78	11619	180	0	0	1111	0	0	694	16525	37006
30	3211	47	70	0	0	0	8	0	0	26	1295	3362
31	227	9	3282	189	37	41	175	3382	107	0	2360	7450
32	6401	21	55	3	0	0	3	0	0	349	2250	6832
SUM	**2467585**	**21474**	**456280**	**14638**	**3466**	**3899**	**36060**	**216075**	**6910**	**82164**	**1376965**	**3308551**

** Totals might not fully match regional projections because calculations were performed using exact numbers from the 2006 Census of Canada, while Metro Vancouver used rounded numbers*

Source: Statistics Canada, 2006 and Metro Vancouver, 2011a

Appendix P: Safe Growth Scenario 2041 – Building and Population Inventory

AOA	Population by building type										TOTAL	
	Wood Frame			Masonry		Concrete Frame				Mobile		
	WLFR	WPB	WLFLR	URMLR	URMMR	CFIW	CFCWLR	CFCWMR	CRCWHR	MH	Dwellings	Population
1	306847	4316	159941	5863	224	252	11908	23086	729	118	217860	513284
2	21118	282	12205	558	0	0	798	414	13	0	17820	35388
3	26881	12	44696	1786	2343	2636	3180	78367	2578	161	95730	162640
4	11533	74	8010	44	8	9	846	1946	61	0	10405	22531
5	34054	535	26385	898	10	11	2034	9006	279	37	29320	73249
6	77617	2613	16046	206	9	10	1577	5238	163	48	43260	103527
7	34796	1365	5221	109	91	102	471	9216	291	160	20995	51823
8	101906	1138	36524	396	22	24	3663	8991	279	472	55250	153415
9	717	50	0	0	0	0	0	0	0	0	275	767
10	17120	142	1528	7	0	0	163	1167	36	115	6150	20279
11	94506	413	33437	139	0	0	3576	448	14	0	24365	132533
12	65752	731	7607	178	0	0	668	795	25	713	25195	76469
13	20455	318	13816	214	0	0	1322	2018	62	0	14045	38205
14	85193	439	22600	48	0	0	2463	118	4	684	45687	111549
15	78429	231	18025	37	0	0	1966	0	0	51	38472	98739
16	365055	1825	132273	624	9	11	14073	5757	179	3229	213829	523035
17	6063	103	1496	2	0	0	164	0	0	233	3282	8062
18	8719	39	5156	29	0	0	544	4303	133	58	8173	18981
19	43103	583	27023	843	94	106	2160	8772	277	23	35886	82985
20	854	34	165	6	0	0	12	0	0	0	350	1071
21	204110	3213	86427	1572	140	157	8031	32836	1025	116	145100	337628
22	41681	284	13552	100	0	0	1406	814	25	0	20348	57862
23	38340	493	12776	117	0	0	1302	971	30	501	22334	54531
24	124774	716	45846	312	0	0	4782	3111	96	467	75260	180103
25	68609	340	21121	84	0	0	2263	0	0	74	37500	92492
26	107020	863	28336	173	0	0	2975	1541	48	491	54773	141445
27	17741	56	4450	12	0	0	483	0	0	82	9785	22823
28	166468	585	41959	34	0	0	4628	25	1	5002	86345	218702
29	19964	78	15247	180	0	0	1514	0	0	22	16525	37006
30	3211	47	70	0	0	0	8	0	0	26	1295	3362
31	4383	6	3784	124	24	27	296	2217	70	0	5283	10933
32	5718	21	793	3	0	0	85	0	0	213	2250	6832
SUM	**2202736**	**21948**	**846517**	**14697**	**2975**	**3347**	**79361**	**201158**	**6417**	**13097**	**1383145**	**3392251**

** Totals might not fully match regional projections because calculations were performed using exact numbers from the 2006 Census of Canada, while Metro Vancouver used rounded numbers*

Source: Statistics Canada, 2006 and Metro Vancouver, 2011a