A Disaster Risk Management Approach to Seismic Risk on Vancouver Island, British Columbia

by

Mark R. Seemann
B.A., University of Alberta, 1987
M.Sc., University of Alberta, 1992

A Dissertation Submitted in Partial Fulfillment of the
Requirements for the Degree of

DOCTOR OF PHILOSOPHY

In the Department of Geography

University of Victoria

Supervisory Committee

A Disaster Risk Management Approach to Seismic Risk
on Vancouver Island, British Columbia

by

Mark R. Seemann
B.A., University of Alberta, 1986
M.Sc., University of Alberta, 1992

Supervisory Committee:

Dr. Denise Cloutier-Fisher, Department of Geography
Supervisor

Dr. Jim Gardner, Department of Geography
Departmental Member

Dr. Les Foster, Department of Geography
Departmental Member

Dr. Bart Cunningham, Department of Public Administration
Outside Member

Supervisory Committee

Dr. Denise Cloutier-Fisher, Department of Geography
Supervisor

Dr. Jim Gardner, Department of Geography
Departmental Member

Dr. Les Foster, Department of Geography
Departmental Member

Dr. Bart Cunningham, Department of Public Administration
Outside Member

ABSTRACT

Communities on Vancouver Island, British Columbia face significant exposure to damaging earthquakes. This seismic risk arises not only from the Island's proximity to crustal, sub-crustal and subduction earthquake sources in the Cascadia Subduction Zone and from their associated aftershock sequences, but also from environmental (natural and human-made) and social vulnerabilities in Vancouver Island communities and their current capacities to respond and recover from a large seismic event. Seeking to 1) assist community officials and the general public to better understand the scope of the earthquake risk on Vancouver Island; 2) raise awareness of the gaps in Vancouver Island's risk assessment; 3) encourage and facilitate comprehensive seismic risk discussions at all levels of governance; and 4) offer quantitative data on which to base sound funding and policy decisions, this dissertation offers three new studies, presented in paper format, toward the comprehensive management of seismic risk on Vancouver Island.

The first paper, reviews the components of risk and, building on international risk management standards and best practices, develops a new, comprehensive Disaster Risk Management (DRM) Framework for practitioners. This DRM Framework is then used to review existing knowledge of Vancouver Island's seismic risk. A number of information gaps are identified, and two in particular, mainshock and aftershock hazard assessment, are targeted for further analysis.

Vancouver Island's mainshock seismic hazard is investigated in the second paper, and it includes source contributions from a full-rupture Cascadia subduction earthquake as well as from crustal and sub-crustal sources. Rather than using engineering parameters to describe seismic hazard, this dissertation research focuses on the development of simplified, readily-understandable earthquake shaking probability estimates. These probabilities, based on the latest available Geological Survey of Canada seismic hazard models are presented as the chance of exceeding one of three shaking intensity levels (Widely-Felt Shaking; the threshold for Non-Structurally-Damaging Shaking; and, the threshold for Structurally-Damaging Shaking) over one of four timeframes (10, 25, 50 and 100 years). In addition to individual source calculations, for the first time aggregate shaking probabilities are calculated to provide the combined shaking hazard from all three seismic sources. Results are calculated for over 50 Vancouver Island locations. Seismic hazard is greatest in the sparsely populated northwest quadrant of Vancouver Island, and on the southern tip of the Island where most of the Island's population is concentrated. Uncertainties associated with these calculations are identified and discussed.

The third paper provides the first estimates of aftershock shaking hazard for communities along the west coast of North America following a full-rupture Cascadia subduction event. Owing to uncertainties associated with the size of the rupture zone, two possible rupture zone scenarios are modeled and presented. Results provide the probabilities of exceeding each of three shaking intensity thresholds identified above. Coastal communities on southern Vancouver Island and along the Washington coast are subject to the greatest Cascadia subduction aftershock hazard.

Research presented in this dissertation contributes to the growing body of disaster risk management literature generally, and the seismic risk literature for Vancouver Island specifically.

Table of Contents

List of Tables

List of Figures

Acknowledgements

At the outset I would like to thank my supervisors: the late Dr. Harry Foster who encouraged me to pursue this research, provided support and mentorship; and Dr. Denise Cloutier-Fisher who stepped in to guide me through the completion of the program. Numerous conversations and the constructive criticism from my committee shaped and considerably strengthened the final dissertation and for this I thank Dr. Jim Gardner, Dr. Les Foster, and Dr. Bart Cunningham for their support and advice. Critical reviews and the constructive input of Dr. Ali Asgary, York University, are much appreciated as is the early input of Dr. Stephanie Chang, University of British Columbia.

Special thanks are also due my co-authors, Dr. Tuna Onur and Dr. John Cassidy for their contributions to the research conducted. Review comments by Dr. Garry Rogers and three unknown reviewers significantly tightened the manuscript for the second paper and Dr. Eleanor Setton deserves a special mention for her GIS and graphics expertise in mapping and presenting the shaking probabilities in Chapter 3.

I would also like to acknowledge the administrative support of Darlene Li, who, regardless of where I was in my travels, provided steadfast support, patience and guidance well beyond that of her job description. I also appreciate the support of Dr. Maycira Costa who at the eleventh hour helped chart a path through the vagaries of a remote defense.

Financial support from the Government of Canada (Stuart Nesbitt White Scholarship), and the Government of British Columbia (Pacific Leaders Scholarships) is gratefully acknowledged.

Above all, however, I thank my wife and my daughter. My wife for her love, support, and guidance over the course of this dissertation and my daughter for her patience as she waited to play while I was writing ‘my book’. Sizi çok ama çok seviyorum.

Dedication

To T and t…

… for all you continue to teach me…

> “It was at night time that the land shook… a big wave smashed into the beach…the Pachena Bay people were lost…”
>
> Pacheenaht Elder, Vancouver Island
> (Arima, 1991)

1.0 INTRODUCTION

Earthquakes have long been a part of life on Vancouver Island, and local communities have had to adjust or adapt to their effects and impacts for hundreds, if not thousands of years (Hutchinson and McMillan, 1997; Ludwin et al, 2007). Today, the southwest region of British Columbia (BC) (See Appendix A for abbreviations and acronyms used) records some 250 earthquakes annually, and Island communities have felt two damaging shaking events in the past century: the 1918 M7.2 earthquake on Vancouver Island’s west coast and the 1946 M7.3 west of Courtenay (Lamontagne, 2007; NRCan, 2012a). Decisions as to how to best prepare for, respond to, and recover from these events, continue to challenge Vancouver Island residents and their community leaders, particularly as the availability of public resources becomes increasingly constrained.

The basis for effective and efficient emergency management rests on credible and comprehensive assessments of the risk to Island communities. To date, no comprehensive multi-hazard risk assessment for Vancouver Island communities exists in the public domain. While seismic hazard assessments are available for scientific and engineering use through the Government of Canada (NRCan, 2012b), local seismic microzonation of site conditions are available for portions of southern Vancouver Island (Klohn-Crippen 1994; Monahan et al., 2000; Wuorinen, 1976), and structural loss estimations for the central business district of Victoria have been conducted (Onur, 2001), to date no published assessment of the seismic risk on Vancouver Island addresses or synthesizes the environmental, physical, social and economic vulnerabilities and resiliencies of Island communities.

The purpose of this dissertation is to begin to identify and address these deficiencies. And while it is beyond the scope of this dissertation to address each of the specific elements of Vancouver Island's seismic risk, the research included herein provides a strategic framework for managing risk and offers two studies addressing the hazard component of seismic risk in a simple, readily-understood format for the non-scientific and non-engineering community.

This dissertation is written in a paper-based format, with individual chapters in various stages of publication. The introductory chapter provides a brief introduction to the study area (Section 1.1), describes the advances in our understanding of earthquakes over the last hundred years (Section 1.2) and highlights the broad paradigm shifts that have occurred in disaster research over the same time span (Section 1.3). Section 1.4 then details the overall dissertation research objective and associated research questions, while Section 1.5 outlines the scope of the research and key definitions used throughout the study. The final section, Section 1.6, provides an overview of the structure of the dissertation.

1.1 Study Area

Vancouver Island is a large northwest-southeast trending island located some 50 kilometres off the southwest coast of British Columbia (BC), Canada (Figure 1.1). Separated from the Lower Mainland by the Salish Sea (including the Strait of Georgia to the east, and Strait of Juan de Fuca to the south), this elongate Island extends some 460km (290 mi) from northwest to southeast, and is up to 80 km (50 mi) wide.

With an areal extent of some 31,788 km^2, Vancouver Island is predominated by steep, rugged topography from sea-level to an elevation of approximately 2200m (Gutherie, 2005).

Figure 1.1 Vancouver Island location map (Go Canada, 2012)

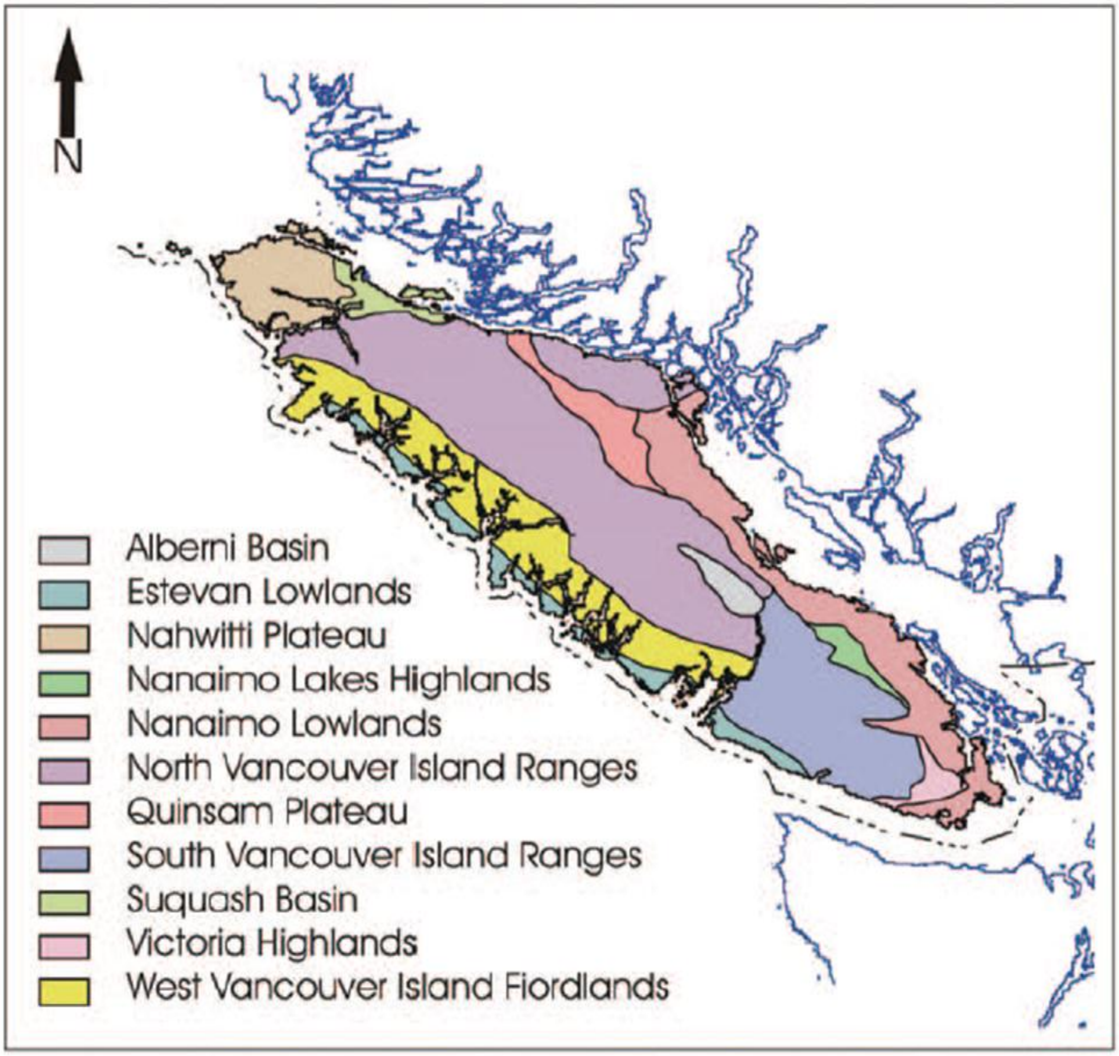


Figure 1.2 Physiographic regions of Vancouver Island (Gutherie, 2005)

Longitudinally bisected by the North and South Vancouver Island Ranges (Figure 1.2), these two physiographic regions predominate on the island and are composed of volcanic and sedimentary rocks with granitic intrusions. The west coast is characterised by long, deep fiords extending east into the heart of the Island, while the northern tip of the island and much of the southeast coast is largely dominated by low-lying plains. The geomorphology and sedimentology of the Island's mountain valley-bottoms and the coastal plains reflect its Late Pleistocene glacial history and lower- to mid-slope sediments are predominated by substantial Pleistocene till and glaciofluvial deposits (Guthrie, 2005; Yorath and Nasmith,1995). The geologically young, post-glacial terrestrial terrains are steep and prone to landslides, which are primarily attributed to large storm events, but also to regional earthquakes (Guthrie, 2005). Similarly steep submarine sediments in the local fiords are also susceptible to landslides and submarine failures are primarily attributed to past seismic events (Blais-Stevens et al., 2011).

Tectonically, the island is located on the geologically active, western margin of the North America tectonic plate where the denser, eastward moving Juan de Fuca plate dips and subducts below the lighter North American plate. The 4 cm per year convergence of the Juan de Fuca and North America plates (Flück et al., 1997), compresses the western margin of the North America plate creating a crustal “bulge” running roughly parallel to the coastline and creating regional uplift of at least 4mm per year (Verdonck, 2006). The dynamic compressional forces at work in this convergent tectonic environment predispose Vancouver Island to earthquakes from three distinct source types. Moderate to major (M5-7.9) intra-plate earthquakes occur in either the North American plate (shallow crustal earthquakes) or the Juan de Fuca plate (deeper sub-crustal earthquakes) and great (>M8) inter-plate earthquakes occur at the interface between the North American and Juan de Fuca plates (subduction interface earthquakes) (NRCan, 2012c). Figure 1.3 illustrates the tectonic setting of the Cascadia subduction zone and the sources of crustal, sub-crustal and subduction interface earthquakes.

Vancouver Island bioclimatic zones vary widely ranging from wet (> 5500 mm per year), temperate rainforest zone in the west, to a much drier quasi-Mediterranean climatic zone in the southeast (< 700 mm per year). Precipitation is seasonal, and with most of the Island's snow and rainfall falling between September and April (Environment Canada, 2011), this seasonality is likely to have a significant influence on the response and recovery following the next damaging earthquake to effect Vancouver Island.

The population of Vancouver Island is approximately 750,000 with most of those individuals residing along the southern and southeastern coast. While there are several small coastal villages in this coastal region, the bulk of the population lives in the greater urban areas of Victoria (374,675), Nanaimo (150,632), Duncan (83,300) and Courtenay/Comox (64,805) (BC Stats, 2011). Forty-one First Nations bands are located on Vancouver Island, and approximately one third of them (15) are located on the Island's west coast. With approximately 25,000 band members living on- and off-reserve on Vancouver Island, First Nations people represent some 3 to 4 per cent of the island's population (BC Aboriginal Relations, 2012). In addition to these permanent residents, Vancouver Island's rugged beauty and mild climate attract an additional 760,000 national and international visitors per year (Tourism British Columbia, 2008).

1.2 Background to Earthquake Research

For generations, explanations for seismic events along the west coast of North America were a mystery wrapped in oral traditions and local mythology (Ludwin et al., 2007; Maud, 1978). In the early 1900s, however, a radical theory entitled "continental drift"

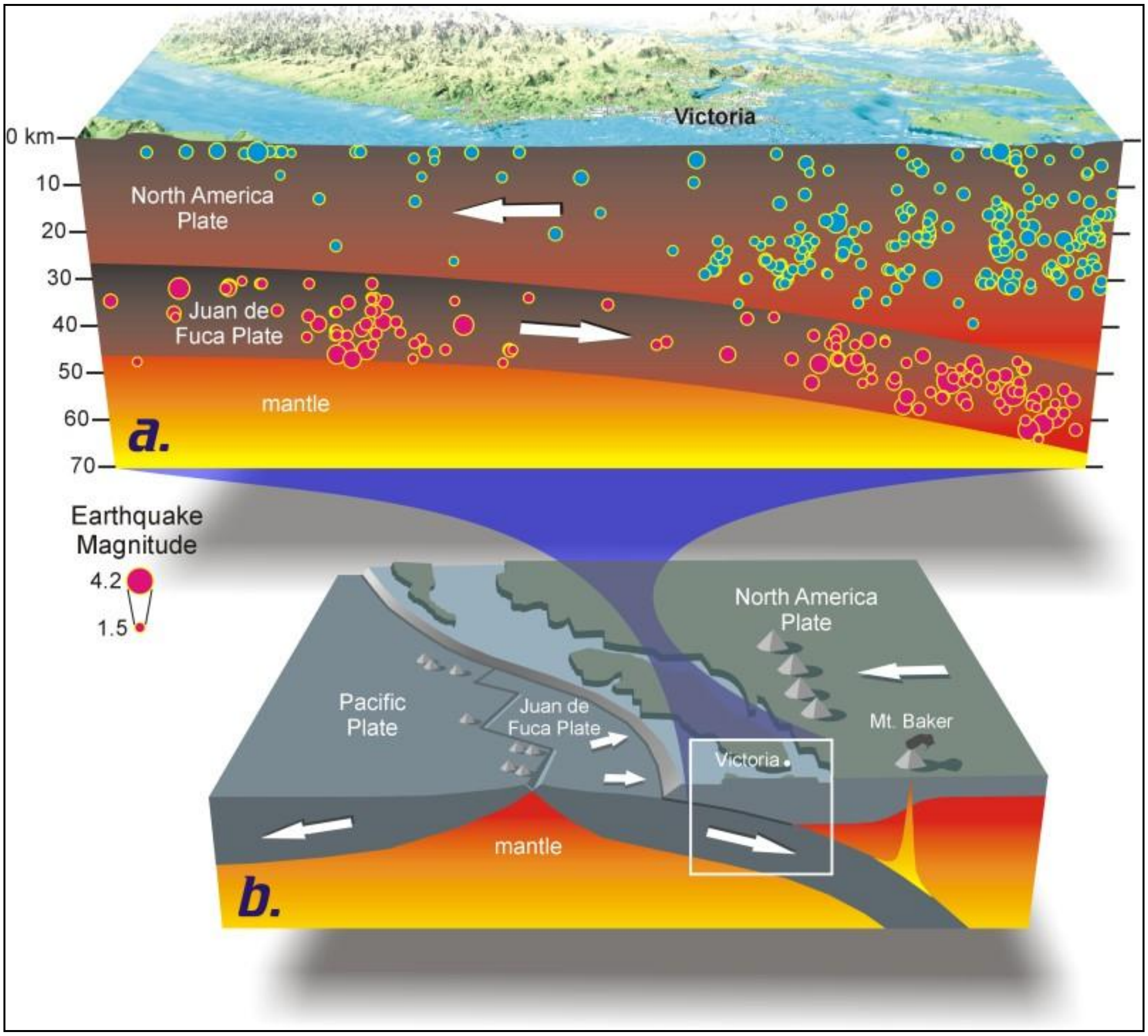


Figure 1.3 Cascadia Subduction Zone (CSZ) tectonic setting. Blue dots represent shallow crustal source earthquakes within the North America plate; Red dots represent deeper sub-crustal source earthquakes within the subducting Juan de Fuca plate; and, great subduction earthquakes along the interface of these two plates (Yorath et al., 2001).

was promoted by German geophysicist Alfred Wegener to explain the origin of the continents and to offer a novel scientific explanation for existence of earthquakes (Kearey et al., 2009; Wegener, 1968). This precursor to the modern "plate tectonic" theory, was not widely accepted until a mechanism for crustal plate movement was proposed by British geologist Arthur Holmes some twenty years later, and then more recently proven by pioneering paleomagnetic research on mid-oceanic ridges by American Harry Hess in the 1940s (Erickson, 2001; Kearey et al., 2009).

By the mid-1960s "plate tectonics," the theory that the earth's crust consisted of a number of plates floating on the earth's asthenosphere, had begun to become more widely accepted in the Canadian and international scientific community (Erickson, 2001; Rogers 1992). With increased seismographic instrumentation deployed across western Canada through the 1950s and 1960s, and with the support of detailed field investigations, it became clear that Vancouver Island itself is located on the western margin of a large tectonic plate, the North America plate, and is situated at its confluence with the eastward subducting Juan de Fuca plate (Basham and Newitt, 1993; Rogers, 1992) in a zone called the Cascadia Subduction Zone (CSZ). While initially thought to be a uniquely quiescent tectonic margin with aseismic slip dissipating the convergent forces of these plates, research through the 1980s confirmed that the zone was in fact a "locked" zone in which the convergent stresses were accumulating (Rogers, 1988). Through the 1990s, various lines of investigation including stratigraphy and dendrochronology (Atwater et al., 1995; Atwater and Hemphill-Haley, 1997), sea floor sedimentology (Adams, 1990)

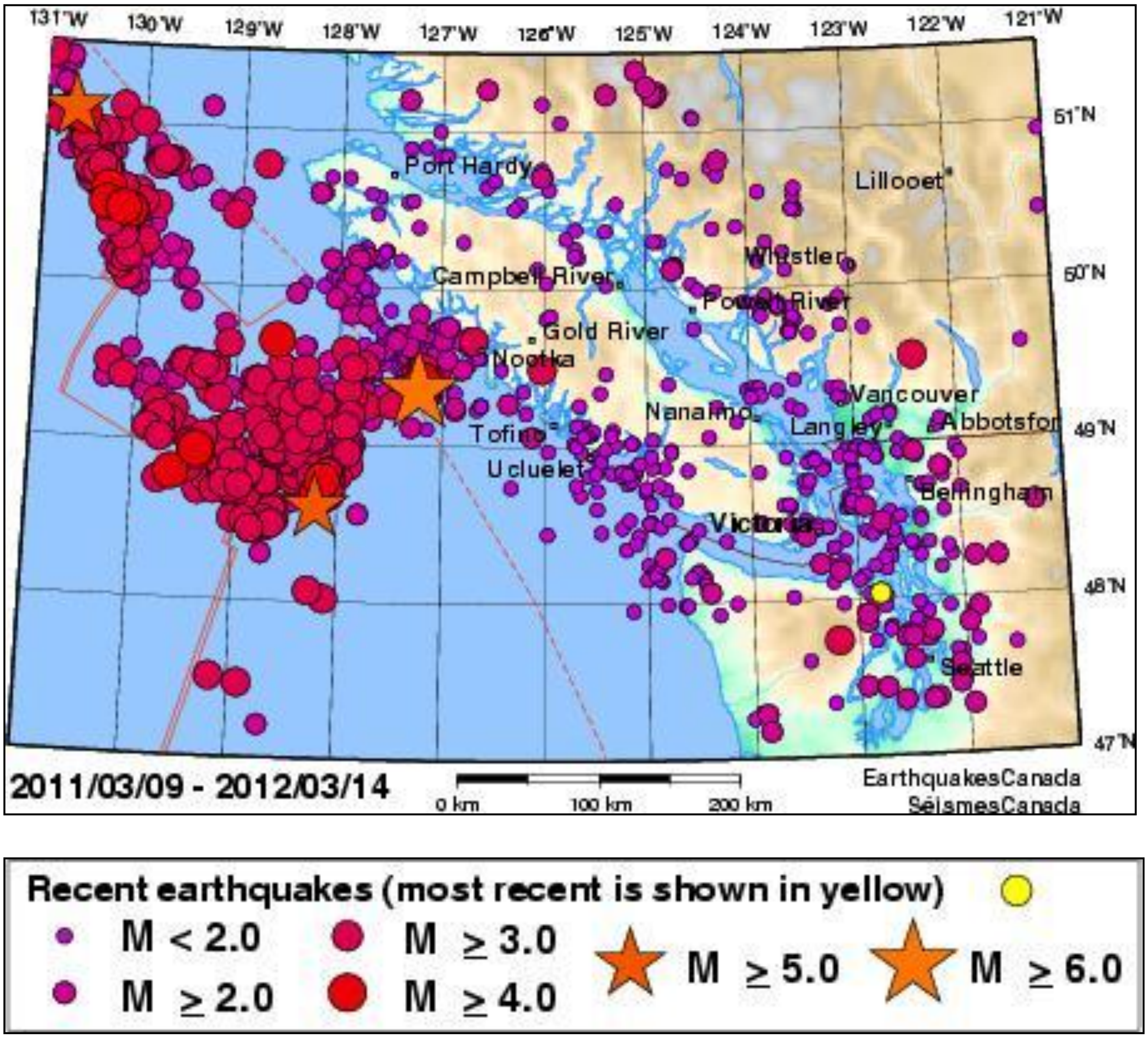


Figure 1.4 Seismicity of Vancouver Island represented by the distribution of earthquakes around Vancouver Island over a one-year period – March 2011 to March 2012 (NRCan, 2012d)

and geodetic monitoring (Dragert et al., 1995), demonstrated that the accumulation of stress in the CSZ is being stored in an increasingly deformed plate margin and that every few hundred years this stress is released in a great earthquake (Satake et al., 1996).

More recent seismic and geodetic monitoring of this dynamic Cascadia plate margin led scientists at the Geological Survey of Canada to discover a new subduction zone phenomenon termed Episodic Tremor and Slip (ETS) (Dragert et al., 2001; Dragert et al., 2004; Rogers and Dragert, 2003). Now recognized to occur in other subduction zones around the world, this phenomenon is characterised by repeated 'silent' reversals in the normal compressional movement of the overriding plate. In the CSZ, this reversal appears to occur over approximately a two-week period every 13-16 months as the warmer, more elastic lower plate transfers energy back to the colder, locked upper portion of the North America plate. This fairly regular stress transfer and cumulative loading of the shallow locked zone may well be the trigger mechanism for the next great Cascadia subduction event (Dragert et al., 2001; Rogers and Dragert, 2003). Based on this possibility, Mazotti and Adams (2004) estimate the weekly probability of a great earthquake occurring during this slip event is 30-100 times higher than any other week of the year.

Today, BC experiences over 1,200 earthquakes each year, 250 of which occur in the southwestern corner of the province (see Figure 1.4) (NRCan, 2012d, e). Most of these crustal and sub-crustal earthquakes are too small to be noticed and the fact that BC has not experienced major damage due to earthquakes in over fifty years (Cassidy et al., 2010; NRCan, 2012e, f), has led to diminished state of earthquake awareness and interest in southwestern BC (Hughes, 2001).

Despite this reduced state of both individual and collective earthquake interest, the seismic threats remain a real, significant, and growing hazard in BC. Onur and Seemann (2004) estimate the exceedance probability that Victoria residents will experience crustal or subcrustal structurally-damaging shaking in the next 10 years to be 4.5%. Over the next 100 years, or roughly the lifetime of our children, the estimate rises to 37% in Victoria. The subduction earthquake occurrence probabilities were calculated to be 7.5% over 10 years and 17% over 100 years. Onur and Seemann's (2004) study, however, does not address the aggregate shaking hazard in Victoria (i.e., crustal, subcrustal and subduction hazard combined), nor does it assess the distribution of seismic hazard across Vancouver Island; key information in assessing the Island's seismic risk.

1.3 Background to Disaster Research

Contemporaneous with the seismological and geotechnical advances in our understanding of earthquakes, social scientists have made similar progress over the past century in the study of disasters in North America. Driven by the physical, social and economic costs of disaster impacts on increasingly urbanized and industrialized societies (Dynes and Quarantelli, 1993), North American disaster research has developed across several disciplines including geophysics, meteorology, anthropology, engineering, sociology, geography, and medicine, but has thrived principally in the fields of sociology and geography (Davidson-Hunt and Berkes, 2000; Harrison, 2003). Geography, in particular, has played a unique, integrative and unifying role in hazards and disaster research historically, owing to the cross-disciplinary nature of its scholarship. This section introduces broad trends in disaster scholarship over the past century and notes academic inquiry has swung, pendulum-like, between foci on the human and physical agents in disasters.

1.3.1 Trends in Natural Hazards and Disaster Research

Conventional hazards research principally focuses on practical or applied approaches within either a geographical or sociological perspective and until recently little attention has been given to the context of hazards research enquiry (Emil and Peet, 1989; May, 1996; Stefanovic, 2003). Consequently, it is challenging in retrospect to impose any sort of philosophical framework on the breadth of hazards research, and the development of such a framework is correspondingly more a matter of interpretation. The following section discerns five broad periods of disaster research enquiry which can be identified in North America: 1) Human Agency Period; 2) Peril Quantification Period; 3) Engineered Solutions Period; 4) Binary Assessment Period; and, 5) Integrated Assessment Period (see Table 1.1).

1.3.1.1 Origins: Human Agency in Disasters – The earliest hazard research in North America was conducted by Samuel Prince, a Canadian at Columbia University, who completed his doctoral dissertation investigating the social impacts of the 1917 Halifax Explosion (Dynes and Quarantelli, 1993; Scanlon, 1988). Prince’s dissertation work “Catastrophe and Social Change” (Prince, 1920) launched the sociological study of hazards and disasters in North America, and early disaster research largely paralleled the evolution of theories and techniques in the broader field of sociology (Dynes and

Quarantelli, 1993). The well-funded Chicago School led the bulk of disaster research through the 1920s, and Robert Park made a notable contribution to disaster research by adapting ecological systems theory from plant ecology to the urban environment, eventually coining the term ‘urban ecology’. This provided a new lens through which to understand society and its component parts (Johnston et al., 2000). Geographer, Harlan Barrows (1923), challenged the purely sociological approach to disaster research and presented a revised social systems theory named ‘human ecology’, to incorporate ‘human adjustment to the physical environment’ as the principle tenet (Johnston et al., 2000). This introduction of the human ecology perspective represented geography’s foray into the field of disaster research in North America and served to provide a more holistic approach to subsequent disaster studies. Through the late 1920s and early 1930s, the human agency perspective predominated in disaster research but slowly yielded to a more empirical interest in the physical nature of ‘natural hazards’. Thus the disaster research pendulum began a swing from the social science-dominated perspective to a more physical science-dominated perspective.

1.3.1.2 Peril Quantification Period – Concurrent with, and as a consequence of, a rising confidence in North American engineering prowess, disaster research priorities shifted toward a focus on quantifying natural hazard events. In order to take advantage of society’s emerging technological and engineering capabilities, there was a demand to empirically define the magnitude and scope of hazard events. Consequently, through the 1930s and 1940s there was an increasing emphasis placed on research that provided empirical data detailing the parameters of hazardous events (Burton et al., 1978). Focus centred on defining such dimensions as: 1) magnitude or size of events; 2) frequency of event occurrence; 3) duration of hazardous event; 4) areal extent of hazard impacts; 5) speed of event onset; 6) variability of impacts within effected areas; and 7) regularity of event occurrence. If society could quantify the perils, then it could engineer solutions to prevent, protect and/or mitigate the impacts of those events and minimize losses. And, indeed, throughout the 1930s several engineering solutions, particularly associated with flood management, demonstrated and reinforced the benefit of mitigating hazards with engineered structures (White, 1973). While this research into the nature of hazards clearly moved the spotlight from the social dimensions of hazard research, it did not extinguish it, and students of Barrows, like Gilbert White, continued to contribute balanced research on human adjustments to disasters (Cutter, 1994).

Table 1.1 Retrospective Analysis of a Century of Hazards and Disaster Scholarship in North America

Date:	**Research Period:**	**Characteristics:**
1920s	Human Agency Period	• Chicago School – Urban Ecology (Sociology) • Introduction of Human Ecology (Geography) • Holistic studies of man and environmental hazards
1930s – 1940s	Peril Quantification Period	• External, nature dominated research • Focus on quantifying natural events: Frequency, Magnitude, Spatial Extent • Applied research to assist structural design: e.g., dykes & levees
1940s - 1960s	Engineered Solutions Period	• Robust technological solutions sought for all hazards • Attempt to minimize “increasing” losses thru more robust technology and more structural mitigation funding. • Heavy handed; little regard for impacts of structures.

Date:	**Research Period:**	**Characteristics:**
1970s – 1980s	Binary Assessment Period	• Re-emergence of human agency and impact of societal structures • Recognition of disasters as being the product of both physical and social forces • Focus on individual and collective adaptive behaviours to natural and technological disasters
1990s –	Integrated Assessment Period	• Conscious reflection on philosophical perspectives • Acceptance of need to integrate natural, technological, social, political and economic research themes

1.3.1.3 Engineered Solutions Period - Through the 1940s, 1950s, and 1960s, and with a growing body of empirical data on the nature of perils and their hazard, robust technical solutions were advocated as an effective approach to mitigating disasters and minimizing losses. In the United States and Canada, billions of dollars were spent on engineered solutions to mitigate the hazards through this period, particularly with respect to flood controls (Henstra and McBean, 2005; Mileti, 1999; White, 1973). Paradoxically, however, economic losses due to hazards grew throughout this period, despite these technical solutions. The benefits received from engineered solutions tended to be short-term, eliminating smaller, more frequent losses at the cost of bigger, less frequent catastrophic losses (Burton et al., 1978). Throughout the 1950s and into the early 1960s the predominant solution to this paradox was to spend more money so as to increase funding for bigger, more robust engineered solutions. However, this overt reliance on the technological approach only increased losses and eventually came to be seen as an arrogant, heavy-handed, and overly simplistic approach to disaster management (Burton et al., 1978; Wisner et al., 2003).

Several spectacular disasters triggered a reassessment of the “Engineered Solutions” perspective, with perhaps the most notable being the 1963 Vaiont Dam disaster in north eastern Italy (Kiersch, 1964). In this disaster, 2,500 people lost their lives when a massive landslide failed into the lake above the dam (Kiersch, 1964). The landslide generated a 250-metre-high wave which overtopped the 262-metre dam before traveling down-valley and impacting seven villages. The fact that the dam remained undamaged served to profile disasters as being more than just engineering problems, and the event helped shift the pendulum of disaster research back toward other, predominantly social, dimensions of disasters.

1.3.1.4 Binary Assessment Period – During the 1960s and 1970s the focus of natural hazards research evolved in parallel with the changes in research found in broader sociological and geographical inquiry. This period was characterised by a strong backlash against the prevailing research paradigms and a movement toward more liberal interpretations and radical approaches in the social sciences (Johnson and Sidaway, 2004). The rise of humanism, structuration theory, and feminist theory, among others, encouraged natural hazards researchers to re-examine the role of human agency in disasters. This re-emergence and focus on human agency and human adjustment in disaster research in the environmental hazards literature was largely led by a group of scientists that came to form what is referred to as “the Conventional Hazards School”

(Emil and Peet, 1989). This school offered more balanced assessments of both the physical and social dimensions of disasters. By the late 1970s, however, researchers from more radical perspectives began to challenge the Conventional Hazards School primarily on the grounds that Conventional School research did not adequately address societal or “collective” adjustments to natural hazards. For example, Tory (1979) criticized the Conventional School for not adequately taking into account anthropological and sociological literatures. Watts (1983) criticized it for not incorporating the structuralist literature and not accounting for the contributions of poverty and societal marginalization. Hewitt (1983) argued that Conventional School researchers, among others, were ignoring the role of public and private sector institutions and institutional failures in disasters - an argument that Hewitt (2004; 2007) continues to advocate. In the final analysis, the 1970s and 1980s were a rich introspective period in which hazards research itself came under scrutiny. Several new perspectives were used to challenge the scope and content of disaster research generally, and the role of human agency in disasters more comprehensively.

1.3.1.5 Integrated Assessment Period – By the late 1980s a number of distinct research perspectives had evolved and were in healthy conflict with one another (Mitchell, 1999). The following decade was characterised by thoughtful struggle to make sense of the breadth of emerging disaster research perspectives. This introspection led to a more philosophical discourse on the nature and direction of hazards research (Stefanovic, 2003; Mitchell, 1999) and two broad research paradigms predominated: Human Ecology and Political Economy. The older, time-honored human ecology perspective continues to focus on individual and group decision-making in response to disasters. The newer political economy perspective developed throughout the 1990s emphasizes research into the role of political, economic and social structures that either create hazardous conditions, or prevent at-risk populations from adequately preparing for hazards (Hewitt, 2004; Mitchell, 1999). Attempts to synthesize these two research paradigms into a 'Political Ecology' paradigm have gained some acceptance, but owing to the breadth and inclusive nature of the human ecology approaches, the wholesale adoption of the new paradigm has not occurred (Herring, 2010). Rather, recent research tends to centre on a post-modern discourse which revels in a diversity of perspectives. Consequently, today there seems to be a more multi-disciplinary, inter-disciplinary and trans-disciplinary focus to applied disaster research and practice. And, recognizing this trend, there appears to be a renewed role for the discipline of geography to, once again, synthesize and [re-]focus diverse lines of inquiry into disaster research.

1.4 Research Goal and Objectives

With three quarters of a million people living in primarily low-lying, coastal areas on Vancouver Island (BC Stats, 2011), communities in this region form one of Canada's highest earthquake risk (NRCanada, 2012b). More importantly, the risk of significant life, property, social and economic loss due to an earthquake is increasing annually in these west coast Canadian communities. This increase can be largely attributed to six factors: 1) increasing population, 2) increasing infrastructure exposure; 3) increasing reliance of the public on government protection, particularly in urban environments; 4) increasing fiscal constraints on governments, 5) aging infrastructure, and 6) increasing probability of a subduction earthquake (Britton, 2004; Hewitt, 2004; Mileti, 1999; Onur and Seemann, 2004).

1.4.1 Research Goal

Given the increasing environmental, physical, human, social, and economic risk on Vancouver Island, and the paucity of regional risk assessments, the need to comprehensively assess the seismic risk to Island communities is pressing. An accurate risk assessment facilitates effective preparedness, response, and recovery decision-making both in the private-sector and at all levels of public sector governance. What are the earthquake threats to Island communities? How likely are these threats to occur? If they do occur, what is the geographic and temporal extent of their impacts? What are the environmental, human, and social vulnerabilities in Island communities? And what capacities exist, locally, regionally, nationally, and internationally to effectively mitigate the effects of a moderate to large earthquake?

Some of this risk information is already available (e.g. seismic hazard calculations). However, much of the available information is in a format and/or forum not readily accessible to community decision-makers. And while scientific knowledge translation and transfer (KTT) has long been recognized as a barrier to efficient and effective societal advancement (e.g., Bennett and Jessani, 2011; Estabrooks et al. 2006; Graham et al., 2006), the issue becomes particularly poignant with respect to natural hazards and risk management (Britton, 2001, 2004; Cardona, 2004; Ferrier and Haque, 2003; Scandlyn et al. 2010). Recognizing these challenges the following objectives are identified to better organize, frame and present the existing seismic risk information for Vancouver Island communities.

1.4.2 Research Objectives

In reviewing the management of seismic risk on Vancouver Island several research challenges emerge, but three in particular become salient. First, little research exists on the operational assessment of disaster risk in Canada (Ferrier and Haque, 2003; Fraser 2009). Second, little information is available to the public to help understand the seismic hazard their communities face from each of the three primary earthquake sources. And third, no research exists with respect to the shaking hazard resulting from the next Cascadia subduction aftershock sequence. To address each of these challenges, three corresponding research objectives are identified and outlined below.

1) Comprehensive Seismic Risk Management of Vancouver Island – This research objective focuses on identifying and detailing effective risk management practices for adoption in the practice of disaster management. Three principle research questions arise: a) what are the core components of a comprehensive risk management framework; b) can these elements be integrated in the practice of disaster and emergency management (DEM); and c) using a disaster risk management framework, has a comprehensive assessment of seismic risk on Vancouver Island been conducted?

2) Shaking Intensity Probabilities for Vancouver Island Communities – Recognizing that the shaking probabilities provided by the Geological Survey of Canada are presented by scientists and engineers in a language and format that is difficult for the general public to comprehend and act upon, this research objective focuses on three research questions a) can Vancouver Island's seismic hazard be presented in ways that are more easily understood and more readily acted upon by elected officials, planners, managers and other non-scientists; b) can seismic hazards be combined to offer a single aggregate shaking probability for the earthquake peril; and c) can any new seismic hazard estimation be presented in a graphic format (i.e. maps) for communities across Vancouver Island.

3) Aftershock Shaking Probabilities for Vancouver Island and the Broader Cascadia Region – While much research has focused on the earthquake hazard posed by the three principal Cascadia earthquake sources including the Cascadia subduction interface earthquakes, the shaking hazard resulting from an aftershock sequence following a Cascadia subduction event has not been quantified to date. This despite the serious consequences of prolonged aftershock sequences evident following recent subduction interface earthquakes such as the 2004 Sumatra and 2011 Tohoku events. This research objective identifies three subordinate research questions: a) can the shaking hazard resulting from a Cascadia subduction aftershock sequence be modeled and quantified; b) can the resultant estimates be presented in simple, meaningful terms that can be readily understood and acted upon by elected officials and other non-scientific audiences; and c) can any new modeling provide seismic hazard estimates for select communities across the Cascadia region?

1.5 Scope and Definitions

This dissertation research focuses on the examination of the seismic risk of Vancouver Island communities from a holistic, human-ecology perspective. It approaches the study of seismic risk as a trans-disciplinary endeavour, centred on the interconnected and reciprocal relationship between humans and their natural, built and social environments. Accordingly, it synthesizes the terminology and research from a variety of fields ranging from engineering and actuarial sciences, to geophysics and seismology, to economics and political science. Recognizing the breadth of this scholarship, establishing some common nomenclature at the outset is critical to the discussion following.

- ***Communities*** consist of individuals sharing similar values, beliefs, interests, social networks and institutions (adapted from Bell and Newby, 1971; Chipuer and Pretty, 1999). The concept of community is scalable, such that both a sub-population of a municipality (e.g., ham radio operators) can be identified as a community, and a nation, or group of nations, can be identified as a community. This scalability and the concept of nested communities is critical in disaster risk management, as the survival of any one community may be linked to the strength of its ties to other, sometimes larger or smaller communities.
- ***Risk*** is the product of a peril or threat’s ‘hazard’ and the ‘consequences’ of the event. While it often focuses on measures of the cost of an event’s occurrence (e.g., human, environmental, economic costs), it also includes measures of the benefits and opportunities afforded by the occurrence of the event.

- ***Peril*** is a category or class of dangerous phenomenon, substance, human activity or condition (e.g., earthquake, flood, hazardous material event, terrorism event).
- ***Threat*** is a specific type of peril (e.g., subduction earthquake; ice dam flood; sulphuric acid spill; cobalt bomb).
- ***Hazard*** is the likelihood that a given peril or threat (dangerous phenomenon, substance, human activity or condition) will occur.
- ***Consequences*** refer to the negative and/or positive effects of a hazard expressed in terms of human, natural-environment, built-environment or social-environment impacts and capacities.
- ***Human consequences*** are usually expressed in quantitative terms to measure of the effects of a hazard on human life. It is commonly expressed as 1) the number of fatalities; 2) the number of severely injured or ill people, and 3) the number of sheltered or displaced people.
- ***Natural-environment consequences*** are a quantitative assessment of the effects of a hazard on the lithosphere, atmosphere, hydrosphere, biosphere in the impacted area. This includes, for example, assessments of post-event air, water, plant and soil contamination.
- ***Built-environment consequences*** are the quantitative and qualitative measures of the effects of a hazard on built structures and infrastructure. This includes buildings, homes, roads, railways, bridges, tunnels, towers, communications infrastructure, industrial facilities, utility cables and piping.
- ***Social-environment consequences*** are the quantitative and qualitative measures of the effects of a hazard on socially constructed systems. This includes measures of the

impacts on educational, informational, political, economic, and financial systems. These impacts incorporate such issues as post-disaster land rights, territorial loss, human rights violations, property rights violations, price-gouging, social psychological impacts, and the loss of cultural assets.

- ***Risk Management*** is the study and practice of managing risk associated with one or more perils or threats. It incorporates the provision of risk context (e.g., scope and parameter definition), risk assessment (risk identification, risk analysis, and risk evaluation), risk treatment (risk prevention, risk protection, risk mitigation), and risk acknowledgement (risk acceptance, risk transfer). Finally, it involves a continual, iterative process of reviewing, reassessing and adjusting to risks. Additional, more specific definitions are included in the following chapters.

1.6 Dissertation Outline

Four chapters follow this introduction. Each of the next three chapters, in turn, addresses one of the three outlined research questions, and is presented as a stand-alone journal paper. Chapter 2 investigates risk, risk management and risk analysis in a disaster management context and with the objective of developing a disaster risk management framework. The new disaster risk management framework then is used to begin to identify gaps in a comprehensive seismic risk assessment of Vancouver Island's communities.

Chapter 3 addresses knowledge transfer challenges with respect to the communication of seismic hazard to Vancouver Island communities. Recognizing that simple, readily understandable seismic hazard assessment data are not currently available for Vancouver

Island community decision-makers and the publics they serve, this research re-calculates the seismic hazard based on the latest Geological Survey of Canada models and generates simple, readily-understandable shaking probabilities likely to result from three Cascadia earthquake sources. Finally, the research presents the first aggregate shaking probability calculations for Vancouver Island communities based on the combined estimates of shaking hazard from each of the three earthquake sources.

The research presented in Chapter 4 focuses on estimating the shaking hazard from Cascadia subduction earthquake aftershocks. By reviewing and analyzing 13 historical circum-Pacific subduction events, and using these events as an analogue, the likelihood of damaging shaking resulting from subduction aftershocks in Cascadia region communities is estimated. The research offers the first subduction aftershock sequence ground shaking estimates for communities along the west coast of North America.

The final chapter (Chapter 5) of the dissertation summarizes the seismic risk studies presented in the previous chapters; highlights the main results provided, and identifies opportunities for further research.

1.7 References

Adams J 1990. Paleoseismicity of the Cascadia subduction zone: evidence from turbidites off the Oregon-Washington margin. *Tectonics,* 9: 569-583.

Arima EY 1991. Between Ports Alberni and Renfrew: Notes On West Coast Peoples. Canadian Museum of Civilization, Hull, QC, Canada.

Atwater BF and Hemphill-Haley E 1997. Recurrence intervals for great earthquakes of the past 3500 years at the northeastern Willapa Bay, Washington. *United States Geological Survey Professional Paper* 1576.

Atwater BF, Nelson AR, Clague JJ, Carver GA, Yamaguchi DK, Bobrowsky PT, Bourgeois J, Darienzo ME, Grant WC, Hemphill-Haley E, Kelsey HM, Jacoby GC, Nishenko SP, Palmer SP, Peterson CD, and Reinhart MA 1995. Summary of coastal geologic evidence for past great earthquakes at the Cascadia subduction zone. *Earthquake Spectra* 11(1): 1-18.

Barrows H 1923. Geography as Human Ecology. *Annals of the Association of American Geographers*, 13, 1-14.

Basham P and Newitt LR 1993. A historical summary of Geological Survey of Canada studies of earthquake seismology and geomagnetism. *Canadian Journal of Earth Sciences*, 30(2): 372-390.

Bell C and Newby H 1971. Community Studies: An Introduction to the Sociology of the Local Community. New York, Praeger Publishers.

Bennett G and Jessani N 2011. The knowledge translation toolkit: bridging the "know-do" gap: a resource for researchers. SAGE Publications and the International Development Research Centre (IDRC), Canada. http://idl-bnc.idrc.ca/dspace/bitstream/10625/46152/1/132642.pdf [Website Last Accessed 28 December 2012].

Blais-Stevens A, Rogers GC, and Clague JJ 2011. A revised earthquake chronology for the last 4,000 years inferred from varve-bounded debris-flow deposits beneath an inlet near Victoria, British Columbia, *Bulletin of the Seismological Society of America*, 101(1): 1-12.

BC Aboriginal Relations 2012. Vancouver Island Region First Nations Listing. Government of British Columbia. http://www.gov.bc.ca/arr/firstnation/maps/map_1.htm. [Website Last Accessed: 14 March 2012].

BC Stats (British Columbia Statistics) 2011. Sub-provincial Population Estimates, Government of British Columbia.

http://www.bcstats.gov.bc.ca/data/pop/popstart.asp [Website Last Accessed: 12 February 2012].

Britton NR 2001. A new emergency management for the new millennium? *Australian Journal of Emergency Management*, 16(4):44-54.

Britton N 2004. Asia-Pacific Perspectives on Managing Risk from Natural Hazards. 1st Annual CRHNet Symposium: Reducing Risk through Partnerships. 18-20 November 2004. Winnipeg, Manitoba, Canada.

Burton I, Kates RW, and White GF 1978. The Environment as Hazard. New York, NY: Oxford University Press.

Cardona OD 2004. The Need for Rethinking Concepts of Vulnerability and Risk from a Holistic Perspective: A Necessary Review and Criticism for Effective Risk Management. In G. Bankof, G. Frerks & D. Hilhorst (Eds.), Mapping Vulnerability: Disasters, Development, and People (pp 37-51). London: Earthscan.

Cassidy JF, Rogers GC, Lamontagne M, Halchuk S, and Adams J 2010. Canada's earthquakes: the good, the bad, and the ugly. *Geoscience Canada*, 37(1): 1-17.

Chipuer HM and Pretty GMH 1999. A review of the Sense of Community Index: Current uses, factor structure, reliability, and further development. *Journal of Community Psychology*, 27(6), 643-658.

Cutter S 1994. Environmental Risks and Hazards. Upper Saddle River, NJ: Prentice Hall, Inc.

Davidson-Hunt IJ and Berkes F 2000. Environment and Society through the Lens of Resilience: Toward a Human-in-Ecosystem Perspective. Local Knowledge, Institutions and Resilience Panel, International Association for the study of common property conference, Indiana University, May 31- June 4, 2000.

Dragert H, Chen X, and Kouba J 1995. GPS monitoring of crustal strain in southwest British Columbia with the western Canada Deformation Array, *Geomatica*, 49(3): 301-313.

Dragert H, Wang K, and James TS 2001. A silent slip event on the deeper Cascadia subduction interface. *Science*, 292: 1525 – 1528.

Dragert H, Wang K, and Rogers G 2004. Geodetic and seismic signatures of episodic tremor and slip in the northern Cascadia Subduction Zone. *Earth Planets Space*, 56: 1143–50.

Dynes RR and Quarantelli EL 1993. The place of the 1917 explosion in Halifax harbor in the history of disaster research: the work of Samuel H. Prince. University of Delaware, Disaster Research Center, Preliminary Paper, #189. http://dspace.udel.edu:8080/dspace/bitstream/handle/19716/576/PP189.pdf?sequence=3 [Website Last Accessed: 3February2012].

Emil J and Peet R1989. Resource management and natural hazards. In Richard Peet and Nigel Thrift, editors, New Models in Geography, London: Unwin Hyman, 49-76.

Environment Canada 2011. Canadian climate normals or averages 1971-2000. Government of Canada. http://www.climate.weatheroffice.gc.ca/climate_normals/index_e.html, [Last Website Accessed: 30 Nov 2011].

Erikson J 2001. Plate tectonics: unraveling the mysteries of the earth. Checkmark Books, New York, NY, USA.

Estabrooks CA, Thompson DS, Lovely JJ, and Hofmeyer A 2006. A guide to knowledge translation theory. *Journal of Continuing Education in Health Professions*, 26(1): 25-36.

Ferrier N and Haque CE 2003. Hazards risk assessment methodology for emergency managers: a standardized framework for application. *Natural Hazards*, 28: 271-290.

Flück P, Hyndman RD and Wang K 1997. Three-dimensional dislocation model for great earthquakes of the Cascadia subduction zone. *Journal of Geophysical Research*, 102: 20539-20550.

Fraser S 2009. Report of the Auditor General of Canada to the House of Commons. Chapter 7 Emergency Management – Public Safety Canada. http://www.oag-bvg.gc.ca/internet/docs/parl_oag_200911_07_e.pdf [Website Last Accessed: June 25, 2012].

Go Canada 2012. Vancouver Island Map. http://gocanada.about.com/od/britishcolumbia/tp/Vancouver_Island_Canada.htm, [Website last accessed, 12 February 2012].

Graham ID, Logan J, Harrison MB, Strauss SE, Tetroe J, Caswell W, and Robinson N 2006. Lost in knowledge translation: time for a map? *Journal of Continuing Education in Health Professions,* 26(1): 13-24.

Guthrie RH 2005. Geomorphology of Vancouver Island: mass wasting potential. Government of British Columbia, Ministry of Environment, Research Report No. RR01, 30p.

http://www.env.gov.bc.ca/wld/documents/techpub/rr01/VImasswaste.pdf. [Website Last Accessed: 30 Nov 2011].

Harrison N 2003. Good governance: complexity, institutions, and resilience. Opening Meeting of the Global Environmental Change Research Community, Montreal, Canada 16-18 October 2003. 22pp.

Henstra D and McBean G 2005. Canadian disaster management policy: moving towards a paradigm shift? *Canadian Public Policy*, 31(3): 303-318.

Herring C 2010. Towards a political ecology of disaster: the urbanization of neoliberalism in New Orleans. World Ecology Research Network, http://www.worldecologyresearch.org/papers2010/Herring_Political_Ecology_disaster.pdf [Website Last Accessed 5 February 2012].

Hewitt K 1983. The Idea of Calamity in a Technocratic Age. Chapter 1 in Hewitt K, editor, Interpretations of Calamity: from the Viewpoint of Human Ecology. Boston: Allen & Unwin Inc., 2-32.

Hewitt K 2004. Institutional failures, hidden damage, and social vulnerability. First Annual Canadian Risk and Hazard Net Symposium, Winnipeg, Manitoba, Canada, November 18- 20, 2004.

Hewitt K 2007. Preventable disasters: addressing social vulnerability, institutional risk, and civil ethics, *Geographisches Rundscahu: International Edition*, 3/1, 43-52.

Hughes L 2001. Personal Communication, Results of an Unpublished Risk Survey. Risk Management Branch, Ministry of Finance, Government of British Columbia.

Hutchinson I and McMillan AD 1997. Archaeological evidence for village abandonment associated with Late-Holocene earthquakes at the northern Cascadia Subduction Zone. *Quaternary Research*, 48: 79-87.

Johnston RJ, Gregory D, Pratt G, and Watts M 2000. The Dictionary of Human Geography, 4th Edition. Malden, MA: Blackwell Publishers.

Johnston RJ and Sidaway JD 2004. Geography and Geographers: Anglo-American Human Geography Since 1945, 6th Edition, London: Arnold Publishers.

Kearey P, Klepeis KA, and Vine FJ 2009. Global Tectonics, Third Edition. Wiley-Blackwell, Hoboken, NJ, USA.

Kiersch GA 1964: Vaiont Reservoir Disaster. *Civil Engineering*, 34: 32-39.

Klohn-Crippen 1994. Preliminary seismic microzonation assessment for British Columbia. Resources Inventory Committee, Government of British Columbia, http://www.ilmb.gov.bc.ca/risc/pubs/earthsci/seismic/index.htm, [Website Last Accessed: February 22, 2012].

LaMontagne M, Halchuk S, Cassidy JF, and Rogers G 2007. Significant Canadian Earthquakes: 1600-2006. *Geological Survey of Canada Open File Report*: 5539, Natural Resources Canada, 32p.

Ludwin RS, Smits GJ, Carver D, James K, Jonientz-Trisler C, McMillan AD, Losey R, Dennis R, Rasmussen J, De Los Angeles A, Buerge D, Thrush C, Clague J, Bowechop J, and Wray J 2007. Folklore and earthquakes: Native American oral traditions from Cascadia compared with written traditions from Japan. *Geological Society of London, Special Publications,* 273(1): 67-94.

Maud R (Editor) 1978. The Salish People, The Local Contribution of Charles Hill-Tout, Volume IV, In The Sechelt and the Southeastern Tribes of Vancouver Island, Talonbooks, Vancouver.

May PJ 1996. Environmental Management and Governance: Intergovernmental Approaches to Hazards and Sustainability. London and New York: Routledge.

Mazzotti S and Adams J 2004. Variability of near-term probability for the next great earthquake on the Cascadia Subduction Zone. *Bulletin of the Seismological Society of America*, 94(5): 1954-1959.

Mileti DS 1999. Disasters by Design: A Reassessment of Natural Hazards in the United States. Washington, DC: Joseph Henry Press.

Mitchell JK 1999. Crucibles of Disaster. Tokyo, Japan: United Nations University Press. 535p.

Monahan PA, Levson VM, Henderson P and Sy A 2000. Composite Relative Earthquake Hazard Map of Greater Victoria, Ministry of Energy and Mines, Government of British Columbia, Geoscience Map 2000-1. http://www.empr.gov.bc.ca/Mining/Geoscience/SurficialGeologyandHazards/VictoriaEarthquakeMaps/composite/Pages/default.aspx [Website last accessed 2February2012].

NRCan (Natural Resources Canada) 2012a. Earthquakes Canada. Government of Canada, http://www.earthquakescanada.nrcan.gc.ca/histor/20th-eme/1918-eng.php [Website Last Accessed: 2 February 2012].

NRCan (Natural Resources Canada) 2012b. Earthquakes Canada. Earthquake Hazard Calculator, Government of Canada, http://www.earthquakescanada.nrcan.gc.ca/hazard-alea/interpolat/index-eng.php [Website Last Accessed: 2 February 2012].

NRCan (Natural Resources Canada) 2012c. Earthquakes Canada. Government of Canada, http://www.earthquakescanada.nrcan.gc.ca/zones/westcan-eng.php#Cascadia [Website Last Accessed: 2 February 2012].

NRCan (Natural Resources Canada) 2012d. Earthquakes Canada. Government of Canada, http://www.earthquakescanada.nrcan.gc.ca/stndon/NEDB-BNDS/bull-eng.php [Website Last Accessed: 14 March 2012].

NRCan (Natural Resources Canada)2012e. Earthquakes Canada. Government of Canada, http://www.earthquakescanada.nrcan.gc.ca/stndon/NEDB-BNDS/bull-eng.php [Website Last Accessed: 2 February 2012].

NRCan (Natural Resources Canada) 2012f. Earthquakes Canada. Government of Canada, http://www.earthquakescanada.nrcan.gc.ca/info-gen/faq-eng.php [Website Last Accessed: 2 February 2012].

Onur T 2001. Seismic Risk Assessment in Southwestern British Columbia. Unpublished Ph.D. Thesis, University of British Columbia, Vancouver, British Columbia, Canada.

Onur T and Seemann MR 2004. Probabilities of significant earthquake shaking in communities across British Columbia: implications for emergency management. In, Proceedings of the13th World Conference on Earthquake Engineering, August 1-6, Vancouver, British Columbia, Canada, Paper 1065, Mira Digital Publishing, St. Louis, MO, USA.

Prince SH 1920. Catastrophe and Social Change: Based Upon a Sociological Study of the Halifax Disaster, Unpublished Doctoral Dissertation, Columbia University, New York, New York.

Rogers GC 1988. An Assessment of the megathrust potential of the Cascadia Subduction Zone; *Canadian Journal of Earth Sciences*, 25, 844-852.

Rogers GC 1992. The history of earthquake studies in British Columbia: from indian legend to satellite technology. In Levson V., compiler, The Earth Before Us: Pioneering Geology in the Canadian Cordillera, *British Columbia Ministry of Energy, Mines and Petroleum Resources, Open File* 1992-19, p. 61-66. http://www.empr.gov.bc.ca/Mining/Geoscience/PublicationsCatalogue/OpenFiles/1992/1992-19/Pages/Earthquake.aspx, [Website Last Accessed: 2 Dec 2011].

Rogers GC and Dragert H 2003. Episodic Tremor and Slip on the Cascadia Subduction Zone: the Chatter of Silent Slip. *Science*, 300(5627): 1942-1943.

Satake K, Shimazaki K, Tsuji Y, and Ueda K 1996. Time and size of a giant earthquake in Cascadia inferred from Japanese tsunami record of January 1700. *Nature*, 379: 246-249.

Scandlyn J, Simon CN, Thomas DSK, and Brett J 2010. Theoretical Framing of Worldviews, Values, and Structural Dimensions of Disasters, In Phillips, BD, Thomas, DSK, Fothergill, A, and Blinn-Pike, L, (eds) Social Vulnerability to Disasters, 27 -50.

Scanlon, J. 1988. Disaster's little known pioneer: Canada's Samuel Henry Prince, *International Journal of Mass Emergencies and Disasters*, 6: 213-232.

Stefanovic I 2003. The contribution of philosophy to hazards assessment and decision making. *Natural Hazards*, 28 (2-3): 229-247.

Tory WI 1979. Hazards, hazes and holes: a critique of the Environment as hazard and general reflections on disaster research. *Canadian Geographer*, 23: 368-83.

Tourism British Columbia: 2008, Vancouver Island, Victoria and the Gulf Islands regional profile: building tourism with insight. http://tourismbc.com/Libraries/Research_VI_Profile/Vancouver_Island_Victoria_and_the_Gulf_Islands_Regional_Profile_2008.sflb.ashx, [Website Last Accessed: January 2010].

Verdonck D 2006. Contemporary vertical crustal deformation in Cascadia. *Tectonophysics*, 417(3-4): 221-230.

Watts M 1983. On the poverty of theory: natural hazard research in context. In K. Hewitt, Editor, Interpretation of Calamity, Boston, MA, USA: Allen & Unwin.

Wegener A 1968. The origin of continents and oceans. Translated by Biram J. London, UK: Methuen.

White GF 1973. Natural hazards research., In Chorley RJ, Editor, Directions in Geography, London, UK: Methuen.

Wisner B, Blaikie P, Cannon T and Davis I 2003. At Risk: Natural Hazards, People's Vulnerability and Disasters. London, UK: Routledge.

Wuorinen V 1976. Seismic microzonation of Victoria - a social response to risk, Foster HD, Editor, In Victoria Physical Environment and Development, Western Geographical Series, 12, Victoria, BC Canada: University of Victoria, 185-219.

Yorath CJ, and Nasmith HW 1995. The geology of Southern Vancouver Island: a field guide., Victoria, British Columbia, Canada: Orca Publishing.

Yorath CJ, Kung R, Franklin R 2001. Geoscape Victoria. Geological Survey of Canada Miscellaneous Report M41-8/74F.

Chapter 2:

Risk Analysis in Disaster and Emergency Management[1]

---

[1] A version of this paper is being submitted for publication to the Journal of Emergency Management

2.0 RISK AND DISASTER MANAGEMENT: A FRAMEWORK FOR INTEGRATION

MARK SEEMANN [1,2]

[1]Department of Geography, University of Victoria, Victoria, BC, V8W 3P5, Canada (Email: mseemann@uvic.ca); [2]School of Peace and Conflict Management, Royal Roads University, Victoria, BC, V9B 5Y2

2.1 Abstract

Risk is a multi-faceted and extensively studied concept. It permeates all aspects of our daily lives and figures prominently in many of society's environmental, social and technical advances. Scholars from a host of disciplines, ranging from engineering and the physical sciences through to sociology, political science and economics have grappled with the concept and contributed much to our understanding of risk. Until recently, however, risk and the management of risk have had a relatively limited role in the practice of disaster management. In fact, despite the current recognition of it as a foundational principle of disaster and emergency management, few disaster and emergency management organizations comprehensively assess risk, and fewer still coordinate with their jurisdictional risk management offices. This paper reviews the risk management processes in the context of disaster and emergency management (DEM) and, based on international best practices, outlines a strategic framework for an interdisciplinary approach to disaster risk management. Finally, the paper uses the new disaster risk management framework to identify gaps in the seismic risk assessment of Vancouver Island, Canada and calls for focused research efforts on these areas to help minimize future life, property and economic losses.

Key Words: Risk, Disaster Management, Disaster Risk Analysis, Seismic Risk, Vancouver Island, Canada

2.2 Introduction

Risk can be broadly defined as uncertainty about an outcome - either negative or positive (Baranoff et al., 2005). Traditionally, however, risk primarily focuses on the uncertainty associated with potential losses and is seen as the product of 1) the chance of a negative event happening, and 2) the consequences of the event should it occur (Ansell and Wharton, 1992; Ropeik and Gray, 2002). Today, the term risk has numerous connotations depending on the disciplinary context in which it is used. Stockbrokers and investors, for example, associate the term with the concept of profit and opportunity, while physicians typically associate the term with health complications and death. Disaster managers, with purview over health, environmental, social, and economic impacts on communities, have not clearly defined the term, nor have they provided guidance on assessing risk (e.g., Fraser, 2009). Correspondingly, the term ‘risk’ in the profession of disaster management is used loosely across a variety of contexts leading to misunderstandings, data incompatibility and confusion. Therefore, there is a need to simply, clearly and objectively define risk, to articulate the role of risk in the disaster management context, to standardize the terminology associated with risk, and to outline a methodical approach to its assessment and management (Britton, 2001; Cardona, 2004; Manyena, 2006; Scandlyn et al., 2010; Schmidt et al., 2011). To this end, this paper presents a strategic risk management approach in disaster management, outlines a generic framework for integrating international risk management standards and best practices into disaster management, and focuses on identification of the fundamental steps required in analyzing disaster risk. Finally, the disaster risk framework is adopted to review the state of seismic risk assessment for Vancouver Island, British Columbia, Canada. Future research opportunities are also identified.

2.2.1 What is Risk Management?

Risk management refers to the functional organization and management of resources (including human and financial resources) in order to minimize the adverse effects of accidental losses and maximize potential gains (adapted from ISO, 2009a). Operationally, risk management can be described as a decision-making process designed to prevent, protect and control for the impacts of one or more perils. Baranoff et al. (2005) suggest that risk management decision-making processes involve six basic steps in managing risk: 1) identifying potential perils (loss exposures); 2) analyzing the negative and positive potential of each of the perils; 3) identifying feasible risk control techniques; 4) evaluating and selecting appropriate risk control techniques; 5) implementing risk control measures; and 6) monitoring and evaluating changes in each of the previous steps. While some or all of these decision-making steps have been variously configured and adopted by organizations both nationally (e.g., AS/NZS, 2004 in Australia and New Zealand; BSI, 2008 in the United Kingdom; and, CSA, 2008; CSE and RCMP, 2007; PS, 2012a in Canada) and internationally (e.g., EC 2010; ISO 2008; ISO 2009a, b), these fundamental steps underpin current standards and best practices in risk management and offer tremendous benefit to disaster and emergency managers if appropriately applied.

2.2.2 Why Incorporate a Risk Management Approach in Disaster and Emergency Management (DEM)?

The management of disaster risk provides individuals, businesses, non-government organizations (NGOs) and governments with a transparent, methodical and structured approach to identifying, controlling and acknowledging risk. It ensures that the management of risks is conducted in a comprehensive, balanced, and justifiable manner. Direct benefits of utilizing a risk management approach in a disaster context include:

1. Saving lives and reducing injuries
2. Protecting the natural environment
3. Protecting the built environment, its contents and property
4. Increasing both the absolute and relative long-term financial and functional stability of organizations/communities
5. Saving money
6. Reducing liability of the individual or entity
7. Protecting the reputation and image of the individual or entity
8. Ensuring a clear understanding of the risk being retained and the risk being transferred
9. Enhancing the ability of an individual or entity to prepare for potential future circumstances (both negative and positive).

While a deliberate focus on the management of disaster risk does not eliminate the risk, the quantification and clear understanding of risks faced allow an individual or entity to prioritize risks and take measured and measurable steps to reduce potential losses and maximize benefits. The question becomes how best to integrate risk management principles into the practice of disaster and emergency management.

2.2.3 Risk Management in Disaster and Emergency Management

Disaster management activities traditionally span three phases of any disaster: before, during and after an event. Correspondingly, practitioners and researchers have historically identified three phases of disaster and emergency management activities - Preparedness, Response, and Recovery – to reflect the three phases of a disaster. Over the past few decades, however, the identified phases of DEM have varied considerably both within and between countries. By the end of the last century, the United Kingdom, for example, had added “Prevention” as a fourth pillar of DEM to profile the advantages of eliminating hazards before they occur. At the same time, the United States, had adopted “Mitigation” as a fourth pillar to profile and promote the need for targeted DEM funding on this particular issue. Canada opted for a hybrid approach and continues to promote Prevention/Mitigation as the fourth pillar of DEM (PS, 2011). Most recently, the United Kingdom has moved to six phases of emergency management- Anticipation, Assessment, Prevention, Preparation, Response and Recovery (Cabinet Office, 2012a) and this past year, the United States has moved back to the traditional three-phase approach recognizing Prevention, Protection, and Mitigation as “core capabilities” of Preparedness (HS, 2012a). Interestingly, while risk management approaches are widely documented as being fundamental to DEM in most countries (Blanchard et al., 2007; HS, 2012b; PS, 2011; Rabjohn, 2008), only the UK currently identifies risk assessment as a discrete, critical phase of DEM.

This paper adopts the traditional three-phase approach to DEM, recognizing that such activities as anticipation, assessment, prevention, protection, and mitigation are all activities that occur before an event and are therefore subcomponents of preparedness. And while it is recognized that risk management activities can be applied in each of the three DEM phases, this paper focuses on the integration of risk management practices into the preparedness phase of disaster management.

2.3 Risk Management and Disaster Preparedness

The integration of a risk management approach into the preparedness phase of DEM can be seen as an iterative process cycling through five principle activities: establishing the risk management context; conducting risk assessments; implementing risk treatments; acknowledging residual risk; and, monitoring and reviewing the risk process. Table 2.1 outlines key components of an effective Disaster Risk Management (DRM) program and presents a standardized generic approach to managing risk that is suitable for the development or enhancement of any DEM program.

2.3.1 Establishing the Disaster Risk Management Context

The first of the five DRM components is the establishment of a clear and transparent risk management context. Principle activities included in this core component are: the assignment of risk management ownership; the identification of risk strategic objectives; the delineation of the scope of the risk; and, the stipulation of the risk parameters. The assignment of risk management ownership establishes the responsible party/parties for disaster risk management. Responsibilities may well cross departmental lines (e.g., Risk Management, Emergency Management, Health, Finance, Treasury Board) and therefore it is important that specific responsibilities be clearly articulated. The assignment of risk management ownership also: 1) ensures clear authorities are established and appropriately delegated to enable the responsible party/parties to effectively operate (e.g., including various acts, regulations, policies and bylaws), and 2) ensures the provision of the required resources, both human and/or financial, to effectively manage the portfolio.

The remaining activities in establishing the risk context each define the risk management process at progressively finer resolutions. Strategic objective activities outline the high-level risk management objectives of the entity given its relationship with its environment. Financial, operational, competitive, organizational, social, cultural, linguistic and legal considerations each have a bearing on this relationship (AS/NZS, 2004) and define the entity's risk management goals in the broadest possible terms. At a finer resolution, the scope of the risk to be managed is explicitly defined, both spatially and temporally, and specific exclusions and inclusions are identified. Finally, with the strategic objectives and scope defined, and recognizing the existing operational and financial realities of the entity, specific 'parameters' are identified to ensure the management of risk is conducted in the most efficient and responsible manner possible. While it might be ideal to assess each and every possible peril in a given area over a given time frame, it would likely be cost-prohibitive. Instead, it may be more efficient to identify specific parameters to assess, for example, the two or three of the most frequent perils and two or three of the largest consequence perils to facilitate the targeted management of the risks faced.

2.3.2 Conducting Risk Assessments

Risk assessment, the second of the five DRM components, includes steps required to evaluate perils, their hazard and potential consequences and to provide a comprehensive assessment of the risk to a given entity or jurisdiction. Specific activities included in the assessment of risk involve the identification of perils, the risk analysis of each peril, the establishment of risk criteria, and the evaluation of the risks from all perils against identified risk tolerances and stipulated acceptable risk limits (ISO, 2009a,b).

The assessment of risk begins with peril awareness and identification. Peril awareness and identification is conducted through a variety of methods which range from the vigilant monitoring for such perils as terrorism, cybercrime and espionage, to the physical monitoring of the earth’s tectonic plates and atmospheric changes. As potential perils become apparent and are confirmed each is then subject to a risk analysis.

While a more in-depth discussion on risk analysis follows in the next section, risk analysis activities focus on the quantitative and qualitative assessment of the identified perils by analyzing specific threats. The result of these risk analyses must then be weighed against societal acceptable risk limits and/or risk tolerance for the threat and peril before the management of the risk associated with that threat or peril can be justifiably acted on by community decision-makers. With both the peril risk analysis and societal risk tolerance measures in hand, the risk posed can be meaningfully evaluated – both within and between perils – and a meaningful discussion can ensue as to which possible risk treatment options can be feasibly implemented.

2.3.3 Assessing and Implementing Risk Treatments

The third component of DRM framework focuses on ensuring risk treatment options are identified, reviewed and implemented to manage the risk deemed to exceed identified tolerances. Risk control options include a wide variety of measures to prevent, protect, and/or mitigate the negative effects of a given peril. Prevention options focus on inhibiting peril occurrence at its source. An example of a preventative measure is the controlled detonation of unstable snow masses to avoid the occurrence of dangerous avalanches. Protection options, in contrast, recognize a peril exists that cannot be prevented, and focuses on a range of measures to stop or deflect the impact of the peril on an exposed individual, site or community. Again using avalanches as an example, measures such as the construction of deflection berms or structures to reroute avalanches around a site or the construction of snowsheds over highways provide for the protection of assets. Mitigation measures, acknowledge the fact that a peril may well impact a community, and they include steps to lessen or minimize the losses associated with the peril in the impacted community. Earthquakes, for example, cannot be prevented nor can communities protect themselves from them, therefore mitigation measures remain the focus for seismically exposed communities seeking to enhance their resilience.

Mitigation measures can be broadly classified as either structural, non-structural, or functional/organizational activities designed to minimize environmental, life, property, and social (including economic) losses. Structural mitigation generally refers to the strengthening of structures against the likely impacts of a hazard, but can also include structural design features that help minimize specific losses (e.g., car frames designed to crumple to dissipate collision energy and protect the seating area). Non-structural mitigation refers to activities that lessen the likelihood of damage to non-structural elements of a building including its contents. This may include measures to strengthen non-structural elements, to protect non-structural elements (e.g., additional strapping for pipes, vents, and conduits), or to restrain non-structural elements from doing damage when they fail (e.g., wire mesh around parapets; plywood sheeting in attic around brick chimneys).

Non-structural mitigation can also include redundancy initiatives, which provide alternative means of ensuring the integrity of a non-structural system. Examples of non-structural redundancy include incorporation of built-in fire suppression systems; the addition of multiple fire extinguishers in buildings; or the integration of generators to ensure a post-event power supply.

Functional mitigation refers to the organizational measures taken to ensure effective emergency response, business continuity, and recovery in the event of a disaster. Examples include a host of measures such as development of emergency staffing plans to the identification of alternate emergency operations centers; land-use planning and the development of building codes to the implementation of education, training, and exercising programs; and, development of warning and alerting systems to establishment of public information plans.

Table 2.1 Disaster preparedness activities incorporating international risk management standards and best practices

DISASTER RISK MANAGEMENT (DRM) FRAMEWORK		
Core Component	**Principle Activities**	**Description**
I. Establish Disaster Risk Context		
	Assigning Disaster Risk Management Ownership	Activities undertaken to regularly review and identify the party/parties responsible for disaster risk management and to ensure the provision of the required authorities and resources to manage the assigned disaster/emergency risk (adapted from AS/NZS, 2004; EC, 2010; ISO, 2009a,b)
	Disaster Risk Objective Identification	Activities undertaken to regularly review and identify the strategic objectives of the risk management initiative and associated processes (adapted from AS/NZS, 2004; EC, 2010; ISO, 2009a,b)
	Disaster Risk Scope Identification	Activities undertaken to identify and delineate the spatial and temporal bounds of specific risk management initiatives (adapted from AS/NZS, 2004; Carpenter, 2001; EC,2010; ISO, 2009 a,b)
	Disaster Risk Parameter Identification	Activities undertaken to identify and define the parameters to be used in managing disaster/ emergency risk (adapted from AS/NZS, 2004; EC, 2010; ISO, 2009a,b)
II. Conduct Disaster Risk Assessment		
	Risk Identification Measures	Activities to anticipate, identify and monitor potential perils and opportunities in a specific area over a given timeframe (adapted from AS/NZS, 2004; Baranof et al., 2005; Cabinet Office, 2012b; CSA, 2008; EC, 2010; ISO, 2009a,b; NFPA, 2010; PS, 2012a)
	Risk Analysis Measures	Activities to quantitatively and qualitatively analyze the risks from identified perils. (adapted from AS/NZS, 2004; Baranof et al., 2005; Cabinet Office, 2012b; CSA, 2008; EC 2010; ISO 2009a, b; NFPA, 2010; PS, 2012a; Schmidt et al., 2012)

DISASTER RISK MANAGEMENT (DRM) FRAMEWORK

Core Component	Principle Activities	Description
	Risk Criteria Development	Activities undertaken to review and transparently establish risk tolerance thresholds and acceptable limits criteria (adapted from AS/NZS, 2004; EC, 2010; ISO 2009b; Schmidt et al., 2012)
	Risk Evaluation	Activities to assess the relative risk of some or all perils in a given area and over a given timeframe against established risk criteria to determine risk acceptability/tolerability (adapted from AS/NZS, 2004; EC 2010; ISO 2009a,b; PS, 2012; Schmidt et al., 2012)
III. Identify and Implement Disaster Risk Treatments		
	Prevention Measures	Activities undertaken to prevent a particular peril from occurring (adapted from AS/NZS, 2004; Cabinet Office, 2012b; CSA, 2008; HS, 2012a; ISO 2009a; NFPA, 2010)
	Protection Measures	Activities undertaken to protect a population from the impact of one or more perils should they occur (adapted from AS/NZS, 2004; CSA, 2008; HS, 2012a; ISO 2009a; NFPA 2010)
	Structural Mitigation Measures	Activities undertaken to reduce and minimize the impact of a peril, primarily through the hardening of structures primarily to enhance structural robustness (adapted from AS/NZS, 2004; Cabinet Office, 2012b; CSA, 2008; HS, 2012a; ISO 2009a; NFPA, 2010; PS, 2011)
	Non-structural Mitigation Measures	Activities undertaken to reduce and minimize the impacts of a peril primarily through the hardening of non-structural and operational elements to enhance robustness and/or redundancy (e.g., windows, HVAC, plumbing, first response equipment, contents) (adapted from AS/NZS, 2004; Cabinet Office, 2012b; CSA, 2008; HS, 2012a; ISO 2009a; NFPA, 2010; PS, 2011)

DISASTER RISK MANAGEMENT (DRM) FRAMEWORK		
Core Component	**Principle Activities**	**Description**
	Organizational Mitigation Measures	Activities undertaken to reduce and minimize the impacts of a peril primarily through social/organizational programming (e.g., Awareness Campaigns, Public Communication and Warning systems, Education, Training, and Exercises; Incident Management Systems; Recovery systems; Finance and Administration systems) (adapted from AS/NZS, 2004; Cabinet Office, 2012b; CSA, 2008; HS, 2012a; ISO 2009a; NFPA, 2010; PS, 2011)
IV. Acknowledge Residual Disaster Risk		
	Residual Risk Calculation	Activities undertaken to estimate the net cost of likely losses from a particular hazard given the existing prevention, protection, and mitigation measures (adapted from AS/NZS, 2004; ISO, 2008; PS, 2012).
	Residual Risk Acceptance Measures	Activities undertaken to absorb the net cost of the calculated residual risk (e.g., establishment of contingency funds) (adapted from AS/NZS, 2004; ISO, 2008)
	Residual Risk Transfer Measures	Activities undertaken to transfer the cost of the risk remaining following the application of risk treatments (e.g., catastrophe bonds, insurance/reinsurance, cost sharing with parent companies or higher-order governments) (adapted from AS/NZS, 2004; Baranof et al., 2005)
V. Review and Monitoring Disaster Risk		
		Prescribed, regular review of risk assessments, treatments, and measures to deal with residual risk (adapted from AS/NZS, 2004; Baranof et al., 2005; Cabinet Office, 2012b; CSA, 2008; HS, 2012a; ISO 2009a, 2008; NFPA, 2010; PS, 2011)

2.3.4 Acknowledging Residual Disaster Risk

The acknowledgement of possible residual negative risk is the fourth component DRM centers on. Risk acknowledgement activities focus on identifying, calculating and reviewing the residual, un-mitigated risks and undertaking measures to manage the net cost associated with that risk. Following the calculation of the amount of residual risk likely to be borne by the entity, an assessment of the relative amounts of the risk to be absorbed or transferred must be conducted. Risk acceptance or absorption levels for a given entity are calculated largely based on the financial solvency and contingencies available to the entity and the size of the excess negative risk to be effectively distributed.

Transfer of risk typically includes planning for the financing of the losses associated with the risk. In the public sector, vehicles to transfer risk include disaster financial assistance agreements with higher levels of government whereby costs over a given amount will be distributed to, and absorbed by, the more senior level of governance. In some cases, public sector entities are now turning to private markets to distribute their risk. Mexico and Morocco, for example, are now both turning to the private market and are using combinations of a variety of instruments to transfer excess sovereign risk (Luna, 2012; Boulif, 2012). In the private sector, the transfer of risk can take many forms including the distribution of residual costs to parent companies, subsidiary organizations, insurance, re-insurance and bonds (Grossi and Kunreuther, 2005). Increasingly, both private sector and public sector entities are using multiple financial instruments in a tiered fashion to distribute the cost of residual risk to other entities (Baranoff et al., 2005; Luna, 2012; Parker, 2012). For any entity, however, the intention to transfer or redistribute residual disaster losses to others must be clearly and transparently conveyed to allow for a) the acceptance of that risk transfer, and b) the accommodation of that risk transfer.

2.3.5 Monitoring and Reviewing the Risk Process

The fifth risk management component focuses on the continuous monitoring and regular review of the first four DRM components. Communities today live in a constant state of flux, as seen by environmental change (e.g., sea level rise), population change (e.g., growth or change in density), by physical changes (e.g., infrastructure degradation), and/or by social changes (e.g., economic downturn). Each of the changes affects the vulnerability of a community as well as its resiliencies, and may in fact change its exposure to particular hazards (e.g., crime, terrorism). Continual monitoring of the human, environmental, physical and social changes occurring in and around a community is essential for the effective assessment of a community's net risk.

This introduction of the generic DRM Framework provides a strategic overview of the model and the input of qualified subject matter experts (SMEs) is important in operationalizing the use of this framework in managing disaster risk. This is particularly so in the risk assessment and risk review stages. Careful selection of the SMEs, their roles and mandates is required to ensure timely, accurate and balanced assessment of perils, the hazard associated with them and their potential consequences on communities. Therefore it is worth a focused look at the disaster risk analysis component of DRM.

2.4 Focus on Disaster Risk Analysis

Disaster risk analysis is the process by which the nature and level of a particular peril's risk is determined. This analysis is central to risk assessment as identified above.

Comprised of five essential activities - the methodical identification of specific threats; the determination of their likelihood of occurrence; the determination of likely exposures associated with an event; the identification and quantification of the vulnerabilities within the exposed zone; and the inherent resiliencies both within and beyond the exposed zone – the disaster risk analysis of a given peril provides the foundation for the comprehensive evaluation of an entity's overall risk.

2.4.1 Analyzing risk

Risk is widely presented as the product of hazard (H) and consequence (C) [Equation 2.1] (ISO 2009a,b). While some researchers, for epistemological reasons, have offered variations on this theme (see for example: Cutter et al., 2008; Handmer, 2003; Lewis and Kelman, 2010; Schmidt, 2012; Wisner et al., 2003), the simple traditional relationship best integrates the essential components of risk across a range of disciplines.

$$R = H \times C \qquad \text{[Equation 2.1]}$$

Table 2.2 synthesizes and presents best practices in conducting a comprehensive risk analysis. The framework builds on foundational concepts from across the physical science, social science, engineering, actuarial science, insurance and business communities and provides a standardized nomenclature for the DEM practitioners.

2.4.2 The Hazard Component

While hazard is perhaps one of the most broadly used words in the DEM community, it is specifically used in the physical science, engineering and insurance literature and refers to the likelihood of a particular threat of a particular intensity occurring (UNISDR, 2009).

There are two elements in the estimation of hazard: Threat Identification and Likelihood Estimation.

2.4.2.1 Threat identification - For any given peril, specific threat types can be identified. Landslides, for example, can present themselves as sloughs, translational or rotational slumps, debris flows, or debris torrents each with its own characteristics. Similarly, earthquakes can be subcategorized as being either crustal, sub-crustal (in-slab), or subduction earthquakes, each with its own spatial and temporal characteristics and impacts; tsunamis can be generated locally (near-field tsunami) or at a great distance (far-field tsunami); floods can be associated with spring freshets, dam failure, storm surge, severe weather; and, terrorist incidents can range from hostage takings, to dirty bombs, to insurgencies. Each of these types of peril has distinct characteristics and will exact

Table 2.2. Elements of a comprehensive risk analysis for a given peril.

Peril Risk Analysis	
Hazard Component	
1. Threat Identification	Activities undertaken to identify and define each of the specific threats associated with a peril/s (adapted from EC 2012; ISO 2009b)
2. Likelihood Estimation	Activities undertaken to quantify the likelihood of a particular threat of a particular scale occurring (adapted from EC 2010; ISO 2009a,b).
Consequence Component	
3. Exposure Estimation	Activities undertaken to estimate the spatial and temporal impact of a particular hazard (adapted from EC 2012; Handmer, 2003; ISO 2009b; UNISDR, 2009).
4. Vulnerability Estimation	Activities undertaken to identify and analyze specific characteristics and circumstances of a community or system that make it susceptible to the adverse effects of a hazard (adapted from EC, 2010; ISO, 2009b; UNISDR, 2009).
5. Resilience Estimation	Activities undertaken to identify and analyze specific capacities to resist, absorb, respond to, and recover from a hazard in a timely and efficient manner (adapted from EC, 2010; UNISDR, 2009).

varying consequences on affected communities or entities. Owing to these differences, each threat type must be identified and its characteristics independently analyzed in terms of 1) their location and spatial extent (geographical analysis), their duration (temporal analysis), their magnitude and intensity (dimensional analysis) (EC, 2012).

2.4.2.2 Likelihood estimation - The second element in estimating hazard is determining the likelihood of an event of a given size occurring over a specific timeframe. Likelihood can be represented as a rate or frequency (e.g., 3/year; 1:200 years) or as a probability (e.g., 12% chance in the next 50 year period). It can be presented in terms of the likelihood of occurrence or the likelihood of exceedance. Occurrence probabilities state the likelihood of a given event occurring in a given timeframe, whereas exceedance probabilities provide the likelihood of a given threshold being exceeded in a given timeframe.

In analyzing a threat it is important to define the likelihood estimate as being based on either the strength of an event at its source or the intensity of an event experienced in the area of impact. DEM practitioners are most interested in intensity information at locations of impact (e.g., earthquake shaking intensity of MMI=VIII in Victoria), but often use strength data as a proxy for the likely intensity at a given site (e.g., an earthquake of Mw=7.6, 97 km West of Victoria, at 10km depth). Various measurement scales are available for use with both strength and intensity, and the selection of the scales adopted should be driven by the needs of community decision-makers.

2.4.3 The Consequence Component

Like the hazard component of risk, the consequence parameter is comprised of distinct but related subcomponents: Exposure, Vulnerability and Resilience. The exposure component estimates potentially affected systems and assets, while the vulnerability and resilience components identify system weaknesses and strengths, respectively, across four fundamental societal dimensions: Human, Natural-Environment, Built-Environment, and Social-Environment within the exposure zone.

2.4.3.1 Exposure - refers to the identification of all systems and assets that could be potentially affected by a given hazard. Determination of exposure levels specifically involves 1) the delineation of the physical and temporal extent of a hazard(s) (i.e. the hazard zone), and 2) the delineation of impact zones across the four societal dimensions defined as:

1) human impacts – measures of the number of people killed, injured or rendered ill, the number of people displaced, and the cost of healthcare;

2) natural-environment impacts – measures of the cost of lost availability of environmental resources, plus the cost of environmental restoration;

3) built-environment impacts - measures of the cost of: damaged structures, the damage assessment, debris removal, disposal and recycling, as well as the cost of reconstruction/replacement of buildings, transportation systems, communications infrastructure, utility services, and property; and

4) social impacts – measures of the degree and cost of cultural, political, and financial loss. Assessment includes addressing such factors as post-disaster anti-social behavior, public outrage, encroachment or loss of territory, sovereignty infringement, loss of international position, loss of economic power, infringements on democratic systems.

The hazard zone is delimited by the geographic, temporal and dimensional analysis conducted in the hazard analysis and represents a measure of the greatest possible impact of a hazard. It also accounts for the geographic and temporal extent of cascading secondary, tertiary and quaternary hazards that may be triggered by the primary event. In some cases, therefore, the hazard zone may grow significantly beyond the limits of the primary hazard alone. Subduction earthquakes, for example, trigger tsunamis which can extend a hazard zone thousands of kilometers beyond the hazard zone of the initiating earthquake.

The second component of exposure identifies systems and assets both within and beyond the delineated hazard zone that could potentially be impacted (i.e., the impact zone). Impact zones can be variously delineated depending on the impact variable being assessed (e.g., human impact zone, structural impact zones, economic impact zones). For example, while a city may be exposed to a given earthquake, only a portion of the city's structures may be negatively impacted due to varying ground conditions and/or construction practices. In this case, the size of the structural impact zone is less than that of the hazard zone. In contrast, a major port city damaged by an earthquake may have an economic impact zone that extends well beyond its hazard zone. For example, distant grain farmers, manufacturers, and exporters reliant on an operational port may be severely economically impacted by its closure.

Both the hazard and impact zones combined define the exposure zone, and both are non-mutually-exclusive subsets of the exposure zone. The size of the exposure zone cannot be smaller than the size of either the hazard zone or an identified impact zone. Determining the size of a peril's or threat's potential exposure zone therefore, provides an important benchmark against which one can later estimate the relative impact of an event.

2.4.3.2 Vulnerability - refers to the characteristics or circumstances of a community, system or asset that make it susceptible to the adverse effects of a hazard (UNISDR, 2009). It is linked to the hazard exposure but is not defined by it (Berkes, 2007). That is to say, vulnerability varies (increases or decreases) independently of exposure but is only realized in its various forms by an event occurrence.

Much debate exists on the definitions of and relationship between vulnerability and resilience (e.g., Cutter et al., 2008; Fuchs et al., 2011; Manyena et al., 2011). This paper argues that, while the two are related concepts, they 1) vary independently of one another (Gaillard, 2007; Manyena, 2006) and, 2) are in constant flux which can be measured at any one point in time to provide a "snap-shot" of their current state (Norris et al., 2008). This recognizes that a community, system, or asset can simultaneously demonstrate increasing vulnerabilities while maintaining or even increasing its resilience. For instance, a city's slums might be growing along a river floodplain, while new funds and equipment are acquired to battle interface fires in suburban communities. Similarly, a community, system or asset, can demonstrate decreasing resilience while simultaneously reducing specific vulnerabilities. Take for example the circumstance in which a community simultaneously loses its only emergency manager (e.g., reducing its resilience), while initiatives to relocate the community's homeless shelters to safer ground receive government funding and approval (e.g., reducing its vulnerability).

Operationally, vulnerability is best viewed as a parameter which measures the susceptibility or weaknesses of specific social-ecological systems and subsystems

(Scandlyn et al., 2010) to specific hazards. Two elements of this definition are important here. First is that a community can simultaneously demonstrate high vulnerability on one or more dimensions (human, built-environment, natural-environment, social-environment) and low on others. A small resource-based community dependent on a river, for example, may exhibit high built-environment and economic vulnerability following a flood, but low human vulnerability due to effective early warning and evacuation systems.

The second key point is that it is important to note that any one system or subsystem may be vulnerable to specific hazards (Carpenter et al., 2001). Consequently when quantifying vulnerability, or resilience, it is essential that system vulnerabilities are specifically identified with respect to a specific hazard. For example, a community may be socially and economically vulnerable to flooding but not to interface fires due to the lack of neighbouring forest fuels.

Assessing vulnerability begins with a cataloguing of the assets existing in the delineated exposure zone. All of the identified assets in an exposure zone are potentially vulnerable to the hazard; however, the degree to which certain assets are more or less vulnerable is the focus of vulnerability analysis. Identification of assets needs to be comprehensively conducted across each of the four principal dimensions: human vulnerabilities (e.g., how many humans reside, work in or transgress the exposure zone), natural-environment vulnerabilities (e.g., is a stipulated water quality or air quality required in the hazard zone); built-environment vulnerabilities (e.g., commercial or residential structures;

transportation, communication or utility structures) and social vulnerabilities (e.g., are cultural, political, financial, economic or other organizational systems vulnerable?). If the defined exposure zone contains socio-ecological systems directly or indirectly affecting humans, then the potential for an emergency or disaster exists.

With the vulnerabilities identified in the exposure zone, the quantitative assessment of the relative vulnerabilities is required. The ensuing vulnerability analysis identifies and measures the vulnerability of assets using indicators specifically developed to assess the degree of vulnerability along each of the four principle dimensions. Depending on the strategic objectives, scope and parameters defined, and the level of detail required, this assessment can be carried out with greater or fewer indicator variables to attain the desired level of precision. While quantitative measures are preferential to obtain reliable data and minimize uncertainty, it is recognized that the use of qualitative measures of subject matter expert opinion may provide for human and financial resource efficiencies, particularly in areas of greater uncertainty.

While the overriding objectives of risk assessment, and risk analysis in particular, are to adopt as comprehensive and holistic an approach as possible (Hewitt, 2004) and minimize uncertainty (Berkes, 2007), it may be impossible to identify and quantify all vulnerabilities in an exposure zone. This fact should not, however, stand in the way of ongoing and focused efforts to identify potential weaknesses using an iterative approach. By starting with broadly-targeted, low-resolution vulnerability assessments, subsequent assessments can then be refined and prioritized as required.

2.4.3.3 Resilience - refers to the capacities of a community, system or asset to 1) resist, absorb, or accommodate the adverse effects of a hazard, and 2) to recover from the adverse effects of a hazard in a timely and efficient manner (adapted from UNISDR, 2009). Regardless of the vulnerabilities in a hazard zone (whether identified or not), it is incumbent on DEM practitioners to develop and strengthen capacities both within and outside the exposure zone to ensure 1) robust and resistant systems, and 2) rapid recovery from the effects of the hazard. At any given time it is unlikely that a DEM professional can know all of the vulnerabilities in a jurisdiction. It is therefore in the best interest of the practitioner to focus on developing resilient systems flexible enough to adapt to any contingency.

Recognizing that resilience is a function of a system's capacities to resist and recover from events, and that these capacities are themselves in a state of flux, resilience, like vulnerability, is a dynamic process and can only be assessed at a single point in time (Norris et al., 2008). Resilience indicators must therefore aggregate the capacities inherent in the system to resist and recover from a hazardous event by assessing:

1) Human Capital – measures of the number of people within and beyond the exposure zone and the degree to which they are educated, trained, prepared and available to resist and recover from a peril.
2) Built-environment Capital – measures of the existence, availability and mobility of the physical resources to resist and recover from a hazard (e.g., Chang et al., 2004).

3) Natural Capital – measures of the availability and mobility of natural resources to sustain life (e.g., security of water and food supplies) and provide materials in response and recovery.

4) Social Capital – measures of the strength of social bonding or links in a community. Social capital indicators include metrics on such dimensions as social structure, good will, strength of mutual aid agreements, insurance constructs, and planning (e.g,. Paton and Johnston, 2006; Putnam, 2000).

Like vulnerability, resilience is a dynamic and fluid concept, constantly changing. Recognizing this, it is possible that an entity's resilience can be waxing in some capacities and waning in others. While a community may see an increase in human capacities due to population growth, it may see a decrease in the social capacities of the community if the new community members fail to connect and effectively integrate with their neighbours.

Table 2.3 presents a matrix of the assessments required to comprehensively evaluate the consequences of a peril. The assessment of the hazard exposures, within and beyond the hazard zone, provides a solid benchmark of all that is at risk from a hazard. The assessment of vulnerabilities and resiliencies across human, built, natural and social dimensions provides a snapshot of the weaknesses inherent in the community as well as the capacities to curtail the impacts of a hazard and quickly recover from their effects. For any given hazard, a full assessment of the hazard's consequences must entail a review of the exposures, vulnerabilities and resiliencies across the four environmental dimensions.

Table 2.3 Risk consequence analysis matrix illustrating that for each consequence component (Exposure, Vulnerability, Resilience), the strengths and weaknesses of that component must be assessed over four dimensions: human, built, natural and social dimensions.

	Human Environment	Built-Environment	Natural-Environment	Social-Environment
Exposure	+ -	+ -	+ -	+ -
Vulnerabilities	+ -	+ -	+ -	+ -
Resilience	+ -	+ -	+ -	+ -

2.4.4 Assumptions and Uncertainty

At each step of the risk analysis, assumptions are made and some level of uncertainty enters the model. It is important that each step of the analysis be thoroughly documented and clearly communicated to the end user. Uncertainties must be identified and quantified throughout the risk management process so as to determine and convey the confidence level of the analysis. Both model and data (epistemic) uncertainties, as well as random chance (aleatory) uncertainties need to be identified and aggregated.

It is imperative that assumptions and uncertainties be communicated with the risk analysis results to allow for the full and balanced assessment of the risk and as a baseline for informed future reassessments. Furthermore, this communication must be in plain language so as to ensure that affected individuals and community leaders are meaningfully informed as to the validity of the analysis and the results. Aggregated uncertainty analysis should present the relative contributions of the each of the identified uncertainties, address predominant sensitivities of contributing variables, and convey an overall sense of the imprecision of the risk results. This will allow researchers, community leaders and DEM professionals to focus on reducing the largest uncertainties that the results are most sensitive to.

2.4.5 Precautionary Principle

Where risk analysis is perceived to be weak - whether owing to the need to make gross assumptions, due to coarse modeling, scarcity of underlying data, or due to exceptionally large uncertainties – subject matter expert opinion should guide recommendations and the precautionary principle should be applied. The risk to humans and/or the environment should be of paramount importance and where the risk analysis is weak, the risk is deemed high, and/or the consequences of a hazard cannot be assessed, the precautionary principle should be applied to manage the potential adverse effects of a hazard. Such decisions should be clearly documented, transparently derived and effectively communicated. Finally, situations in which the precautionary principle is applied necessarily warrant further investigation. Additional, targeted research should be aimed at addressing weaknesses in the risk analysis.

2.5 Seismic Risk Assessment of Vancouver Island

Vancouver Island, on the southwest coast of British Columbia, Canada is located in a seismically active region of the Pacific called the Cascadia Subduction Zone (Figure 1.4). Despite long being recognized as a region exposed to crustal, subcrustal and subduction interface earthquakes, it is not clear that any single or composite entity has undertaken a comprehensive risk assessment to estimate the safety of Island residents. In 2009, the Canadian government’s lack of action in assessing the risk to Canadians was documented in an Auditor's General report on public safety and emergency management (Fraser, 2009). Fraser's review found "…that Public Safety Canada lacked an all-hazards risk assessment that identified potential hazards to public safety or security – whether malicious, natural, or accidental" (Fraser, 2009). Similarly, a 2009 cross-ministry internal audit of the government of British Columbia's emergency preparedness and business continuity planning indicates that an all-hazards risk analysis has not been conducted (Newton, 2009a; 2009b).

Analyzing Vancouver Island's seismic risk using the generic framework outlined above exposes some notable data gaps in our appreciation of the seismic risk to Island populations. Examining the hazard analysis component, the seismic threat identification is fairly well quantified (NRCan, 2012). It recognizes three seismic sources (crustal, subcrustal and subduction) and identifies one process (episodic tremor and slip) which could affect the assessment of hazard likelihood. The likelihood of earthquake shaking is provided in terms of peak ground acceleration (PGA) and spectral acceleration (SA) (NRCan, 2012). Unfortunately, as most citizens are not familiar with these metrics, this information is largely inaccessible to all but the scientific and engineering communities. The next chapter addresses this issue by providing more understandable intensity-based shaking probabilities for Vancouver Island communities.

The current seismic hazard analysis for Vancouver Island, also does not address the aftershock threat following the next Cascadia subduction event. Chapter 4 of this dissertation addresses this issue by analyzing historical subduction aftershock records to estimate what might be an analogous aftershock sequence along the North American coast.

Relatively little data exists in the public domain with respect to the consequences of an earthquake on Vancouver Island. Most of the existing seismic research pertaining to Vancouver Island identifies potential or likely geologic impacts based on physical evidence (e.g., Clague et al., 2000 - Subduction; VanDine and Evans, 1993 - Landslides; Hutchinson et al., 2000 - Tsunami; Monahan et al., 2000 - Liquefaction). Few studies attempt to estimate the human, environmental, structural or social impacts associated with these events. Wourinen (1976) was likely the first attempt to link the societal impacts of earthquake shaking on Vancouver Island with varying geological substrates in Victoria and Oak Bay. In 2001, Onur linked building-code level ground shaking with mean damage ratios and estimated building structural and non-structural economic loss in central Victoria. Until recently, research documenting specific seismic exposures, community vulnerabilities, and community resiliencies on Vancouver Island is largely non-existent. Stoner (2011) presents preliminary social vulnerability assessment research in the Capital Regional District. While she notes sampling and technical challenges, her mixed-methods approach suggests high social vulnerability exists on southern Vancouver Island, particularly in the more densely populated areas. A more recent study investigating human vulnerabilities to seismic hazard in two Greater Victoria hospitals found that while a focus on seismic hazard issues exists within the Vancouver Island Health Authority, an overall lack of planning, coordination and exercising with external agents undermines the effectiveness and efficiency of post-earthquake healthcare (Jaswal, 2012).

Focused research efforts targeting the identification of local, regional, and national exposures are required to begin to analyze the risk faced by Island communities. Similarly, the paucity of information as to Vancouver Island's human, built, natural and social vulnerabilities and resiliencies is marked. As a geographically isolated region, exposed to significant seismic hazard, and housing British Columbia's provincial capital, a clear understanding of the Island's structural vulnerabilities, as well as its food, water and utility vulnerabilities is essential to mitigating the system weaknesses found in Island communities. Similarly, a clear understanding of the human, built, natural, and social resiliencies that exist on Vancouver Island are critical in estimating the Island's seismic risk. Without this critical information, community decision-makers are operating in an information vacuum and their ability to plan for effective, efficient response and recovery from seismic hazards is significantly undermined.

2.6 Discussion and Conclusions

Recognition of the inherent value in using a risk management approach in disaster management is increasing across the disaster and risk management professions (e.g., HS, 2012a; IAEM, 2012; NFPA, 2010; Parker, 2012; PS, 2012a). Despite this, there has been limited, piecemeal integration of risk management approaches into the practice of disaster management. And while several contributions have provided important conceptual insights (e.g., CSA, 2008; Ferrier and Haque, 2003; Grossi and Kunreuther, 2005) and/or valuable operational tools (e.g., HAZUS-MH in the United States-FEMA, 2004; PerilAus in Australia - Risk Frontiers, 2012; RiskScape in New Zealand - Reese et al., 2007), efforts have yet to holistically integrate risk management best practices and standards. Notably absent in current efforts is the integration of a ‘cradle to grave’ risk management approach, one in which disaster managers clearly define the risk management context, complete comprehensive risk assessments, efficiently prioritize and implement risk treatments, acknowledge residual risk, and constantly review the risk management process (e.g. Britton, 2001; Cardona, 2004; Manyena, 2006). By integrating internationally standardized risk management practices into a disaster management preparedness framework, disaster managers can ensure the methodical and coordinated assessment, treatment, and acknowledgement of disaster risk.

This paper presents a generic Disaster Risk Management (DRM) framework founded on international risk management best practices and standards. Five core components of DRM are recognized: 1) Establishing a Risk Management Context; 2) Conducting Risk Assessments, 3) Implementing Risk Treatments, 4) Acknowledging Residual Risk, and 5) Monitoring and Reviewing Risk Management processes. The benefits of this approach to disaster risk management include a strategically-oriented generic structure to disaster management; flexible, non-prescriptive operational guidance to disaster management; a standardized terminology; and a well-vetted risk-based framework based on international best practices.

The transparent use and communication of each of the identified risk management steps ensures clear understanding of the risks faced by all members of a community, of the measures taken to prevent, protect, or mitigate that risk, and of the residual risk to be managed.

As most countries adopt a bottom-up approach to disaster, where responsibility for individual safety is either transferred to or resides with the individual, there is a moral and ethical as well as economic responsibility for governments, corporations and other socially constructed entities, to ensure this information is gathered and openly discussed.

On Vancouver Island, a transparent comprehensive risk-management approach to seismic hazards does not appear to exist. Much work is required to effectively and comprehensively manage the risk posed by the earthquake peril, and to quantify and analyse the risk to Island communities. Seismic hazard analysis, available in terms of PGA, is not transparently and meaningfully available to the non-scientific community for crustal, subcrustal and subduction hazards. In addition, no estimation of the subduction aftershock threat currently exists. While targeted research on these two issues is the focus of the balance of this dissertation, a vast amount of research remains to be undertaken 1) to identify and quantify the systems and assets in Vancouver Island’s seismic exposure zone, 2) to identify and analyse specific vulnerabilities in Island communities, and 3) to identify and assess the inherent resiliencies in communities both on and off Vancouver Island.

2.7 References

Ansell J and Wharton F 1992. Risk: Analysis, Assessment, and Management. John Wiley and Sons, Chicester, NY, USA.

AS/NZS (Australia/New Zealand Standards) 2004. Risk Management. Australia/New Zealand Standard 4360:2004, 28p. http://www.standards.org.au/Pages/default.aspx [Website last accessed: July 14, 2011].

Baranoff EG, Harrington SE, and Niehaus GE 2005. Risk Assessment. Insurance Institute of America, Malvern, Pennsylvania, USA.

Berkes F 2007. Understanding uncertainty and reducing vulnerability: lessons from resilience thinking. *Natural Hazards*, 41(2): 283-295.

Blanchard W, Canton L, Cwiak C, Goss K, McEntire D, Newsome L, Selves M, Sorchik E, Stenson K, Turner J, Waugh W, and West D 2007. Principles of Emergency Management Supplement, Monograph, http://www.iaem.com/publications/documents/PrinciplesofEmergencyManagement.pdf, [Website last accessed: July 14, 2011].

Boulif MN 2012. Moroccan Risk Management Policy. Global Risk Forum, Davos, Switzerland. August 24-30th, 2012, Plenary Session Five http://www.idrc.info/pages_new.php/Plenary-5/1085/1/831/ [Website last accessed: October 10, 2012].

BSI (British Standards Institute) 2008. Risk Management: Code of Practice, BSI 31100, British Standards Institute, 46p.

Britton NR 2001. A new emergency management for the new millennium? *Australian Journal of Emergency Management*, 16(4):44-54.

Carpenter SR, Walker BH, Anderies JM, and N Abel. 2001. From metaphor to measurement: resilience of what to what? *Ecosystems*, 4:765–781.

Cabinet Office 2012a. Integrated Emergency Management, United Kingdom, http://www.cabinetoffice.gov.uk/content/emergency-preparedness, [Website last accessed: June 1, 2012].

Cabinet Office 2012b. Civil Contingencies Act Enhancement Programme (CCAEP), Revision to Emergency Preparedness, Chapter 1, United Kingdom, http://www.cabinetoffice.gov.uk/sites/default/files/resources/Chapter-1-Introduction_amends_16042012.pdf, [Website last accessed: June 7, 2012].

CSA (Canadian Standards Association) 2008. Emergency Management and Business Continuity Programs, CAN/CSA Z1600, Mississauga, Ontario, 58p.

Cardona OD 2004. The Need for Rethinking Concepts of Vulnerability and Risk from a Holistic Perspective: A Necessary Review and Criticism for Effective Risk Management. In G. Bankof, G. Frerks & D. Hilhorst (Eds.), Mapping Vulnerability: Disasters, Development, and People (pp 37-51). London: Earthscan.

Carpenter SR, Walker BH, Anderies JM, and Abel N 2001. From metaphor to measurement: resilience of what to what? *Ecosystems*, 4:765–781.

Chang SE and Shinozuka M 2004. Measuring Improvements in the Disaster Resilience of Communities. *Earthquake Spectra*, 20 (3), 739-755.

Clague J, Atwater B, Wang K, Wang Y, and Wong I 2000. Great Cascadia Earthquake Tricentennial. Geological Survey of Canada, Open File 3938. Natural Resources Canada.

CSE (Communications Security Establisment) and RCMP (Royal Canadian Mounted Police) 2007. Threat and Risk Assessment Methodology. Government of Canada, http://www.cse-cst.gc.ca/documents/publications/tra-emr/tra-emr-1-e.pdf, [Website last accessed: July 12, 12].

Cutter SL, Barnes L, Berry M, Burton C, Evans E, Tate E, and Webb J. 2008. A place-based model for understanding community resilience to natural disasters. *Global Environmental Change*, 18:598-606.

EC (European Commission) 2010. Risk Assessment and Mapping Guidelines for Disaster Management. SEC(2010) 1626 Final, Brussels, Belgium, 42p.

FEMA (Federal Emergency Management Agency) 2004. Using HAZUS-MH for risk assessment HAZUS-MH risk assessment and user group series. FEMA 433, United States Government.

Ferrier N and Haque CE 2003. “Hazards Risk Assessment Methodology for Emergency Managers: A Standardized Framework for Application”, *Natural Hazards*, 28: 271-290.

Fraser S 2009. Report of the Auditor General of Canada to the House of Commons. Chapter 7 Emergency Management – Public Safety Canada. http://www.oag-bvg.gc.ca/internet/docs/parl_oag_200911_07_e.pdf [Website Last Accessed: June 25, 2012].

Fuch S, Kuhlikcke C, and Meyer V 2011. Editorial for the special issue: vulnerability to natural hazards – the challenge of integration. *Natural Hazards*, 58(2): 609-619.

Gaillard J 2007. Resilience of traditional societies in facing natural hazards. *Disaster Prevention and Management*, 16(4): 522-544.

Grossi P and Kunreuther H 2005. Catastrophe Modelling: a new approach to managing Risk. New York: Springer Science+Business Media, 245.

Handmer J 2003. We are all vulnerable. *Australian Journal of Emergency Management*, 18(3): 55-60.

Hewitt K 2004. A synthesis of the symposium and reflection on reducing risk through partnerships. Paper presented at the conference of the Canadian Risk and Hazards Network (CRHNet) Symposium, November 18-24, Winnipeg, Manitoba, Canada.

HS (Homeland Security) 2012a. National Preparedness Report. United States Government, Washington, D.C., United States of America.

HS (Homeland Security) 2012b. Threat and Hazard Identification and Risk Assessment Guide, CPG 201, United States Government, Washington, D.C, United States of America.

Hutchinson I, Guilbault J-P, Clague JJ, and Bobrowsky PT 2000. Tsunamis and tectonic deformation at the northern Cascadia margin: a 3000-year record from Deserted Lake, Vancouver Island. *The Holocene*, 10, 429-439.

IAEM (International Association of Emergency Managers) 2012. Principles of Emergency Management. http://www.iaem.com/EMPrinciples/documents/PrinciplesOfEmergencyManagement.pdf [Website last accessed: June 14, 2012].

ISO (International Standards Organization) 2008. Information technology -- Security techniques -- Information security risk management. ISO/IEC 27005:2008. Geneva, Switzerland.

ISO (International Standards Organization) 2009a. Risk Management – Principles and guidelines on implementation - ISO 31000. Geneva, Switzerland.

ISO (International Standards Organization) 2009b. Risk Management – Risk Assessment Techniques - ISO 31010. Geneva, Switzerland.

Jaswal, HK 2012. Seismic Preparedness of Hospitals in Victoria, British Columbia, Canada, Unpublished Master’s Thesis, University of Victoria, Victoria, British Columbia, Canada, 194p.

Lewis J and Kelman I 2010. Places, people and perpetuity: Community capacities in ecologies of catastrophe. ACME: An International E-Journal for Critical Geographies, 9(2), 191-220.

Luna D 2012. Mexico’s Approach to Disaster Risk Management. Global Risk Forum, Davos, Switzerland. August 24-30th, 2012, Plenary Session Five http://www.idrc.info/pages_new.php/Plenary-5/1085/1/831/ [Website last accessed: October 10, 2012].

Manyena SB 2006. The concept of resilience revisited. *Disasters*, 30(4): 433–450.

Manyena SB, O’Brien G, O’Keefe P, and Rose J 2011. Disaster resilience: a bounce back or bounce forward ability? *Local Environment*,16(5): 417–424.

Monahan PA, Levson VM, Henderson P and Sy A 2000. Composite Relative Earthquake Hazard Map of Greater Victoria, Ministry of Energy and Mines, Government of British Columbia, Geoscience Map 2000-1. http://www.empr.gov.bc.ca/Mining/Geoscience/SurficialGeologyandHazards/VictoriaEarthquakeMaps/composite/Pages/default.aspx [Website last accessed February 22, 2012].

NFPA (National Fire Protection Association) 2010. NFPA 1600, Standard on Disaster/emergency Management and Business Continuity Programs, 2000 Edition. Quincy, Massachusetts, USA.

NRCan (Natural Resources Canada) 2012. Earthquakes Canada. Government of Canada, http://www.earthquakescanada.nrcan.gc.ca/histor/20th-eme/1918-eng.php [Website Last Accessed: 2 February 2012].

Newton S 2009a. Report on the Cross Government Review of Business Continuity Management, Audit & Technical Services Internal Audit & Advisory Services, Ministry of Finance, Government of British Columbia, http://www.fin.gov.bc.ca/ocg/ias/pdf_Docs/BCM%20Report%20Release.pdf [Website last accessed: June 25, 2012].

Newton S 2009b. Report on Emergency Management Preparedness and Response. Audit & Technical Services Internal Audit & Advisory Services, Ministry of Finance, Government of British Columbia, http://www.fin.gov.bc.ca/ocg/ias/pdf_Docs/Emergency%20Management%20Report%20Release.pdf [Website last accessed: June 25, 2012].

Norris FH, Stevens S, Pfefferbaum B,.Wyche K, Pfefferbaum R 2008. Community Resilience as a Metaphor, Theory, Set of Capacities, and Strategy for Disaster Readiness, *American Journal of Community Psychology*, 41: 127-150.

Parker M 2012. Country Risk Management and Financial Preparedness for Disasters. Chair, Swiss Re Plenary Session, Global Risk Forum, Davos, Switzerland. August 24-30th, 2012, http://www.idrc.info/pages_new.php/Plenary-5/1085/1/831/ [Website last accessed: October 10, 2012].

Paton D and Johnston D 2006. Disaster Resilience: An Integrated Approach. Charles C. Thomas, Springfield,IL.

PS (Public Safety Canada) 2011. An Emergency Management Framework for Canada, Second Edition. Government of Canada, http://www.publicsafety.gc.ca/prg/em/emfrmwrk-2011-eng.aspx, [Website last accessed: June 7, 2012].

PS (Public Safety Canada) 2012a. All Hazards Risk Assessment Methodology Guidelines. Government of Canada, http://www.publicsafety.gc.ca/prg/em/emp/2012-ahra/_fl/2012-ahra-eng.pdf, [Website last accessed: July 12, 2012].

Putnam R 2000. Bowling Alone: The Collapse and Revival of American Community, Simon and Schuster, New York, New York, 544p.

Rabjohn A 2008. Global Application of the Principles of Emergency Management. Proceedings of the International Disaster and Risk Conference, Global Risk Forum, August 25-29th, Davos, Davos, Switzerland, 163.

Reese S, Bell RG, King AB 2007. RiskScape—a new tool for comparing risk from natural hazards. *Water Atmosphere* 15(3): 24–25.

Risk Frontiers 2012. PerilAus Project. http://www.riskfrontiers.com/perilaus.htm, [Website Last Accessed: October 3, 2012].

Ropeik D and Gray G 2002. Risk: A Practical Guide For Deciding What's Really Safe And What's Really Dangerous In The World Around You. Houghton Mifflin Company, New York, NY, USA.

Scandlyn J, Simon CN, Thomas DSK, and Brett J 2010. Theoretical Framing of Worldviews, Values, and Structural Dimensions of Disasters, In Phillips, BD, Thomas, DSK, Fothergill, A, and Blinn-Pike, L, (eds) Social Vulnerability to Disasters, 27 -50.

Schmidt J, Matcham I, Reese S, King A, Bell R, Henderson R, Smart G, Cousins J, Smith W, and Heron D 2011. Quantitative multi-risk analysis for natural hazards: a framework for multi-risk modeling. *Natural Hazards*, 58:3, 1169-1192.

Stoner S 2011. Exploring Social Vulnerability to Earthquakes in the Capital Regional District, British Columbia Canada, Unpublished Master's Thesis, University of Victoria, Victoria, British Columbia, Canada, 134 p.

UNISDR (United Nations International Strategy for Disaster Reduction) 2009. United Nations ISDR Terminology for Disaster Risk Reduction, 35p.

http://www.unisdr.org/files/7817_UNISDRTerminologyEnglish.pdf [Website last accessed: June 30, 2012].

VanDine DF and Evans SG 1993. Large landslides on Vancouver Island, British Columbia. *Geohazards*, 193-201.

Wisner B, Blaikie P, Cannon T, and Davis I 2003. At Risk: Natural Hazards, People's Vulnerability and Disasters. London: Routledge.

Wuorinen V 1976. Seismic Microzonation of Victoria - A Social Response to Risk. In Foster HD (editor), Victoria Physical Environment and Development, Western Geographical Series, Vol. 12, University of Victoria, 185-219.

Chapter 3:

Earthquake Shaking Probabilities for Communities on Vancouver Island, British Columbia, Canada[1]

---

[1] A version of this paper was accepted for publication in the journal Natural Hazards

3.0 EARTHQUAKE SHAKING PROBABILITIES FOR COMMUNITIES ON VANCOUVER ISLAND, BRITISH COLUMBIA, CANADA

MARK SEEMANN[1], TUNA ONUR[2], and DENISE CLOUTIER-FISHER[3]

[1]Department of Geography, University of Victoria, Victoria, BC, V8W 3P5, Canada (Email: mseemann@uvic.ca); [2]Risk Management Solutions, Inc., Newark, CA, 94560 United States of America; [3]Department of Geography, University of Victoria, Victoria, BC, V8W 3P5, Canada

3.1 Abstract

Comprehensive risk assessments are fundamental to effective emergency management. These assessments must identify the range of hazards (or perils) an entity is exposed to, and quantify the specific threats associated with each of those hazards. While hazard identification is commonly, if not formally, conducted in most circumstances, specific threat analysis is often overlooked for a variety of reasons, one of which is poor communication with subject matter experts (SMEs). This poor communication is often attributable to an adherence to scientific jargon and missed opportunities to simplify information. In Canada, for example, earthquake hazard calculations have been readily available to engineers and scientists for decades. This hazard information, however, is expressed in terms of peak ground accelerations (PGA) or spectral accelerations (SA) which are foreign concepts to most emergency managers, community decision-makers and the public-at-large. There is, therefore, a need to more clearly, simply and effectively express seismic hazard information to the wider community.

This paper provides crustal, sub-crustal and subduction-interface earthquake shaking probabilities, expressed as simple percentages for each of 57 locations across Vancouver Island, British Columbia, Canada. Calculations present the likelihood of earthquake shaking on Vancouver Island as the probabilities of exceeding each of three shaking intensity thresholds ("widely-felt"; onset of "non-structurally-damaging" shaking; and onset of "structurally-damaging" shaking) over four time frames (10, 25, 50, and 100 years). Results are based on the latest Geological Survey of Canada hazard models used for the 2010 National Building Code and are presented in both tabular and graphic formats. This simplified earthquake hazard information is offered to aid local residents, organizations, and governments in understanding and assessing their risk, and to facilitate future earthquake risk research.

Key words: seismic hazard, Cascadia Subduction Zone, crustal/sub-crustal shaking exceedance probabilities, subduction occurrence probabilities, Vancouver Island, Pacific Northwest

3.2 Introduction

Fundamental to any emergency management portfolio is a comprehensive risk assessment that details not only the potential hazards to the entity in question, but also the specific threats, and the likelihood of those threats occurring. Additionally, risk assessments must also outline the likely impacts of each threat, the populations and assets vulnerable to those impacts, and the capacity of the entity (e.g., individual, organization or community) to minimize losses and recover from the resultant environmental, life, property and economic losses. Developing such thorough assessments requires the integration of both physical and social science research and necessarily calls upon the scientific community to provide risk-specific information in support of the assessments. All too often, however, the bridge between the emergency management community and the scientific community is either left uncrossed (due to such factors as intimidation, time pressures, or physical separation); or information is poorly conveyed (often resulting from limited collaboration, use of unfamiliar vocabulary and concepts, and/or poorly formatted and presented data). In either case, the quality of risk assessments is undermined resulting in reduced levels of community preparedness and resilience.

Like most jurisdictions, British Columbia’s legislated emergency management framework outlines a “bottom-up” structure, in which individuals are ultimately responsible for their own safety. Local, regional, provincial, national and international support structures are then in turn tasked with providing and coordinating assistance depending on the size of the event and the level of assistance required.

Recognizing this type of emergency management structure, it is therefore incumbent on individuals to be aware of their local hazards and to prepare themselves and their dependents accordingly. At the same time, it is the responsibility of government to share new and emerging hazard information to their constituents in a clear, simple and timely manner, so as to encourage effective individual preparedness based on respective risk tolerances.

This paper focuses on earthquake hazard on Vancouver Island, British Columbia. In Canada, seismic hazard is well studied and discussed within science and engineering communities. Indeed, estimates of the earthquake hazard are a fundamental input for the design of buildings, bridges, and other structures (e.g., National Research Council (2010); Canadian Standards Association (2006)). These earthquake hazard estimates are expressed, for a specified probability of exceedance (or return period), as peak ground accelerations (PGA) or spectral accelerations (SA) at given periods, and unfortunately are not easily understood by those outside engineering and science circles. Not surprisingly, then, hazard information expressed as ‘there is a 2% chance in the next 50 years that a community will experience a peak ground acceleration of one quarter the acceleration of gravity or greater’ is challenging for the lay person or elected official to comprehend, let alone act upon. There is, therefore, a need to present seismic hazard information to the general public, elected officials and other community decision-makers in clear, simple, readily understandable terms that can be internalized and acted upon.

This paper outlines a methodology for simplifying seismic hazard information and presents earthquake ground shaking exceedance probabilities in a more meaningful format for the general public. The methodology relies on standard hazard analysis techniques and existing national earthquake hazard models and data. Using Vancouver Island as a study area, this paper provides an overview of the tectonic setting and historical seismicity on Vancouver Island, and outlines the methodology used to calculate earthquake hazard probabilities. The paper concludes with the presentation of results and a discussion of the uncertainties associated with these calculations.

3.2.1 Study Area

Vancouver Island is a mountainous, northwest-southeast trending island off the southwest coast of the province of British Columbia (BC), Canada. Geographically situated immediately north of the Olympic Peninsula in the United States, the Island extends some 450km (280mi) in length and is approximately 120km (70mi) across at its widest. Victoria, the BC provincial capital is located on the southern end of Vancouver Island, some 100km (60mi) northwest of Seattle, WA and 80km (50mi) south of Vancouver, BC. (Figure 1.4)

The Island itself is bisected by the Vancouver Island Ranges (maximum elevation 2,195m (7,200ft)) and exhibits a wet, temperate rainforest climatic zone to the west of the divide and a distinctly dryer quasi-Mediterranean climatic zone to the east. Vancouver Island is home to some 750,000 residents working primarily in the forestry, tourism, fishing, and service sectors (BC Stats, 2011). Over 760,000 international visitors are welcomed to the Island each year (Tourism British Columbia, 2008).

3.2.2 Regional Seismicity and Tectonic Setting

The distribution of earthquakes in and around Vancouver Island, British Columbia over the past five years is presented in Figure 3.1. Located in a seismically active region, much of Vancouver Island's earthquake activity is attributed to build-up and release of stress as the Juan de Fuca plate is subducted beneath the North America plate in what is called the Cascadia Subduction Zone. This seismic zone creates three types of earthquakes: shallow crustal earthquakes in the North America plate (blue dots in Figure 3.2); deeper sub-crustal earthquakes in the subducting Juan de Fuca plate (red dots in Figure 3.2); and, very large (greater than M8) subduction interface earthquakes at the interface of the two plates.

3.2.2.1. Crustal Earthquakes - Beneath Vancouver Island, most crustal earthquakes occur within approximately 20 to 30km of the surface. These crustal events and their associated aftershocks are usually less than M7.5 events and have a typical duration of less than a minute. Owing to the fact that these earthquakes are relatively shallow events, their potential proximity to built-up urban areas poses a significant threat to Vancouver Island communities. Crustal seismicity on Vancouver Island area has been characterised by numerous, small events (Figure 3.1) which do not exhibit distinct patterns that would indicate the locations of active faulting (Rogers, 1998). The most recent damaging crustal earthquake in the region was the M7.3 1946 Courtenay event on eastern Vancouver Island.

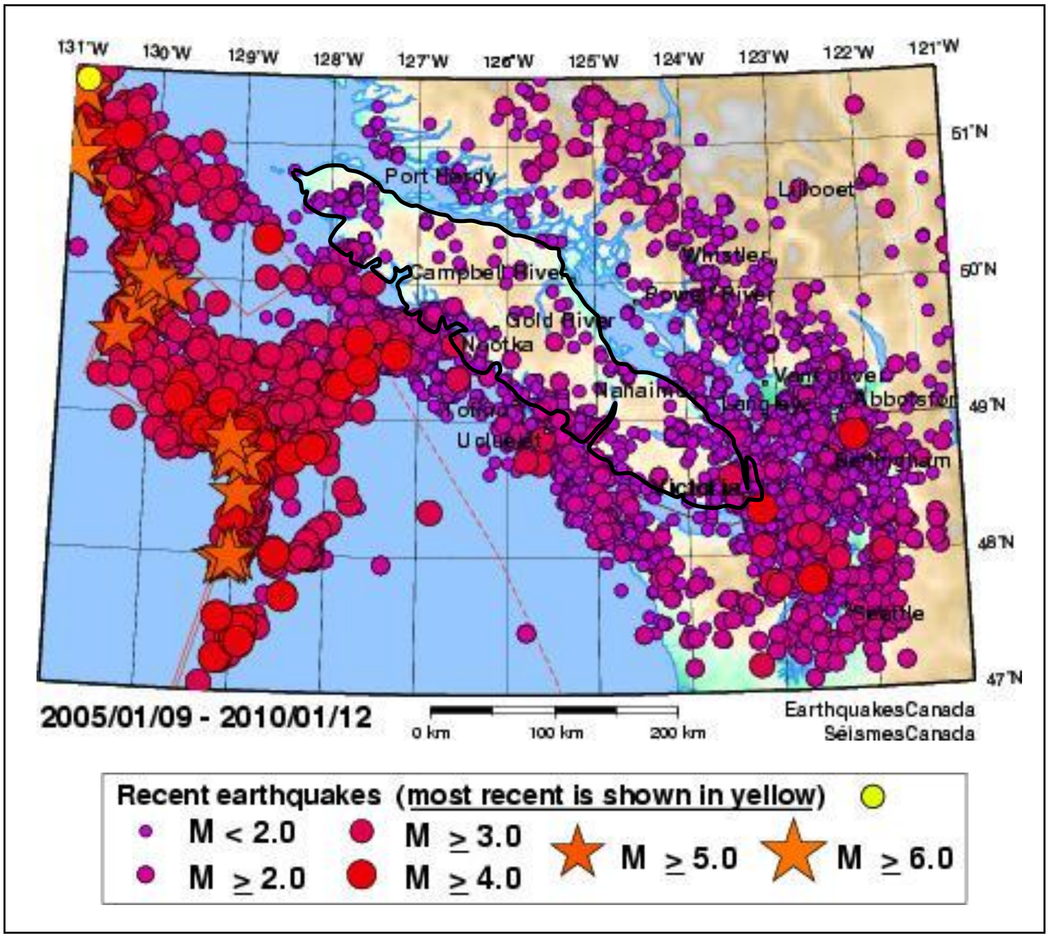


Figure 3.1 Recent seismicity (last 5 years) in the Vancouver Island Region (NRCan, 2010)

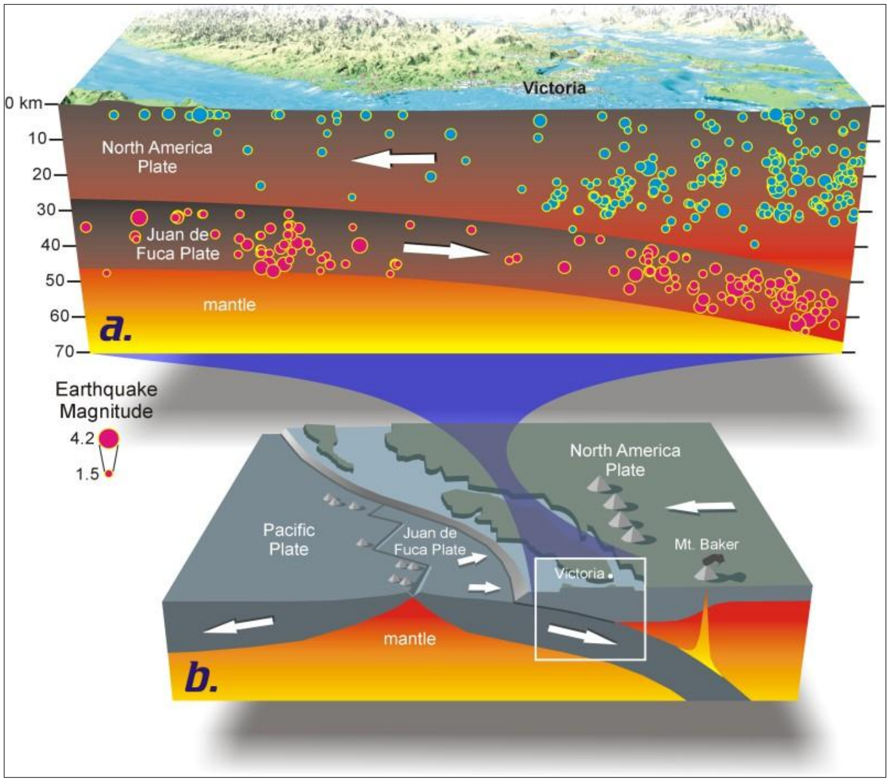


Figure 3.2. British Columbia’s Tectonic Setting (after Yorath et al., 2001)

3.2.2.2. Sub-crustal Earthquakes - Deeper sub-crustal earthquakes and their associated aftershocks typically occur between 30 to 45km depth under Vancouver Island and deeper beneath the Georgia Strait and Puget Sound to the east. Like the crustal earthquakes, these earthquakes are generally less than M7.5 events with shaking typically lasting less than a minute. As sub-crustal earthquakes are deeper events, damage may be less severe but may affect a larger area than similar sized crustal events. A concentration of sub-crustal earthquakes has been recorded beneath the Georgia Strait and Puget Sound and these events have the potential to affect major urban areas in the region (Rogers, 1998). The most recent damaging sub-crustal earthquake in the region was the M6.8 2001 Nisqually, WA event.

3.2.2.3. Subduction Interface Earthquakes - The largest earthquakes recorded around the world are subduction interface earthquakes, sometimes called “megathrust” events. These earthquakes occur when a slip along the locked interface of two convergent tectonic plates takes place, and the stored energy in the overlying plate is released along a length of the plate margin. These events are typically greater than M8 and are associated with shaking in excess of two or three minutes. Most of these events also cause tsunamis and typically trigger hundreds to thousands of aftershocks in the weeks and months that follow (Lay et al., 2005; Mishra et al., 2007). The size of one or two of the earthquakes in the aftershock sequence can be within an order of magnitude of the main event. Recent subduction earthquakes include the M9.0 Tohoku, Japan earthquake; the M8.8 2010 Maule, Chile Earthquake, and the M9.1 2004 Sumatra, Indonesia earthquake in which over 225,000 people lost their lives - primarily due to the large tsunami generated (USGS, 2009).

The Cascadia Subduction Zone extends some 1200km (800mi) along the west coast of North America from northern Vancouver Island to northern California (Figure 3.3). Based on evidence of the past 12 Cascadia events, these megathrust earthquakes recur roughly between 200 to 1200 years of the previous earthquake and are estimated to have an average return period of 500-600 years (Adams, 1990; Atwater et al., 1995; Clague and Bobrowsky, 1999; Witter et al., 2003). The last damaging Cascadia subduction earthquake is estimated to have been a M9 event which took place on January 26, 1700 (Satake et al., 1996).

3.3 Methodology

In this study, crustal and sub-crustal probability estimation is grouped and treated separately from the subduction earthquake probabilities. This is largely due to the fact that we adopt the Geological Survey of Canada's national seismic hazard model, which treats the Cascadia subduction interface earthquakes deterministically. This is a reflection of the unique characteristics of Cascadia megathrust events, such as their relatively well-defined rupture plane, their constrained magnitude, and the discernable number of previous Cascadia subduction events in the paleoseismic record.

3.3.1 Time-Independent Exceedance Probability Calculations for Crustal and Subcrustal Earthquakes

The probability calculations for crustal and sub-crustal earthquakes follow conventional probabilistic seismic hazard analysis (PSHA) procedures (Cornell, 1968) and are calculated using EZ-FriskTM Software (Risk Engineering, Inc., 1997). The exceedance probability calculations are based on a Poisson distribution that assumes each event is discrete and independent of all other events. Therefore the length of time since the last earthquake in the region is not a factor in the calculations.

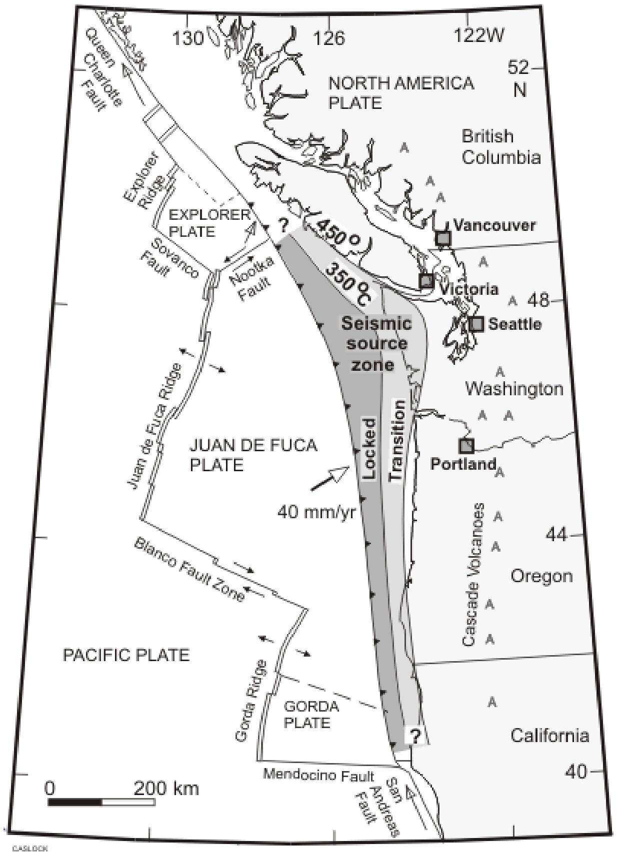


Figure 3.3. The Cascadia Subduction Zone (CSZ**)** (Flück et al, 1997)

Several inputs are required to set up the hazard models for a given region. These include seismic source zones in the study area, attenuation relationships that describe the propagation of seismic waves through the crust, and selection of the shaking intensity levels of interest.

The regional probability calculations for Vancouver Island are based on source zones defined by the Geological Survey of Canada (GSC) (Adams and Halchuk, 2003) and used for hazard calculations adopted in the 2010 edition of the National Building Code (NBC) of Canada. Two seismic source zone models are currently used by the GSC, H-Model and R-Model (Figure 3.4), and while both are based on the same western Canadian catalogue of recorded earthquakes, they represent different interpretations of seismicity and tectonics in British Columbia. Both the H- and R-models are used independently in this study to calculate annual rates of exceedance. Model results are combined by taking the arithmetic mean to provide a mean annual rate of exceedance, which allows the maintenance of a fully probabilistic hazard output. This differs from the approach used in the NBC, where the models are combined by taking the larger of the two hazard values calculated from each model.

The ground motion attenuation relationships used are those adopted by the GSC (Adams and Halchuk, 2003) and it is important to recognize that these attenuation relationships drive the format of the model outputs and determine the parameters in which ground shaking is presented. The GSC outputs are expressed as either PGA (i.e. the maximum ground acceleration measured by an accelerometer at a specific location during a given event) or SA at certain periods (i.e. the maximum acceleration of structures with certain natural periods of vibration during a given event).

An easier-to-understand measure of ground shaking is the qualitative Modified Mercalli Intensity (MMI) scale, a 12-point descriptive scale that describes ground shaking in terms of its observed effects on humans and structures (Table 3.1). Empirical relationships between PGA and MMI enable researchers to link quantitative measures of ground shaking intensity with qualitative ones (Atkinson and Sonley, 2000; Trifunac and Brady, 1975; Wald et al., 1999). As the Wald et al. (1999) relationship is currently the most widely used crustal PGA-MMI relationship and provides conservative results for the

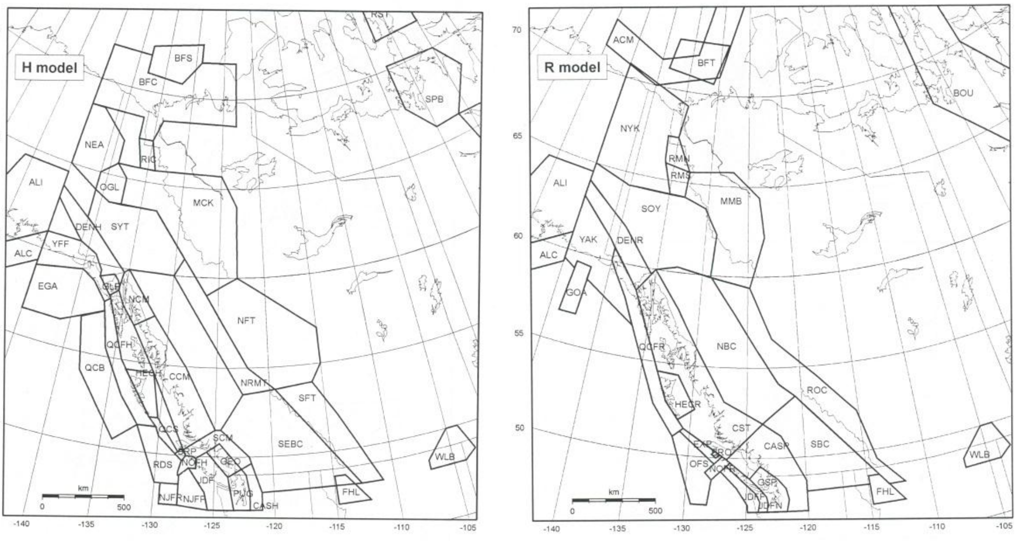


Figure 3.4 Western Canada seismic source zones: H Model and R Model (after Adams and Halchuk, 2003)

purposes of this study, we adopt it for crustal earthquakes. Recognizing none of the existing PGA-MMI relationships are specifically developed for sub-crustal earthquakes, we adopt the Wald et al. (1999) relationship for sub-crustal earthquakes as well. The relationship between PGA and MMI for sub-crustal earthquakes may differ from that for crustal earthquakes; however the difference is not likely to be dramatic (Wald, 2009).

Three levels of ground shaking were considered to be of interest in this study: MMI V (“widely felt” shaking), MMI VI (onset of “non-structurally-damaging” shaking), and MMI VII (onset of “structurally-damaging” shaking) (Table 3.1). As these shaking

Table 3.1. Description of selected MMI levels (adapted from Wood and Neumann, 1931)

MMI LEVEL	SHAKING LEVEL	DESCRIPTION OF EFFECTS
V	**“Widely Felt Shaking”**	Felt indoors by practically all, outdoors by many or most. Buildings tremble throughout. Broken dishes, glassware to some extent. Hanging objects, doors swing generally. Pictures knocked against walls or swung out of place.
VI	**“Non-Structurally-Damaging Shaking”**	Felt by all, indoors and outdoors. General excitement, some alarm. Damage slight in poorly built buildings. Fall of plaster, cracks in plaster and fine cracks in chimneys in some instances. Broken dishes, glassware in considerable quantity, as well as some windows. Overturned furniture in many instances.
VII	**“Structurally-Damaging Shaking”**	General alarm, all run outdoors. Some or many find it difficult to stand. Damage negligible in buildings of good design, slight to moderate in ordinary buildings and considerable in poorly built or badly designed buildings. Cracked chimneys to considerable extent and walls to some extent. Fall of plaster in considerable to large amounts. Dislodged brick and stone. Overturned heavy furniture.

intensity levels are onset thresholds, it should be noted that the onset of structurally damaging shaking implies that structural damage would be observed mainly in poorly built or badly designed structures. Conversion of these shaking thresholds from MMI to PGA using Wald et al. (1999) yields PGAs of 0.067g ± 0.018g, 0.13g ± 0.04g, and 0.24g ± 0.07g, for MMI V, VI, and VII, respectively.

Given the GSC’s regional source zone models, the appropriate attenuation relationships for the source zones, and the select ground motion intensity levels, EZ-Frisk Version 4.0

(Risk Engineering, 1997) was used to calculate the annual rates of exceedance for each PGA (0.067g, 0.13g, and 0.24g) at 57 sites across Vancouver Island. The sites selected represent the more populous communities on Vancouver Island and are augmented by additional sites to ensure a homogeneous geographic distribution. The annual rates of exceedance are calculated for uniform ‘firm-ground’ conditions as described in Adams and Halchuk (2003). This reference ground condition (RGC), defined as sites exhibiting an average shear wave velocity of between 360 and 750 m/s in the upper 30m of material, conforms with the RGC’s used in the National Building Code of Canada and minimizes the uncertainties associated with de-amplification factors on very hard ground (e.g., rock) and amplification factors on very soft ground (e.g., alluvium). The annual rates of exceedance are used to calculate 10, 25, 50 and 100-year probability rates using the conventional Poisson-exponential probability model.

3.3.2 Time-Dependent Occurrence Probability Calculations for Subduction Interface Earthquakes

Owing to the recurring nature of the Cascadia subduction interface earthquakes, subduction event probabilities can be calculated on a time-dependent basis in which probabilities of occurrence can be estimated based on past events. In this case, rather than directly estimating the probability of a certain level of earthquake shaking within a given area using a probabilistic hazard model, we use the recurrence rate of Cascadia subduction events to calculate time-dependent occurrence probabilities for various time frames.

Several lines of evidence indicate recurring megathrust events take place off the west coast of North America and suggest at least 12 discernible events have taken place during the past 7000 years (Adams, 1990; Atwater et al., 1995; Clague, 1997, 2002; Kelsey et al., 2002; Witter et al., 2003). And while there is general agreement on the date of the last Cascadia subduction event, the timing of previous events is less well defined. Two studies are commonly referred to with respect to estimating the recurrence of Cascadia subduction events. Adams and Weichert (1994) estimate a mean return period of 590 ± 105 years. Atwater and Hemphill-Haley (1997) find a shorter mean return period of between 500 and 540 years (mean = 520 years) but with wider variability in return periods. The shortest return periods estimated by these authors ranges from 30 – 350 years (mean = 190 years) while the longest return period is estimated to range from 700 – 1300 years (mean = 1000 years). In determining the mean return period found by Atwater and Hemphill-Haley (1997) we use their best estimate for mean return period (520 years) and a constrained range limited by the mean of the shortest return period (± 330 years). This recognizes the physical limitation of the shortest return period and that a minimum amount of time must pass to generate sufficient strain to trigger the next megathrust event at the interface.

Given the two estimates for Cascadia subduction return periods (590 ± 105 years; 520 ± 330 years), two sets of occurrence probabilities were modelled using a lognormal probability distribution function based on the respective means and standard deviations of the return periods, and the date of the last event (i.e. 1700)(Figure 3.5). The difference between the two probability curves reflects the uncertainty in the estimates and the mean provides a best estimate of the probability of occurrence of the next Cascadia subduction event.

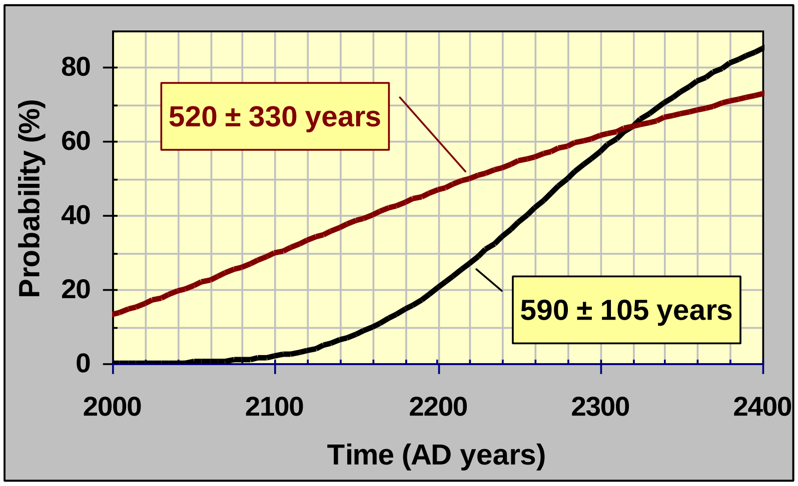


Figure 3.5 The effect of return periods on the probability estimations

3.3.3 Aggregate Exceedance Probability Calculations for Crustal, Sub-Crustal and Subduction Earthquakes

The crustal/sub-crustal probabilities presented above are exceedance probabilities while the probabilities related to subduction earthquake activity are occurrence probabilities. To combine these two probabilities, we need to 1) standardize the occurrence/exceedance probabilities, and 2) convert the probabilities to summable annual rates of exceedance.

3.3.3.1. Standardization of Occurrence/Exceedance Probabilities - In order to combine the subduction interface earthquake occurrence probabilities with the crustal/sub-crustal exceedance probabilities, we need to establish the conditional probabilities that a subduction interface earthquake will cause ground shaking levels that exceed MMI V, VI, and VII on sites across Vancouver Island. This can be determined in one of several different ways. One approach is to use a conversion factor between MMI and PGA, and determine in which parts of Vancouver Island the corresponding PGA would be exceeded. One problem with this approach is that the ground motion characteristics of a subduction interface earthquake is significantly different from crustal and sub-crustal earthquakes, which necessitates the use of a PGA-MMI relationship specifically developed for subduction interface earthquakes. Currently, no applicable MMI-PGA relationship exists to serve this purpose.

A second issue in using this approach is that PGA is inadequate in representing certain characteristics of ground shaking that are specific to subduction interface earthquakes. These characteristics include the comparatively long duration of subduction earthquake shaking (which even if the shaking intensity is low, long duration may cause higher levels of damage), and ground shaking that is rich in low-frequencies (which coincide more closely with natural periods of vibration of most types of structures, and therefore may result in higher levels of damage).

The second approach to establishing the conditional probability of subduction earthquake shaking exceeding certain MMI levels across Vancouver Island is the use of an empirical MMI-based attenuation relationship developed for subduction interface earthquakes. Unfortunately, no applicable MMI-based attenuation relationships currently exist.

The third approach is to examine the distribution of recorded MMI levels during recent subduction interface earthquakes in analogous subduction zones around the world. Given the problems associated with the first two approaches, we adopt this latter approach and use 2004 Sumatra and 2010 Chile subduction interface earthquakes as analogous references.

Given the Sumatra subduction zone's similar size, dip angle, convergence rates, and deformation patterns (Cassidy et al., 2005), the effects observed following the 2004 M9.1 Sumatra-Andaman subduction event are likely indicative of the potential effects associated with the next Cascadia subduction earthquake along the west coast of North America. Shaking intensity observed during the December 26, 2004 event peaked at MMI IX at some locations within two hundred kilometres of the subduction zone. While pockets of higher damage may be due to soft soil conditions, the larger areas of a given intensity of shaking can be used for a comparison. The 2004 Sumatra ShakeMap derived from observed and estimated intensities, indicate that intensity VII zone extends to approximately 150km from the edge of surface rupture (USGS, 2010). In Cascadia, the comparable MMI VII zone would then extend beyond Vancouver Island to roughly the location of Vancouver on the BC mainland.

Similarly, the 2010 M8.8 Chile subduction earthquake ShakeMap reports the MMI VII zone extending up to about 100km from the edge of surface rupture as estimated by USGS (USGS, 2010). In the Cascadia Subduction Zone, this would correspond with intensity VII shaking extending to just east of Vancouver Island.

Given the reported shaking intensities of these subduction events, we assume a 100% chance that a full-rupture Cascadia interface earthquake would cause MMI VII ground shaking intensities across Vancouver Island. The likelihood of MMI V and VI being exceeded is also therefore a certainty. The exceedance probabilities for MMI V, VI, and VII due to a Cascadia subduction interface earthquake are therefore probability of occurrence multiplied by the conditional probability of exceedance – which in this case is 1.0.

3.3.3.2 Calculation of Annual Rates of Exceedance - As probabilities cannot be summed, the exceedance probabilities for the subduction interface earthquakes need to be converted to effective annual rates of exceedance, which can then be aggregated with the annual rates of exceedance calculated for crustal and sub-crustal earthquakes. We use the Poisson probability distribution to harmonize the subduction rates with the crustal/sub-crustal rates. Our approach is similar to that used by USGS and California's Work Group on Earthquake Probabilities (WGCEP, 1995) which integrates time-dependent probabilities calculated for California faults with probabilistic (Poisson) background seismicity models for the state. Recognizing the time-dependent nature of the subduction interface occurrence probabilities, we calculate the effective annual rates of exceedance for each of the four timeframes of interest (i.e. 10, 25, 50, and 100 years) before combining these rates with the crustal/subcrustal rates. The aggregated crustal/subcrustal and subduction interface rates are then used to re-calculate the ground shaking probabilities over the time periods of interest using a Poisson distribution.

3.4 Results

3.4.1 Crustal and Sub-Crustal Earthquake Probabilities

Crustal and sub-crustal earthquake shaking probabilities are calculated for 57 sites located on Vancouver Island, BC (Appendix B). Represented for each location are the probabilities of exceeding each of three levels of shaking (widely-felt, onset of non-structurally-damaging, and onset of structurally-damaging shaking) over four different time frames (10, 25, 50, and 100 years). Table 3.2 presents results for a subset of the nine most populous Vancouver Island communities. Mapping of the hazard probabilities was conducted using ArcInfo Geographic Information System (GIS) software package to interpolate the point data derived and illustrate the spatial distribution of the hazard across Vancouver Island. Figure 3.6 presents a matrix of the Vancouver Island probability maps for each of the three shaking levels over the four time periods.

In general, while the whole of Vancouver Island is prone to earthquake shaking, the results indicate there are two regions of increased hazard from crustal and sub-crustal earthquakes on Vancouver Island: the northwest and south. In the coastal northwest, where ‘widely-felt’ shaking probabilities exceed 40% in 10 years and over 90% in 100 years, populations are sparse. The probability of at least ‘non-structurally-damaging’ shaking occurring in this region exceeds 10% in 10 years and over 75% in 100 years. The probability of at least ‘structurally-damaging’ shaking occurring in this region ranges from less than 10% in 10 years to over 20% in 100 years.

Table 3.2 Time-independent crustal and sub-crustal earthquake probabilities for the nine most-populous Vancouver Island communities.

Community	**"Widely Felt" P[MMI ≥ V] (%) in:**				**"Non-structurally-Damaging" P[MMI ≥ VI] (%) in:**				**"Structurally-Damaging" P[MMI ≥ VII] (%) in:**			
	10 years	**25 years**	**50 years**	**100 years**	**10 years**	**25 years**	**50 years**	**100 years**	**10 years**	**25 years**	**50 years**	**100 years**
Campbell River	13	30	51	76	2.3	5.7	11	21	0.44	1.1	2.2	4.3
Courtenay	14	32	54	79	2.7	6.6	13	24	0.51	1.3	2.5	5.0
Duncan	30	59	84	97	11	26	45	70	3.5	8.6	16	30
Nanaimo	24	49	74	93	7.7	18	33	55	2.2	5.3	10	20
Port Alberni	16	36	59	83	3.7	9.1	17	32	0.81	2.0	4.0	7.8
Port Hardy	23	48	73	93	2.0	5.0	9.7	19	0.16	0.40	0.79	1.6
Port Renfrew	21	45	70	91	6.3	15	28	48	1.6	4.0	7.9	15
Tofino	16	35	57	82	2.1	5.1	10	19	0.35	0.88	1.8	3.54
Victoria	35	66	88	99	14	32	53	78	4.5	11	21	37

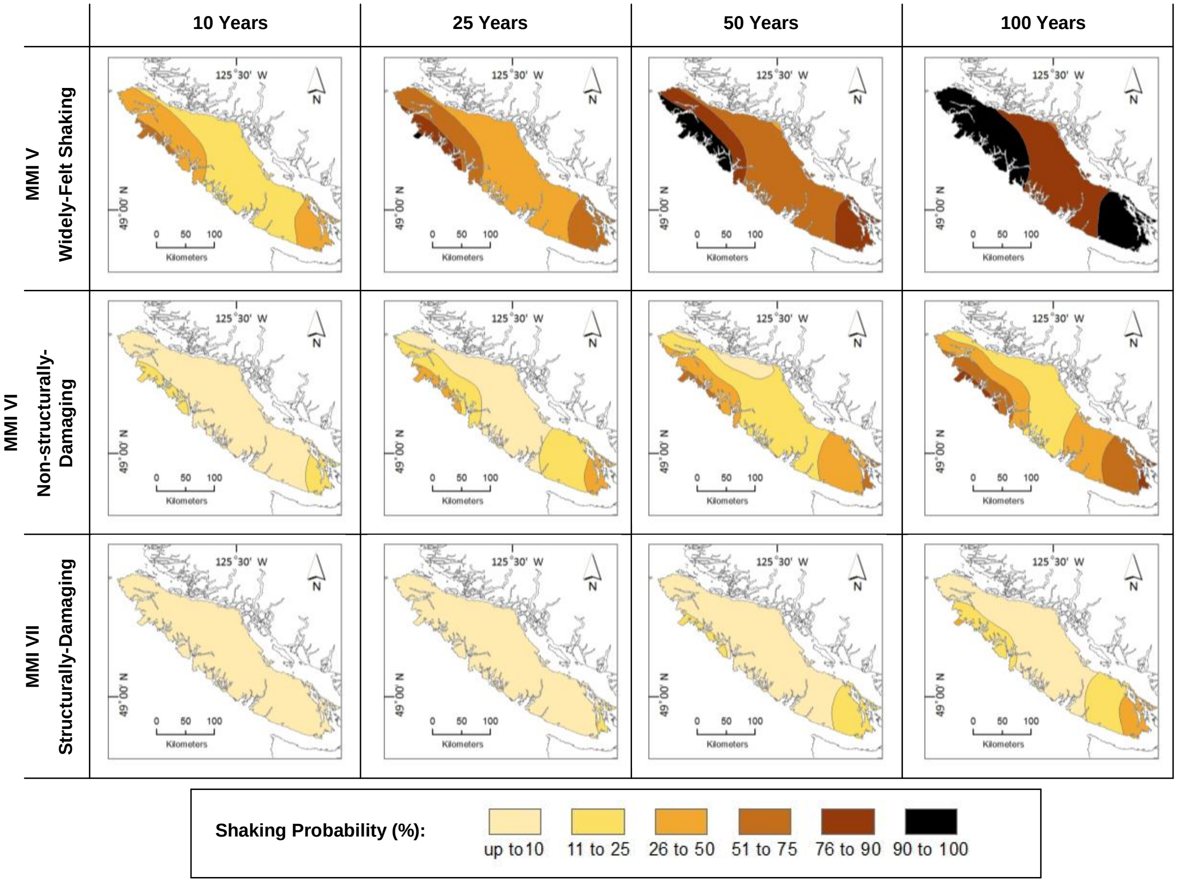


Figure 3.6 Crustal and sub-crustal shaking probability matrix for Vancouver Island**.** This matrix illustrates the earthquake shaking probabilities at three shaking intensity levels over four timeframes (10, 25, 50, and 100 years). Probabilities assume homogeneous firm ground conditions and do not include the subduction earthquake shaking contribution. See Appendix D for individual maps.

At the south end of Vancouver Island, where almost half of the Island's population resides and the provincial seat of government is located, the 'widely-felt' shaking probabilities due to crustal and sub-crustal earthquakes are similar to those in the northwest - exceeding 25% over 10 years and over 90% in 100 years. The likelihood of 'non-structurally-damaging' or stronger earthquake shaking ranges from over 10% in 10 years to75% in 100 years. In the greater Victoria metropolitan area, the probability of at least 'structurally-damaging' shaking increases from approximately 5% over 10 years (1 in 20) to over 30% over 100 years (1 in 3).

The lowest shaking probabilities resulting from crustal and sub-crustal sources were generally found across central and north-eastern Vancouver Island. Ironically, the only wide spread structurally-damaging earthquake recorded on Vancouver Island was the M7.3 Courtenay earthquake in 1946, which occurred in the eastern half of the mid-island in one of the Island's lowest earthquake shaking probability areas. With recorded shake intensities of up to VIII near the 1946 epicentre, it is instructive to note 1) that the shaking probability values represent probabilities of at least the stated level of shaking occurring (i.e. a site can experience stronger shaking), and 2) that even a small probability means there is some chance of strong ground shaking being experienced at the site.

3.4.2 Subduction Earthquake Probabilities

The Cascadia subduction earthquake hazard is calculated as a probability of occurrence and results account for the length of time since the last subduction event (January 26, 1700). Table 3.3 presents our best occurrence probability estimates for 10, 25, 50, and

100 year time periods and includes lower and upper estimates for each. Given that these subduction occurrence estimates are time-dependent, the estimated probabilities will increase with the length of time since the past event. Currently, there is approximately a 1 in 10 chance of a subduction earthquake occurring in the next 50 years.

3.4.3 Aggregate Earthquake Probabilities

To provide a comprehensive assessment of Vancouver Island's earthquake hazard from mainshock events, the contribution of crustal/sub-crustal earthquakes is aggregated with the contribution from subduction interface earthquakes for each of 57 sites (Appendix C). Table 3.4 presents the aggregate ground shaking probability results for a subset of the nine most populous Vancouver Island communities. Figure 3.7 presents a matrix of the Vancouver Island aggregate probability maps for each of the three shaking levels over the four time periods.

Assuming the next Cascadia subduction event will induce ground shaking levels of MMI VII or higher across Vancouver Island, the aggregate shaking probabilities for Island communities are significant. Like the crustal/sub-crustal probabilities, the aggregate ground shaking probabilities indicate two regions of Vancouver Island with increased seismic hazard: the Island's northwest and south. In both of these areas, the aggregate probability of widely-felt ground-shaking exceeds 25% over 10 years and increases to over 90% in 100 years. The probability of at least non-structurally-damaging shaking occurring on the island ranges from between 10-25% over 10 years to over 75% in the south and northwest over 100 years; while the probability of at least structurally-

Table 3.3. Cascadia megathrust earthquake probabilities occurring within 10, 25, 50, and 100 years of the year 2010.

Cascadia megathrust earthquake occurrence probability (%) within the next:											
10 years			**25 years**			**50 years**			**100 years**		
Lower	**Best**	Upper	Lower	**Best**	Upper	Lower	**Best**	Upper	Lower	**Best**	Upper
0.046	**8.0**	16	0.11	**9.6**	19	0.39	**12**	23	2.66	**17**	31

Table 3.4. Aggregate earthquake shaking probabilities for the nine most-populous Vancouver Island communities. These probabilities include contributions from crustal, sub-crustal and subduction earthquake sources.

Community	**"Widely Felt" P[MMI ≥ V] (%) in:**				**"Non-structurally-Damaging" P[MMI ≥ VI] (%) in:**				**"Structurally-Damaging" P[MMI ≥ VII] (%) in:**			
	10 years	**25 years**	**50 years**	**100 years**	**10 years**	**25 years**	**50 years**	**100 years**	**10 years**	**25 years**	**50 years**	**100 years**
Campbell River	20	37	57	80	10	15	22	34	8.4	11	14	21
Courtenay	21	38	59	82	10	16	23	37	8.5	11	14	21
Duncan	36	63	86	98	18	33	52	75	11	17	26	42
Nanaimo	30	54	77	94	15	26	41	63	10	14	21	33
Port Alberni	23	42	64	86	11	18	27	43	8.7	11	15	23
Port Hardy	29	53	77	94	10	14	21	32	8.1	10	13	18
Port Renfrew	28	50	73	92	14	23	37	57	10	13	19	30
Tofino	22	41	62	85	10	14	21	33	8.3	10	14	20
Victoria	40	69	90	99	21	38	59	82	12	19	30	48

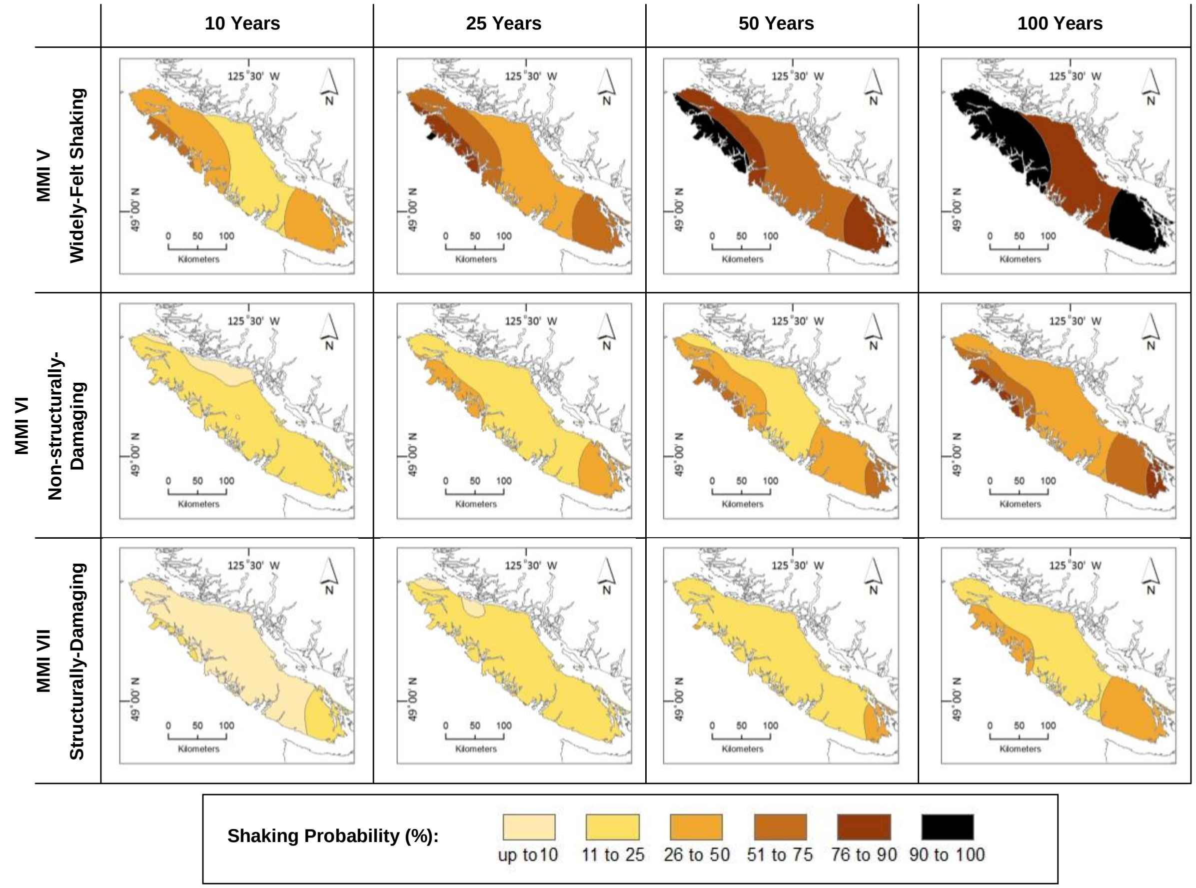


Figure 3.7 Aggregate (crustal, subcrustal, and subduction earthquake) shaking probability matrix for Vancouver Island. This matrix illustrates the earthquake shaking probabilities at three shaking intensity levels over four timeframes (10, 25, 50, and 100 years). Probabilities assume homogeneous firm ground conditions. See Appendix E for individual maps.

damaging shaking ranges from between 10-25% over 10years to between 25-50% over 100 years in the south and northwest.

Community-specific data indicate that the aggregate probability for ‘widely-felt’ shaking in Victoria ranges from 40% over 10 years to 99% over 100 years. More importantly, the ‘non-structurally-damaging’ aggregate probabilities for this community of over 300,000 people are 21%, 38%, 59% and 82% over 10, 25, 50 and 100 years, respectively. In other words, the probabilities of Victorians experiencing non-structurally damaging ground shaking ranges from 1 in 5 over 10 years to 4 in 5 in 100 years. The aggregate probability ‘structurally-damaging’ ground shaking in Victoria is 12%, 19%, 30%, and 48% over the next 10, 25, 50 and 100 years respectively. This equates to approximately a 1 in 10 chance of structurally-damaging earthquake shaking over 10 years, and a 1 in 2 chance over 100 years.

3.5 Discussion of Uncertainties

3.5.1 Crustal/ Sub-Crustal Calculations

There are a number of assumptions and uncertainties associated with the estimates calculated in this study. To the greatest extent possible, we identify and control for these and the presented results are best estimates for Vancouver Island given the seismic hazard model used. As ongoing research offers further refinement of the factors involved, opportunities will arise to revise and refine the estimates. The ground motion exceedance probability calculations are subject to both aleatory and epistemic uncertainties associated with ground motion attenuation, MMI-PGA conversion relationships, source zone definitions, recurrence relationships, and surficial geology.

3.5.1.1. Ground Motion Model - Ground motion uncertainty is one of the largest sources of uncertainty in seismic hazard calculations. In this study, the ground motion models used were those adopted by the Geological Survey of Canada for calculating hazard for the 2010 National Building Code (Adams and Halchuk, 2003). The incorporation of more recent attenuation relationships and quantification of uncertainties associated with ground motions will be the subject of future work.

3.5.1.2. MMI-PGA Conversion - As mentioned earlier, there are several MMI-PGA conversion relationships in use today and the specific relationship used can influence the probability outcomes. Moreover, within a single relationship, each MMI level (for example MMI VI) corresponds to a range of PGAs. In this study, the Wald et al. (1999) relationship was adopted. While this relationship was developed to convert PGA to MMI (rather than MMI to PGA), it works reasonably well in the reverse conversions, particularly in the mid-MMI range (Wald, 2009). To provide best estimates for Vancouver Island, the mean PGA value for each MMI level was used.

3.5.1.3. Source Zone Definitions - Variability in the source zone definitions also influences probability results. This study uses the two Geological Survey of Canada source zone models used for hazard calculations in the 2010 NBC: H-Model and R-Model. Differences between the two models reflect variations in interpretation of contributing factors to area seismicity. Calculations were carried out using both models (once using H model and once using R model) and the mean of the two results provided the best estimate for each location.

3.5.1.4. Recurrence Parameters - The recurrence relationship parameters for each source zone are an additional source of uncertainty in estimating crustal and sub-crustal earthquake probabilities. Onur and Seemann (2004) test the limits of these parameters at two sites in British Columbia: Victoria and Vancouver. In addition to presenting 'shaking probability' best estimates for these two sites, they bracket the uncertainty by providing the lower and upper range of probability estimates based on recurrence parameter variability. In this paper, best estimates alone are used to estimate the shaking probabilities at a given site.

3.5.1.5. Surficial Geology - While recognizing the significant influence of surficial geology on ground response (e.g., site amplification, liquefaction, slope failure), probabilities in this study were calculated for a standard homogeneous ground condition. Given the glacial history of Vancouver Island and the prevalence of tills within a range of harder and softer surficial materials, 'firm ground' surface conditions was adopted as the standard across the study area.

Recognizing that a uniform, standard ground material was adopted across the study area, and that surficial materials can vary dramatically within the relatively small area of a city block (see for example, Monahan and Levson, 2000 for Victoria), it is important to be cognizant of the fact that resultant probabilities may be higher or lower than those stated depending on local substrates. Generally, sites underlain by bedrock can expect lower probabilities than estimated, while sites underlain by unconsolidated sediments can expect higher probabilities than estimated. This is particularly important for communities built on low-lying, unconsolidated alluvial/deltaic deposits where soil amplification and/or liquefaction may significantly increase the risk; or built in proximity to steeper slopes prone to failure. Estimating the relative impact of various ground conditions on the probabilities is beyond the scope of this current study, but will be a focus of future research.

3.5.2 Subduction Calculations

The occurrence probability estimates for the next Cascadia subduction earthquake were developed separately from the crustal/sub-crustal exceedance probability estimates. As the time-dependent nature of the subduction event estimates can be quantified using past events, a different approach to probability calculations was used and the associated uncertainties differ from the exceedance probability calculations.

3.5.2.1. Probability Distribution - Subduction occurrence probabilities are sensitive to the type of probability distribution used to model the earthquake recurrence. Onur and Seemann (2004) investigated several distribution functions (i.e. Lognormal, Brownian, Gaussian, Poissonian) and found that lognormal distribution is widely used for earthquake recurrence in subduction zones, is similar to Brownian Passage Time model that is commonly used in California, and is particularly reliable through the mid-ranges of the distribution. Therefore, the lognormal distribution was used to estimate the occurrence probabilities for the Cascadia subduction interface earthquake.

3.5.2.2. Return Period Variance - Various studies suggest differences in the timing of past Cascadia subduction interface earthquakes. Accordingly, there is limited agreement on the mean and standard deviation of full-rupture Cascadia return periods. The two widely referred to estimates, 590 ± 105 (Adams and Weichert, 1994) years and 520 ± 330 years (Atwater and Hemphill-Haley, 1997) are used to provide lower and upper estimates, respectively, despite their sizeable error margins. Further research refining the timing of past events would provide clarity to actual recurrence periods and would enable a narrowing of the error margin associated with the reported best estimates.

3.6 Conclusions

Comprehensive risk assessments based on quantitative analysis are essential for the estimation of individual, local, regional and national risk. Fundamental to comprehensive risk assessments is a hazard analysis that clearly and simply expresses the probability of a hazard occurring. Building on the hazard models developed by the Geological Survey of Canada, this paper presents new earthquake shaking results for Vancouver Island communities. These same procedures can be applied anywhere probabilistic hazard modelling exists, and can provide simple, meaningful hazard estimates for use by community decision-makers and the general public.

This study provides earthquake hazard probability calculations for communities on Vancouver Island, BC and estimates the hazard contributions from regional crustal/sub-crustal earthquake sources, as well as the Cascadia subduction source. Additionally, it aggregates the hazard from both of these sources and offers the combined ground-shaking hazard probabilities for each community.

The crustal/sub-crustal earthquake shaking hazard is presented in terms of the likelihood of exceeding each of three shaking intensity levels (widely-felt shaking; onset of non-structurally-damaging shaking; and, onset of structurally-damaging shaking). These time-independent exceedance probabilities are expressed as simple percentage values representing best estimates of at least the stated level of shaking occurring over one of four periods (10, 25, 50, and 100 years). In Victoria, for example, the probability of structurally-damaging shaking occurring as a result of crustal/sub-crustal ground shaking is 5%, 11%, 21% and 37% over 10, 25, 50 and 100 years, respectively

Owing to the unique characteristics of the Cascadia subduction interface earthquakes and the time-dependent nature of the recurrence, we estimate the time-dependent probability of occurrence based on the timing of the last subduction earthquake (January 26, 1700). Calculated estimates for the probability of the next Cascadia event occurring is 8.0%, 9.6%, 12%, and 17% over 10, 25, 50, and 100 years, respectively. These estimates are calculated for the year 2010, and will increase over time until the next Cascadia interface earthquake.

The combined crustal/sub-crustal and subduction interface earthquake hazard calculations express aggregate shaking probabilities for communities across Vancouver Island. Results are based on annual rates of exceedance calculations and, like the subduction earthquake probabilities, will increase slowly over time. In Victoria, in the year 2010, for example, the aggregate crustal, sub-crustal and subduction earthquake structurally-damaging ground shaking probabilities are 12%, 19%, 30% and 48% over 10, 25, 50, 100 years, respectively.

It is important to note that given the number and range of the identified uncertainties, the relative probability values are more important than small differences in the absolute values between adjacent communities.

Similarly, it is also important to note that the probabilities presented are calculated for homogeneous ‘firm ground’ geologic conditions. In general, areas primarily underlain by bedrock can expect lower probabilities while those situated predominantly on very soft, unconsolidated sediments can expect higher probabilities. We continue to review and refine these probabilities, and are currently focusing on quantifying the influence of varying site geological conditions on the resultant probabilities.

The results provided are regional ground shaking probabilities and are meant to be used at a municipal level. This means that results presented are not appropriately used with respect to individual buildings or structures as the specific site conditions, building design and construction characteristics will vary. For example, a “20% chance that there will be structurally-damaging shaking in 100 years" does not imply that a specific building will be damaged, but that within the municipality of interest, there will be some buildings (likely those with poor construction) that suffer structural damage.

The earthquake aftershock threat to Vancouver Island communities is not addressed in this study. However, as recently reported following the 2011 Tohoku, Japan subduction event, the 2010 Maule, Chile subduction event and 2010 Haiti crustal event, the impacts of these aftershock sequences can be far reaching - not only in terms of the physical threat of additional shaking affecting already compromised structures, but also in terms of pervasive psycho-social effects on residents and aid workers. The next paper (Chapter 4) addresses the Cascadia subduction aftershock probability question, and offers preliminary estimations of the shaking hazard posed by the next Cascadia subduction aftershock sequence in communities along the west coast of North America.

While the aggregate crustal, subcrustal and subduction earthquake shaking probabilities appear high enough to demand comprehensive earthquake preparedness, response and recovery planning, these probabilities must be weighed in light of the threat from other hazards (e.g., floods, forest fires, pandemic). Accordingly, no subjective classification of the probabilities has been imposed (such as 'low', 'medium', or 'high' hazard), and it is left to individuals, their communities, and governments to determine their respective tolerances to the estimated earthquake hazard.

For individuals, this simplified earthquake hazard information is intended to deepen their understanding of the earthquake threat and to encourage a reassessment of their level of family earthquake preparedness. For elected officials, this study is intended to estimate the earthquake threat in their community, to encourage hazard comparisons to other perils, and to facilitate evidence-based funding decisions to ensure adequate preparedness activities are undertaken. For municipal planners and emergency managers the results are intended to help highlight the earthquake risk within their jurisdiction and to encourage appropriate planning activities to minimize environmental, life, property and economic losses resulting from future seismic shaking.

3.7 References

Adams J 1990. Paleoseismicity of the Cascadia subduction zone: evidence from turbidites off the Oregon-Washington margin. *Tectonics*, 9: 569-583.

Adams J and Halchuk S 2003. Fourth generation seismic hazard maps of Canada: Values for over 650 Canadian localities intended for the 2005 National Building Code of Canada. *Geological Survey of Canada Open File* 4459, Natural Resources Canada.

Adams J and Weichert D 1994. Near-term probability of the future Cascadia megaquake. Proceedings of the Workshop on Paleoseismology, *United States Geological Survey Open-File Report* 94-568.

Atkinson GM and Boore DM 2003. Empirical ground-motion relations for subduction-zone earthquakes and their application to Cascadia and other regions. *Bulletin of the Seismological Society of America*, 93(4): 1703-1729.

Atkinson GM and Sonley E 2000. Empirical relationships between Modified Mercalli Intensity and response spectra. *Bulletin of the Seismological Society of America*, 90(2), 537-544.

Atwater BF and Hemphill-Haley E 1997. Recurrence intervals for great earthquakes of the past 3500 years at the northeastern Willapa Bay, Washington. *United States Geological Survey Professional Paper* 1576.

Atwater BF, Nelson AR, Clague JJ, Carver GA, Yamaguchi DK, Bobrowsky PT, Bourgeois J, Darienzo ME, Gran, WC, Hemphill-Haley E, Kelsey HM, Jacoby GC, Nishenko SP, Palmer SP, Peterson CD, and Reinhart MA 1995. Summary of coastal geologic evidence for past great earthquakes at the Cascadia subduction zone. *Earthquake Spectra*, 11(1): 1-18.

Boore DM, Joyner WB, and Fumal TE 1993. Estimation of response spectra and peak accelerations from western North American earthquakes: an interim report. *United States Geological Survey Open-File Report* 93-509.

Boore DM and Atkinson GM 2008. Ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods between 0.01s and 10.0s. *Earthquake Spectra*, 24(1): 99-138.

BC Stats (British Columbia Statistics) 2011. Population and Demographics, Government of British Columbia. http://www.bcstats.gov.bc.ca/data/pop/popstart.asp, [Website Last Accessed: December 4, 2011].

Campbell KW and Bozorgnia Y 2008. NGA ground motion model for the geometric mean horizontal component of PGA, PGV, PGD, and 5%-damped linear elastic response spectra for periods ranging from 0.01 to 10s. *Earthquake Spectra*, 24(1): 139-171.

Canadian Standards Association 2006. Canadian Highway Bridge Design Code, CAN/CSA-S6-06, Canadian Standards Association, Mississauga, Ontario.

Cassidy JF, Rogers GC, Dragert H, and Wang K 2005. The 26 December 2004, M 9.0 Sumatra earthquake: implications for Cascadia, *Abstract in Seismological Research Letters*, 76(2): 220.

Chiou BS-J and Young RR 2008. An NGA model for the average horizontal component of peak ground motion and response spectra. *Earthquake Spectra*, 24(1): 173-215.

Clague JJ 1997. Evidence for large earthquakes at the Cascadia Subduction Zone. *Reviews of Geophysics*, 35(4): 439-460.

Clague JJ 2002. The earthquake threat in southwestern British Columbia: a geologic perspective. *Natural Hazards*, 26: 7-34.

Clague JJ and Bobrowsky P 1999. The geological signature of great earthquakes off Canada's west coast. *Geoscience Canada*, 26(1): 1-15.

Clague JJ, Atwater BF, Wang K, Wang Y, and Wong I 2000. Great Cascadia earthquake tricentennial. *Geological Survey of Canada Open File* 3938. Natural Resources Canada.

Cornell CA 1968. Engineering seismic risk analysis, *Bulletin of the Seismological Society of America*, 58(5): 1583-1606.

Flück P, Hyndman RD and Wang K 1997. Three-dimensional dislocation model for great earthquakes of the Cascadia subduction zone, *Journal of Geophysical Research*, 102: 20539-20550.

Lay T, Kanamori H, Ammon CJ, Nettles M, Ward SN, Aster RC, Beck SN, Bilek SL, Brudzinski MR, Butler R, Deshon HR, Edstrom G, Satake K, and Sipkin S 2005. The great Sumatra–Andaman earthquake of 26 December 2004. *Science*, 308: 1127–1133.

Monahan PA and Levson VM 2000. Quaternary geological map of greater Victoria, British Columbia. Geological Survey, Ministry of Energy and Mines, Geoscience Map 2000-2.

Mishra OP, Kayal JR, Chakrabortty GK, Singh OP, and Ghosh D 2007. Aftershock investigation in the Andaman-Nicobar Islands of India and its seismotectonic implications. *Bulletin of the Seismological Society of America*, 97: S71-S85.

Munich Re 1992. A study of the economic impact of a severe earthquake in the lower mainland of British Columbia. A publication of the Munich Reinsurance Company of Canada, Toronto, ON.

National Research Council 2010. National Building Code. Institute for Research in Construction, Government of Canada, Ottawa, Canada.

NRCan (Natural Resources Canada) 2010. Southwestern British Columbia earthquakes of the last five years. Geological Survey of Canada, Natural Resources Canada. http://earthquakescanada.nrcan.gc.ca/recent/maps-cartes/index-eng.php?maptype=5y&tpl_region=swbc, [Website Last Accessed: January 12, 2010].

Onur T and Seemann MR 2004. Probabilities of significant earthquake shaking in communities across British Columbia: implications for emergency management, Proceedings of the 13th World Conference on Earthquake Engineering, August 1-6, Vancouver, British Columbia, Canada, Paper 1065.

Risk Engineering, Inc. 1997. EZ-FriskTM (Version 4.0) User's Manual.

Satake K, Shimazaki K, Tsuji Y, and Ueda K 1996. Time and size of a giant earthquake in Cascadia inferred from Japanese tsunami record of January 1700. *Nature*, 379: 246-249.

Tourism British Columbia 2008. Vancouver Island, Victoria and the Gulf Islands regional profile: building tourism with insight. http://tourismbc.com/Libraries/Research_VI_Profile/Vancouver_Island_Victoria_and_the_Gulf_Islands_Regional_Profile_2008.sflb.ashx, [Website Last Accessed: January 12, 2010].

Trifunac MD and Brady AG 1975. On the correlation of seismic intensity with peaks of recorded strong ground motion. *Bulletin of the Seismological Society of America*, 65(1): 139-162.

USGS (United States Geological Survey) 2009. Earthquake summary report. http://earthquake.usgs.gov/earthquakes/eqinthenews/2004/usslav/ [Website Last Accessed: January 2, 2010].

USGS (United States Geological Survey) 2010. ShakeMap archive, http://earthquake.usgs.gov/earthquakes/shakemap/list.php?x=1 [Website Last Accessed October 28, 2010].

Wald D, Quitoriano V, Heaton T, Kanamori H, Scrivner C, and Worden C 1999. TriNet shakemaps: rapid generation of peak ground motion and intensity maps for earthquakes in southern California. *Earthquake Spectra*, 15: 537-555.

Wald D 2009. Personal Communication. Annual Meeting of the Seismological Society of America, Monterey, CA, USA, 8-10 April 2009.

WGECP (Working Group on California Earthquake Probabilities) 1995. Seismic hazards in southern California: probable earthquakes, 1994–2024, *Bulletin of the Seismological Society of America*, 85: 379–439.

Witter R, Kelsey H, and Hemphill-Haley E 2003. Great Cascadia earthquakes and tsunamis of the past 6700 years, Coquille River estuary, southern coastal Oregon. *Geological Society of America Bulletin*, 115(10): 1289-1306.

Yorath C, Kung R, and Franklin R 2001. Geoscape Victoria, Geological Survey of Canada Miscellaneous Report M41-8/74F, Natural Resources Canada.

Youngs RR, Chiou S-J, Silva WJ, and Humphrey JR 1997. Stochastic point-source modeling of ground motions in the Cascadia thrust, *Seismological Research Letters*, 68(1): 58-73.

Chapter 4.0

Probabilities of Significant Ground Shaking Due to Aftershocks Following a Cascadia Subduction Earthquake [1]

---

[1] A version of this paper is being submitted for publication in the journal of emergency management

4.0 PROBABILITIES OF SIGNIFICANT GROUND SHAKING DUE TO AFTERSHOCKS FOLLOWING A CASCADIA SUBDUCTION EARTHQUAKE

MARK SEEMANN[1], TUNA ONUR[2], and JOHN CASSIDY[3]

[1]Department of Geography, University of Victoria, Victoria, BC, V8W 3P5, Canada (Email: mseemann@uvic.ca); [2]Risk Management Solutions, Inc., Newark, CA, 94560 United States of America; [3]Natural Resources Canada, Sidney, BC, V8L 4B2, Canada

4.1 Abstract.

Some of the world’s largest earthquakes, subduction events with magnitudes greater than 8, occur along the west coast of North America between northern California and southern British Columbia. This region, known as the Cascadia subduction zone (CSZ), has experienced 13 subduction earthquakes that ruptured the full length of the CSZ during the past 6000 years, the most recent of which was a M9 event on January 26, 1700. These subduction, or megathrust, earthquakes are typically followed by hundreds if not thousands of aftershocks, several of which may exceed M6.0. Owing to the strength and sheer number of these aftershocks, their temporal clustering within a few months of the main event, and their potential proximity to urban centres, these events can be more damaging than the mainshock itself and therefore pose a significant threat to communities across the western Cascadia region, including major centres like: Victoria, BC; Vancouver, BC; Seattle, WA; Olympia, WA; and Portland, OR. Additionally, as these aftershocks follow a very large mainshock event, they strike in areas which have recently experienced strong and/or prolonged ground shaking. Consequently, the aftershocks impact already compromised environmental, social, economic, and infrastructure systems, and they inhibit effective and efficient response and recovery efforts. While much research exists with respect to the Cascadia subduction zone, to date little attention has been given to quantifying and assessing the aftershock activity following a full-rupture Cascadia subduction earthquake. The probability of the next great Cascadia megathrust earthquake occurring within the next 100 years is estimated to be approximately one in five. Based on an analysis of recorded aftershock sequences at similar circum-Pacific subduction zones, this paper estimates ground shaking probabilities associated with aftershock activity following a full-rupture Cascadia subduction earthquake. Calculations provide the likelihood of an aftershock exceeding each of three ground shaking intensity levels (Modified Mercalli Intensity (MMI) V - widely felt; MMI VI - threshold for non-structural damage; and, MMI VII - threshold of structural damage) for 22 Cascadia communities. Results presented in this paper are offered: 1) to assist community officials and the general public in appreciating the nature and full scope of the Cascadia subduction earthquake threat (i.e. beyond the “big” mainshock); 2) to encourage and facilitate comprehensive seismic hazard discussions and planning; and, 3) to provide quantitative data on which to base sound funding and policy decisions.

Key Words: seismic hazard, Cascadia Subduction Zone, subduction aftershock shaking probabilities, British Columbia, Washington, Oregon, California

4.2 Introduction

Subduction zones are known to create the largest recorded earthquakes around the world (typically greater than M8.0). These ‘megathrust’ earthquakes, are characterized by prolonged shaking (longer than three minutes), by the generation of tsunamis, and by the triggering of hundreds, even thousands, of aftershocks. In many cases, some of these aftershocks are likely to exceed M7 (Båth, 1965) and, depending on their proximity to communities, they may be more damaging than the main event. Consequently, megathrust aftershock sequences can be a significant and underappreciated source of environmental, life, property and economic loss.

The 2004 Sumatra subduction earthquake (M9.0), for example, was followed by over 18,000 recorded aftershocks within three months of the mainshock (Lay et al., 2005; Mishra et al., 2007a). Twenty-eight of those aftershocks were greater than M6.0, four were greater than M6.5, and one was greater than M7.0. Over a one-year period, two of the event's aftershocks reached M7.5 and the persistent regional seismic activity was found to not only exacerbate losses, but to lead to heightened states of anxiety and panic among individuals in the affected area (Mishra et al, 2007b).

Similarly, following the more recent 2010 Chilean subduction interface earthquake (M8.8), the Maule region of Chile experienced over 1300 aftershocks greater than M4 within 30 days of the mainshock. In the two months following the February 28th mainshock, 304 aftershocks larger than M5 were recorded, 21 of which were equal to or greater than M6.0 (EERI, 2010; USGS, 2010). Over 12 million people (72% of the Chilean population) are estimated to have experienced 'structurally-damaging' levels of ground shaking resulting from either the mainshock or one of its aftershocks (i.e. Modified Mercalli Intensity (MMI) leveI VII or higher) (EERI, 2010).

Understanding the impact of megathrust event aftershock sequences on communities is important for a number of reasons. First, compared with other types of earthquakes, and owing to the much larger plate displacements involved, the larger-magnitude megathrust earthquakes typically generate both higher magnitude aftershocks and a greater number of aftershocks over a much larger area. Second, felt megathrust aftershocks can continue for months or even years after the main event, which is in stark contrast to the shallow crustal earthquake aftershock sequences that typically only continue for days or weeks. Third, while the megathrust mainshock typically takes place off-shore, at depth, and some distance from communities, the area in which subduction aftershocks occur can extend beyond the rupture zone (Mishra et al., 2007a) and closer to coastal communities. Fourth, community structures affected by megathrust aftershocks may already be compromised by the prolonged (and possibly strong) ground shaking associated with the mainshock. Fifth, response activities are likely to be hampered by on-going episodic shaking (CREW, 2005; Mishra et al., 2007b). And sixth, the psychological and physiological impact of cumulative stress resulting from continual aftershock activity on area residents, visitors, aid-workers is significant and hampers both short and long-term recovery.

Given the scope and magnitude of hazards resulting from a Cascadia subduction earthquake, the intent of this paper is to quantify and present the likely aftershock probabilities for Cascadia communities. To this end, the paper analyzes ten historical circum-Pacific megathrust earthquakes and their aftershock sequences to develop two likely aftershock scenarios for the Cascadia Subduction Zone. These two scenarios are then used to estimate the likelihood of one of three levels of ground shaking being exceeded in each of 22 Cascadia-region communities. Current results present the likelihood that communities will experience ground shaking exceeding a) widely-felt shaking levels (MMI V), b) non-structurally-damaging shaking levels (MMI VI), or c) structurally-damaging shaking levels (MMI VIII) from aftershock activity following the next Cascadia megathrust earthquake.

4.2.1 Cascadia Subduction Zone

The Cascadia Subduction Zone (CSZ) forms one segment of what has been called the "Pacific Ring of Fire", a zone of high seismicity ringing the Pacific Ocean. The CSZ is located along the western margin of the North America plate and extends some 1100 km (680 mi) from southwestern British Columbia, Canada to northern California in the United States of America (Figure 4.1). To its north is the Queen Charlotte strike-slip fault zone which extends to Alaska, and to its south is the San Andreas strike-slip fault zone which runs through western California and into Mexico. This relatively young (less than 10 million years ago) subduction zone ranges between 40 and 150 km (25 and 95 mi) wide and is characterized by the oceanic Juan de Fuca plate moving to the northeast beneath the continental North America plate at a rate of approximately 40mm/year (Clowes and Hyndman, 2002). The upper interface between these two plates is 'locked', causing the western margin of the North America plate to compress and 'bulge' upward with the convergence of the two plates (Mazzotti et al., 2003). Various lines of terrestrial and marine evidence indicate this 'locked' Cascadia zone 'unlocks' episodically, triggering great earthquakes (larger than M8) (Atwater et al., 1995; Clague, 1997;

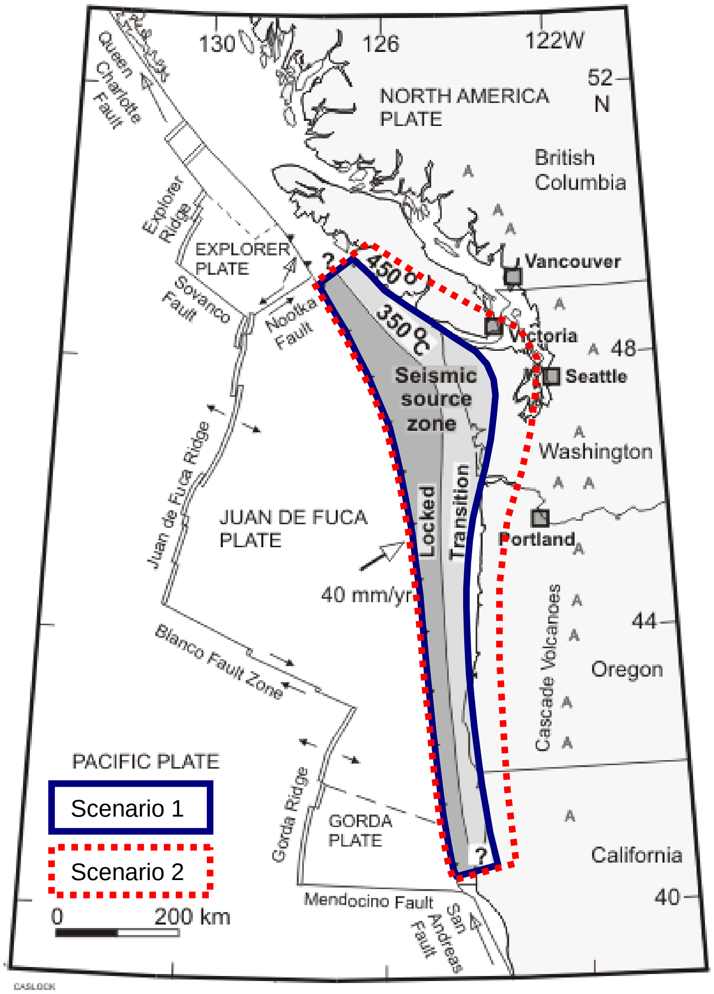


Figure 4.1. Tectonic setting of the Cascadia Subduction Zone with both the co-seismic slip (scenario one) and effective transition (scenario two) aftershock source zones indicated (adapted from Flück et al., 1997).

Frankel and Petersen, 2008; Goldfinger et al., 2003). At these times the western margin of the North American plate suddenly moves westward by several metres causing a rapid deflation of ‘the bulge’. Thirteen such rupture events are identified to have occurred over the last eight thousand years (Goldfinger et al., 2003; in press) and the estimated mean return period for these Cascadia subduction earthquakes is approximately 500-600 years

(590 ± 105 - Adams and Weichert, 1994; 520 ± 330 years - Atwater and Hemphill-Haley, 1997). The range of recorded recurrence intervals, however, spans from a few hundred years to over a thousand years (Goldfinger et al., in press; Witter et al., 2003).

The last Cascadia megathrust earthquake occurred on January 26, 1700 and, based on the size of the tsunami recorded along coastal Japan, this earthquake is estimated to have been a M9 event generated by the full rupture of the Cascadia Subduction interface (Satake et al., 1996, 2003). The fact that this event took place over 300 years ago, infers that sufficient time has passed for the next recurrence window to have opened. Seemann et al. (2011) estimate the probability of a full-rupture Cascadia megathrust earthquake occurring within the next 10, 25, 50, and 100 years to be 8.0%, 9.6%, 12%, and 17%, respectively. Their 50-year estimate agrees well with the earlier 50-year estimate of Mazzotti and Adams (2004). The likely geologic impacts of such a subduction event have been well-studied and this research is synthesized and published in a scientific consensus statement (Clague et al., 2000). Additionally, a generalized description of regional response and recovery vulnerabilities are outlined in a subduction scenario developed by the Cascadia Region Earthquake Working group (CREW, 2005).

Table 4.1. List of subduction interface earthquakes compiled in this study with associated Gutenberg-Richter (G-R) values.

Event Year	Event Name	Mainshock Magnitude (Mw)	Number of Aftershocks (Source)	Rupture Zone Area (km^2)	Completeness Magnitude (Mw)	G-R a-values	G-R b-values
1957	Andreanof	8.4	32 (NEIC)	210,000	--	--	--
1960	Chile	9.5	47 (NEIC)	322,000	--	--	--
1964	Alaska	9.2	962 (AEIC/NEIC)	225,000	5.0	7.4	1.0
1985	Mexico	8.1	31 (NEIC)	8,500	--	--	--
1985	Chile	8.0	259 (NEIC)	18,700	5.2	5.5	0.8
1986	Aleutians	8.0	442 (NEIC)	24,700	4.6	7.8	1.2
1995	Chile	8.0	196 (NEIC)	12,000	5.3	5.8	0.9
1995	Mexico	8.0	56 (NEIC)	12,000	--	--	--
2001	Peru	8.4	348 (NEIC)	32,000	4.7	5.2	0.7
2003	Hokkaido	8.3	293 (NEIC)	24,000	4.9	7.2	1.1
2004	Sumatra	9.0	3267 (NEIC)	385,000	5.2	8.0	1.1
2005	Sumatra	8.6	1841 (NEIC)	68,000	4.3	7.2	1.0
2007	Peru	8.0	156 (NEIC)	20,000	4.3	5.9	0.9
2010	Chile	8.8	1953 (NEIC)	100,000	4.2	7.5	1.0
Cascadia Scenario 1		9.0	--	97,000	--	7.0	1.0
Cascadia Scenario 2		9.0	--	150,000	--	7.2	1.0

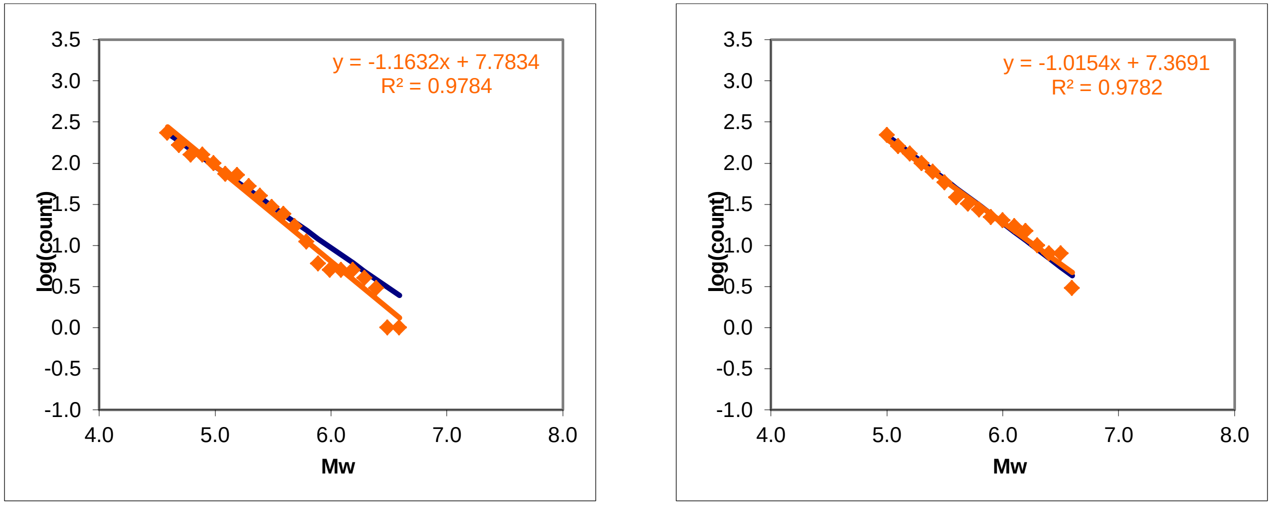
4.3 Methodology

4.3.1 Estimation of Mean Subduction Aftershock Sequence Activity Rate

To estimate the activity rate of aftershocks following the next Cascadia megathrust event, a review of recorded megathrust events from similar subduction zones was undertaken. Fourteen circum-pacific megathrust events with magnitudes equal or greater than M8.0 were identified in the National Earthquake Information Center's (NEIC) global earthquake catalogue, and their aftershock sequences for a one-year period were collected for analysis (Table 4.1). In the case of the Sumatra events, aftershocks were separated into those associated with the December 2004 event and those associated with the March 2005 event, based on the rupture zones of their respective mainshocks.

Of the 14 subduction events captured, four were excluded from the analysis due to limited aftershock records (1957 Andreanof, 1960 Chile, 1985 Mexico, and 1995 Mexico). The recent M9.0 Tohoku, Japan subduction earthquake was not used in this analysis as a complete (i.e. one year) aftershock record is not yet available. The remaining ten datasets were standardized by converting all aftershock magnitudes to a moment magnitude (Mw) scale (Utsu, 2002; Sipkin, 2003). Subject subduction source zone size was obtained from respective seismological event reports (1964 Alaska - Ichinose et al., 2007; 1985 Chile - Comte et al., 1986; 1986 Aleutians - Boyd and Nábělek, 1988; 1995 Chile - Carlo et al., 1999; 2001 Peru - Giovanni et al., 2002; 2003 Hokkaido - Honda et al., 2004; 2004 Sumatra – Ammon et al., 2005; 2005 Sumatra – Walker et al, 2005; 2007 Peru – EERI, 2007; 2010 Chile – Rhea et al., 2011). As

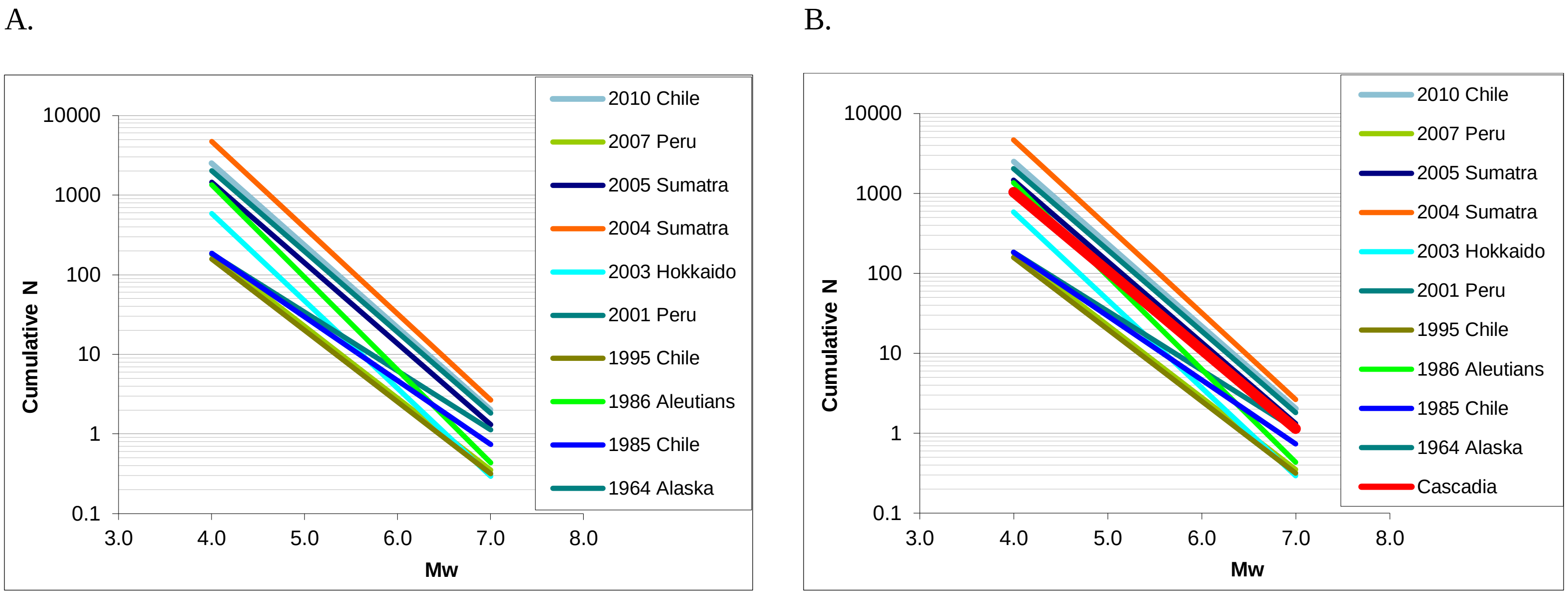
Figure 4.2 Sample Gutenberg-Richter magnitude recurrence plots for the circum-Pacific subduction events. The orange regression line represents a "least squares" regression, while the blue regression line represents a maximum-likelihood regression.



A. 1964 Alaska

B. 1986 Aleutians

Figure 4.3 (A) Magnitude recurrence plots for each of the ten historical megathrust events, and (B) the Cascadia Scenario 1 magnitude recurrence plot (red line), included for comparison to historic events plots.



potentially-damaging shallow aftershock activity in Cascadia is of most interest, the aftershock databases were further refined by considering only crustal aftershocks occurring in the North America plate. Accordingly, earthquakes below 40 km were not included. Completeness analysis was conducted by creating magnitude-recurrence charts to determine at which minimum magnitude rates began to drop off. No effort was made to remove ambient steady-state or background seismicity from the aftershock dataset.

Frequency-magnitude plots were created for each subduction aftershock sequence and Gutenberg-Richter relationships (Equation 4.1) were developed to describe each aftershocks sequence. Relationship values are presented in Table 4.1.

$$\log(NEQ) = a - b*M, \qquad \text{[Equation 4.1]}$$

Where,

NEQ represents the number of earthquakes

a represents the y-intercept

b represents distribution slope, and

M represents the moment magnitude

In calculating Gutenberg-Richter (G-R) a- and b-values, both least squares and maximum-likelihood regression analysis was calculated and compared. Owing to the fact that the datasets used in this study are relatively recent (and generally complete above M4) and recurrence of large magnitude aftershocks within a one-year period is well-defined, the least squares method was adopted. Figure 4.2 presents the least squares (orange line) and maximum likelihood (blue line) magnitude-recurrence calculations for sample megathrust events and illustrates the respective ‘fits’. Figure 4.3 presents the least squares recurrence plots for each of the ten studied megathrust events as well as the estimated Cascadia recurrence.

Based on these magnitude-recurrence calculations, mean a-values of 7.0 (Scenario 1) and 7.2 (Scenario 2) (Table 4.1) were used as a proxy for estimating the activity rate of aftershocks following a future Cascadia megathrust earthquake. Resultant b-values (Table 4.1) were found to range between 0.9 and 1.1, which agrees well with Shcherbakov et al. (2004), who note that aftershock sequences demonstrate good agreement with the G-R equation and have b-values that are not statistically different from the values for mainshocks. In developing the Cascadia models we therefore use a mean b-value of 1.0.

In developing a G-R relationship for Cascadia aftershocks, this study assumes that future Cascadia subduction events will reflect the characteristics of the last great event in 1700 (Satake et al., 1996; 2003) and that the entire length of the Juan de Fuca subducting plate is anticipated to rupture in a M9.0 event. Consequently, based on records from past subduction earthquakes and Båth’s law for the difference in magnitude between a mainshock and its largest aftershock, we assume that Cascadia aftershocks will have magnitudes of less than M8.0 (Båth, 1965; Shcherbakov et al., 2004). Hence we use a maximum aftershock magnitude of M7.9 as the upper bound in the hazard calculations. We also adopt a lower bound aftershock magnitude of M4.0 for the hazard analysis since completeness in our reference events does not extend below M4.0 and magnitudes lower than 4.0 are not likely to be significant in terms of generating widely-felt earthquake shaking.

The aftershock activity rates were standardized with respect to the rupture zone areas by calculating the activity rate per square kilometre for each subduction zone. The average activity rate/km^2 was then used to estimate probable Cascadia aftershock activity by multiplying it by the modeled Cascadia source areas, hence the two different a-values for Scenario 1 and Scenario 2.

4.3.2 Modeling of the Spatial Extent of the Cascadia Subduction Aftershock Sequence

The size and geometry of the Cascadia aftershock source zone is fundamental to the assessment of regional ground shaking probabilities. In modeling the Cascadia subduction zone, basic assumptions regarding the length and the width of the rupture zone guided the development of two probable source areas. With respect to the length of the rupture zone, we assume a full rupture of the subduction zone in both scenarios. This is based on the marine and terrestrial evidence of Holocene Cascadia subduction events (Atwater et al., 1995; Clague, 1997; Frankel and Petersen, 2008; Goldfinger et al., 2003; Satake, 1996). The width of the likely Cascadia rupture zone is less clear, and we develop two scenarios based on Wang et al.'s (2003) revised Cascadia dislocation model. Cascadia Scenario 1 uses the estimated area of co-seismic slip, while Cascadia Scenario 2 uses the larger estimated effective transition area (Figure 4.1). In each case the geometry of the source zones reflects the modeled subduction plate configuration based on geodetic deformation data and thermal regimes (Flűck et al., 1997; Hyndman and Wang, 1995; Wang et al., 2003).

4.3.3 Calculating CSZ Ground-Shaking Probabilities for Cascadia Communities

With the mean circum-Pacific subduction aftershock recurrence information calculated as above and with the likely Cascadia event source zone parameters defined (i.e. Scenario 1 and 2), seismic hazard was calculated using conventional Probabilistic Seismic Hazard Assessment (PSHA) procedures. PSHA assumes uniform distribution of earthquakes spatially and temporally within a source zone, and therefore aftershock occurrence was modeled as a uniformly distributed process over each of the source zone parameters in a one-year time frame. This means the probability of any one aftershock occurring is modeled as being independent of the time of previous seismic events and does not take into account clustering, directivity, and the transfer of stress from nearby faults. It also means that modeling does not address temporal decay of the aftershock activity over the one-year period. Instead, it captures the average activity rate uniformly over a one-year period. Given Omori's law of aftershock decay (Omori, 1894; Utsu et al., 1995), larger ground shaking probabilities can be assumed to take place within the first six months of the aftershock sequence and are most likely to occur within the first three months.

The ground motion attenuation relationship used significantly influences the resultant probabilities in this study. In this hazard analysis, we adopt the current North American attenuations standard, "Next Generation Attenuation" (NGA) relationships (i.e., Abrahamson and Silva, 2008; Boore and Atkinson, 2008; Campbell and Bozorgnia, 2008; and Chiou and Youngs, 2008), in our calculations. Each of the four relationships is independently used to model earthquake attenuation in both of the two scenario source zones. Results are averaged, with equal weights on each relationship, to provide a mean estimate of the shaking probabilities. Standard deviations about the mean values are also presented. We assume homogeneous “firm ground” conditions throughout, as defined by an average shear wave velocity of 760 m/s within the 30 m of the earth’s surface so as to minimize the uncertainties associated with amplification on softer materials and de-amplification on harder materials.

Finally, three ground shaking intensity levels were determined to be of importance to individuals at the community level: the threshold for ‘widely-felt’ shaking (MMI V); the threshold for ‘non-structurally damaging’ shaking (MMI VI) and the threshold for ‘structurally-damaging shaking (MMI VII) (Table 3.1). Note that these intensity levels are lower bound exceedance thresholds. Consequently, while MMI VII ground shaking will likely not cause structural damage in well-built structures or new structures built according to recent seismic design codes, the ground motions are strong enough to cause structural damage in poorly built or older, pre-code buildings.

Since the recently developed attenuation relationships used in this study do not allow calculation of MMI directly, conversion from the MMI thresholds to Peak Ground Acceleration (PGA) thresholds is carried out based on the conversion factors of Wald et al. (1999). MMI V, VI, and VII, were determined to have PGA equivalents of 0.067g, 0.13g, and 0.24g, respectively.

Ground shaking probabilities exceeding these PGA thresholds are calculated for twenty-two coastal and inland Cascadia communities (Table 4.2 and 4.3). Communities were selected on the basis of population size, proximity to the subduction zone, and spatial distribution. The annual rate of exceedance for each of these ground-shaking thresholds is calculated for twenty-two communities using EZ-Frisk (Risk Engineering, 1997).

4.4 Results and Discussion

Probabilities presented in Tables 4.2 and 4.3 represent the likelihood of ground shaking levels exceeding MMI V, MMI VI and MMI VII in selected Canadian and U.S. communities as a result of aftershocks occurring within 12-months of a full-rupture Cascadia megathrust earthquake. Two scenarios are offered to reflect two probable extents of aftershock distribution. Results from both scenarios are presented for a subset of communities in Figure 4.4 which graphically illustrates the geographic distribution of the aftershock hazard along the western North American coast.

In both scenarios, coastal communities located closer to the rupture zone, such as Tofino, BC, Long Beach, WA, Newport, OR, and Crescent City, CA have the highest aftershock shaking probabilities. The likelihood of these coastal communities experiencing ‘widely-felt’ ground shaking from aftershocks rises from approximately one-in-two in Scenario One (S1) to a virtual certainty in Scenario Two (S2). Similarly, the probability of non-structurally damaging shaking resulting from Cascadia aftershocks for these communities rises from roughly one-in-ten (S1) to nine-in-ten (S2) due to the proximity of the modeled

Table 4.2 Scenario 1 probabilities of exceeding MMI V (Widely-felt shaking), VI (Non-structurally-damaging shaking), and VII (Structurally-damaging shaking) in select communities over 12 months. Calculations are based on an assumption of firm ground conditions, and would be expected to be higher in areas of soft, unconsolidated sediments, and lower on bedrock. Values are rounded to the nearest whole number.

Community	**Widely-Felt Shaking (%)**			**Non-structurally Damaging Shaking (%)**			**Structurally Damaging Shaking (%)**		
	-1SD	**Mean**	+1SD	-1SD	**Mean**	+1SD	-1SD	**Mean**	+1SD
Campbell River, BC	0	**1**	1	0	**0**	0	0	**0**	0
Nanaimo, BC	1	**2**	2	0	**0**	0	0	**0**	0
Tofino, BC	49	**56**	64	9	**12**	15	1	**2**	2
Port Renfrew, BC	34	**40**	45	5	**7**	8	1	**1**	1
Vancouver, BC	0	**1**	1	0	**0**	0	0	**0**	0
Victoria, BC	5	**6**	8	0	**1**	1	0	**0**	0
Abbotsford, BC	0	**0**	1	0	**0**	0	0	**0**	0
Forks, WA	70	**78**	85	18	**23**	29	2	**3**	5
Seattle, WA	1	**1**	2	0	**0**	0	0	**0**	0
Olympia,WA	4	**5**	7	0	**1**	1	0	**0**	0
Longview,WA	3	**4**	5	0	**0**	1	0	**0**	0
Oceanshores, WA	70	**77**	85	17	**24**	31	2	**4**	5
Long Beach, WA	56	**66**	76	12	**18**	24	1	**3**	4
Rockaway Beach,	33	**39**	45	5	**7**	9	0	**1**	1
Portland, OR	1	**2**	2	0	**0**	0	0	**0**	0
Salem, OR	2	**3**	4	0	**0**	0	0	**0**	0
Eugene, OR	2	**3**	3	0	**0**	0	0	**0**	0
Coos Bay, OR	37	**43**	49	6	**8**	10	1	**1**	1
Newport, OR	33	**38**	44	5	**7**	8	0	**1**	1
Medford, OR	1	**1**	2	0	**0**	0	0	**0**	0
Crescent City, CA	39	**45**	51	7	**9**	10	1	**1**	1
Eureka, CA	49	**56**	64	10	**13**	15	1	**2**	2

Table 4.3 Scenario 2 probabilities of exceeding MMI V (Widely-felt shaking), VI (Non-structurally-damaging shaking), and VII (Structurally-damaging shaking) in select communities over 12 months. Calculations are based on an assumption of firm ground conditions, and would be expected to be higher in areas of soft, unconsolidated sediments, and lower on bedrock. Values are rounded to the nearest whole number.

Community	**Widely-Felt Shaking (%)**			**Non-structurally Damaging Shaking (%)**			**Structurally Damaging Shaking (%)**		
	-1SD	**Mean**	+1SD	-1SD	**Mean**	+1SD	-1SD	**Mean**	+1SD
Campbell River, BC	39	**48**	57	3	**6**	9	0	**0**	1
Nanaimo, BC	97	**98**	99	40	**47**	54	4	**7**	9
Tofino, BC	100	**100**	100	86	**89**	93	19	**26**	34
Port Renfrew, BC	100	**100**	100	87	**90**	93	19	**28**	36
Vancouver, BC	53	**61**	68	6	**9**	13	0	**1**	1
Victoria, BC	100	**100**	100	85	**89**	93	19	**27**	36
Abbotsford, BC	25	**33**	41	2	**4**	5	0	**0**	0
Forks, WA	100	**100**	100	87	**90**	94	20	**29**	38
Seattle, WA	83	**88**	93	19	**25**	30	2	**3**	4
Olympia,WA	100	**100**	100	66	**73**	81	11	**18**	24
Longview,WA	89	**93**	96	24	**30**	37	2	**3**	5
Oceanshores, WA	100	**100**	100	87	**90**	94	20	**30**	40
Long Beach, WA	100	**100**	100	86	**90**	93	20	**30**	41
Rockaway Beach,	100	**100**	100	84	**88**	92	19	**30**	41
Portland, OR	44	**53**	62	4	**7**	10	0	**1**	1
Salem, OR	65	**72**	79	9	**13**	18	1	**1**	2
Eugene, OR	49	**57**	66	5	**8**	12	0	**1**	1
Coos Bay, OR	100	**100**	100	84	**88**	92	19	**29**	38
Newport, OR	100	**100**	100	83	**87**	92	18	**30**	41
Medford, OR	17	**26**	34	1	**2**	4	0	**0**	0
Crescent City, CA	100	**100**	100	84	**88**	92	18	**26**	34
Eureka, CA	100	**100**	100	84	**88**	92	18	**25**	32

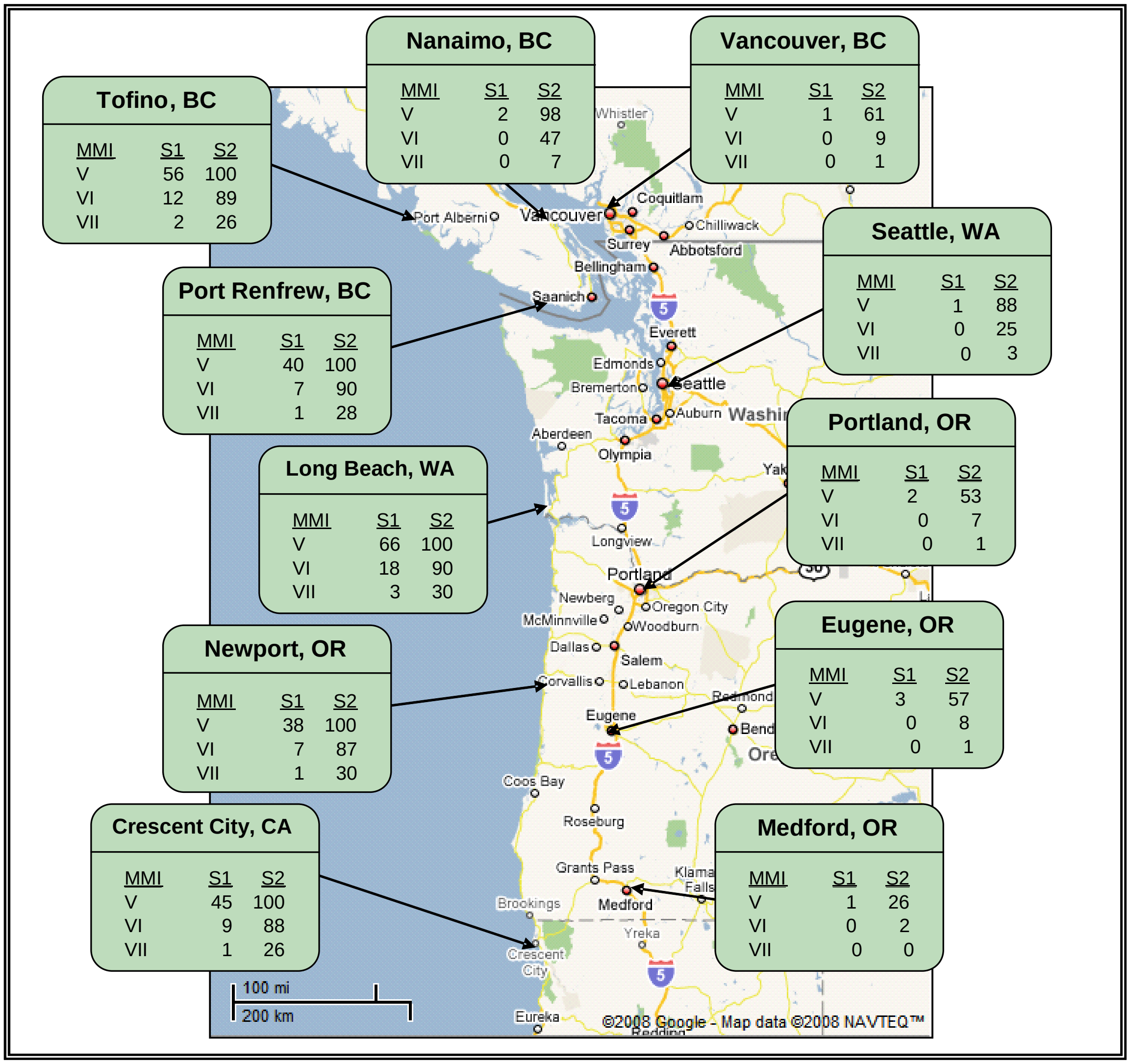


Figure 4.4 Earthquake shaking probabilities in a subset of eleven communities resulting from subduction aftershocks within 12 months of a Cascadia megathrust earthquake (assuming firm ground conditions).

source zone. Coastal community structurally-damaging shaking probabilities are lower than the non-structurally-damaging, and the one-year aftershock probabilities are one-in-one hundred for S1 and one-in-four for S2.

One hundred kilometers (60 miles) inland from the Pacific Ocean, communities along the US Interstate 5 corridor, have much reduced shaking probabilities due to their distance from the modelled rupture zones. Here, the probabilities of damaging shaking are essentially non-existent in S1, and the likelihood of structurally-damaging shaking is approximately one-in-one hundred in S2. For non-structurally-damaging shaking levels, these inland community probabilities are typically less than one-in-ten (S2), except in the lower Puget Sound area (i.e. Seattle) where the probabilities reach one-in-four in S2 due to the geometry of the Cascadia subduction interface.

4.4.1 Model Uncertainties

These results are subject to a number of model uncertainties and are affected by several extraneous variables. Model uncertainties, comprised of a number of aleatory (chance) and epistemic (model) uncertainties, include 1) the degree of similarity between the Cascadia subduction zone and the subduction earthquakes used as proxies in this study, 2) data limitations affecting a- and b-value calculations, 3) the ground motion attenuation relations used, 4) uncertainties associated with the PGA-MMI conversion, and 5) the modelled extent of Cascadia aftershock activity.

Aftershock activity rate was calculated as the mean of a number of proxy subduction aftershock sequences recorded from around the Pacific. This mean rate assumes that the characteristics inherent in the Cascadia subduction process are similar to the characteristics of the proxy source zones and that the activity rate measured in each of these events reflect the likely activity rate in the Cascadia subduction zone. As discussed earlier, the b-values of the aftershock sequences appear to be reasonably stable around 1.0, however the a-values vary by such factors as magnitude and extent of rupture area. Differences in the proxy source zone characteristics; in the calculation of the proxy source zone sizes; and in the instrumentation and calculation of the proxy aftershock record all contribute to uncertainty inherent in using proxy events as a surrogate for Cascadia. Despite these limitations, given the paucity of recorded subduction events these events were adopted recognizing that they offer a first approximation of subduction aftershock sequence activity for the CSZ.

The attenuation relationship used in calculating the resultant ground motions was found to be a significant contributor to the uncertainty in the overall probability estimates. In some cases the difference between relationships in probability estimates was as much as 20-30%. Typically, the Abrahamson and Silva (2008) relationship was found to produce the highest ground motion estimates, while that of Chiou and Youngs (2008) produced the lowest. The equally weighted mean of the four was used for attenuation of ground motion due to crustal aftershocks.

Several MMI-PGA conversion relationships exist. Each provides slightly varying results and therefore some modeling uncertainty exists as to which is the most representative. We adopt Wald et al. (1999) owing to its development and use in association with the widely-used and accepted USGS ShakeMap products. We note, however, that this relationship was developed for the conversion of PGA to MMI and this study uses it to convert MMI to PGA. A bi-directional, fully probabilistic conversion relationship would be preferred to reduce the uncertainties surrounding this step of the calculations.

Finally, it is important to note that there is some evidence to indicate the aerial extent of the actual subduction aftershock zones may be larger than their respective subduction rupture zones.

In both the 2004 and 2005 Sumatra-Andaman earthquakes, for example, the actual aftershock zones were approximately one and one half times the size of the rupture zone (2004 = 162%; 2005 = 155%)(Ammon et al., 2005; Walker et al., 2005). Given the similarity of the CSZ to the Sumatra earthquake zone (Cassidy et al., 2005; Goldfinger and McNeill, 2006;), should this hold true for the CSZ (Figure 4.4), the actual aftershock source zone could be larger than either of the two modeled Cascadia rupture zones in this study. In this case, the estimated aftershock ground-shaking probabilities would be expected to be higher, most notably for the larger metropolitan areas of Vancouver, BC, Seattle and Olympia, WA and Portland, OR.

Recognizing the cumulative contribution of these uncertainties to the model, the relative rankings of results for each of the communities within a given scenario are more important than small differences in the values between communities. Future research will focus on refining the model by minimizing these uncertainties and quantifying their relative contribution to our estimates of the aftershock hazard.

4.4.2 Model Considerations and Their Effect on Shaking Probabilities

Beyond the identified model uncertainties, users of these results must also consider a number of factors influencing the estimates provided:

4.4.2.1 Ground Conditions - As the calculations and results are based on homogeneous “firm ground” site conditions, actual community probabilities will vary according to their specific site conditions. Communities and structures built on soft, unconsolidated sediments (particularly beach, dune, alluvial or deltaic sands) should expect their hazard probabilities to be higher than presented, while communities built on bedrock should expect their probabilities to be somewhat lower. The degree to which the probabilities vary with ground conditions will be the focus of future investigations.

4.4.2.2 Exceedance vs. Occurrence - It is important to note that these “ground shaking exceedance” probabilities are not, and should not be mistaken for, probabilities of “earthquake occurrence”. Study results present probabilities of exceeding each of three specific levels of ground shaking at a given location within a one-year period, regardless of the number or relative strength of earthquakes occurring near that location.

4.4.2.3 Threshold Exceedance - It is also worth noting that these aftershock probabilities estimate the likelihood of a given threshold being exceeded at least once. A community may in fact experience “threshold” ground shaking more than once within the one-year aftershock period.

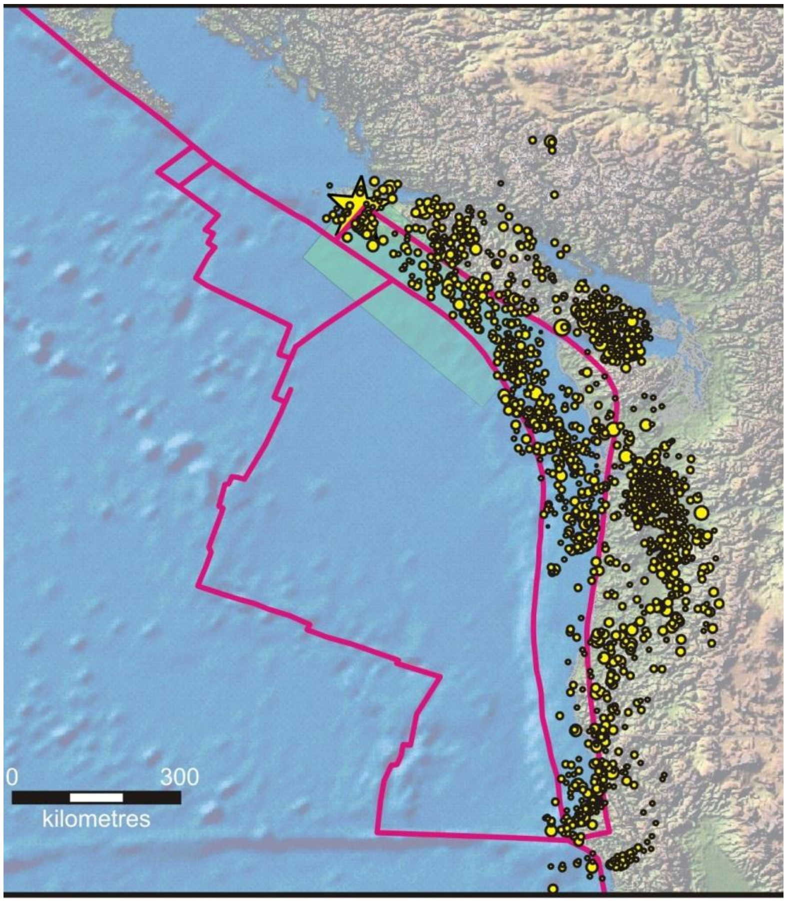


Figure 4.5 Aftershock plots from the 2004 Sumatra-Andaman subduction earthquake transposed over the similar Cascadia subduction zone (Cassidy et al., 2005).

4.4.2.4 Subcrustal Earthquake Contribution - The modelled aftershock probabilities do not include modelling of subcrustal aftershocks (i.e. those occurring below 40km in the subducting Juan de Fuca plate). Subcrustal aftershocks are likely to occur and could potentially cause significant ground shaking, however, due to the relatively lower potential of damage compared with crustal aftershocks and large uncertainties in depth determinations of particularly the older aftershock sequences, they were not included in this study.

4.4.2.5 Damage Thresholds - Depending on the duration and strength of shaking resulting from the Cascadia megathrust mainshock, structures may be predisposed to failing at lower ground motion (PGAs) levels than defined in the model (0.067g, 0.13g, and 0.24g for MMI V, VI, and VII, respectively). Accordingly, estimated probabilities are likely to be higher than presented in areas that experience structural fatigue and damage from the mainshock ground motions or secondary hazards. This is particularly true of communities located in closer proximity to the Cascadia subduction interface where mainshock ground motions are likely to be high enough to cause significant damage (e.g., Tofino, Forks, Coos Bay, Eureka).

4.4.2.6 Directivity and Clustering - The results presented here do not take into account any directivity or clustering parameters that may exist. While evidence suggests wave/energy direction and subsurface geologic conditions can focus and amplify ground motion, or counteract and de-amplify ground effects, insufficient information currently exists to incorporate such parameters in our modeling. Similarly, while some evidence of aftershock clustering exists (see for example Figure 4.4), the current model assumes a homogeneous aftershock distribution across the identified source zones. In both of these cases, actual ground motions may be higher or lower based on the relative influence of these factors.

4.5 Conclusions

The Cascadia Subduction Zone presents a significant seismic hazard to those living in southwestern British Columbia, western Washington and Oregon, and northwestern California; not only due to the pending Cascadia megathrust earthquake and ensuing tsunami(s), but also due to the hundreds of aftershocks certain to follow the mainshock. The subduction aftershock threat is a significant hazard, owing to the strength of the subduction aftershocks; the number of aftershocks; the potential proximity of aftershocks to built-up areas; the fact that they impact mainshock-compromised structures; they halt and hamper response and recovery efforts; and they have widespread psychosocial impacts on residents, visitors and aid-workers.

This paper offers preliminary estimates of the subduction aftershock ground-shaking hazard for 22 communities located in the Cascadia Subduction Zone based on an analysis of analogous circum-Pacific subduction earthquakes. Results are presented as simple, easy-to-understand exceedance probabilities expressed as percentage values for each of three ground-shaking levels: widely-felt shaking; non-structurally-damaging shaking; and structurally-damaging shaking.

These initial estimates of the Cascadia aftershock ground-shaking hazard are subject to a number of aleatory and epistemic uncertainties. Given these uncertainties, the methodology adopted uses a ‘best estimate’ central-tendency approach. Refining these results by addressing and quantifying each of the identified uncertainties will be the focus of future research.

No subjective hazard classification scheme is imposed on the results (e.g., ‘low’, ‘medium’, or ‘high’ hazard). Accordingly, it is left to individual communities to determine their respective tolerances to the Cascadia megathrust aftershock hazard based on the values provided.

Source zone size and geometry are central to the estimation of shaking probabilities in this study. As discussed, the current aftershock model reflects a CSZ full-rupture - 1,100 km (680 mi) - scenario based on historic and geophysical evidence. While we currently cannot attest to the likelihood of one scenario occurring over the other, we note that both scenarios adopt source zones that fall well within the current area of recorded strain and crustal deformation in the North America plate (Wang et al., 2003). And as the 2004 and 2005 Sumatra events suggest the Cascadia aftershock zone may be significantly larger than modeled in this study, the precautionary principle suggests Scenario 2 be used to provide the more likely estimate on which to base future planning and preparedness activities.

The aftershock shaking probabilities presented here are large enough at each location to demand substantive and coordinated earthquake preparedness, response and recovery planning by local community members and governments. Given the magnitude, duration, and geographic extent of the Cascadia subduction earthquake hazard, the secondary and tertiary hazards associated with a megathrust event, and the scale of regional, national and international economies impacted, these results appear sufficient to warrant comprehensive coordination of disaster management activities at local, provincial/state, federal, and international levels.

4.6 References

Abrahamson N and Silva W 2008. Summary of the Abrahamson and Silva NGA ground-motion relations. *Earthquake Spectra*, 24(1): 67-97.

Adams J and Weichert D 1994. Near-term probability of the future Cascadia megaquake. Proceedings of the Workshop on Paleoseismology, United States Geological Survey Open-File Report 94-568.

Ammon C, Ji C, Thio H, Robinson D, Ni S, Hjorleifsdottir V, Kanamori H, Lay T, Das S, Helmberger D, Ichinose G, Polet J, Wald D 2005. Rupture process of the 2004 Sumatra-Andaman earthquake, *Science*, 308: 1133-1139.

Atwater BF and Hemphill-Haley E 1997. Recurrence intervals for great earthquakes of the past 3500 years at the northeastern Willapa Bay, Washington. United States Geological Survey Professional Paper 1576.

Atwater BF, Nelson AR, Clague JJ, Carver GA, Yamaguchi DK, Bobrowsky PT, Bourgeois J, Darienzo ME, Grant WC, Hemphill-Haley E, Kelsey HM, Jacoby GC, Nishenko SP, Palmer SP, Peterson CD, and Reinhart MA 1995. Summary of coastal geologic evidence for past great earthquakes at the Cascadia subduction zone. *Earthquake Spectra*, 11(1): 1-18.

Båth M 1965. Lateral inhomogeneities in the upper mantle. *Tectonophysics*, 2: 483–514.

Boore DM and Atkinson GM 2008. Ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods between 0.01s and 10.0s, *Earthquake Spectra*, 24(1): 99-138.

Boyd TM and Nábělek JL 1988. Rupture process of the Andreanof Islands earthquake of May 7, 1986. *Bulletin of the Seismological Society of America*, 78(5): 1653-1673.

Campbell KW and Bozorgnia Y 2008. NGA ground motion model for the geometric mean horizontal component of PGA, PGV, PGD, and 5%-damped linear elastic response spectra for periods ranging from 0.01 to 10s. *Earthquake Spectra*, 24(1): 139-171.

Carlo DL, Lay T, Ammon CJ, Zhang J 1999. Rupture process of the 1995 Antofagasta subduction earthquake (Mw=8.1). *Pure and Applied Geophysics,* 154: 677–709.

Cassidy JF, Rogers GC, Dragert H, and Wang K 2005., The 26 December 2004, M 9.0 Sumatra earthquake: implications for Cascadia. Abstract in *Seismological Research Letters*, 76(2): 220.

Chiou BS-J and Young RR 2008. An NGA model for the average horizontal component of peak ground motion and response spectra. *Earthquake Spectra*, 24(1): 173-215.

Clague JJ 1997. Evidence for large earthquakes at the Cascadia Subduction Zone. *Reviews of Geophysics*, 35(4): 439-460.

Clague J, Atwater B, Wang K, Wang Y, and Wong I 2000. Great Cascadia earthquake tricentennial. Geological Survey of Canada Open File 3938. Natural Resources Canada. 158pp.

Clowes RM and Hyndman RD 2002. Geophysical studies of the northern Cascadia Subduction Zone of western Canada and their implications for great earthquake seismotectonics: a review. In Seismotectonics in Convergent Plate Boundaries, Y. Fujinawa and A. Yoshida, Editors, Terra Scientific Publishing Company (Terrapub), Tokyo, Japan, p 1-23.

Comte D, Eisenberg A, Lorca E, Pardo M, Ponce L, Saragoni R, Singh SK and Suárez G, 1986. The 1985 central Chile earthquake: a repeat of previous great earthquakes in the region? *Science, New Series*, 233(4762): 449-453.

CREW (Cascadia Region Earthquake Workgroup) 2005. Cascadia Subduction Zone earthquakes: a magnitude 9.0 earthquake scenario. Oregon Department of Geology and Mineral Industries Open File Report O-05-05.

EERI (Earthquake Engineering Research Institute) 2007. The Pisco, Peru earthquake of August 15, 2007. Earthquake Engineering Research Institute (EERI) Special Earthquake Report – October 2007. http://www.eeri.org/lfe/pdf/peru_pisco_eeri_preliminary_reconnaissance.pdf [Website Last Accessed: August 23, 2010].

EERI (Earthquake Engineering Research Institute) 2010. The Mw 8.8 Chile earthquake of February 27, 2010. Earthquake Engineering Research Institute (EERI) Special Earthquake Report – June 2010, http://www.eeri.org/site/images/eeri_newsletter/2010_pdf/Chile10_insert.pdf [Website Last Accessed: August 23, 2010].

Flück P, Hyndman RD and Wang K 1997. Three-dimensional dislocation model for great earthquakes of the Cascadia subduction zone. *Journal of Geophysical Research,* 102: 20539-20550.

Frankel AD and Petersen MD 2008. Cascadia Subduction Zone, Appendix L, In The Uniform California Earthquake Rupture Forecast, version 2 (UCERF 2): U.S. Geological Survey Open-File Report 2007-1437L and California Geological Survey Special Report 203L, 7 p.

Giovanni M, Beck S and Wagner L 2002. The June 23, 2001 Peru earthquake and southern Peru subduction zone. *Geophysical Research Letters*, 29(21): 2018, 14:1 – 14:4.

Goldfinger C and McNeill LC 2006. Sumatra and Cascadia: Parallels Explored. Eos, Transactions, *American Geophysical Union*, 87(52), Fall Meeting Supplement, Abstract U44A-06.

Goldfinger C, Nelson CH, Johnson JE, and the Shipboard Scientific Party 2003. Deep-water turbidites as Holocene earthquake proxies: the Cascadia subduction zone and Northern San Andreas Fault systems, *Annuals Geophys.*, 46(5): 1169-1194.

Goldfinger C, Nelson CH, Johnson JE, Morey AE, Gutiérrez-Pastor J, Karabanov E, Eriksson AT, Gràcia E, Dunhill G, Patton J, Enkin R, Dallimore A, Vallier T, and the Shipboard Scientific Parties (in press). Turbidite event history: methods and implications for holocene paleoseismicity of the Cascadia subduction zone. USGS Professional Paper 1661-F, 130p.

Honda R, Aoi S, Morikawa N, Sekiguchi H, Kunugi T and Fujiwara H 2004. Ground motion and rupture process of the 2003 Tokachi-oki earthquake obtained from strong motion data of K-NET and KiK-net, *Earth Planets Space*, 56, 317-322.

Hyndman RD and Wang K 1995. The rupture zone of Cascadia great earthquakes from current deformation and the thermal regime. *Journal of Geophysical Research*, 100:22133–22154.

Ichinose G, Somerville P, Thio HK, Graves R and O'Connell D 2007. Rupture process of the 1964 Prince William Sound, Alaska earthquake from the combined inversion of seismic, tsunami, and geodetic data, *Journal of Geophysical Research*, 112: B07306, doi 10.1029/2006JB004728.

Lay T, Kanamori H, Ammon CJ, Nettles M, Ward SN, Aster RC, Beck SN, Bilek SL, Brudzinski MR, Buttler R, Deshon HR, Edstrom G, Satake K, and Sipkin S 2005. The great Sumatra–Andaman earthquake of 26 December 2004. *Science*, 308: 1127–1133.

Mazzotti S, Dragert H, Henton J, Schmidt M, Hyndman R, James T, Lu Y, and Craymer M 2003. Current tectonics of northern Cascadia from a decade of GPS measurements, *Journal of Geophysical Research*, 108(B12): 2554.

Mazzotti S, and Adams J 2004. Variability of near-term probability for the next great earthquake on the Cascadia subduction zone. *Bulletin of the Seismological Society of America*, 94(5):1954-1959.

Mishra OP, Kayal JR, Chakrabortty GK, Singh OP, and Ghosh D 2007a. Aftershock investigation in the Andaman-Nicobar Islands of India and its seismotectonic implications, *Bulletin of the Seismological Society of America*, 97: S71-S85.

Mishra OP, Singh OP, Chakrabortty GK, Kayal JR, and Ghosh D 2007b., Aftershock Investigation in the Andaman-Nicobar Islands: An Antidote to Public Panic? *Seismological Research Letters*, 78(6): 591-600.

Omori F 1894. On the aftershocks of earthquakes. *Journal of the College of Science*, Imperial University of Tokyo, 7: 111–200.

Rhea S, Hayes G, Villasenor A, Furlong KP, Tarr AC, and Benz H 2011. Seismicity of the Earth: Nazca Plate and South America. USGS Poster, http://earthquake.usgs.gov/earthquakes/eqarchives/poster/regions/nazca.pdf, [Website Last Accessed: December 5, 2011].

Risk Engineering, Inc. 1997. EZ-FriskTM (Version 4.0) User's Manual.

Satake K, Wang K, and Atwater B 2003. Fault slip and seismic moment of the 1700 Cascadia earthquake inferred from Japanese tsunami descriptions, *Journal of Geophysical Research*, 108(B11): 2535.

Satake K, Shimazaki K, Tsuji Y, and Ueda K 1996.. Time and size of a giant earthquake in Cascadia inferred from Japanese tsunami record of January 1700. *Nature*, 379: 246-249.

Seemann MR, Onur T, and Cloutier-Fisher D 2011. earthquake shaking probabilities for communities on Vancouver Island, British Columbia, Canada, *Natural Hazards*, 58(3): 1253-1273.

Shcherbakov R, Turcotte DL, and Rundle JB 2004. A generalized Omori's law for earthquake aftershock decay. *Geophysical Research Letters*, 31: L11613, doi:10.1029/2004GL019808.

Sipkin SA 2003. A correction to body-wave magnitude mb based on moment magnitude Mw. *Seismological Research Letters* 74(6): 739-742.

USGS (United States Geological Survey) 2010. earthquakes hazard program, significant earthquakes, M8.8 Offshore Biobio, Chile, http://earthquake.usgs.gov/earthquakes/eqinthenews/2010/us2010tfan/ [Website Last Accessed: June 14, 2010].

Utsu T 2002. Relationship between magnitude scales. In International Handbook of Earthquake & Engineering Seismology Part A, WHK Lee, H Kanamori, PCJennings, and C Kisslinger, Editors, San Diego, California, USA: Academic Press, 733-746.

Utsu T, Ogata Y, and Matsu'ura RS 1995. The centenary of the Omori formula for a decay law of aftershock activity, *Journal of Physics of the Earth*, 43: 1–33.

Wald D, Quitoriano V, Heaton T, Kanamori H, Scrivner C, and Worden C 1999. TriNet shakeMaps: rapid generation of peak ground motion and intensity maps for earthquakes in southern California. *Earthquake Spectra*, 15: 537-555.

Walker KT, Ishii M, and Shearer PM 2005. Rupture details of the 28 March 2005 Sumatra Mw 8.6 earthquake imaged with teleseismic P waves. *Geophysical Research Letters*, 32: L24303, 4p.

Wang K, Wells R, Mazzotti S, Hyndman R, and Sagiya T 2003. A revised dislocation model of interseismic deformation of the Cascadia subduction zone. *Journal of Geophysical Research*, 108(B1), 2026, ETG 9-1 – 9-13.

Witter RC, Kelsey HM, and Hemphill-Haley E 2003. Great Cascadia earthquakes and tsunamis of the past 6700 years, Coquille River estuary, southern coastal Oregon. *Geological Society of America Bulletin*, 115(10): 1289-1306.

5.0 CONCLUSIONS

Risk, or the uncertainty about a future outcome, is conventionally expressed as the product of ‘event likelihood’ and ‘event consequence’. Closer analysis indicates that risk is comprised of a number of component elements which combine to provide a comprehensive understanding of hazard, consequence, and, ultimately, risk. While integrating risk management approaches in disaster management is currently lauded by the disaster management profession, by businesses and by governments at all levels, the implementation of risk management approaches in practice remains largely piecemeal.

5.1 Disaster Risk Management

Chapter 2 of this dissertation addresses the first research objective (Section 1.4.2). It identifies the core components of risk management, provides a framework for integrating risk management practices into disaster management, and identifies information gaps in Vancouver Island’s seismic risk management.

The model developed outlines a five-step framework to disaster risk management (DRM) which calls for the methodical presentation of risk context, risk assessment, risk treatment, risk acknowledgement and risk review practices. The new DRM framework is based on international best practices, and the paper’s focus on the disaster risk analysis process identifies fundamental areas in which information is required in order to comprehensively assess disaster risk.

This foundational disaster risk analysis involves the risk assessment of the peril/s in question (e.g., earthquake risk in Victoria over 50 years) by identifying and estimating specific hazards, and the consequences of those hazards actually occurring. The hazard analysis requires the identification of specific threats (e.g., subduction earthquake) and the estimation of the likelihood of that threat occurring. With the identification of each of these components, the specific hazard can be determined (e.g., the subduction earthquake hazard in Victoria, BC, Canada is 17% in the next fifty years).

The ‘consequence’ component of disaster risk analysis requires that likely outcomes of a particular event should that event occur be identified. As with the assessment of hazard, consequence assessments are found to in turn be a function of three components: exposure estimation, vulnerability assessment and resilience analysis. Exposure estimation identifies the extent to which the peril in question impacts man and his environment. Exposure estimation involves the delineation of the hazard zone and the impact zone, and the quantification of the systems and assets exposed in both of the zones. At its most robust, the exposure estimation provides a comprehensive assessment of all human, natural-environment, built-environment, and social-environment exposures to a given threat or peril, and provides a benchmark against which actual event consequences can be measured.

Vulnerability assessment and resilience analysis are two independent consequence metrics that provide insight into the weaknesses and strengths of assets and systems exposed to a given threat or peril. Both are measured along the same four dimensions as exposures and may be found within and/or beyond the hazard zone. Resilience analysis focuses on the various capacities of an entity to 1) respond to and minimize the damaging effects of a natural hazard, as well as 2) to recover and optimize the quick and efficient re-vitalization of the social-ecological system within and/or beyond the impacted area. Resiliencies (or capacities to respond and recover), unlike vulnerabilities to a hazard, can be identified and quantified beyond the exposure zone.

Adopting this risk analysis framework to assess progress towards a comprehensive risk assessment of the seismic risk on Vancouver Island, significant information gaps were identified in both the physical science and social science research. These include knowledge translation and transfer issues with respect to the mainshock seismic hazard and non-existent aftershock hazard information; limited research pertaining to the definition of the Island exposures (hazard and impact zones) as well as specific human, natural, manmade and social vulnerabilities; and next to no research on Island human, natural, manmade and social resiliencies. While it is beyond the scope of this dissertation to address each of the gaps identified, it is clear much research is required to enable any comprehensive risk assessment. Two key areas of seismic risk assessment were prioritized for further investigation in this research: 1) the need to better quantify and present Vancouver Island's seismic shaking hazard from each of the three principle earthquake sources: crustal, subcrustal and subduction; and 2) the need to estimate and present the seismic shaking hazard from a Cascadia subduction aftershock sequence. Addressing these two needs provides a common reference point from which individuals, businesses, organizations, and governments can discuss and evaluate their community seismic hazard. It also facilitates the development of other seismic risk management components, including societal seismic risk tolerance, near field and far field exposures, as well as specific vulnerability and resilience parameters. Research addressing these two gaps is presented as two discreet journal articles (Chapter 3, Chapter 4). The results and conclusions are summarized below, followed by an outline of research opportunities resulting from this work.

5.2 Calculating Crustal, Sub-crustal and Subduction Earthquake Hazard

Chapter 3 addresses the second research objective (Section 1.4.2) by calculating simplified seismic hazard estimates for Vancouver Island communities, by aggregating Vancouver Island seismic hazard from all three mainshock sources and by presenting the simplified hazard information in formats (tables and maps) readily understood by the general public. Results are presented as simple shaking probabilities (i.e. percentage probabilities) in a tabular format for 57 sites across the Island (Appendix B) and are interpolated to provide graphic representations of the distribution of the hazard across the Island (e.g., Figures 3.6). Time-dependent occurrence estimates are calculated for the next Cascadia Subduction earthquake (Table 3.3) and exceedance probabilities are calculated for both crustal and sub-crustal earthquakes over the next 10, 25, 50, and 100 years (Table 3.2). Finally, aggregate shaking probabilities are provided for the three earthquakes combined – crustal, subcrustal, subduction (Table 3.4; Figure 3.7).

All probability calculations are based on current seismic hazard models developed by the Geological survey of Canada and used in the National Building Code of Canada. The exceedance probabilities presented estimate the likelihood that ground shaking at any one location would exceed one of three nominal shake intensity levels: a widely-felt shaking threshold (MMI V; PGA= 0.067g ± 0.018g); a non-structurally-damaging shaking threshold (MMI VI; PGA = 0.13g ± 0.04g); and a structurally-damaging shaking threshold (MMI VII; PGA= 0.24g ± 0.07g).

Subduction earthquake results suggest Vancouver Island communities have approximately a one-in-five chance of experiencing a 'great' earthquake in the next 100 years. Aggregate earthquake exceedance probabilities, incorporating shaking probabilities from crustal, sub-crustal and subduction sources, suggests structurally-damaging 100-yr shaking probabilities range from approximately 'one-in-five' for the northeastern Island communities to 'one-in-two' for south Island communities.

Over this 100-year time frame, the city of Victoria, for example, is almost certain to experience widely-felt shaking (99%), has a four-in-five chance of experiencing non-structurally damaging shaking (82%); and, has a one-in-two chance of experiencing structurally-damaging shaking (48%). Over a shorter time frame, the provincial capital has approximately a one-in-five chance of experiencing non-structurally damaging shaking; and, a one-in-ten chance of experiencing a structurally damaging earthquake in the next 10 years.

5.3 Calculating the Subduction Earthquake Aftershock Sequence Hazard

The third paper (Chapter 4) addresses the dissertation's final research objective (Section 1.4.2). It investigates a fourth source of seismic hazard on Vancouver Island – subduction aftershock sequences, proposes a methodology to quantify subduction aftershock shaking hazard, and offers the first estimates of likely Cascadia aftershock ground shaking. As experienced following the 2004 Sumatra-Andaman earthquake in Indonesia and the more recent 2011 Tohoku subduction earthquake in Japan, thousands of crustal and subcrustal aftershocks will follow the next Cascadia megathrust event. These aftershock events will not only hamper disaster response in the initial days and weeks following the mainshock, but also impede the longer term recovery of regional communities and economies.

Results are presented as simple ground-shaking exceedance probabilities and are calculated at the same three nominal thresholds as in the previous paper. Shaking estimates are calculated for 22 communities across British Columbia, Washington, Oregon and California, and are based on two modeled full-rupture source zones: Scenario 1 - a more limited rupture scenario as defined by the area of co-seismic slip; and, Scenario 2 - a wider Cascadia rupture source zone defined by the modeled effective transition area (Figure 4.1). Results are calculated using the mean of the four Next Generation Attenuation (NGA) relationships which were adopted by the United States Geological Survey to estimate seismic hazard and were incorporated into the current International Building Code.

While calculations in both scenarios indicate a marked reduction in shaking probabilities with distance from the coast (and the rupture zone), they also suggest that the size of the estimated rupture zone is paramount in estimating the aftershock shaking probabilities (Figure 4.3). Scenario 1 (i.e. limited rupture) results indicate that coastal communities from Tofino, BC to Crescent City, CA can expect, on average, approximately a one-in-two chance of experiencing widely-felt ground shaking; approximately a one-in-ten chance of experiencing a non-structurally damaging earthquake shaking; and approximately a one-in-one hundred chance of experiencing structurally-damaging shaking. Inland communities, located some 100km (60 mi) from the coast along the Interstate 5 (I5) corridor, however, are estimated to have approximately a one-in-one hundred chance of experiencing a widely felt earthquake.

Scenario 2 (i.e. the wider Cascadia rupture) brings the seismic source zone much closer to the built environment in western North America, and, as a consequence, the ground shaking probabilities are much higher in western Cascadia communities. In this scenario, coastal community aftershock shaking probabilities increase to certainty for widely-felt shaking; nine-in-ten for non-structurally-damaging shaking; and approximately one-in-three for structurally-damaging shaking. Of the inland communities studied along the interstate highway I5 corridor, shaking probabilities are greatest in Seattle, WA where there is a nine-in-ten chance of widely-felt-shaking, a one-in-four chance of non-structurally damaging shaking; and approximately a one-in-one hundred chance of structurally-damaging shaking. These probabilities diminish to the north and south, with I5 corridor communities in southwestern BC, southern WA, and Oregon exhibiting shaking probabilities of one-in-two (widely-felt); one-in-ten (non-structurally damaging); and one-in-one hundred (structurally damaging).

5.4 Directions for Future Research

This research offers initial work in the comprehensive assessment of seismic risk on Vancouver Island, Canada. The study provides a basis for approaching, understanding and assessing risk on Vancouver Island, and presents some preliminary findings to support the assessment of Vancouver Island's seismic risk within this new framework.

Much research is required to refine and expand on this initial work, and to begin to address the remaining gaps in our understanding of Vancouver Island's seismic risk. Without this body of research, the comprehensive assessment of the Island's seismic risk remains incomplete, and effective, efficient disaster policy and preparedness decisions are hampered at enormous cost to society.

5.4.1 Disaster Risk Management Framework Refinement Opportunities

While the DRM Framework is built on international best practices, the configuration of the framework has yet to be operationally tested in detail. The probability papers presented here fit well within the structure of the DRM framework, yet these represent the 'low-hanging-fruit' with respect to validating the framework. Much work needs to be done to assess various components of the framework and confirm its broader utility. Specifically, three key areas for future work on the DRM framework are identified:

1) ***Development of risk tolerance assessment tools.*** Critical to the risk evaluation process is the assessment of societal or community risk tolerance. Future research to develop and validate an effective tool in measuring collective risk tolerance will be pivotal in aiding community decision-makers in addressing the potential gap between community risk management expectations and the existing physical and financial realities.

2) ***Development of standardized impact/vulnerability assessment instruments.*** Recognizing the need to meaningfully assess hazard exposures over four distinct dimensions, a significant body of work is required in identifying

standardized parameters to assess the impacts of a hazard across human, environmental, built and social dimensions.

3) ***Development of standardized capacity/resilience assessment instruments.*** Like the vulnerability instrument requirement discussed above, a similar tool is required to assess human capacities, natural-environment capacities, built-environment capacities, and social capacities to respond to and recover from a given peril or threat.

5.4.2 Probability Model Refinement Opportunities

A number of epistemic research opportunities exist to refine the current shaking probability results, six of which are considered below:

1) ***Revision of ground motion uncertainties.*** One of the largest sources of uncertainty in the probability estimation is the uncertainty associated with ground motion modeling. The incorporation of the most recent attenuation relationships is likely to significantly influence the crustal and sub-crustal probabilities presented for Vancouver Island.

2) ***Revision of frequency of occurrence uncertainties.*** A growing body of research is suggesting that spatial and temporal clustering of earthquakes may occur. Effecting both subduction earthquakes, as well as crustal/subcrustal earthquakes, the quantification of each of the associated clustering effects will likely effect the calculated shaking probabilities. For example, if the Cascadia subduction earthquakes are found to cluster in sets of three following a one-thousand year hiatus, the fact that we’ve had only one subduction event in the past 1300 years suggests we may be in the middle of a CSZ cluster and the

probabilities of a subduction event on Vancouver Island are likely to be higher than currently reported.

3) Incorporating the effects of varying geology on the shaking probabilities. The modeling presented in this manuscript assumes homogeneous 'firm' ground conditions (760 m/s) throughout Cascadia. As this clearly does not reflect the varied ground conditions in the Pacific Northwest, quantifying the influence of variable ground conditions (from soft unconsolidated sediments to bedrock) on the shaking probabilities is paramount in enhancing the accuracy of these estimates. While this follow-up research is likely to influence the probabilities presented in both chapters 3 and 4, the extent to which it dampens or amplifies the resultant probabilities is as yet unknown.

4) Refining MMI-PGA conversion uncertainties. While Wald et al. (1999) was used for MMI-PGA conversion, there are a number of other conversion relationships available. A comparative analysis of the effects of the various conversion relationships would reduce the uncertainty associated with the use of this one relationship. In addition, a comparative analysis of the range of PGAs associated with a single MMI would quantify the error associated with the adoption of the mean PGA in both chapter 3 and chapter 4.

5) Reviewing relative source zone and aftershock zone size of historical circum-Pacific subduction events. Recognizing the importance of accurately defining the relationship between a subduction source zone and its associated aftershock zone, a detailed comparative analysis of historic subduction events is warranted.

6) ***Refining the size and configuration of the modeled Cascadia aftershock zone.*** Given the demonstrable influence of Cascadia rupture zone size on aftershock ground shaking in western North American communities, refinement of the likely Cascadia rupture zone size is essential in accurately estimating the effects of a Cascadia aftershock sequence on regional communities. Questions remain as to the linkage between the subducting Juan de Fuca plate and smaller satellite plates to its north (e.g., Explorer plate) and south (e.g., Gorda plate). Should these plates be likely to fail synchronously with the Juan de Fuca plate, the size of the Cascadia rupture zone will be considerably longer, thereby increasing the rupture zone size, the likely magnitude, and the aftershock shaking probabilities of adjacent communities. Similarly, by refining the width of Cascadia's likely zone of rupture, the geographic extent and proximity of the source zone to regional communities can be defined.

5.4.3 Ancillary Research Opportunities

In addition, a number of ancillary research avenues have arisen from this research as enumerated below.

1) ***Assessing the efficacy of the "simpler" hazard representations presented in this dissertation*** – While simple percentage probabilities are more easily understood, it would be worthwhile actually testing public perception of various data presentation formats of seismic hazard. This research could be undertaken in a larger study estimating seismic hazard perceptions, knowledge and understanding on Vancouver Island, perhaps by sampling both resident and non-

resident populations, aboriginal populations, as well as rural and urban populations.

2) Defining the temporal extent of the Cascadia subduction shaking event - Duration of damaging subduction ground shaking is likely to have a significant impact on regional geology, structures and infrastructure. Particularly, as compromised structures are then exposed to crustal and sub-crustal aftershocks over an extended period. To date, the effects of 'duration of shaking' have not been addressed, and are not currently accounted for in the National Building Code of Canada.

3) Identifying and quantifying the impact of secondary, tertiary and quaternary perils. A number of ancillary perils, ranging from tsunamis and landslides to fires and hazardous material releases, are likely to be associated with Vancouver Island earthquakes. Research is required to identify each of these perils, their threats, and probabilities as well as their likely impacts, vulnerabilities, and resiliencies. Landslide hazard studies, for example, while conducted for various interests (e.g. forestry) need to be revised and expanded to link to Island communities and their lifelines (e.g., transportation corridors, cell towers, power lines, telecommunications lines, water systems, sewage systems, gas lines).

4) Quantifying Vancouver Island's seismic building stock and infrastructure vulnerabilities. A host of vulnerabilities, at individual, community, regional, or indeed on a national scale, can be attributed to the resilience of the built environment. Research modeling and quantifying the structural vulnerability of both specific high-value assets (e.g., Liquid Natural Gas plants, ports, bridges, National Emergency Stockpiles warehouses, emergency operations centres) and regional structural response to ground shaking is required. Derivative research can then begin to estimate the number of casualties to be expected, the transportation corridors likely to be closed, the likely impact of business and government, the number of displaced, the volume of hazardous and non-hazardous waste likely to be generated.

Numerous derivative research opportunities also exist in assessing Vancouver Island vulnerabilities and identifying specific island capacities to respond and recover. Three of the more salient research areas requiring attention are:

1) Identifying and quantifying the environmental and structural vulnerabilities of Vancouver Island's water supply. A review and assessment of the potable water supply and distribution mechanisms within identified seismic impact zones is required. Assuming structural vulnerabilities exist, a review of the Island's social vulnerabilities and resiliencies then need to be identified in the procurement of bulk water for vulnerable communities. Specifically, this includes a review of contingency planning for bulk water testing, treatment, transportation and distribution systems.

2) Identifying and quantifying the environmental and structural vulnerabilities of Vancouver Island's food supply. Research is required into food security issues associated with a disruption to the normal food supply and distribution systems on Vancouver Island following a subduction earthquake.

This is particularly important for communities located on islands where ferry and/or air transportation systems might be compromised for an extended period of time.

3) Identifying and quantifying the vulnerabilities and resiliencies associated with Vancouver Island's utilities. Power, sewer, and telecommunications services are the backbone of modern societies and understanding both the dependencies and interdependencies associated with these systems is critical to effectively managing disaster response. For example, as Vancouver Island does not have its own power generation capabilities, residents, visitors and commerce is reliant on an uninterrupted power supply from the mainland. Understanding the weaknesses and strengths of the primary and redundant power supply systems on allows for the effective management of the risk associated with this particular system.

The research presented in this dissertation is offered to encourage and facilitate comprehensive seismic disaster risk management on Vancouver Island. Results are intended to assist in the understanding of earthquake risk on Vancouver Island; to offer empirical data on which to base sound disaster risk management decisions; and to raise awareness of the gaps in Vancouver Island's risk assessment.

6.0 Appendices

Appendix A: Acronyms and Abbreviations Used

Appendix B: Crustal and Subcrustal Shaking Probabilities for Vancouver Island Sites

Appendix C: Aggregate (Crustal, Subcrustal and Subduction) Shaking Probabilities for Vancouver Island Sites

Appendix D: Enlarged Crustal and Subcrustal Shaking Probability Maps

Appendix E: Enlarged Aggregate Seismic Shaking Probability Maps

Appendix A: Acronyms and Abbreviations Used

AS/NZS	Australia Standard/New Zealand Standard
BC	British Columbia
BSI	British Standards Institution
CA	California
CREW	Cascadia Region Earthquake Working Group
CSA	Canadian Standards Association
CSZ	Cascadia Subduction Zone
CSE	Communications Security Establishment (Canada)
DEM	Disaster and Emergency Management
DRM	Disaster Risk Management
EC	European Commission
EERI	Earthquake Engineering Research Institute
ETS	Episodic Tremor and Slip
FEMA	Federal Emergency Management Agency
G-R	Gutenberg-Richter Relationship
GSC	Geological Survey of Canada
HS	Homeland Security, United States of America
HVAC	Heating, Ventilation, and Air Conditioning
IAEM	International Association of Emergency Managers
ISO	International Standards Organization
Ma	Million years ago
MMI	Modified Mercalli Intensity
M	Magnitude
Mw	Moment Magnitude
NBC	National Building Code (Canada)
NEIC	National Earthquake Information Centre
NFPA	National Fire Protection Association
NGA	Next Generation Attenuation
NGO	Non-governmental Organization
NRCan	Natural Resources Canada

OR	Oregon
PGA	Peak Ground Acceleration
PS	Public Safety Canada
PSHA	Probabilistic Seismic Hazard Analysis
RCMP	Royal Canadian Mounted Police
RGC	Referenced Ground Conditions
SA	Spectral Acceleration
SD	Standard Deviation
SME	Subject Matter Expert
UK	United Kingdom
UNISDR	United Nations International Secretariat for Disaster Reduction
USGS	United States Geological Survey
WA	Washington
WGCEP	Working Group on California Earthquake Probabilities

Appendix B: Crustal and Sub-crustal Shaking Probabilities for Vancouver Island Sites

Community	Coordinates		MMI V - "Widely Felt" Probabilities (%)				MMI VI - "Non-structurally Damaging" Probabilities (%)				MMI VII - "Structurally-Damaging" Probabilities (%)			
			PGA (g) = 0.067 (H & R "Best")				PGA (g) = 0.13 (H & R "Best")				PGA (g) = 0.24 (H & R "Best")			
	Lat.	Long.	10 yrs	25 yrs	50 yrs	100 yrs	10 yrs	25 yrs	50 yrs	100 yrs	10 yrs	25 yrs	50 yrs	100 yrs
Alberni	49.27	-124.80	16.0	36.0	59.0	83.0	3.7	9.1	17.0	32.0	0.8	2.0	4.0	7.8
Bamfield	48.83	-125.13	15.0	33.0	55.0	80.0	3.1	7.6	15.0	27.0	0.7	1.6	3.2	6.4
Campbell River	50.02	-125.24	13.0	30.0	51.0	76.0	2.3	5.7	11.0	21.0	0.4	1.1	2.2	4.3
Clo-oose	48.66	-124.83	17.0	37.0	60.0	84.0	4.1	10.0	19.0	34.0	0.9	2.3	4.6	9.0
Courtenay	49.68	-124.98	14.0	32.0	54.0	79.0	2.7	6.6	13.0	24.0	0.5	1.3	2.5	5.0
Crofton	48.87	-123.65	30.0	59.0	83.0	97.0	11.0	26.0	45.0	70.0	3.5	8.5	16.0	30.0
Duncan	48.78	-123.70	30.0	59.0	84.0	97.0	11.0	26.0	45.0	70.0	3.5	8.6	16.0	30.0
Earl's Cove	49.75	-124.00	16.0	35.0	58.0	83.0	3.8	9.2	17.0	32.0	0.8	2.0	3.9	7.7
Gold River	49.68	-126.12	22.0	46.0	70.0	91.0	3.0	7.3	14.0	26.0	0.4	1.1	2.2	4.3

Community	Coordinates		MMI V - "Widely Felt" Probabilities (%)				MMI VI - "Non-structurally Damaging" Probabilities (%)				MMI VII - "Structurally-Damaging" Probabilities (%)			
			PGA (g) = 0.067 (H & R "Best")				PGA (g) = 0.13 (H & R "Best")				PGA (g) = 0.24 (H & R "Best")			
	Lat.	Long.	10 yrs	25 yrs	50 yrs	100 yrs	10 yrs	25 yrs	50 yrs	100 yrs	10 yrs	25 yrs	50 yrs	100 yrs
Holberg	50.67	-128.04	35.0	66.0	88.0	99.0	3.9	9.5	18.0	33.0	0.3	0.8	1.5	3.0
Kyuquot	50.03	-127.37	56.0	87.0	98.0	100.0	15.0	34.0	56.0	81.0	2.9	7.0	13.0	25.0
Ladysmith	48.99	-123.82	27.0	54.0	79.0	96.0	9.5	22.0	39.0	63.0	2.8	6.9	13.0	25.0
Lake Cowichan	48.82	-124.05	26.0	53.0	77.0	95.0	8.8	21.0	37.0	60.0	2.5	6.2	12.0	23.0
Nanaimo	49.17	-123.93	24.0	49.0	74.0	93.0	7.7	18.0	33.0	55.0	2.2	5.3	10.0	20.0
North Vancouver	49.32	-123.07	24.0	50.0	75.0	94.0	7.8	18.0	33.0	55.0	2.1	5.2	10.0	19.0
Phillips Arm	50.55	-125.35	11.0	26.0	45.0	70.0	1.9	4.8	9.3	18.0	0.4	1.0	1.9	3.8
Port Hardy	50.73	-127.50	23.0	48.0	73.0	93.0	2.0	5.0	9.7	19.0	0.2	0.4	0.8	1.6
Port McNeill	50.59	-127.10	22.0	46.0	71.0	92.0	2.1	5.1	10.0	19.0	0.2	0.5	1.0	1.9
Port Renfrew	48.56	-124.40	21.0	45.0	70.0	91.0	6.3	15.0	28.0	48.0	1.6	4.0	7.9	15.0

Community	Coordinates		MMI V - "Widely Felt" Probabilities (%)				MMI VI - "Non-structurally Damaging" Probabilities (%)				MMI VII - "Structurally-Damaging" Probabilities (%)			
			PGA (g) = 0.067 (H & R "Best")				PGA (g) = 0.13 (H & R "Best")				PGA (g) = 0.24 (H & R "Best")			
	Lat.	Long.	10 yrs	25 yrs	50 yrs	100 yrs	10 yrs	25 yrs	50 yrs	100 yrs	10 yrs	25 yrs	50 yrs	100 yrs
Qualicum Beach	49.35	-124.45	18.0	39.0	63.0	86.0	4.6	11.0	21.0	38.0	1.1	2.7	5.3	10.0
Saturna	48.79	-123.18	34.0	65.0	87.0	98.0	14.0	30.0	52.0	77.0	4.4	11.0	20.0	36.0
Sayward	50.36	-125.92	14.0	32.0	53.0	78.0	1.9	4.8	9.3	18.0	0.4	0.9	1.7	3.4
Sidney	48.65	-123.40	34.0	65.0	88.0	98.0	14.0	31.0	52.0	77.0	4.3	11.0	20.0	36.0
Sooke	48.38	-123.72	31.0	60.0	84.0	97.0	11.0	26.0	45.0	70.0	3.4	8.4	16.0	29.0
Sullivan Bay	50.88	-126.82	13.0	30.0	51.0	76.0	1.1	2.7	5.4	11.0	0.1	0.3	0.6	1.2
Tahsis	49.92	-126.67	37.0	68.0	90.0	99.0	8.0	19.0	34.0	57.0	1.4	3.6	7.0	13.0
Tofino	49.15	-125.90	16.0	35.0	57.0	82.0	2.1	5.1	10.0	19.0	0.4	0.9	1.8	3.5
Ucluelet	48.93	-125.55	14.0	31.0	52.0	77.0	2.2	5.4	10.0	20.0	0.4	1.0	2.0	4.0
Victoria	48.43	-123.37	35.0	66.0	88.0	99.0	14.0	32.0	53.0	78.0	4.5	11.0	21.0	37.0

Community	Coordinates		MMI V - "Widely Felt" Probabilities (%)				MMI VI - "Non-structurally Damaging" Probabilities (%)				MMI VII - "Structurally-Damaging" Probabilities (%)			
			PGA (g) = 0.067 (H & R "Best")				PGA (g) = 0.13 (H & R "Best")				PGA (g) = 0.24 (H & R "Best")			
	Lat.	Long.	10 yrs	25 yrs	50 yrs	100 yrs	10 yrs	25 yrs	50 yrs	100 yrs	10 yrs	25 yrs	50 yrs	100 yrs
Woss	50.22	-126.60	24.0	50.0	75.0	94.0	2.9	7.0	13.0	25.0	0.3	0.7	1.4	2.8
Youbou	48.88	-124.20	24.0	49.0	74.0	93.0	7.6	18.0	33.0	55.0	2.1	5.3	10.0	19.0
Yuquot	49.60	-126.62	38.0	70.0	91.0	99.0	9.2	21.0	38.0	62.0	1.8	4.5	8.7	17.0
Zeballos	49.99	-126.84	40.0	72.0	92.0	99.0	8.6	20.0	36.0	59.0	1.5	3.6	7.0	14.0
1 - NW Coast	51.00	-129.20	48.0	80.0	96.0	100.0	8.4	20.0	36.0	59.0	1.2	3.0	5.9	11.0
2 - North Coast	51.00	-128.60	31.0	61.0	85.0	98.0	3.0	7.3	14.0	26.0	0.2	0.5	1.1	2.1
3 - North Coast	51.00	-128.00	21.0	45.0	70.0	91.0	1.6	4.0	7.9	15.0	0.1	0.3	0.7	1.3
4 - NE Coast	51.00	-127.40	15.0	34.0	56.0	81.0	1.2	2.9	5.6	11.0	0.1	0.3	0.6	1.2
5 - W Coast	50.50	-128.20	49.0	81.0	97.0	100.0	8.9	21.0	37.0	60.0	1.3	3.2	6.3	12.0
6 - S of Port Alice	50.30	-127.50	46.0	79.0	96.0	100.0	10.0	23.0	41.0	65.0	1.5	3.7	7.3	14.0

Community	Coordinates		MMI V - "Widely Felt" Probabilities (%)				MMI VI - "Non-structurally Damaging" Probabilities (%)				MMI VII - "Structurally-Damaging" Probabilities (%)			
			PGA (g) = 0.067 (H & R "Best")				PGA (g) = 0.13 (H & R "Best")				PGA (g) = 0.24 (H & R "Best")			
	Lat.	Long.	10 yrs	25 yrs	50 yrs	100 yrs	10 yrs	25 yrs	50 yrs	100 yrs	10 yrs	25 yrs	50 yrs	100 yrs
7 - Robson Bight	50.50	-126.50	17.0	37.0	60.0	84.0	1.7	4.2	8.2	16.0	0.2	0.5	1.0	2.0
8- Brooks Pen	50.00	-128.00	71.0	96.0	100.0	100.0	23.0	48.0	73.0	93.0	4.7	11.0	21.0	38.0
9 - S Nimkish Lk	50.30	-127.00	31.0	60.0	84.0	97.0	3.8	9.3	18.0	32.0	0.4	0.9	1.7	3.4
10 - N Mt. Judson	50.00	-126.00	18.0	39.0	63.0	86.0	2.4	5.9	12.0	22.0	0.4	1.0	2.0	3.9
11 - W Flores Isl	49.20	-126.50	24.0	50.0	75.0	94.0	2.7	6.7	13.0	24.0	0.3	0.6	1.3	2.5
12 - E Buttle Lk	49.70	-125.50	15.0	33.0	55.0	80.0	2.3	5.8	11.0	21.0	0.4	1.1	2.1	4.1
13 - W Sproat Lk	49.30	-125.40	15.0	33.0	55.0	80.0	2.5	6.2	12.0	23.0	0.5	1.2	2.4	4.7
14 - W Swiftsure	48.50	-125.00	14.0	32.0	54.0	79.0	3.0	7.3	14.0	26.0	0.6	1.4	2.9	5.7
15 - NE Nitnat Lk	48.90	-124.60	19.0	41.0	65.0	88.0	5.3	13.0	24.0	42.0	1.3	3.3	6.4	12.0
16 - E Flores	49.40	-125.90	17.0	38.0	61.0	85.0	2.4	5.9	11.0	22.0	0.4	1.0	2.0	4.0

Community	Coordinates		MMI V - "Widely Felt" Probabilities (%)				MMI VI - "Non-structurally Damaging" Probabilities (%)				MMI VII - "Structurally-Damaging" Probabilities (%)			
			PGA (g) = 0.067 (H & R "Best")				PGA (g) = 0.13 (H & R "Best")				PGA (g) = 0.24 (H & R "Best")			
	Lat.	Long.	10 yrs	25 yrs	50 yrs	100 yrs	10 yrs	25 yrs	50 yrs	100 yrs	10 yrs	25 yrs	50 yrs	100 yrs
17 – Jord. R. Dam	48.60	-123.90	28.0	57.0	81.0	96.0	10.0	24.0	41.0	66.0	3.0	7.4	14.0	26.0
18 - W Nanaimo	49.10	-124.30	21.0	45.0	70.0	91.0	6.3	15.0	28.0	48.0	1.7	4.1	8.1	16.0
19 - Viscount Isl	50.70	-126.20	12.0	28.0	48.0	73.0	1.4	3.4	6.6	13.0	0.2	0.5	0.9	1.9
20 - NW Van Isle	49.00	-128.30	77.0	98.0	100.0	100.0	26.0	54.0	79.0	95.0	5.5	13.0	25.0	43.0
21 - SW Van Isle	48.30	-127.30	23.0	48.0	73.0	93.0	2.0	5.0	9.8	19.0	0.2	0.5	1.0	2.0
22 - NE Van Isle	51.00	-124.50	9.4	22.0	39.0	63.0	1.9	4.7	9.1	17.0	0.4	1.0	1.9	3.8
23 - E Van Isle	50.20	-123.50	13.0	29.0	49.0	74.0	2.6	6.4	12.0	23.0	0.5	1.2	2.4	4.8
24 - W Buttle Lk	49.75	-125.70	16.0	35.0	58.0	82.0	2.3	5.7	11.0	21.0	0.4	1.0	2.0	4.0

Appendix C: Aggregate (Crustal, Subcrustal and Subduction) Shaking Probabilities for Vancouver Island Sites

Community	Coordinates		MMI V - "Widely Felt" Probabilities (%)				MMI VI - "Non-structurally Damaging" Probabilities (%)				MMI VII - "Structurally-Damaging" Probabilities (%)			
			PGA (g) = 0.067 (H & R "Best")				PGA (g) = 0.13 (H & R "Best")				PGA (g) = 0.24 (H & R "Best")			
	Lat.	Long.	10 yrs	25 yrs	50 yrs	100 yrs	10 yrs	25 yrs	50 yrs	100 yrs	10 yrs	25 yrs	50 yrs	100 yrs
Alberni	49.27	-124.80	23.0	42.1	64.0	86.1	11.4	17.8	27.2	43.3	8.7	11.4	15.5	23.5
Bamfield	48.83	-125.13	21.6	39.5	60.5	83.3	10.9	16.5	24.9	39.5	8.6	11.1	14.8	22.3
Campbell River	50.02	-125.24	20.3	36.9	57.1	80.2	10.1	14.7	21.7	34.3	8.4	10.6	13.9	20.5
Clo-oose	48.66	-124.83	23.4	42.8	64.8	86.7	11.8	18.6	28.7	45.5	8.9	11.7	16.1	24.5
Courtenay	49.68	-124.98	21.1	38.5	59.2	82.2	10.5	15.6	23.3	36.9	8.5	10.8	14.2	21.2
Crofton	48.87	-123.65	35.6	62.9	85.2	97.6	18.3	32.9	51.5	74.8	11.2	17.3	26.3	41.8
Duncan	48.78	-123.70	35.9	63.3	85.5	97.8	18.5	33.2	52.0	75.3	11.2	17.4	26.5	42.0
Earl's Cove	49.75	-124.00	22.7	41.6	63.2	85.5	11.5	17.9	27.4	43.5	8.7	11.4	15.4	23.4
Gold River	49.68	-126.12	27.9	50.9	74.0	92.8	10.8	16.2	24.4	38.8	8.4	10.6	13.9	20.6

Community	Coordinates		MMI V - "Widely Felt" Probabilities (%)				MMI VI - "Non-structurally Damaging" Probabilities (%)				MMI VII - "Structurally-Damaging" Probabilities (%)			
			PGA (g) = 0.067 (H & R "Best")				PGA (g) = 0.13 (H & R "Best")				PGA (g) = 0.24 (H & R "Best")			
	Lat.	Long.	10 yrs	25 yrs	50 yrs	100 yrs	10 yrs	25 yrs	50 yrs	100 yrs	10 yrs	25 yrs	50 yrs	100 yrs
Holberg	50.67	-128.04	40.2	69.2	89.8	98.9	11.6	18.2	28.0	44.4	8.3	10.3	13.3	19.5
Kyuquot	50.03	-127.37	59.3	88.2	98.5	100.0	22.0	40.1	61.4	84.0	10.6	15.9	23.9	37.9
Ladysmith	48.99	-123.82	32.8	58.8	81.7	96.4	16.7	29.5	46.5	69.3	10.6	15.8	23.7	37.6
Lake Cowichan	48.82	-124.05	31.7	57.1	80.2	95.8	16.1	28.1	44.4	66.9	10.3	15.2	22.6	35.9
Nanaimo	49.17	-123.93	29.8	54.1	77.3	94.5	15.1	26.0	41.0	62.7	10.0	14.4	21.1	33.3
North Vancouver	49.32	-123.07	30.3	54.8	78.0	94.8	15.2	26.2	41.3	63.1	10.0	14.3	20.9	33.0
Phillips Arm	50.55	-125.35	18.5	33.1	51.9	75.2	9.8	13.9	20.2	31.8	8.4	10.5	13.7	20.1
Port Hardy	50.73	-127.50	29.4	53.4	76.6	94.1	9.9	14.1	20.6	32.4	8.1	10.0	12.7	18.3
Port McNeill	50.59	-127.10	28.3	51.5	74.7	93.1	9.9	14.2	20.8	32.8	8.2	10.0	12.8	18.6
Port Renfrew	48.56	-124.40	27.6	50.4	73.5	92.5	13.8	23.3	36.6	56.9	9.5	13.2	18.9	29.6

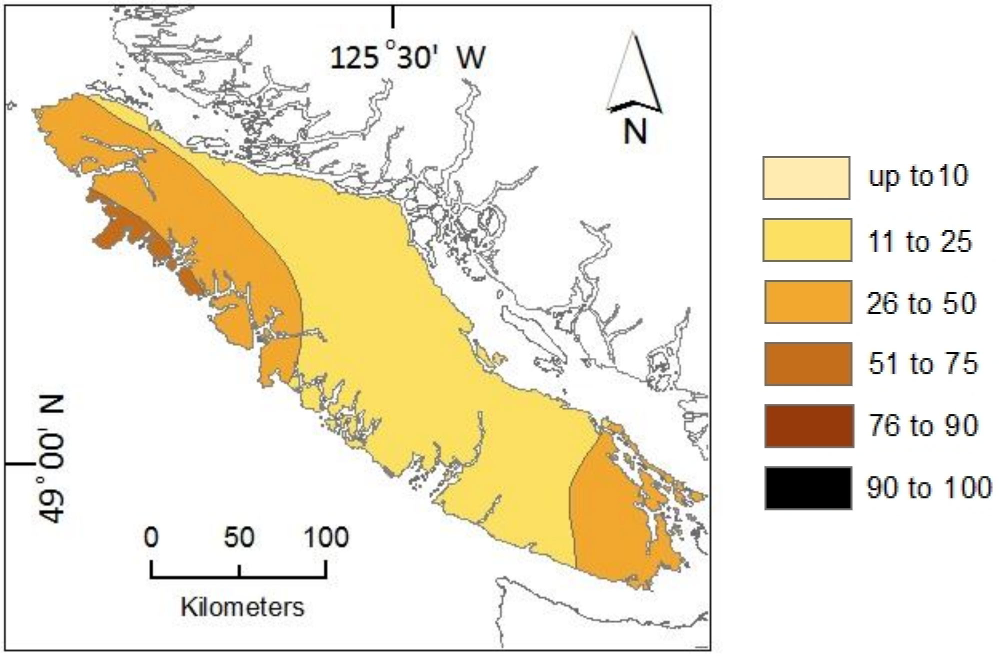
Community	Coordinates		MMI V - "Widely Felt" Probabilities (%)				MMI VI - "Non-structurally Damaging" Probabilities (%)				MMI VII - "Structurally-Damaging" Probabilities (%)			
			PGA (g) = 0.067 (H & R "Best")				PGA (g) = 0.13 (H & R "Best")				PGA (g) = 0.24 (H & R "Best")			
	Lat.	Long.	10 yrs	25 yrs	50 yrs	100 yrs	10 yrs	25 yrs	50 yrs	100 yrs	10 yrs	25 yrs	50 yrs	100 yrs
Qualicum Beach	49.35	-124.45	24.5	44.9	67.3	88.5	12.2	19.7	30.5	48.2	9.0	12.0	16.6	25.5
Saturna	48.79	-123.18	39.3	68.0	89.0	98.7	20.5	37.2	57.5	80.6	12.0	19.1	29.6	46.8
Sayward	50.36	-125.92	21.0	38.2	58.8	81.8	9.8	13.9	20.2	31.7	8.3	10.4	13.5	19.8
Sidney	48.65	-123.40	39.3	68.1	89.0	98.7	20.5	37.2	57.6	80.7	12.0	19.1	29.5	46.8
Sooke	48.38	-123.72	36.3	63.9	86.0	97.9	18.5	33.2	52.0	75.3	11.2	17.2	26.1	41.5
Sullivan Bay	50.88	-126.82	20.1	36.5	56.6	79.8	9.0	12.1	16.8	25.7	8.1	9.9	12.5	18.0
Tahsis	49.92	-126.67	41.9	71.3	91.1	99.2	15.4	26.6	42.0	63.9	9.3	12.8	18.2	28.2
Tofino	49.15	-125.90	22.3	40.8	62.3	84.8	9.9	14.2	20.8	32.7	8.3	10.4	13.5	19.9
Ucluelet	48.93	-125.55	20.5	37.3	57.7	80.8	10.0	14.5	21.2	33.5	8.4	10.5	13.8	20.3
Victoria	48.43	-123.37	40.3	69.3	89.9	98.9	21.0	38.2	58.8	81.8	12.1	19.4	30.1	47.6

Community	Coordinates		MMI V - "Widely Felt" Probabilities (%)				MMI VI - "Non-structurally Damaging" Probabilities (%)				MMI VII - "Structurally-Damaging" Probabilities (%)			
			PGA (g) = 0.067 (H & R "Best")				PGA (g) = 0.13 (H & R "Best")				PGA (g) = 0.24 (H & R "Best")			
	Lat.	Long.	10 yrs	25 yrs	50 yrs	100 yrs	10 yrs	25 yrs	50 yrs	100 yrs	10 yrs	25 yrs	50 yrs	100 yrs
Woss	50.22	-126.60	30.3	54.9	78.1	94.9	10.6	15.9	23.9	37.9	8.3	10.2	13.3	19.4
Youbou	48.88	-124.20	29.7	53.9	77.1	94.4	15.0	25.9	40.8	62.4	10.0	14.4	21.0	33.1
Yuquot	49.60	-126.62	43.4	73.2	92.3	99.4	16.5	29.0	45.7	68.4	9.7	13.6	19.7	30.9
Zeballos	49.99	-126.84	44.9	74.9	93.2	99.5	15.9	27.9	44.0	66.4	9.3	12.8	18.2	28.3
1 - NW Coast	51.00	-129.20	51.9	82.1	96.6	99.9	15.8	27.5	43.3	65.6	9.1	12.3	17.2	26.4
2 - North Coast	51.00	-128.60	36.7	64.5	86.4	98.0	10.8	16.2	24.4	38.8	8.2	10.1	12.9	18.8
3 - North Coast	51.00	-128.00	27.5	50.2	73.3	92.3	9.5	13.2	18.9	29.5	8.1	9.9	12.6	18.1
4 - NE Coast	51.00	-127.40	22.1	40.3	61.6	84.2	9.1	12.2	17.0	26.1	8.1	9.9	12.5	18.0
5 - W Coast	50.50	-128.20	53.0	83.1	96.9	99.9	16.1	28.3	44.6	67.2	9.2	12.5	17.5	27.1
6 - S of Port Alice	50.30	-127.50	50.8	81.1	96.1	99.8	17.2	30.5	48.0	71.0	9.4	13.0	18.5	28.7

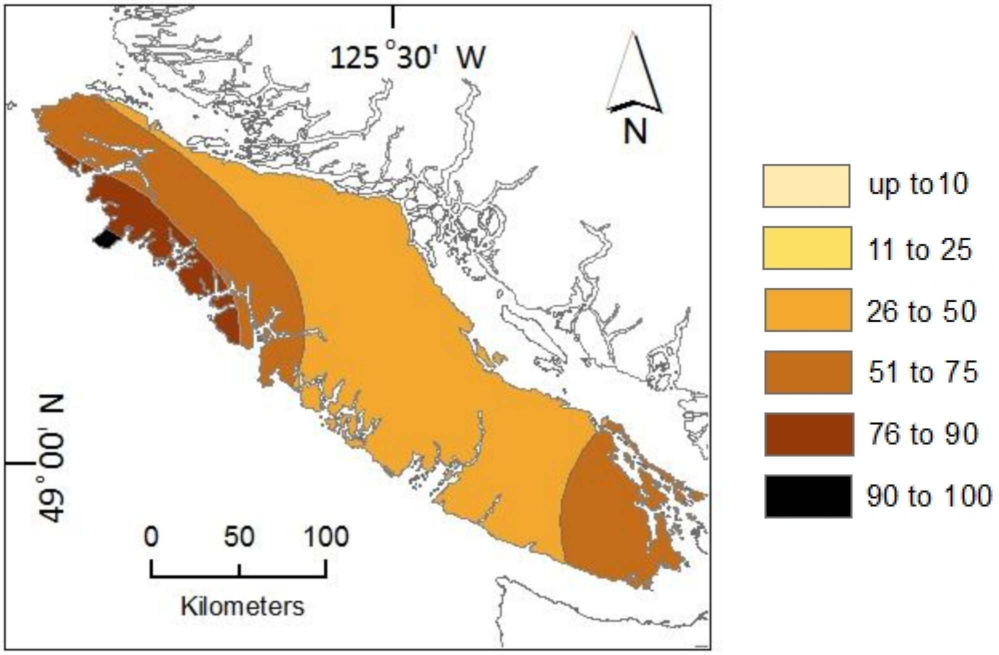
Community	Coordinates		MMI V - "Widely Felt" Probabilities (%)				MMI VI - "Non-structurally Damaging" Probabilities (%)				MMI VII - "Structurally-Damaging" Probabilities (%)			
			PGA (g) = 0.067 (H & R "Best")				PGA (g) = 0.13 (H & R "Best")				PGA (g) = 0.24 (H & R "Best")			
	Lat.	Long.	10 yrs	25 yrs	50 yrs	100 yrs	10 yrs	25 yrs	50 yrs	100 yrs	10 yrs	25 yrs	50 yrs	100 yrs
7 - Robson Bight	50.50	-126.50	23.4	42.8	64.8	86.7	9.6	13.4	19.3	30.1	8.2	10.0	12.9	18.6
8- Brooks Pen	50.00	-128.00	73.5	96.0	99.8	100.0	29.2	53.0	76.2	93.9	12.3	19.8	30.7	48.5
9 - S Nimkish Lk	50.30	-127.00	36.2	63.8	85.9	97.9	11.5	18.0	27.7	43.9	8.3	10.4	13.5	19.8
10 - N Mt. Judson	50.00	-126.00	24.4	44.7	67.1	88.4	10.2	15.0	22.1	35.0	8.4	10.5	13.7	20.2
11 - W Flores Isl	49.20	-126.50	30.2	54.7	77.9	94.8	10.5	15.6	23.4	37.0	8.2	10.2	13.1	19.1
12 - E Buttle Lk	49.70	-125.50	21.6	39.5	60.6	83.3	10.2	14.8	21.8	34.5	8.4	10.6	13.8	20.4
13 - W Sproat Lk	49.30	-125.40	21.5	39.3	60.3	83.1	10.3	15.2	22.7	35.9	8.4	10.7	14.1	20.9
14 - W Swiftsure	48.50	-125.00	21.2	38.6	59.4	82.3	10.7	16.2	24.4	38.7	8.5	10.9	14.5	21.7
15 - NE Nitnat Lk	48.90	-124.60	25.6	46.9	69.6	90.1	12.8	21.0	32.9	51.7	9.2	12.6	17.7	27.3
16 - E Flores	49.40	-125.90	23.9	43.7	65.9	87.5	10.2	15.0	22.1	35.0	8.4	10.5	13.8	20.4

Community	Coordinates		MMI V - "Widely Felt" Probabilities (%)				MMI VI - "Non-structurally Damaging" Probabilities (%)				MMI VII - "Structurally-Damaging" Probabilities (%)			
			PGA (g) = 0.067 (H & R "Best")				PGA (g) = 0.13 (H & R "Best")				PGA (g) = 0.24 (H & R "Best")			
	Lat.	Long.	10 yrs	25 yrs	50 yrs	100 yrs	10 yrs	25 yrs	50 yrs	100 yrs	10 yrs	25 yrs	50 yrs	100 yrs
17 – Jord. R. Dam	48.60	-123.90	34.1	60.8	83.5	97.1	17.4	30.9	48.5	71.6	10.8	16.3	24.5	38.9
18 - W Nanaimo	49.10	-124.30	27.5	50.1	73.2	92.3	13.8	23.2	36.4	56.7	9.5	13.3	19.1	29.9
19 - Viscount Isl	50.70	-126.20	19.2	34.7	54.1	77.4	9.3	12.6	17.8	27.6	8.2	10.0	12.8	18.5
20 - NW Van Isle	49.00	-128.30	79.1	97.8	99.9	100.0	32.3	58.1	81.1	96.2	13.0	21.5	33.6	52.7
21 - SW Van Isle	48.30	-127.30	29.1	52.8	76.0	93.8	9.9	14.2	20.6	32.5	8.2	10.1	12.9	18.7
22 - NE Van Isle	51.00	-124.50	16.7	29.5	46.4	69.2	9.7	13.8	20.0	31.5	8.4	10.5	13.7	20.2
23 - E Van Isle	50.20	-123.50	19.6	35.5	55.1	78.4	10.4	15.4	23.0	36.4	8.5	10.7	14.1	21.0
24 - W Buttle Lk	49.75	-125.70	22.6	41.3	62.9	85.3	10.1	14.8	21.8	34.5	8.4	10.5	13.8	20.3

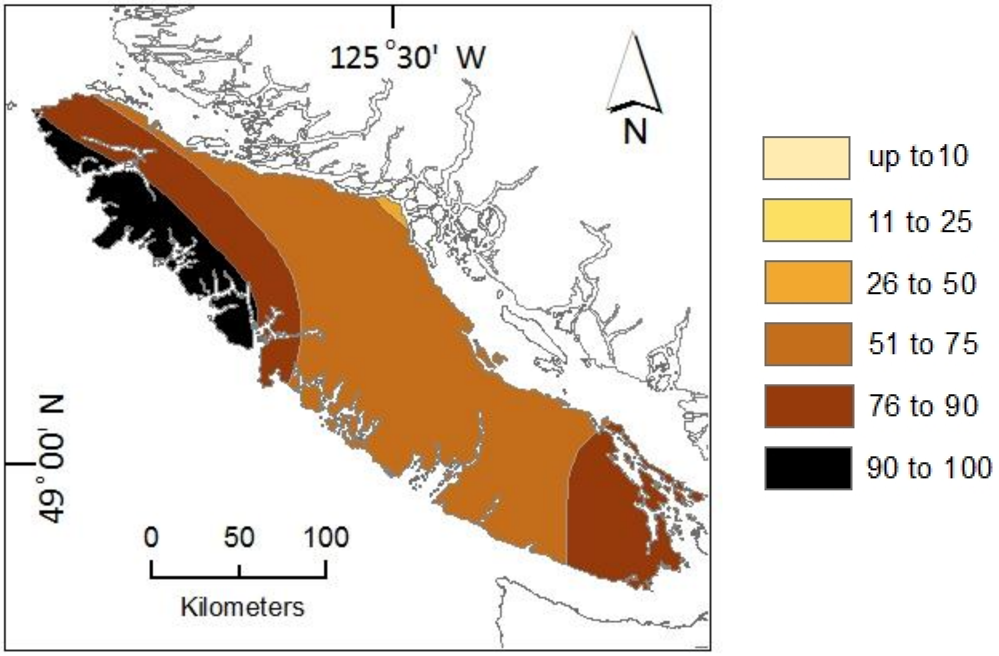
Appendix D: Crustal and Subcrustal Shaking Probability Maps for Vancouver Island



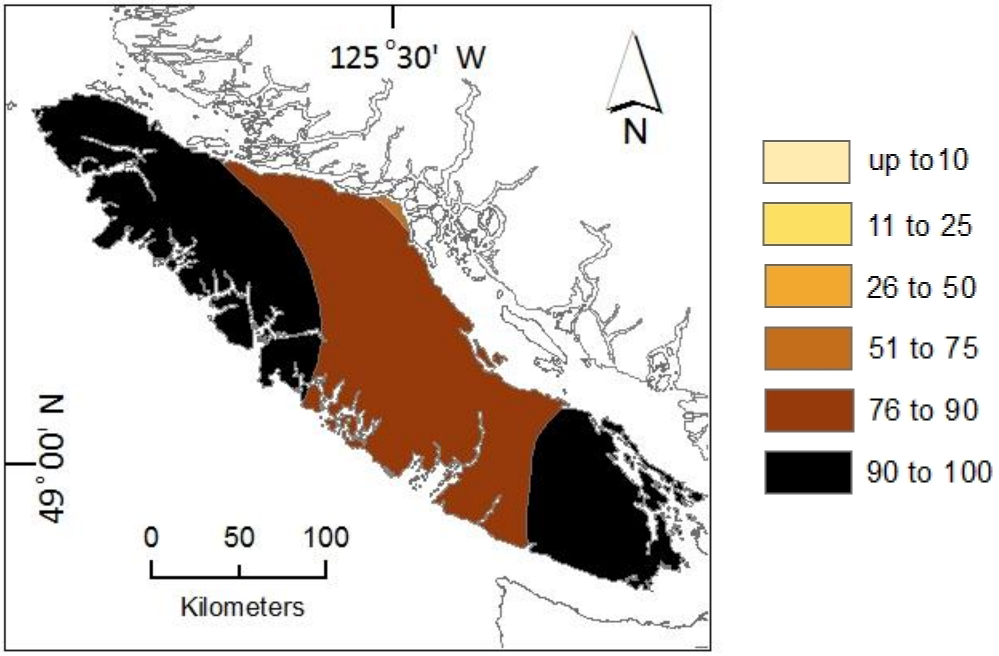
Crustal and Subcrustal Shaking Probability: MMI V in 10 years



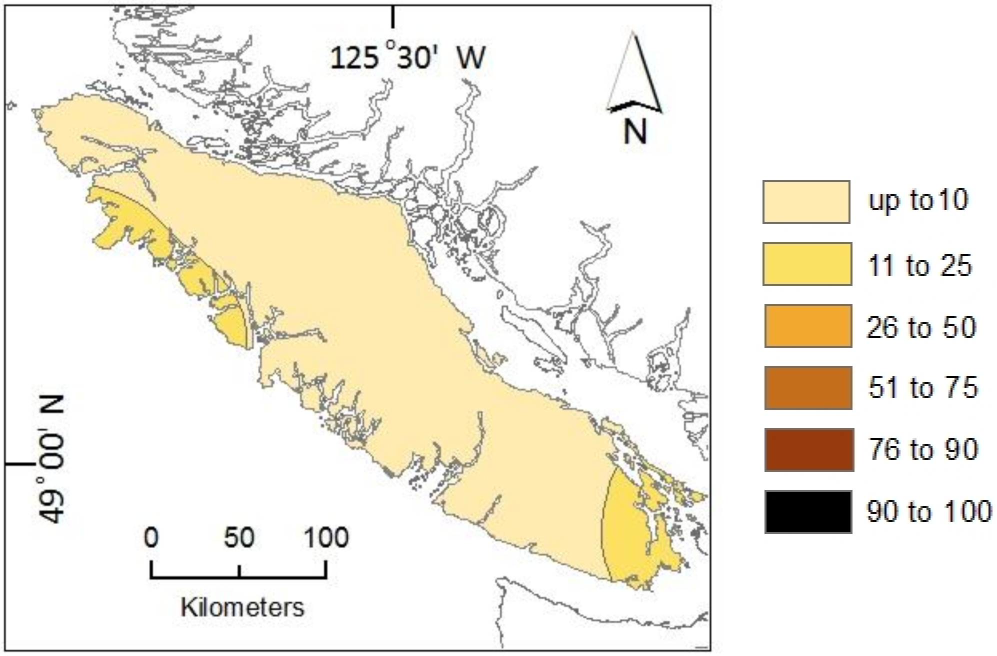
Crustal and Subcrustal Shaking Probability: MMI V in 25 years



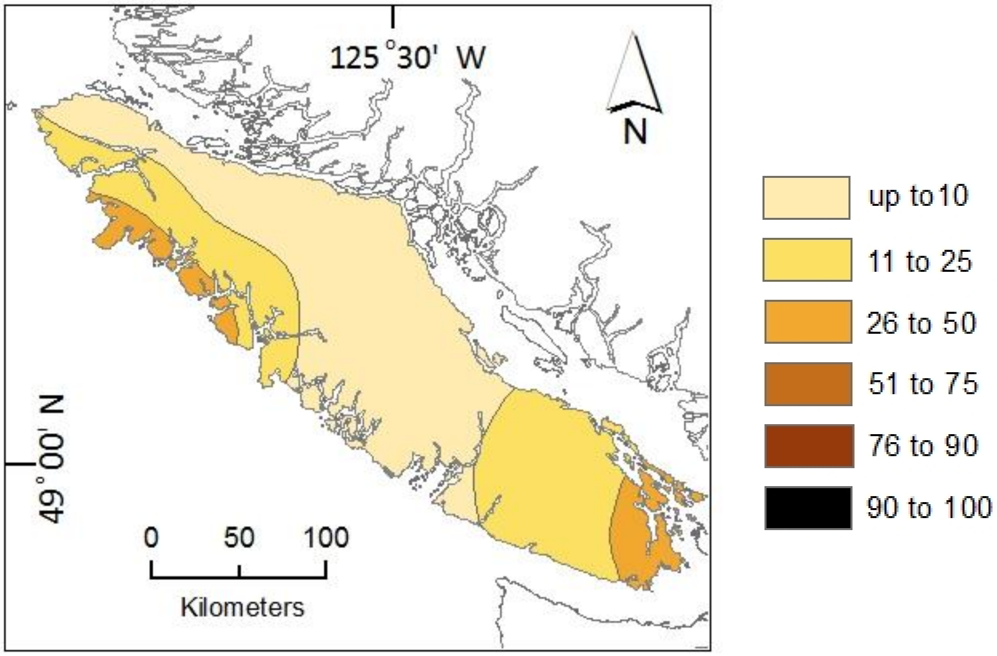
Crustal and Subcrustal Shaking Probability: MMI V in 50 years



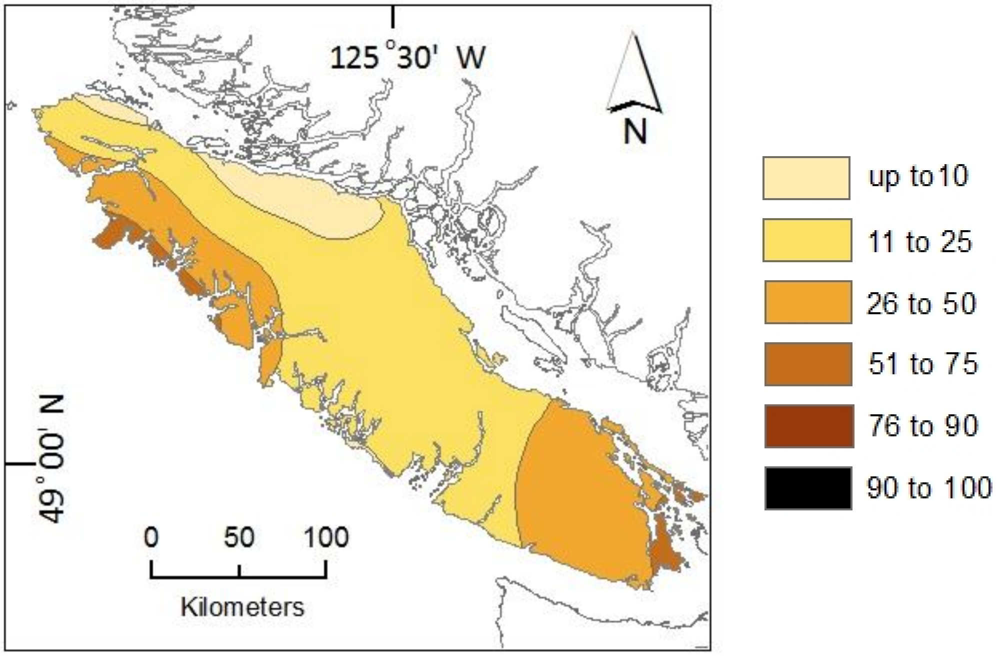
Crustal and Subcrustal Shaking Probability: MMI V in 100 years



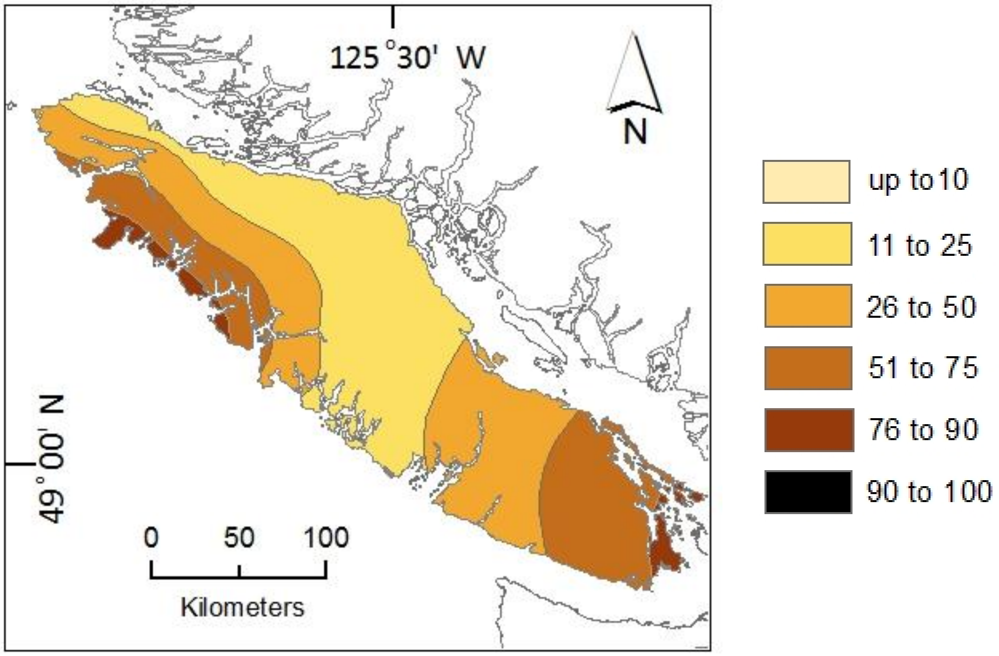
Crustal and Subcrustal Shaking Probability: MMI VI in 10 years



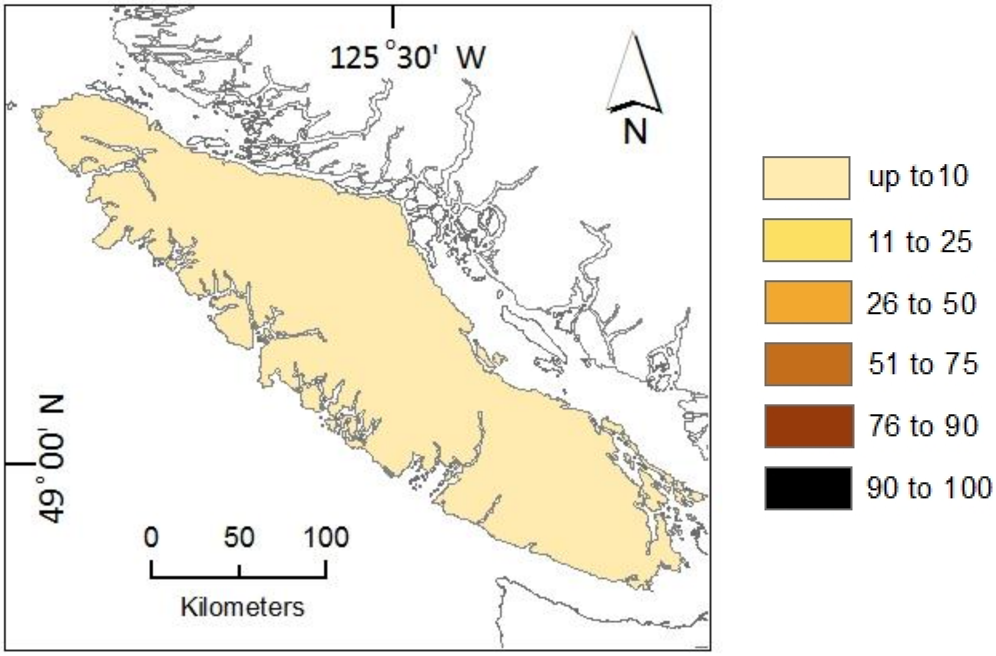
Crustal and Subcrustal Shaking Probability: MMI VI in 25 years



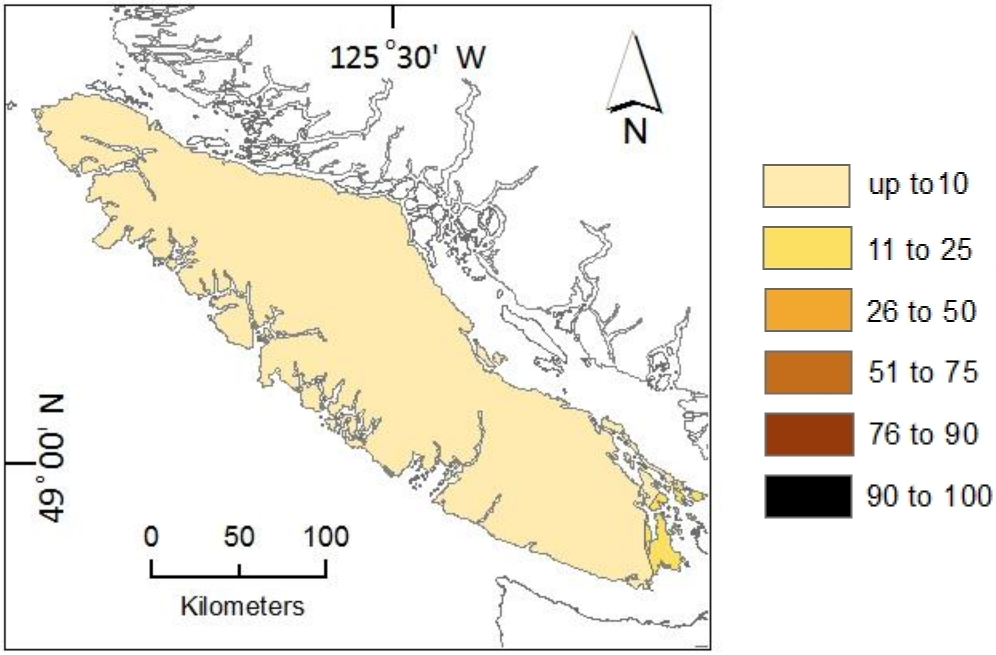
Crustal and Subcrustal Shaking Probability: MMI VI in 50 years



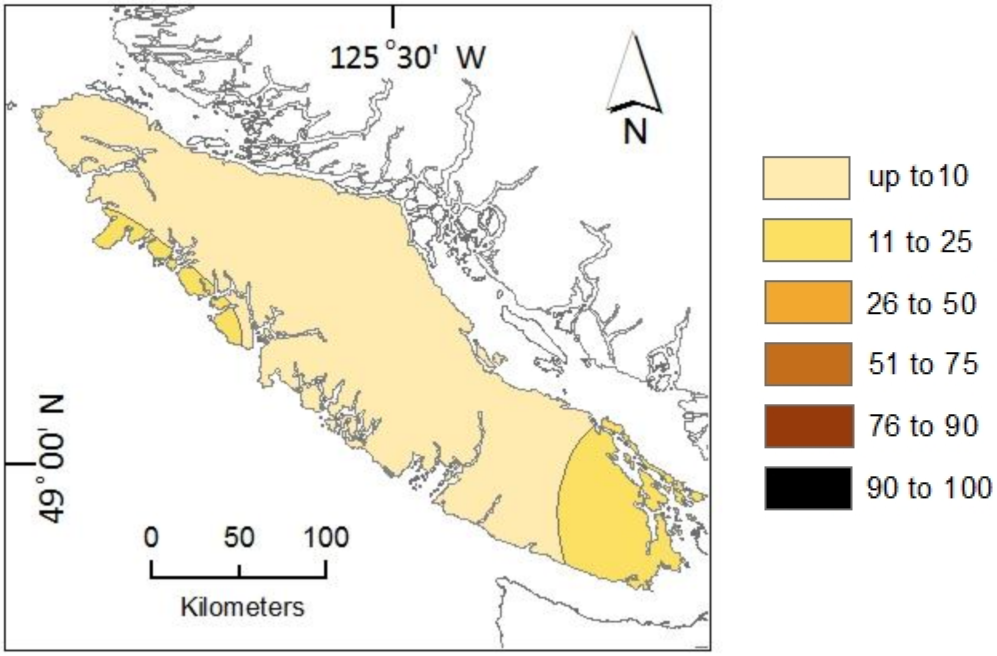
Crustal and Subcrustal Shaking Probability: MMI VI in 100 years



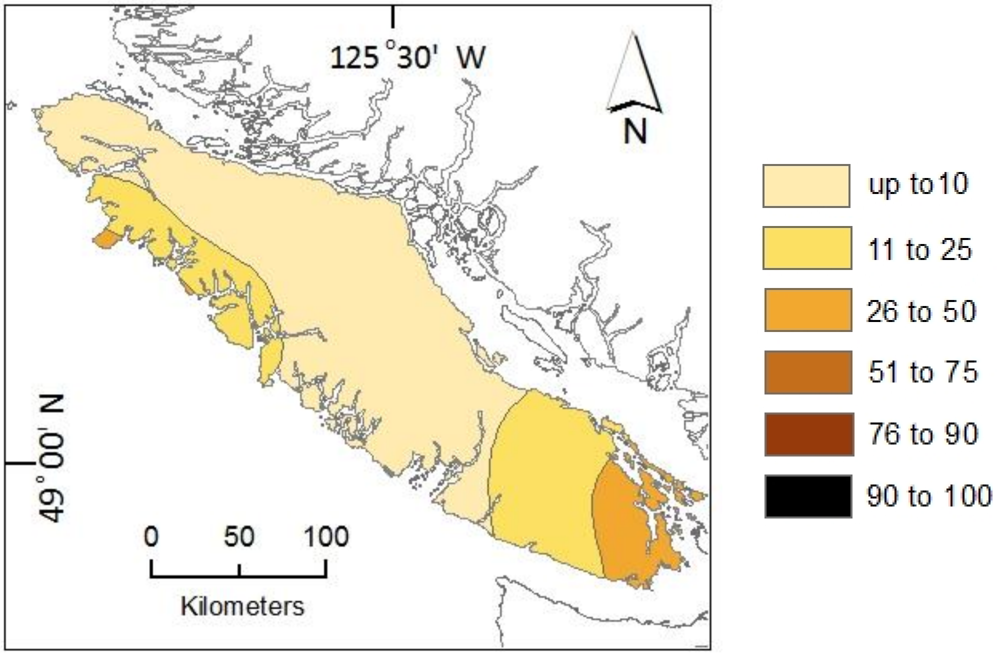
Crustal and Subcrustal Shaking Probability: MMI VII in 10 years



Crustal and Subcrustal Shaking Probability: MMI VII in 25 years

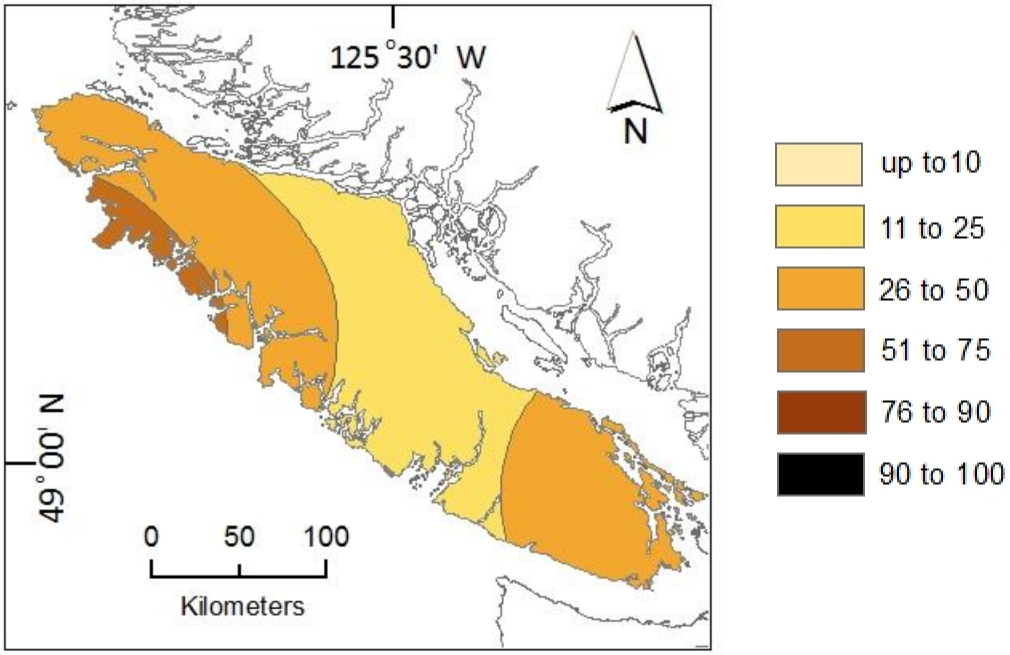


Crustal and Subcrustal Shaking Probability: MMI VII in 50 years

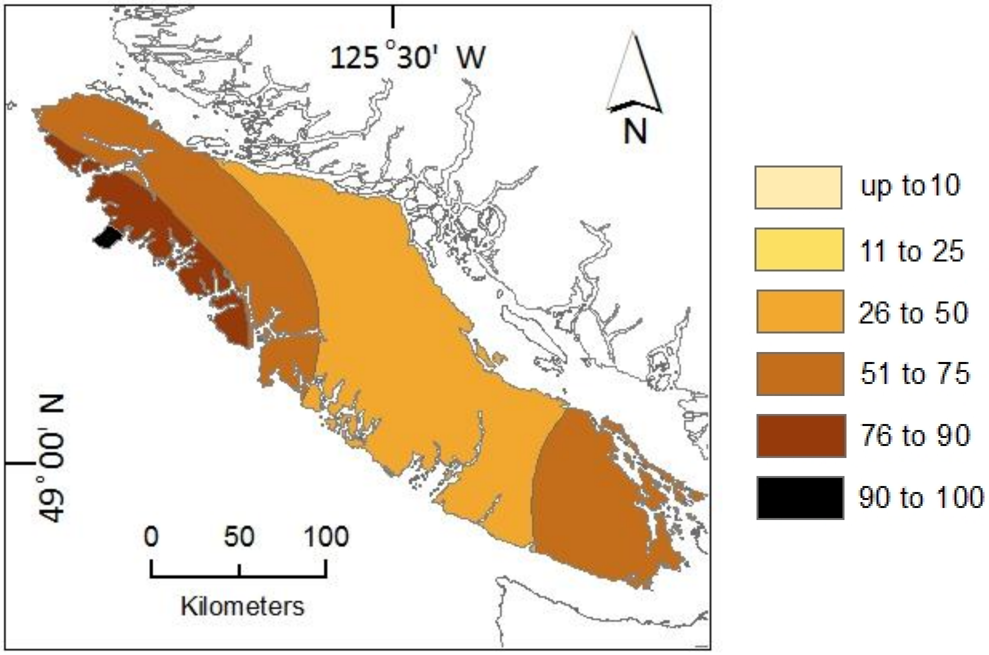


Crustal and Subcrustal Shaking Probability: MMI VII in 25 years

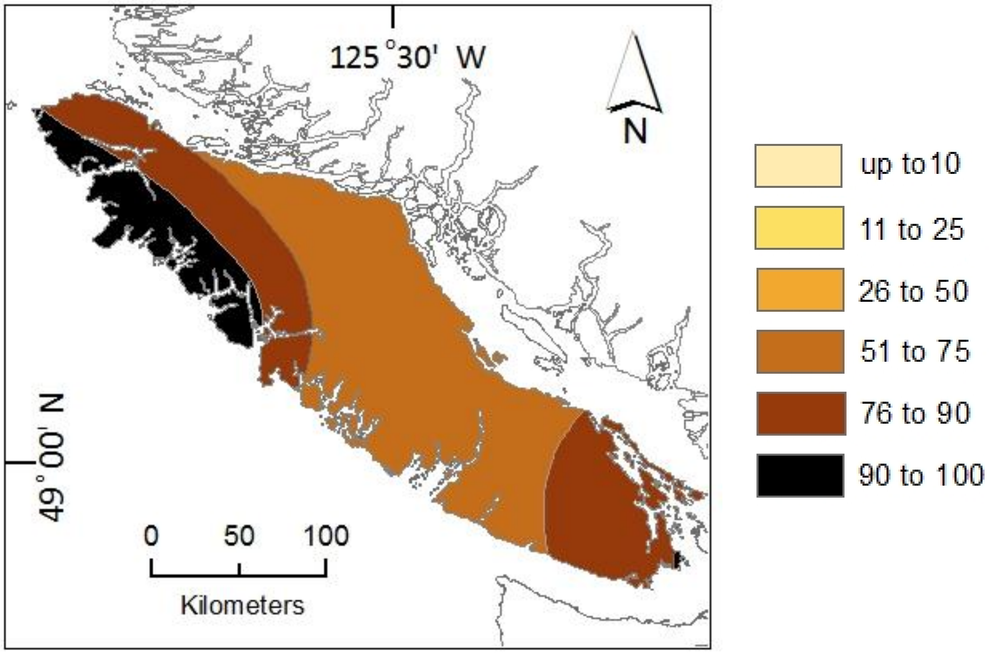
Appendix E: Aggregate (Crustal, Subcrustal and Subduction) Shaking Probability Maps for Vancouver Island



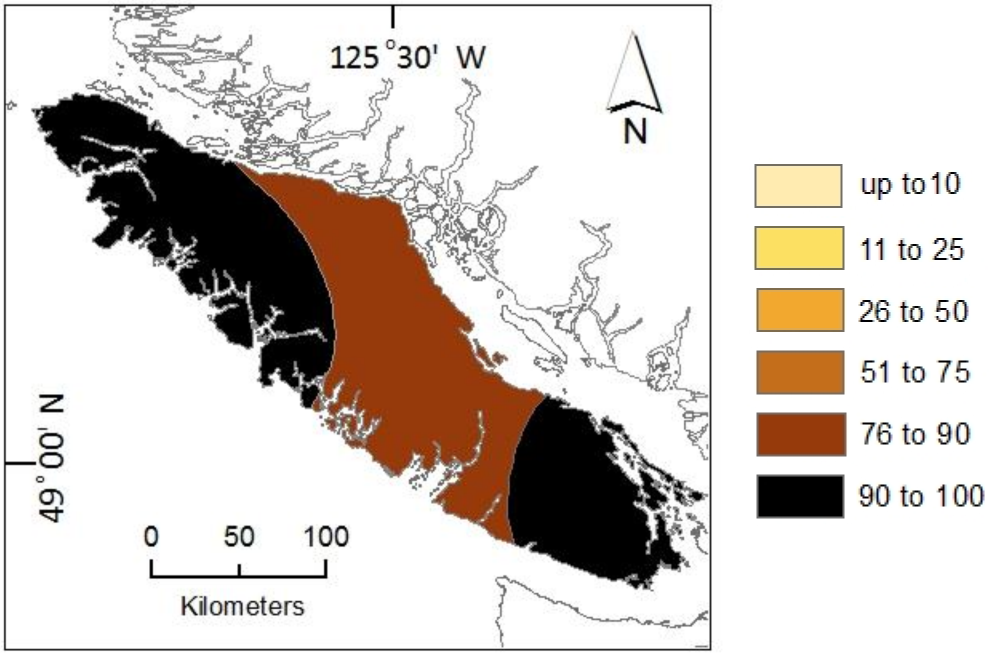
Aggregate Shaking Probability: MMI V in 10 years



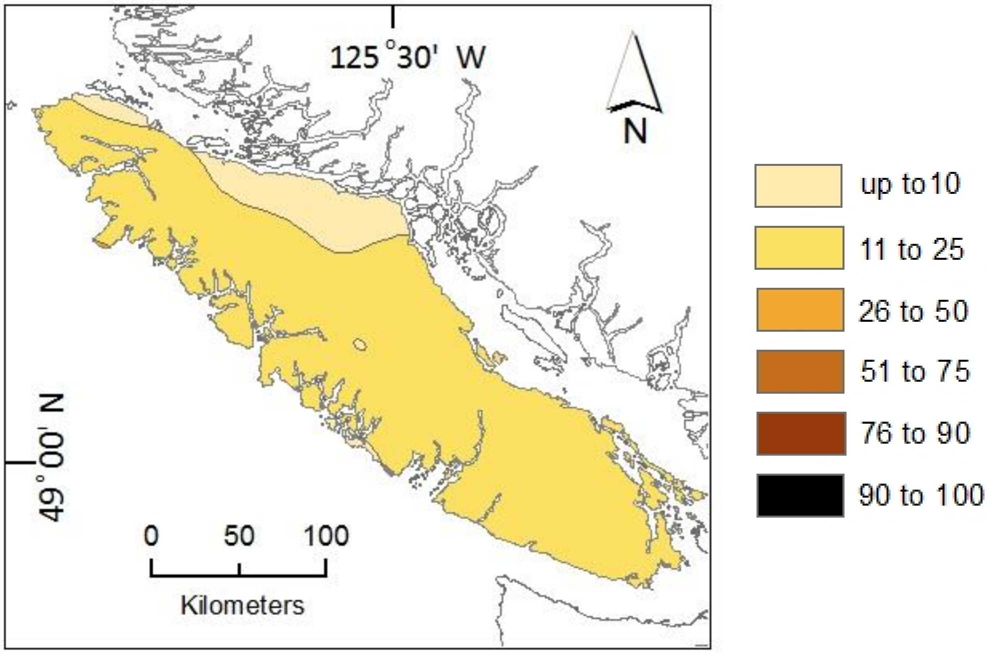
Aggregate Shaking Probability: MMI V in 25 years



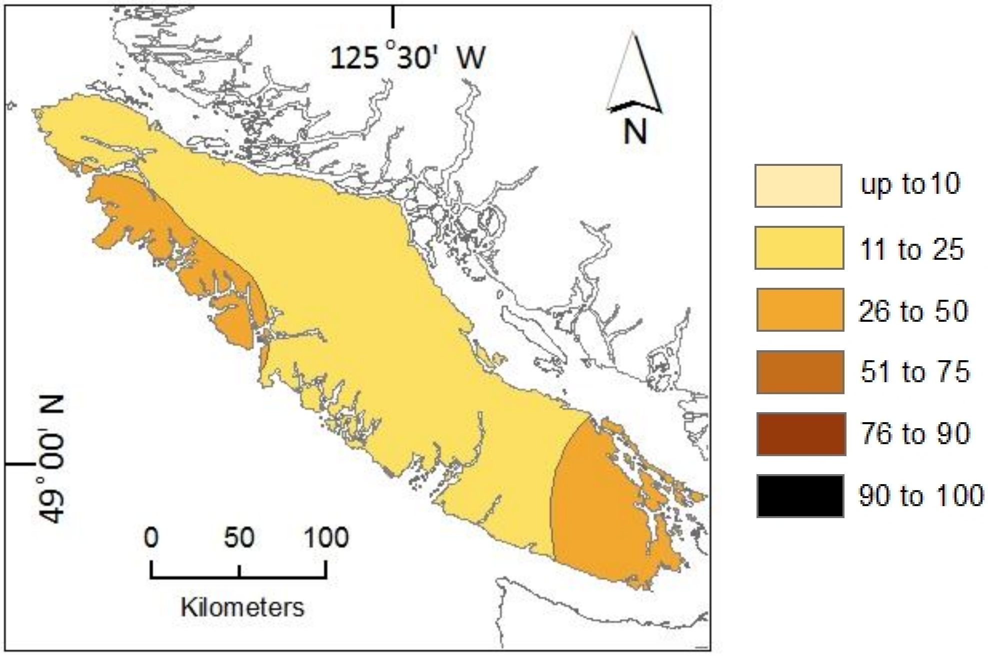
Aggregate Shaking Probability: MMI V in 50 years



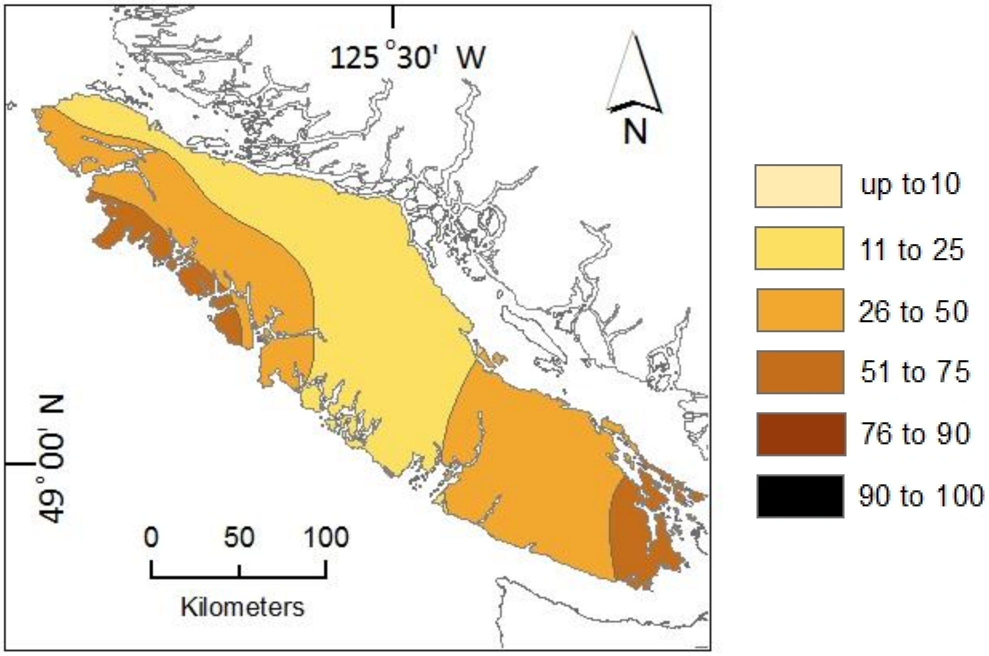
Aggregate Shaking Probability: MMI V in 100 years



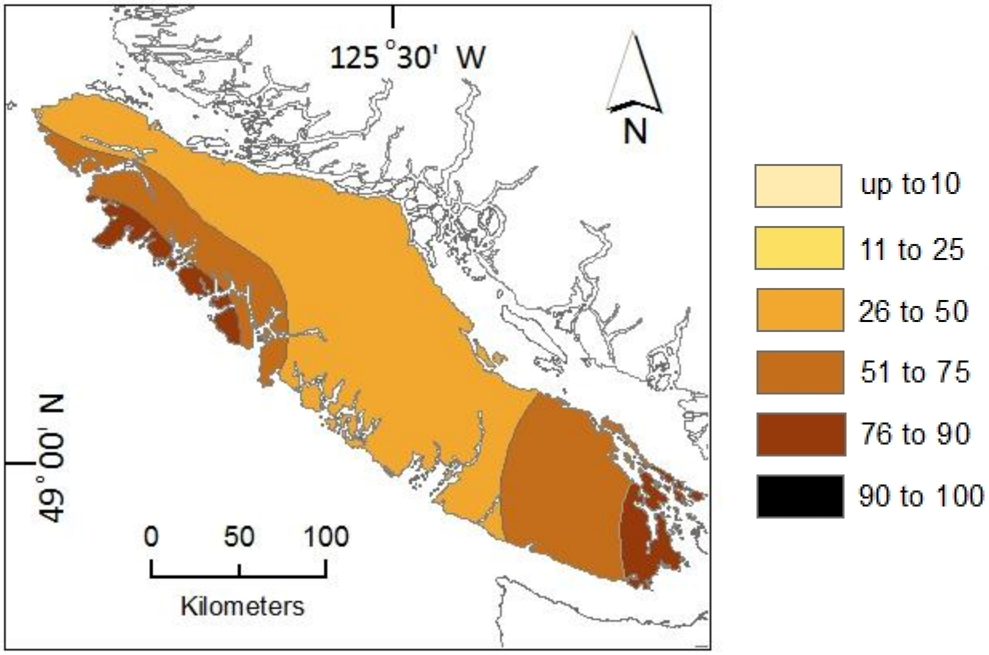
Aggregate Shaking Probability: MMI VI in 10 years



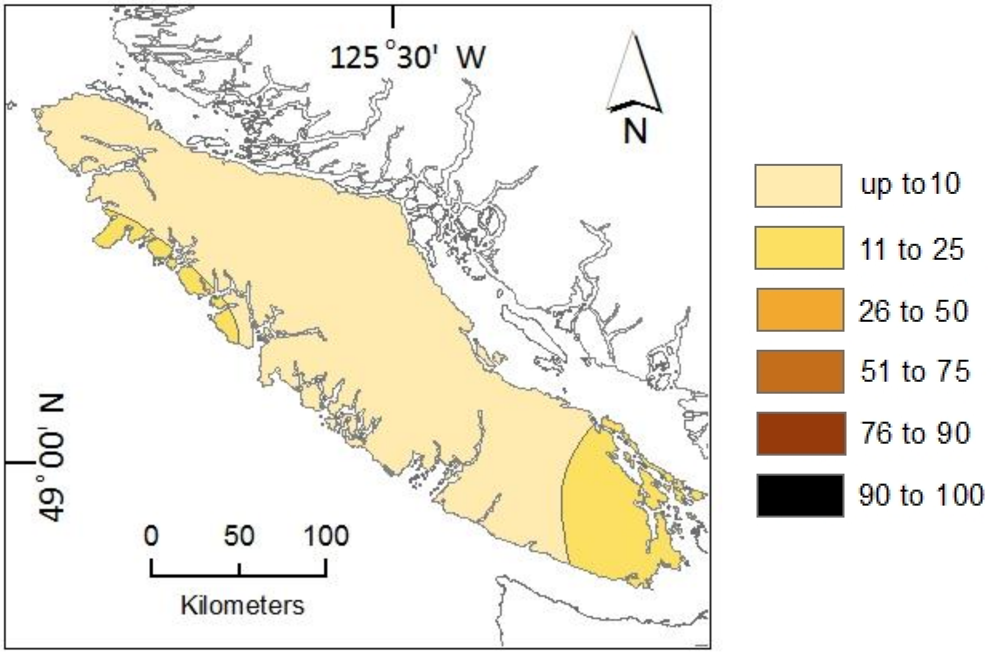
Aggregate Shaking Probability: MMI VI in 25 years



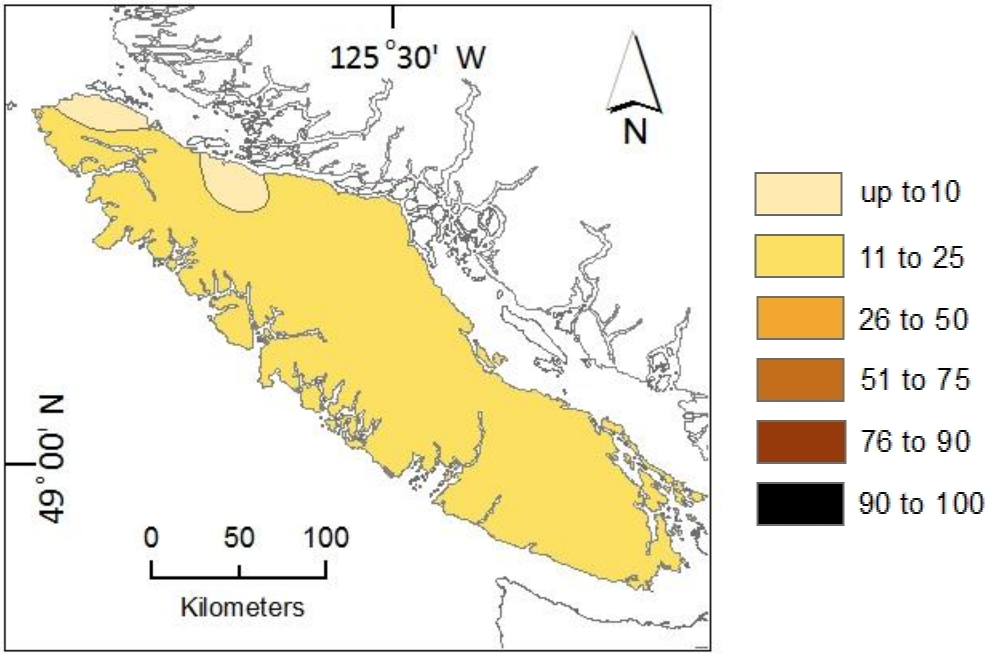
Aggregate Shaking Probability: MMI VI in 50 years



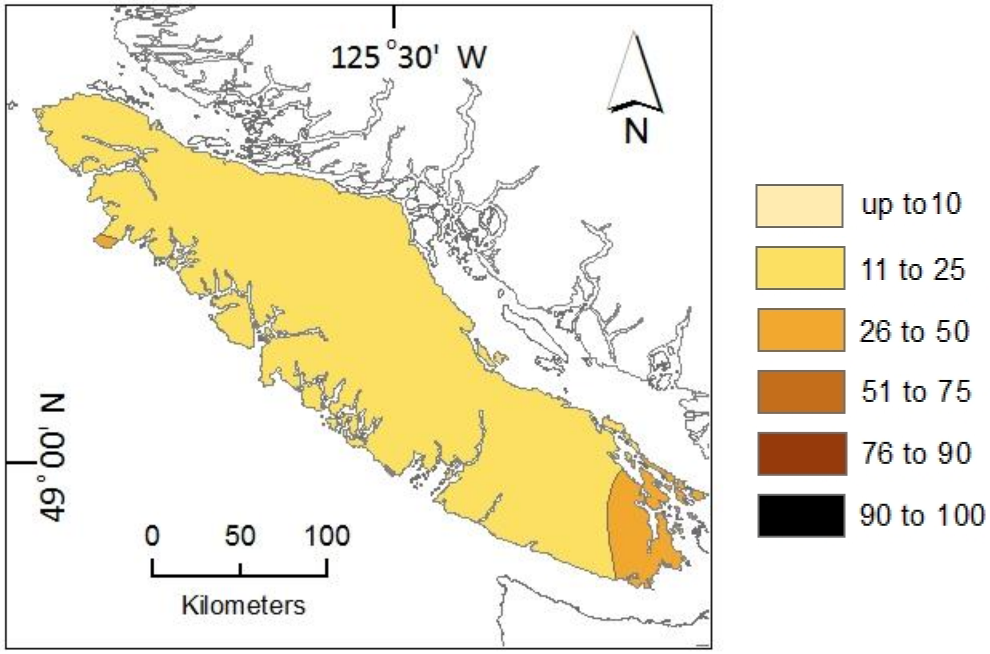
Aggregate Shaking Probability: MMI VI in 100 years



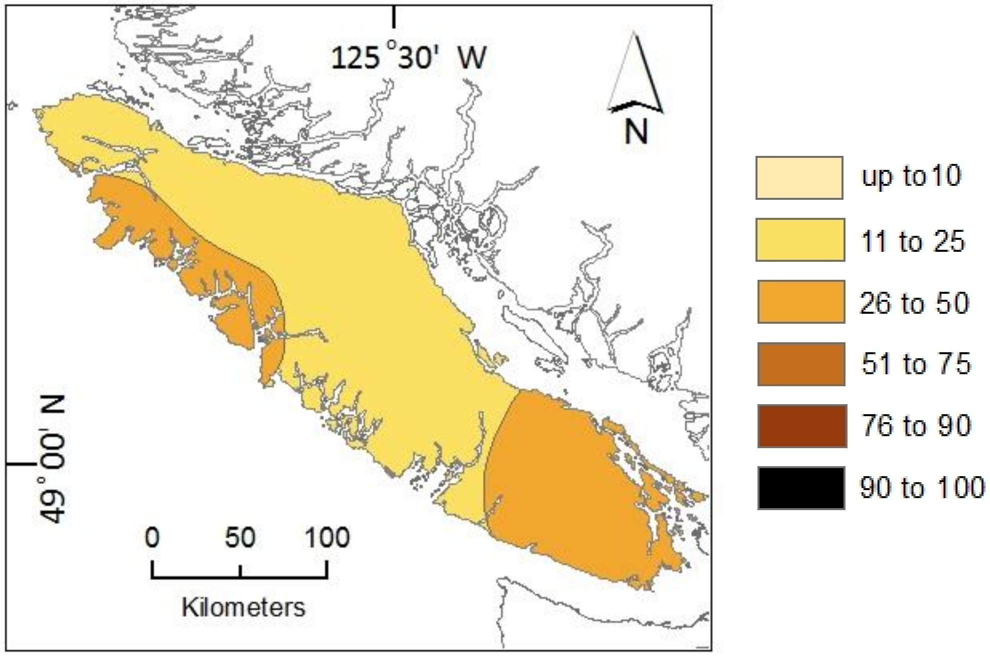
Aggregate Shaking Probability: MMI VII in 10 years



Aggregate Shaking Probability: MMI VII in 25 years



Aggregate Shaking Probability: MMI VII in 50 years



Aggregate Shaking Probability: MMI VII in 100 years