GIS-BASED MULTIPLE HAZARD RISK ASSESSMENT: A CASE STUDY FOR THE CITY OF KELOWNA

by

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ABSTRACT

In 2003, the Okanagan Mountain Park Fire caused significant damage to the local infrastructure, real estate, landscape and resources in Kelowna, BC, Canada. Furthermore, given its geographic location, the city is vulnerable to seismic hazard, consequently, in this thesis, a multiple hazard (earthquake, fire) risk assessment study has been undertaken. To select appropriate tool for the seismic vulnerability assessment, six established building vulnerability assessment methods, such as FEMA 154, Euro Code 8, New Zealand guideline, Modified Turkish method, Hybrid method, and NRC guidelines, are evaluated and ranked. It is observed that the 'Hybrid' (which includes the local site specific issues as well as the results from non destructive testing and experimental data) method adequately satisfies all the criteria necessary for their use in seismic risk assessment. To highlight utility of the different vulnerability assessment methods, over 0.5 km × 0.5 km grids, a case study for the city is conducted. From the Hybrid method, 48% and 52% of buildings in Kelowna are found to be in moderate and low seismic vulnerability states, respectively. Furthermore, using a GIS-based RADIUS method, a seismic damage estimation study has been undertaken. Damage distributions are quantified and mapped over 0.5 km × 0.5 km grids. The assessment reveals that, with a Mw8.5 Cascadian earthquake scenario, there is a possibility of 62 buildings (mostly wooden structures) collapsing and 13 people being injured. The assessment result also reveals that downtown Kelowna is expected to suffer highest amount of damage. Finally, a GIS-based wildfire risk assessment shows that, 26 %, 12% and 63% area in Kelowna are assessed to be in a high, moderate and low risk category, respectively. Not only can the total amount of the damage but the weak points of the city be measured with the spatial analysis. This measure could be leveraged as a benchmark for a scenario-based contingency plan for multiple hazards for the City of Kelowna.

Improving the quality of information and understanding of disaster risk will facilitate the authority to manage effective multiple hazard risk reduction measures, including preparedness, emergency response activities, recovery actions and policies.

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LIST OF NOTATIONS

AHP	Analytical Hierarchy Process
CFCWHR	Concrete Frame with Concrete Walls High Rise
DBT	Dry Bulb Temperature
FDI	Fire Danger Index
FEMA	Federal Emergency Management Agency
FII	Fire Initiation Index
FVI	Fire Vulnerability Index
Gal	Galileo = 1 cm/s^2
GBR	GIS-based RADIUS
GHI	GeoHazards International
GIS	Geographical Information System
MCDM	Multi Criteria Decision Making
MDF	Mean Damage Factor
MMI	Modified Mercalli Intensity
NK	Not Known
NRC	National Research Council
NZ	New Zealand
PGA	Peak Ground Acceleration
POC	Paid on Call
RC	Reinforced Concrete
RF	Average Rainfall
RADIUS	Risk Assessment Tools for Diagnosis of Urban Areas against Seismic Disasters
RH	Relative Humidity
T	Maximum Dry Bulb Temperature
TOPSIS	Technique for Order preference by Similarity to Ideal Situation
Vs 30	Shear-Wave Velocity at 30 m Depth
WS	Average Wind Speed
WLFR	Wooden Light-Frame Low-Rise Residential
URM	Unreinforced Masonry

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DEDICATED TO MY PARENTS

Chapter 1: INTRODUCTION AND THESIS ORGANIZATION

1.1 GENERAL

Canadian communities are increasingly exposed to noticeable risks from natural disasters. According to Canadian Disaster Database, in the last few decades, over a 300% increase in the number of natural disasters are reported (PSC 2007). The City of Kelowna, B.C., is one of the vulnerable cities exposed to wildfires (www.iclr.org). Given its geographic location, the city is also vulnerable to seismic hazard (gsc.nrcan.gc.ca). The study primarily focuses on the risk assessment for two above stated hazards within the region. At first, a comparative analysis of different seismic vulnerability assessment techniques is done with a case study for the city. For regional seismic risk estimation, a multi-disciplinary evaluation is also necessary to assess the potential physical damage, the number and type of causalities for a particular event (Cardona and Hurtado 2000). In this study, damage scenarios for particular seismic events are assessed, which will facilitate the decision makers in developing scenario-based contingency plans. Besides, a GIS-based wildfire risk assessment framework is also developed for the City of Kelowna. In 2003, the Okanagan Mountain park fire caused damage to 239 buildings on the southern edges of the City of Kelowna, forcing evacuation of 27,000 people, which made the community concerned about the wildfire risk (http://www.kelowna.ca/CM/page129.aspx).

1.2 OBJECTIVE OF THE STUDY

The key objectives of the current research are to

1. Develop and implement a methodology for ranking the existing seismic vulnerability assessment techniques that would assist risk assessors to select the proper tool.
2. Develop and integrate a GIS-based RADIUS (Risk Assessment Tools for Diagnosis of Urban Areas against Seismic Disasters) methodology for seismic damage estimation for the City of Kelowna.
3. Develop and integrate a GIS-based tool to assess wildfire risk for the city.

1.3 SCOPE OF THE RESEARCH

In order to achieve the above objectives, existing seismic vulnerability assessment techniques are utilized from the literature review. A Hybrid method is proposed in order to provide a unified vulnerability assessment technique. The study also presents the state-of-the-art and current methods used to estimate the losses due to seismic hazard, as well as the risk assessment techniques for wildfire hazard. The tasks performed to achieve the stated objectives of the study are as follows:

1. An innovative scoring method is developed to rank existing seismic vulnerability assessment techniques. A critical overview of the methods is conducted as well to develop the scoring system. To check the applicability of the selected techniques, a case study is conducted for the City of Kelowna.

2. The RADIUS (2000) risk assessment software is integrated into a GIS platform to visualize probable losses, arising from different scenario earthquakes. Validation of the RADIUS tool is conducted for the 1978 Thessaloniki (Greece) Earthquake (M_w6.5). Finally, an in-depth case study is performed with data collected for the Kelowna city with different scenarios of earthquake.
3. A qualitative wildfire risk assessment technique is proposed, which considers the wildfire initiation probabilities and vulnerabilities. A case study is performed with data collected for the city.

1.4 THESIS ORGANIZATION

This thesis is arranged in six chapters which are shown in Figure 1-1 . In the current chapter a short preface and the objectives and scope are presented.

In **Chapter 2**, a comprehensive review on available seismic vulnerability assessment techniques is conducted. This chapter examines the application of various techniques developed for seismic loss and damage estimation. A comprehensive literature review is also conducted on the available wildfire risk assessment methodologies.

In **Chapter 3**, a scoring method is developed to rank different seismic vulnerability assessment techniques. This helps the decision makers to select a suitable tool for assessing the seismic vulnerability of a particular area. To assess the sensitivity of different methods, a case study for the Kelowna city, Canada is conducted.

In Chapter 4 a GIS-based seismic damage estimation methodology is proposed. RADIUS (2000) software is integrated with the GIS interface to assess the seismic damage of a particular area in terms of building damage and causalities. Finally, Kelowna case study is conducted to assess the applicability of the proposed method.

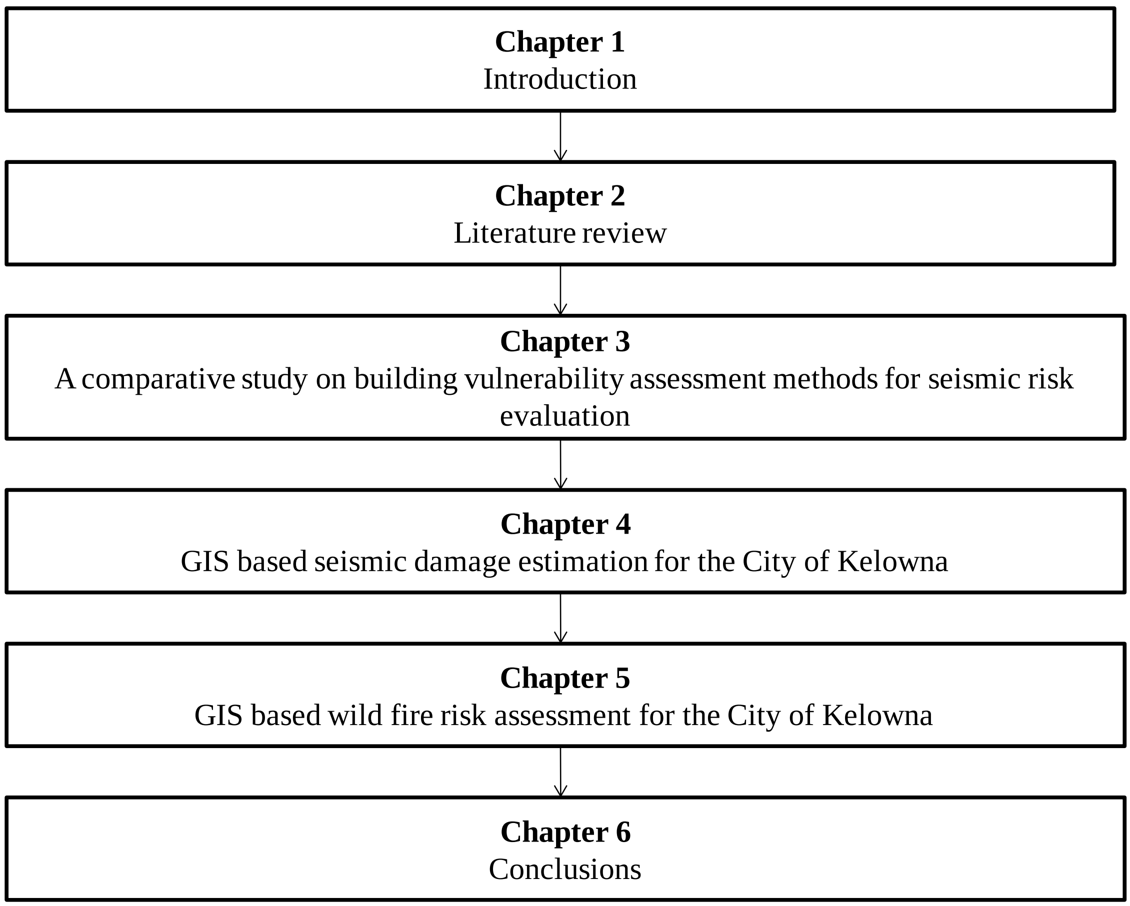


Figure 1-1: Thesis organization

In Chapter 5 a GIS-based wildfire risk assessment tool is developed. An equation is proposed to assess the initiation probability of wildfire considering the natural factors. A semi qualitative risk assessment framework is integrated with the GIS, which provides the spatially distributed risk of different areas. Finally, a case study for the City of Kelowna is conducted to show utility of the proposed method.

Finally, **Chapter 6** summarizes the key conclusions of this research. Few specific recommendations for future research have also been suggested.

Chapter 2: LITERATURE REVIEW

2.1 GENERAL

The increased vulnerability and corresponding risk for multiple hazards in many urban areas has become a major concern in the last decades (Munich 2000). Therefore, emphasis should be given in risk reduction. It is noted that such measure and materialization requires an assessment of potential damage to make recommendations for prevention, preparedness and response (Ingleton 1999). World Meteorological Organization (WMO) states that, the assessment of the expected damages for a potential disaster essentially consists of risk evaluation (WMO 1999). This chapter provides a comprehensive review on widely used seismic vulnerability assessment techniques. Furthermore, a detailed review of studies related to the seismic damage estimation techniques in various localities is provided. In addition, a comprehensive review on wildfire risk assessment is provided. This chapter provides a benchmark which facilitates in developing a multiple hazard (earthquake and wildfire) risk assessment framework for a particular area.

2.2 HAZARD, VULNERABILITY AND RISK

The risk assessment process provides the base for a mitigation planning process. Hazard identification, asset inventory collection, vulnerability assessment and loss estimations are four basic components of the risk assessment. By assessing the vulnerability of people, buildings, and infrastructure, this process assesses the potential casualty, and property damage resulting from natural hazards (http://www.fema.gov). In this thesis, risk (Hardy 2005, Camia *et al.* 2004) is defined as the expected damage due to a particular hazard on a specific spatial and temporal exposure. The simplistic definition of risk is viewed as the Equation 2-1, which establishes the relationship between three terms hazard, vulnerability and risk (Chen *et al.* 2003).

$$risk = \text{hazard} \times \text{vulnerability} \qquad \text{Equation 2-1}$$

Equation 2-1 covers two different components in risk assessment, (i) hazard, which corresponds to the probability of occurrence (likelihood of happening) of a particular disastrous event in a specific area and (ii) vulnerability, that refers to the potential damage, that a hazard will cause, when it occurs (Blanchi *et al.* 2002). Vulnerability can be defined as a system which integrates a lot of variables (natural and human), the spatial and temporal dynamic of which can produce situations which can be harmful for an exposed society. One of the major goals of a risk assessment strategy is to identify the factors (variables) that are the source of the vulnerability. The major task in risk assessment is to express vulnerability in measurable units or indices in order to be used for further assessment of the total risk (Coburn *et al.* 1994). In this thesis risk is expressed as a degree of damage or percent loss (or index) of a specific physical component for a given hazard severity level (Blanchi *et al.* 2002).

2.3 REVIEW OF EXISTING SEISMIC VULNERABILITY ASSESSMENT METHODS

Seismic vulnerability is defined as the degree of damage to buildings resulting from the occurrence of an earthquake event (Coburn and Spence 2002). There is an increasing research in the development of seismic vulnerability assessment techniques (e.g. Calvi *et al.* 2006, Okada and Takai 2000, Gueguen *et al.* 2007, Lang and Bachmann 2004, Lantada *et al.* 2010, Martinelli *et al.* 2008, Roca *et al.* 2006, Spence *et al.* 2008, Sucuoglu *et al.* 2007, Tesfamariam and Saatcioglu 2010).

In this section, six well established approaches are discussed in detail, namely, 'Hybrid' method, FEMA 154 (Rapid Visual Screening), Euro Code 8, New Zealand guideline, Modified Turkish Method and NRC guidelines, to find a suitable alternative to be used in seismic risk assessment.

2.3.1 Seismic vulnerability factors

In regional seismic risk assessment, a large number of buildings are dealt with. The seismic vulnerability of buildings varies widely with the functional and aesthetic purposes of buildings (Hugo 2002). Several structural features are considered as the seismic vulnerability factors for buildings including soft story, heavy overhang, short column, pounding possibility between adjacent buildings, and visible ground settlement. According to the Turkish method (Bommer *et al.* 2002), the level of building damage during earthquakes depends on the apparent building quality which, in turn, is related to the quality of construction materials and building maintenance. Figure 2-1 and Figure 2-2 show some of the devastating effects of earthquakes during the last decades, which show that, the seismic vulnerability is one of the main causes of building collapse during an earthquake.

(a) Building collapse due to soft storey effect (b) Shear collapse

Figure 2-1: Building collapses in 2006 Yogyakarta earthquake (http://mae.cee.illinois.edu/news/archive/yogyakarta.html)

Figure 2-2: Effect of topography in Sichuan earthquake 2008 (Chinadigitaltimes.net)

Moreover, the existing building codes, regulations and the building types also play a vital role in seismic vulnerability of an area. Compared to the Chile earthquake of February 2010 (M_w8.8, 100 km away from the capital), the Haiti earthquake of January 2010 (M_w7 with an epicentre 25 km west of Haiti's capital) caused more casualties due to the existing building types (Figure 2-3) and codes (http://www.huffingtonpost.com).

Figure 2-3: Effects of earthquakes in Chile and Haiti, 2010 (http://www.huffingtonpost.com)

A soft storey exists if the stiffness of one story is noticeably less than that of most of the others. It is difficult to verify the soft stories without the proper knowledge of the building design. The ground floor becomes soft due to large window openings for display purposes in many commercial buildings. Parking spaces commonly found in ground floors of apartment buildings is also a common example of soft story (FEMA 2002) in urban areas. Figure 2-4 shows some of the examples of soft story (ground floors being used as shop or open) in Bangladesh.

Figure 2-4: Examples of soft story in Bangladesh

Moreover, heavy overhanging floors (e.g. Figure 2-5) in multi-storey buildings lead to irregularity in stiffness and mass distributions (Hugo 2002). From the view point of earthquake engineering, this irregularity is undesirable as it causes inappropriate dynamic behaviours when subjected to horizontal earthquake ground motion.

Figure 2-5: Typical heavy overhangs found in Bangladesh

The shear failure of short columns is also one of the major causes of building collapse during a seismic event (FEMA 2002). By unintentional addition of parapet infill in frame structures, slender columns can be converted into short columns. In case of short columns with considerable bending capacity, under horizontal actions of a seismic event, enormous moment gradient and thus a large shear force results, which often leads to a shear failure before reaching the plastic moment capacity (Hugo 2002).

Damage due to pounding can be observed after almost every earthquake events. Different vibration periods and non-synchronized vibration amplitudes cause the close buildings to knock together. Buildings subjected to pounding receive heavier damage on higher stories. The New Zealand Code states that, all new constructions must have a seismic separation of 1.5% of the height of taller building between two adjacent buildings to prevent pounding (NZSEE 2000, 2003). Figure 2-6 shows pounding possibility of buildings in Bangladesh.

Figure 2-6: Pounding possibility in Bangladesh

Building shape and plan irregularities also play a vital role in building damage during a seismic event for all types of buildings. Buildings with re-entrant corners are the most common examples of plan irregularities, where damage is likely to occur. Buildings that are wedge-shaped or triangular in plan are susceptible to twisting (torsion) around a vertical axis, which might cause damage to the structure. In most cases, the concern of plan irregularities is prevalent in case of wooden, reinforced masonry and unreinforced masonry construction, although, it can occur in any type of building structures (FEMA 2002). Figure 2-7 shows a typical shape or plan irregularity in the City of Kelowna.

Figure 2-7: Building plan irregularity in Kelowna city, Canada

Similarly, elevation irregularities of building are another important factor responsible for building damage during an earthquake. FEMA (2002) describes different vertical irregularity which includes buildings with setbacks and hillside buildings that are shown in Figure 2-8 and Figure 2-9. To define the vertical irregularity characteristics, a considerable judgment and experience are required, which might make the identification procedure difficult.

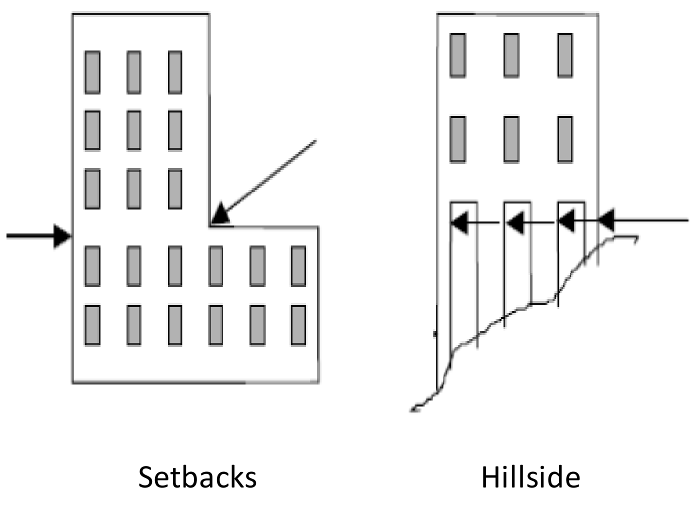


Figure 2-8: Elevation views showing vertical irregularities, with arrows indicating locations of particular concern (after FEMA 2002)

Figure 2-9: Example of vertical irregularities in Kelowna city, Canada

Topographic amplification may increase ground motion intensity on hilltops during earthquakes. For example, if the building is located on steep slopes (more than 30 degrees) of a hill, the horizontal stiffness along the lower side may become different from the uphill side. Moreover, the stiff short columns in the up-slope direction will attract the seismic forces and may fail (FEMA 2002). Figure 2-10 shows some buildings in slope land in an area of high seismicity in Bangladesh.

Figure 2-10: Building in slope land (Rangamati, Bangladesh)

2.3.2 Seismic vulnerability assessment techniques

In this thesis, six established building vulnerability assessment methods, such as FEMA 154, Euro Code 8, New Zealand guideline, Modified Turkish method, Hybrid method, and NRC guidelines are selected for their relevance to the predominant building classes as well as to the contemporary practices in seismic vulnerability assessment of buildings. A 'Hybrid' tool is proposed for the vulnerability assessment incorporating FEMA 310 and IITK GSDMA methods, to cover the location-specific physical components present both in developed as well as developing countries. Other vulnerability assessment tools are selected from a wide range of published papers in the fields of seismology, structural vulnerability, and earthquake engineering. Different seismic vulnerability assessment methods utilize several vulnerability factors, which have been described in Table 2-1. Moreover, the vulnerability scales differ in different methods. In the cases of New Zealand guideline, Euro Code 8, Turkish method and NRC guidelines, the vulnerability scales are classified in 3 different classes (e.g. low, medium and high), whereas in the case of FEMA 154 vulnerability is classified in only 2 groups, i.e. low and high. Moreover, the suggested Hybrid method comprises four different classes of vulnerability, such as low, moderate, high and very high. A correlation among all these methods is summarized in Table 2-2.

Table 2-1: Major factors considered in different seismic vulnerability assessment methods

	Vulnerability Assessment Methods	Soft Storey	Heavy Overhang	Short Column	Pounding Possibility	Structure age	Building Height	Uncertainty
1	FEMA 154	N	N	N	N	Y	Y	N
2	FEMA 310	Y	Y	Y	Y	Y	Y	N
3	IITK GSDMA	Y	Y	Y	Y	Y	Y	N
4	Euro Code8	-	-	-	N	Y	Y	Y
5	New Zealand Code	Y	Y	Y	Y	Y	Y	Y
6	NRC Guidelines (NRCC)	Y	N	Y	Y	Y	-	N
7	Modified Turkish Method	Y	Y	Y	Y	Y	Y	N

"N"= Not Considered, "Y"= Considered, "-"= Not Clearly Mentioned

Table 2-2: Comparison of vulnerability scales for different seismic vulnerability assessment techniques

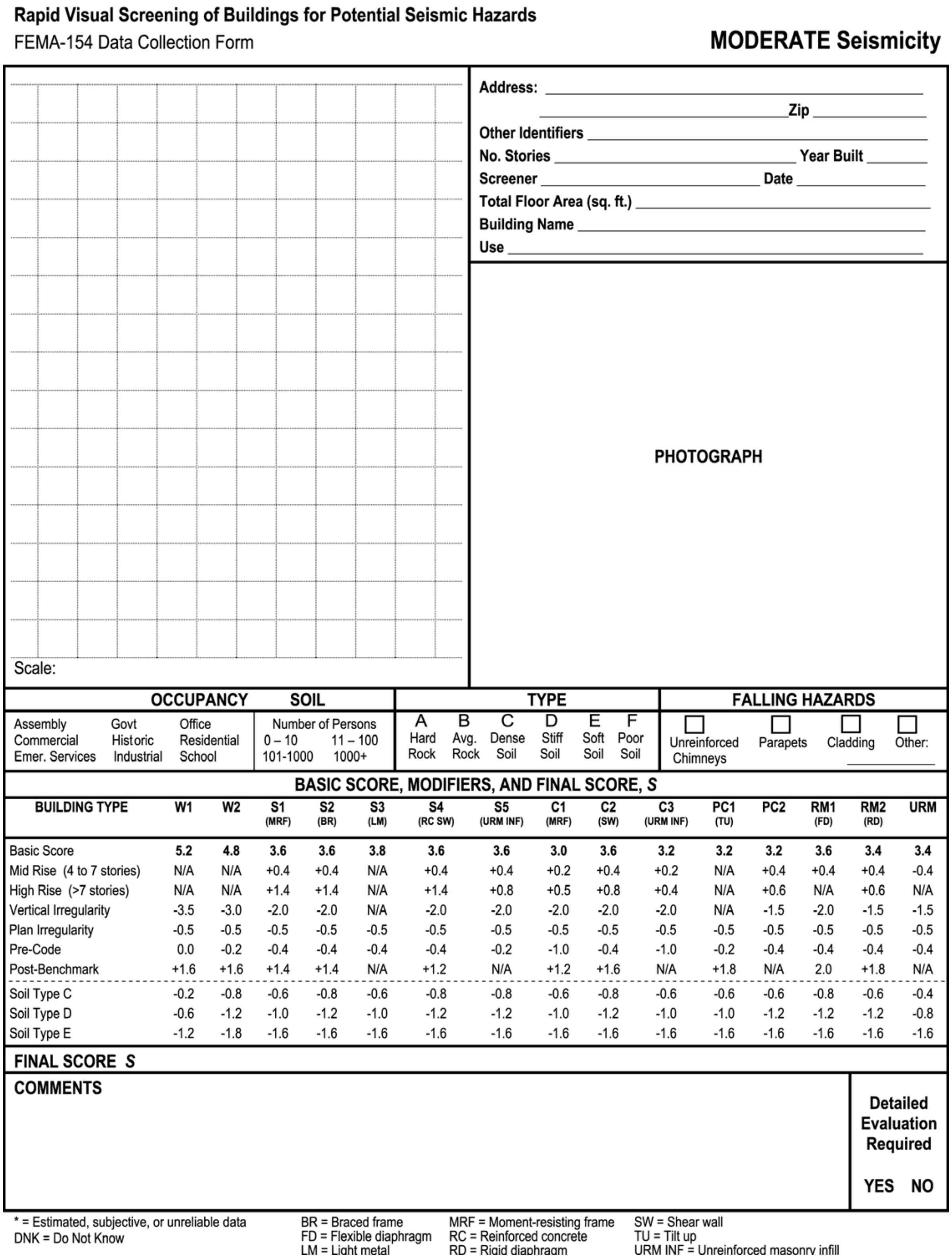
Seismic Vulnerability Assessment Technique	Vulnerability Scales			
New Zealand guideline	Low	Medium	High	
Euro Code 8	Damage Limitation (low)	Significant Damage (Medium)	Near Collapse (High)	
Turkish	Low	Moderate	High	
NRC guideline	Low	Medium	High	
FEMA 154	Low		High	
Hybrid Method (Proposed)	Low	Moderate	High	Very High

2.3.2.1 FEMA 154

To identify and rank the seismically vulnerable buildings, a Rapid Visual Screening (RVS) procedure was developed in FEMA 154 (2002). RVS method has been applied in different projects to estimate the seismic vulnerability of the existing structures (Sadat *et al.* 2010, Srikanth *et al.* 2010, Tesfamariam and Saatcioglu 2010). FEMA 154 is a quick procedure to develop a list of potentially risky buildings, without expensive detailed seismic analysis of individual buildings. A 'sidewalk survey' approach is included in the method which allows the surveyors to classify the buildings into two classes, e.g. buildings with acceptable seismic risk or buildings which may be seismically hazardous. Finally, a cut-off score (S) is developed, based on limited observed and analytical data, and the probability of collapse. For example, a cut-off score, S = 0.2 implies that the probability of collapse of the particular building is 1 in $10^{0.2}$, or 39%. Civil Engineering Research Laboratory (CERL) of the U.S. Army Corps of Engineers has utilized a cut-off score of 2.5, with the particular intent of a more conservative approach (FEMA 2002). A high score (i.e. above the cut-off score) indicates the adequate seismic resistance of a building, whereas if a building receives a low score, it should be assessed in detail by a professional engineer. Details of the FEMA 154 method are provided in Table 2-3. The check list for a moderate seismicity area has been depicted in Figure 2-11.

Table 2-3: Details of FEMA 154

Topic	Description
General Description	Mainly based on a probabilistic approach to vulnerability assessment via rapid visual inspections.
Main Applications	Rapid Visual Screening, 'side walk survey' to short-list the buildings to which simplified vulnerability assessment procedure should be applied.
Sources/ data Set	• ATC 14, Evaluating the Seismic Resistance of Existing Buildings (ATC, 1987), Seismic Evaluation of Existing Buildings (ASCE, 2003). • Studies of the existing U. S. inventory during development of ATC 14, evaluating the Seismic Resistance of Existing Buildings (ATC, 1987).
Main Features	• First-level categorization of a building into a FEMA Model Building Type and a second-level identification of risk characteristics e.g. (age, height, configuration irregularities, and site soil type). • The final result is a numerical score intended to be used to rank buildings by relative risk.
Limitations	Not applicable for detailed assessment of buildings, whereas even the most basic structural characteristics of buildings can seldom be identified without a level of effort approaching evaluation.



Rapid Visual Screening of Buildings for Potential Seismic Hazards
FEMA-154 Data Collection Form

MODERATE Seismicity

Address: ____________________
____________________ **Zip** __________
Other Identifiers ____________________
No. Stories ____________ **Year Built** ________
Screener ____________ **Date** ________
Total Floor Area (sq. ft.) ____________________
Building Name ____________________
Use ____________________

PHOTOGRAPH

Scale:

OCCUPANCY **SOIL** **TYPE** **FALLING HAZARDS**

Assembly Govt Office
Commercial Historic Residential
Emer. Services Industrial School

Number of Persons
0 – 10 11 – 100
101-1000 1000+

A Hard Rock, B Avg. Rock, C Dense Soil, D Stiff Soil, E Soft Soil, F Poor Soil

☐ Unreinforced Chimneys ☐ Parapets ☐ Cladding ☐ Other: ________

BASIC SCORE, MODIFIERS, AND FINAL SCORE, S

BUILDING TYPE	W1	W2	S1 (MRF)	S2 (BR)	S3 (LM)	S4 (RC SW)	S5 (URM INF)	C1 (MRF)	C2 (SW)	C3 (URM INF)	PC1 (TU)	PC2	RM1 (FD)	RM2 (RD)	URM
Basic Score	**5.2**	**4.8**	**3.6**	**3.6**	**3.8**	**3.6**	**3.6**	**3.0**	**3.6**	**3.2**	**3.2**	**3.2**	**3.6**	**3.4**	**3.4**
Mid Rise (4 to 7 stories)	N/A	N/A	+0.4	+0.4	N/A	+0.4	+0.4	+0.2	+0.4	+0.2	N/A	+0.4	+0.4	+0.4	-0.4
High Rise (>7 stories)	N/A	N/A	+1.4	+1.4	N/A	+1.4	+0.8	+0.5	+0.8	+0.4	N/A	+0.6	N/A	+0.6	N/A
Vertical Irregularity	-3.5	-3.0	-2.0	-2.0	N/A	-2.0	-2.0	-2.0	-2.0	-2.0	N/A	-1.5	-2.0	-1.5	-1.5
Plan Irregularity	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5
Pre-Code	0.0	-0.2	-0.4	-0.4	-0.4	-0.4	-0.2	-1.0	-0.4	-1.0	-0.2	-0.4	-0.4	-0.4	-0.4
Post-Benchmark	+1.6	+1.6	+1.4	+1.4	N/A	+1.2	N/A	+1.2	+1.6	N/A	+1.8	N/A	2.0	+1.8	N/A
Soil Type C	-0.2	-0.8	-0.6	-0.8	-0.6	-0.8	-0.8	-0.6	-0.8	-0.6	-0.6	-0.6	-0.8	-0.6	-0.4
Soil Type D	-0.6	-1.2	-1.0	-1.2	-1.0	-1.2	-1.2	-1.0	-1.2	-1.0	-1.0	-1.2	-1.2	-1.2	-0.8
Soil Type E	-1.2	-1.8	-1.6	-1.6	-1.6	-1.6	-1.6	-1.6	-1.6	-1.6	-1.6	-1.6	-1.6	-1.6	-1.6

FINAL SCORE *S*

COMMENTS

Detailed Evaluation Required

YES NO

* = Estimated, subjective, or unreliable data
DNK = Do Not Know
BR = Braced frame
FD = Flexible diaphragm
LM = Light metal
MRF = Moment-resisting frame
RC = Reinforced concrete
RD = Rigid diaphragm
SW = Shear wall
TU = Tilt up
URM INF = Unreinforced masonry infill

Figure 2-11: FEMA 154 score sheet (FEMA 2002)

2.3.2.2 FEMA 310

FEMA 310 (1998) is one of the most advanced seismic evaluation procedures for existing buildings available in the literature (Yakut 2004, Srikanth *et al*. 2010, UNDP/ERRRP 2009). Based on the document, NEHRP Handbook for Seismic Evaluation of Existing Buildings (FEMA 1992), FEMA 310 describes a three-tiered procedure of increasing detail for the seismic evaluation of existing buildings. Overall procedure of FEMA 310 is outlined in Figure 2-12, whereas, the details and limitations of the method are described in Table 2-4.

Structural, non-structural and foundation aspects of a structure are discussed in the Tier 1 screening phase in the form of checklists for the chosen level of performance and given region of seismicity. In case of Tier 2, a complete analysis of the building addressing all of the deficiencies identified in Tier 1 is conducted. A Tier 3 evaluation is performed only if Tier 1 and/or Tier 2 assessments are found to be too conservative and there would be a significant economic or other advantage to a more detailed evaluation. A more generalized approach is provided in FEMA 310 for seismic evaluation, which is thorough and consists of different levels of assessment with varying degree of complexity suitable for different types of structures (wooden, masonry, concrete, etc.). However, a higher degree of understanding on the part of design professionals is required for the higher level assessment.

Table 2-4: Details of FEMA 310

Topic	Description
General Description	Mainly based on a probabilistic approach to vulnerability assessment which is a three-tiered process for seismic evaluation of existing buildings in any region of seismicity.
Main Applications	Buildings are evaluated to either the Life Safety or Immediate Occupancy Performance Level.
Sources/ data Set	• This method is based on the NEHRP Handbook for Seismic Evaluation of Existing Buildings (FEMA 178). • The groups of "building types" defined in ATC-14 are considered in this method.
Main Features	• Three tiered approach with increasing complexity and decreasing conservatism, very thorough and detailed method.
Limitations	Model building codes typically exempt certain classes of buildings from seismic requirements pertaining to new construction. The set of FEMA Model Building Types is not particularly useful for older concrete buildings without a well defined (or designed) lateral system.

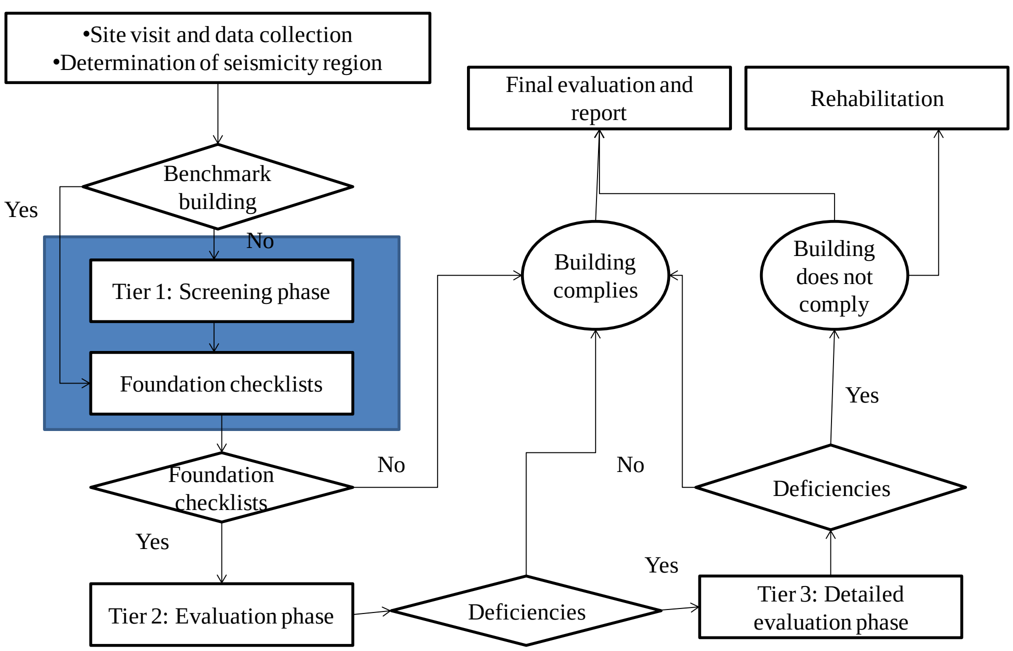


Figure 2-12: FEMA 310 procedure (after FEMA 1998)

2.3.2.3 Euro Code 8

The Euro Code 8 was approved by Comité Européen de Normalization (CEN) as a prospective standard for provisional application (CEN 2004). One of the main aims of this document is to provide criteria for the seismic evaluation of existing structures. The application of the method can be found in the literature (Mihaylov 2006, Lupoi 2003). In Euro Code 8, the assessment process accounts both non-seismic and seismic actions for an existing building, for the period of its intended lifetime. A model uncertainty factor covering the additional uncertainties related to the analysis of the pertinent structure is incorporated. Jalayer *et al.* (2010) utilized this method to validate the influence of structural modeling uncertainties in seismic evaluation of reinforced concrete structures. The detailed procedure of Euro Code 8 is provided in Table 2-5 and Figure 2-13 . After data collection and analysis, the model is verified against uncertainty considering the model uncertainty factor related to the analysis of the pertinent structure (γ_{Sd}), design action-effects under the actual conditions of the structure ($E_{new,d}$), model uncertainty factor used for computing the structural elements' resistance (γ_{Rd}) and the design resistance values of cross-sections of the structural elements ($R_{new,d}$). Finally, structural intervention decisions can be developed from the analysis results

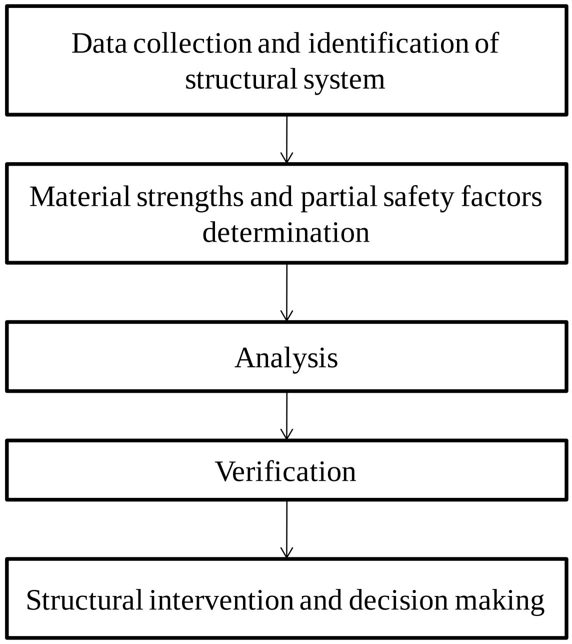


Figure 2-13: Euro Code 8 procedure (after CEN 2004)

Table 2-5: Details of Euro Code 8

Topic	Description
General Description	Sound principles for two tiered assessment.
Main Applications	Evaluation consists of the verification of the seismic resistance of an existing damaged or undamaged building, taking into account both non- seismic and seismic actions for the period of its intended life time.
Sources/ data Set	Euro Code 8 (CEN 2004).
Main Features	• A complete load path should be available, from top to bottom of the structure. • At any storey, the maximum displacement in the direction of the seismic forces should not exceed the average storey displacement by more than 20%. • Mass of the individual storey should remain constant or reduce gradually, without abrupt changes, from the base to the top. • Criteria for regularity in plan and elevation are checked.
Limitations	Lack of specific procedures. No provision for pounding effects.

2.3.2.4 New Zealand guideline

The New Zealand guideline (NZSEE 2000, 2003) describes the key steps and procedures involved in assessing existing buildings of various material types and configurations. Earthquake Risk Reduction and Recovery Preparedness Programme (EERP) of United Nations have utilized this method to assess the seismic vulnerability of existing buildings in Nepal (UNDP/ERRRP 2009, and http://errrp.org.np).

The New Zealand guideline begins with a rapid evaluation procedure based on a visual screening procedure of ATC 21 (1988). The structural score of this assessment is based on fourteen structural criteria which are the indicators of potential building damage. The total structural score has two components: a basic structural score which reflects the standard used for original design and earthquake damage potential of the respective building types and a modification to the basic score on account of unfavourable characteristics present in the building. The detailed structural assessment in the New Zealand guideline is performed at the component level. To account for the uncertainty with regard to the reliability of available information on the configuration and condition of a component, a knowledge factor (K) is introduced (Oliver and Mackenzie 2011). Details of New Zealand guideline are described in Table 2-6, and the overall procedure is outlined in Figure 2-14.

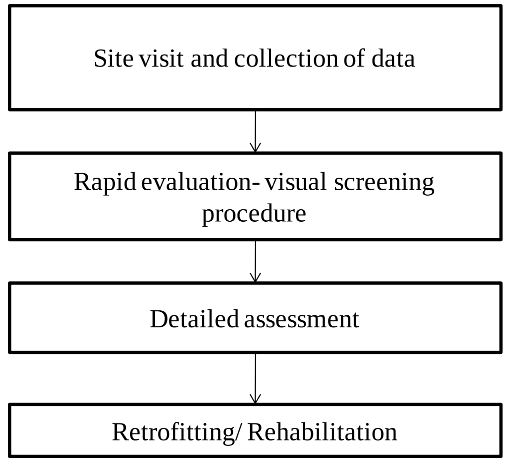


Figure 2-14: New Zealand guidelines procedure (after NZSEE 2000)

Table 2-6: Details of New Zealand guideline

Topic	Description
General Description	Based on basic principles, detailed analysis is available.
Main Applications	The basic aim of this guideline is to provide a set of procedures that are helpful to Territorial Authorities, consultants and building owners, and that can be applied consistently to assess the earthquake performance of a building.
Sources/ data Set	The Building Act 2004 (NZSEE 2003).
Main Features	• Full details of the Initial Evaluation Procedures. • Assessment procedures for reinforced concrete, steel, timber and unreinforced masonry buildings. • Outcome of the assessment described as green (apparently ok), yellow and red (risky) buildings. • Displacement-based approach. • Strengthening and retrofitting incorporated.
Limitations	No provision for effective mass of the structure.

2.3.2.5 Modified Turkish method

In the Modified Turkish method a multiple level seismic vulnerability assessment for the existing reinforced concrete (RC) buildings is provided (Bommer *et al.* 2002). The method is successfully applied in various studies worldwide (Kaplan *et al.* 2008, Sadat *et al.* 2010, Otani 2000). The Modified Turkish vulnerability assessment method can be classified in three main groups depending on their level of complexity. The first one is a walk down evaluation, which does not require any analysis and determines the priority levels of buildings that require immediate intervention. Preliminary assessment methodologies (PAM) are utilized if more in-depth evaluation is required. Data on the dimensions of the structural and non-structural elements in the most critical story are required for this level of assessment. Whereas, the third level assessment applies linear or nonlinear analyses of the selected structures, which requires the as-built dimensions and the reinforcement details of all structural elements.

2.3.2.6 IITK-GSDMA method

IITK-GSDMA method has been developed to assess the seismic vulnerability of different types of buildings within the Indian Sub-Continent region (Durgesh 2005). The guideline is generated based on many years of practice of seismic evaluation of existing buildings in different seismically risky countries of the world. Various documents, such as FEMA 310 (1998), FEMA 356 (2000), New Zealand Code (NZSEE 2000, 2003) and Euro Code (CEN 2004) were reviewed to develop the guideline. Application of the method is found in various literatures in Indian Sub-Continent region (Alam *et al.* 2010, Kumar and Venkatesh 2010). Particular classes of buildings, e.g. unreinforced masonry (URM) and non-ductile reinforced concrete (RC) frame buildings are given special consideration for the assessment within this method.

2.3.2.7 NRC guidelines

National Research Council of Canada (NRCC) proposed a building vulnerability assessment technique termed as NRC guidelines (NRCC 1993) based on the ATC-21 (ATC 1988). The method is utilized in various studies found in literature (Srikanth *et al.* 2010, Potty and Sirajuddin 2011). The method consists of both structural and non-structural hazards and the importance of the building is determined from the use and occupancy classes. The methods was generated from the preliminary version of NEHRP Handbook for Seismic Evaluation of Existing Buildings (FEMA 1992), which is adapted to be compatible with Canadian building construction practice and the requirements of National building code of Canada (NBCC 1990). An overall procedure of the method is depicted in Figure 2-15. Both structural (SI) and non-structural (NSI) indices are evaluated in this method.. The NRC manual suggests that the buildings should be prioritized according to a seismic priority index (SPI), which is the summation of both SI and NSI. A building with SPI value less than 10 indicates low vulnerable building, from 10 to 20 indicates medium, and over 20 indicates highly vulnerable building. A building with SPI score more than 30 is considered as a potentially hazardous building. The details of NRC method are described in Table 2-7.

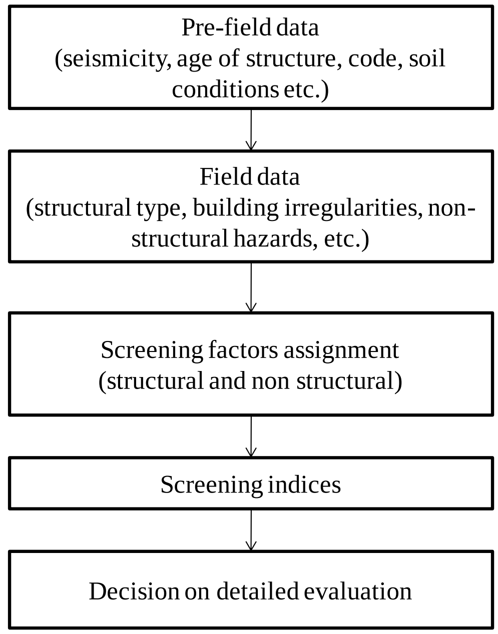


Figure 2-15: Flow chart of NRC seismic screening method (after NRCC 1993)

Table 2-7: Details of NRC seismic screening method

Topic	Description
General Description	Mainly based on a probabilistic approach to vulnerability assessment via rapid visual inspections.
Main Applications	To short-list the buildings to which simplified vulnerability assessment procedure should be applied.
Sources/ data Set	• FEMA 154 (FEMA 2002).
Main Features	• First-level categorization of a building into a FEMA Model Building Type and a second-level identification of risk characteristics e.g. (age, height, configuration irregularities, and site soil type) are included. • Both structural as well as non structural indices are being evaluated.
Limitations	Not applicable for detailed assessment of buildings.

2.4 SEISMIC DAMAGE ESTIMATION METHODOLOGIES

For decision making and emergency management purposes, seismic risk can be defined in terms of potential economic, social and environmental losses from a particular earthquake event (Carreño *et al.* 2011).

For regional seismic risk estimation, a multi-disciplinary evaluation is required to assess the potential physical damages and the number and type of causalities for a particular seismic event (Cardona and Hurtado 2000). Several seismic loss estimation methods are developed from different perspectives during the last decades under the umbrella of United Nations Disaster Relief Organization (UNDRO 1980). In the civil engineering point of view, physical damage estimation is given the most emphasis (Carreño *et al*. 2011). ATC-13 of Applied Technology Council is one of the first major projects regarding the assessment of the seismic risk in terms of damage probability matrices proposed by Whitman *et al*. (1973) based on which numerous approaches and methodologies are developed all over the world.

Different seismic risk assessment tools that integrate information from existing building inventory and site seismicity are found in the literature (www.itc.nl). A basic subdivision of the tools can be made between the commercial and non-commercial ones within the established seismic risk quantification methods. Commercial catastrophe modeling techniques developed for seismic damage estimation include the REDARS (risks from earthquake damage to roadway systems) (http://www.dot.ca.gov), EQEHAZARD (EQECAT), EPEDAT (early post-earthquake damage assessment tool, Image Cat, www.itc.nl), etc. which are developed by different insurance and government organizations. The non-commercial loss estimation models are freely available software for which the manuals and software can be downloaded from the internet. The natural hazards electronic map and assessment tools information system (NHEMATIS) is developed by Emergency Preparedness Canada to "provide emergency planners with a tool that supports the definition and execution of elaborate models which will assist in predicting/estimating the potential impact of a natural hazard/disaster in a defined area of interest." (Brun *et al.* 1997). MAEviz, developed by a joint effort between the MAE Center and the National Center for Supercomputing Applications (NCSA) is one of the modern platform independent open source seismic risk assessment software (http://cet.ncsa.uiuc.edu). It can be utilized for pre-disaster planning, mitigation as well as for rapid response assessment after a disaster. However, the complexity of using this software may require skilled technical persons, which may lead to a certain amount of cost. The HAZUS (Hazard US) software is an interactive software released by the Federal Emergency Management Agency (FEMA 2004) and National Institute for Building Sciences (NIBS). HAZUS-MH (Hazard US-Multi hazard) is developed in an ARCGIS platform, where full datasets on a micro level can be obtained for the entire United States (Kircher *et al.* 2006). However, it is difficult to apply the HAZUS methodology in other parts of the world, due to the complexity and large quantity of the input data required. The comparison of some of the well established non-commercial seismic loss estimation processes are summarized in Table 2-8.

Table 2-8: Comparison of various non-commercial seismic loss estimation methodologies (after www.nset.org.np/)

Methodologies	Stakeholders Involvement: Professionals	Stakeholders Involvement: Authorities	Stakeholders Involvement: Community	Motivation to Community	Accuracy	Resource Required	Possibility of use in developing countries
RADIUS	M	H	M	H	M	L	YES
GIS GRID	H	L	L	L	M-H	H	YES
SLARIM	H	M	L	L	H	H	YES
COMMUNITY WATCHING	L	M	H	H	L	L	YES
HAZUS	H	L	L	L	H	H	YES

H: High, M: Medium, L: Low, S: Simple, C: Complex

The recent development of GIS technology have introduced the GIS as a media concept (Sui and Goodchild 2001), which replaced the traditional use of GIS as only the database-mapping spatial analytical tool. This new advancement emphasizes more on the communication of the geographical information to a larger community. Seismic hazard and risk investigations have become more and more complex in terms of handling a large amount of spatial data with subsequent analysis. Geographical Information Systems (GIS) technology could be a suitable tool to cope with these complexities (Pessina *et al*. 2009).

The International Institute for Geo information Science and Earth Observation (ITC) launched a research project with the acronym SLARIM, which stand for Strengthening Local Authorities in Risk Management in 2002.

The main goal of the project was to develop generic methodologies for GIS-based risk assessment and decision support that can be beneficial for local authorities in medium-sized cities in developing countries (www.itc.nl). However, it needs high levels of professional involvement as well as better accuracy in database and resources. Community watching can also useful, however, the level of accuracy is not good enough to make the decisions (www.nset.org.np). The 1990's was declared by the United Nations (UN, 1987) as the International Decade for Natural Disaster Reduction (IDNDR). RADIUS (Risk Assessment Tools for Diagnosis of Urban Areas against Seismic Disasters) project (GHI, 2004) is one of the major initiated projects within this period. Although, the level of accuracy in RADIUS is not sufficient for designing any structures, it is good enough for decision making, considering the financial and temporal aspects. The integration of GIS (Geographical Information System) with RADIUS can enhance the accuracy of the results.

The methodology described by GIS-based RADIUS, GBR (UNISDR 1999) guideline possesses the main objectives of raising awareness in the community of the seismic risk and the actions that could be taken to manage it, and of incorporating all the stakeholders of the community in the risk management process. The utilization of RADIUS and GIS in seismic loss estimation is found in literature separately, which is shown in Table 2-9. A few reported application of RADIUS in North American cities have been found in the literature. The current case study for the City of Kelowna would be the one of the first initiatives for North American cities.

Table 2-9: Recent seismic damage estimation studies

Authors	Comments
GeoHazards International 1994.	GeoHazards International has applied the RADIUS methodology to actual risk management projects implemented in cities like Quito, the capital of Ecuador.
NSET 2001; UNDP 1994; AUDMP 2003, 2007 (www.adpc.net); UNDP 1994;	NSET, Nepal has applied the RADIUS methodology to actual risk management projects implemented in Kathmandu, the capital of Nepal.
Okazaki 2000, 2003.	The authors presented the case studies of 58 cities around the world (27 cities in Asia, 12 cities in Europe and Africa and 19 cities in Latin America) with utilization of the RADIUS tool.
Codermatz *et al.* 2003.	GIS can effectively be utilized to assess the seismic risk of a particular zone. The authors applied the GIS technology to infrastructure in the Friuli-Venezia Giulia region of North East Italy. A GIS-based HAZUS methodology was applied to the tunnels and bridges of a highway network to generate the probable seismic risk of the infrastructure. The study depicted the strength of GIS technology in categorization, detailing, and mapping spatial data for a specific zone.
Anagnostopoulos *et al.* 2008.	The authors developed geographic information systems (GIS) scenario-based system software called SEISMOCARE to estimate the regional damage for a particular seismic event. It provides an avant-garde approach for seismic risk management in terms of hazard identification, vulnerability assessment and risk assessment in spatial manner.
Barbat *et al.* 2010.	The authors argued that GIS can be used to show the risk spatially for scenarios of the probable hazards for a particular zone. A case study of a pilot urban area, the city of Barcelona, Spain has been presented to investigate and compare the most relevant seismic vulnerability and risk analysis methods of different research projects. In this study, GIS has been utilized to describe the spatial distributions of expected damages from a probable earthquake.

2.5 WILDFIRE RISK ASSESSMENT TECHNIQUES

Wildfires are one of the major hazards in the British Columbia region, Canada where, on average, seventy five thousand hectares of agricultural areas are burned every year (http://bcwildfire.ca). Wildfire risk assessment is, therefore, at the heart of disaster prevention policies in the region. The term wildfire risk refers to the hazard posed by the forest fire, expressing both the probability of initiation of fire as well as the existing vulnerabilities of the community. For a proper emergency plan of a community, a regional wildfire risk assessment framework is imperative. Food and Agriculture Organization (FAO) and United Nations International Strategy for Disaster Reduction (UNISDR) defined wildfire risk management as the activities necessary for the protection of existing forests to meet the defined objectives of the authorities (UNISDR 2011, FAO 1999a). European Forest Institute (EFI) describes that an appropriate wildfire risk management requires the location, period and causes of fire initiation (Bajocco *et al.* 2009) as well as the existing vulnerabilities of the community. European forest institute (EFI 2010) proposed an integrated fire management framework (Figure 2-16) to manage the fire effectively. The framework suggests the full combination of fire use in the prevention and suppression strategies which encourages the positive use of fire by prescribed burning. Hence, the framework suggests the necessity of wildfire risk assessment for a risk-based contingency plan.

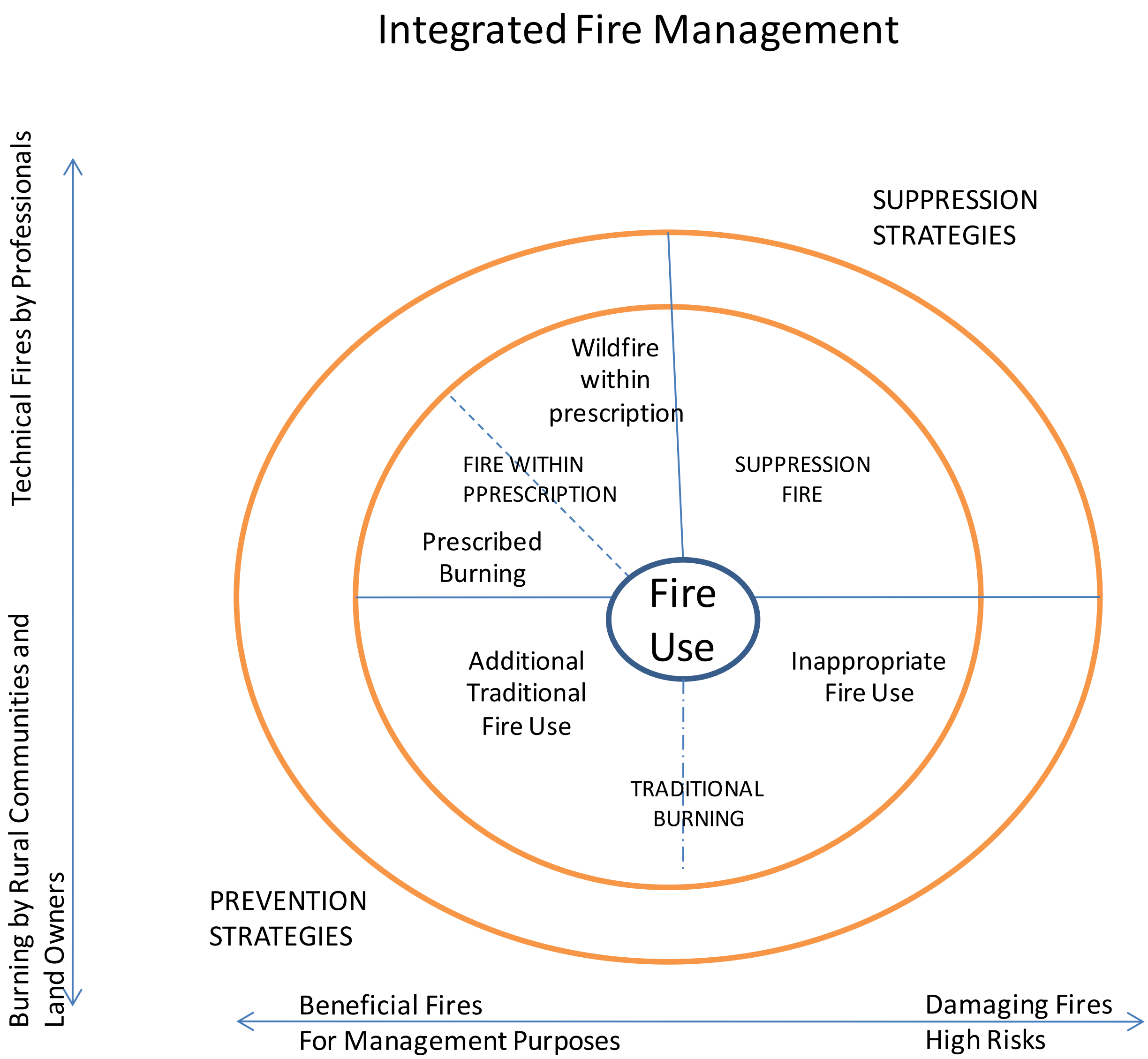


Figure 2-16: Central role of fire use in integrated fire management, from a fire use perspective (after EFI 2010)

2.5.1 Wildfire initiation risk

Wildfire initiation risk is defined differently in different literatures. FAO (1986) defines fire initiation risk as the fire danger index, which is an essential parameter to assess the wildfire risk within a community. The definition of fire danger can also be obtained from the glossary of wildland fire terminology of National Wildfire Coordinating Group (NWCG 2006).

Nitschke and Innes (2008) described the wildfire initiation potential mainly based on climate factors. Burnett (2005) described the possible effects of climatic factors on wildfire risk, which leads to the decision of prioritization of wildfire risk assessment in emergency planning. Vasconcelos *et al.* (2001) developed a meteorological data based wildfire ignition risk scheme, which considers the geo-spatial fire risk of the study area of Lesvos Island, Greece. An AHP-based fire ignition index (FII) is developed, considering the weather conditions, hazard conditions as well as the risk condition within the region.

EFI (2010) described a wildfire initiation which is related to human activities, fuel flammability as well as the fire policies and practices within the fire regions. The institute also described the wildfire propagation methodology which includes the human activities. Figure 2-17 shows the various causes of wildfire initiations in European region (http://www.efi.int/). From the figure, it is evident that, human related factors have become one of the main factors of wildfire initiation during the last decades in Europe.

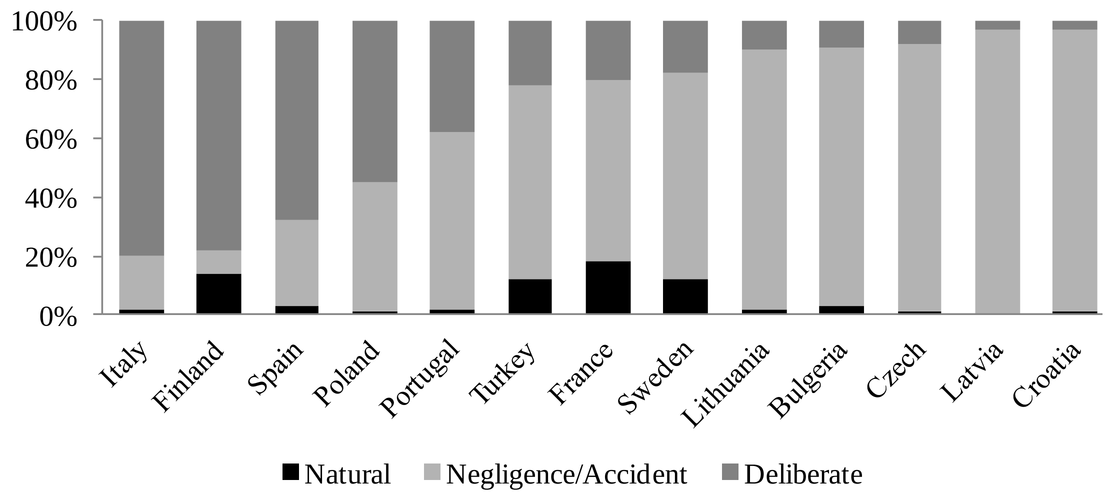


Figure 2-17: Major causes of wildfires in Europe. Data extracted from the fire database of the European forest fire information system (EFFIS) during the period of 1998–2007 (after EFI 2010)

Wildfire initiation differs in different ecosystems and demographics (Yang *et al.* 2007, Catry *et al.* 2009) which are shown in Figure 2-18. The human related factors for wildfire initiation are discussed in other literatures (Lloret *et al.* 2002, Turner and Romme 1994).

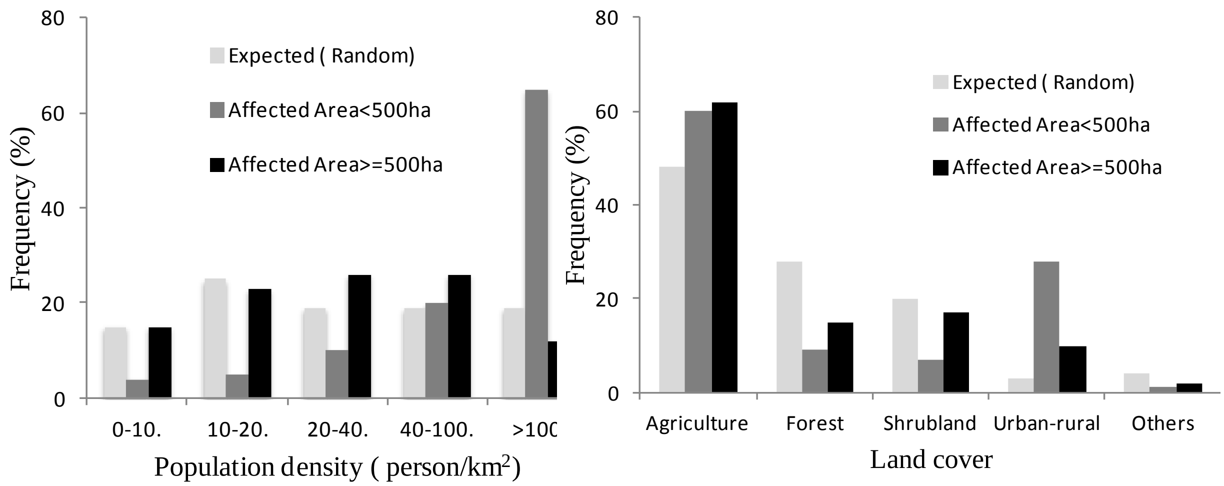


Figure 2-18: Comparison between fire ignitions with population density and land cover in European context (after Catry et al. 2008)

Human factors are also found to be a major factor in fire initiation in North American urban areas (http://bcwildfire.ca). Each year about $110 million losses of property and resources occur within the British Columbia. From the history, it is found that, on an average, 1800 fires occur within the region, 44% of which are caused by human factors, and the rest are caused by the climatic factors. Figure 2-19 shows the major causes of fire initiations within the region.

More importantly, the existing fire policies and practices are the major causes of the fire initiation (FAO 1999b), that might necessitates the risk assessment tools. The occurrence of a wildfire also depends on some other factors. For example, Bajocco *et al.* (2009) assessed the seasonality of wildfires in Italy, which is mostly during summer times. Whereas, Trigo *et al.* (2006) proposed to consider the climate factors and vegetation types more importantly in case of large fires.

Chou and Minnich (1993) considered the spatial neighbourhood effects, in addition to climatic and human factors in wildfire risk assessment, which can be useful to develop a proper risk map.

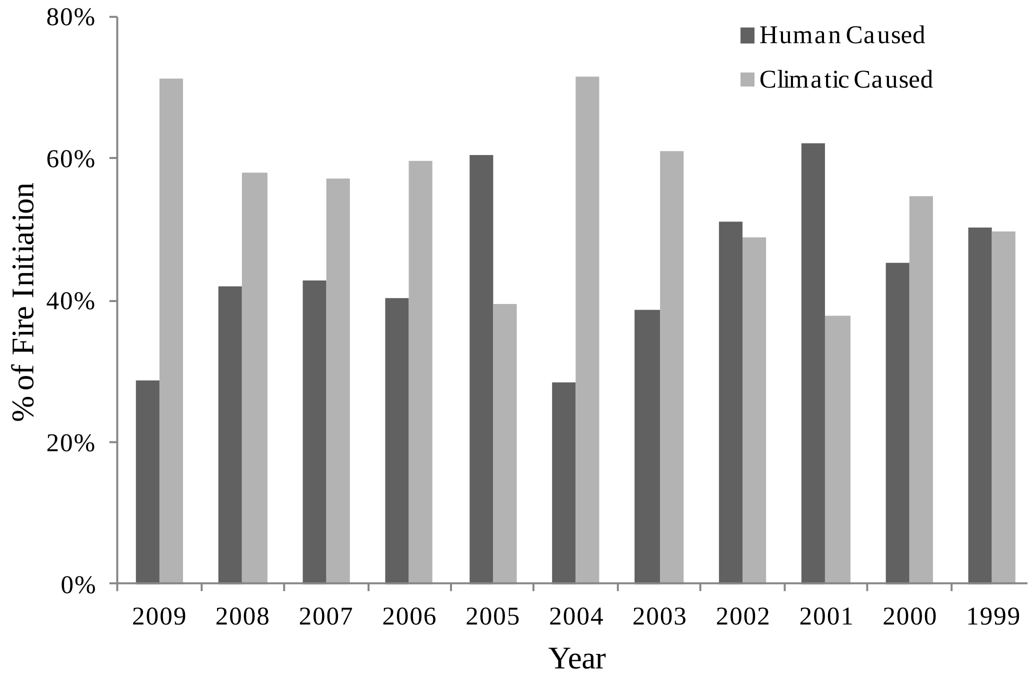


Figure 2-19: Fire initiation causes in British Columbia, Canada (after http://bcwildfire.ca)

2.5.2 Wildfire vulnerability and risk modeling

EFI (2010) proposed fire modeling as a suitable tool to reduce the amount of observations necessary for understanding and predicting fire behaviour. The authors argued that a number of empirical models are available currently in Australia, Canada, and the United States. The authors also argued that, a GIS-based model can automatically calculate the fire risk under different terrain, fuel and weather conditions. In case of vulnerability assessment, there exists number of different concepts in literature (Gallopin 2006). Blanchi *et al.* (2002) described a fire risk assessment with a cartography approach, which includes the spatial distribution of the input variables as well as output risks.

The author also defined the vulnerability in terms of a set of vulnerable factors which are normally shown as a percentage loss for a particular hazard severity level. This percentage can be converted in measurable indices with knowledge-based or historical approaches (Coburn *et al.* 1994).

Currently, a number of methodologies exist throughout the world for assessing the wildfire risk of region. Chen *et al.* (2007) developed an improved fire susceptibility index based on the current probability index, which considered the live fuel as well as the dead fuel using the remotely sensed database. The authors argued that, the proposed index is better in high fire risk ranges compared to the existing indices. Gabban *et al*. (2008) proposed two indices i.e., fire weather index (FWI) and the normalized difference vegetation index (NDVI). The assessment considered all the area regardless of the past history of fire occurrence. After conducting qualitative and quantitative assessments, the authors concluded that, the FWI has more enhanced performance over NDVI in identifying risky areas. The qualitative risk assessment is normally conducted with the expert opinions. In case of Mt Roland Wildfire Risk Assessment (http://www.ses.tas.gov.au), a qualitative risk matrix is formed to assess the level of risk in linguistic term (e.g. low, moderate, high etc.). Gonzales *et al.* (2003) describes another method of qualitative risk assessment for the Los Alamos National Laboratory in New Mexico considering the probability of occurrences. In case of fire risk modeling, Galiana *et al.* (2011) developed a GIS and remote sensing-based regional wildfire risk assessment technique in Mediterranean areas. Unlike the traditional local scale approach, the methodology proposed as a progressive multi-scale approach, based on landscape analysis. Manzo *et al.* (2009) constructed a logistic model of wildfire risk assessment incorporating both the static and the dynamic predictive variables.

The normalized difference vegetation index (NDVI), land surface temperature (LST), and cloud cover is incorporated from National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) images (www.class.ngdc.noaa.gov). The system described that, the February LST, the January NDVI, vegetation type and slope had the greatest influence on the distribution of forest fires, however, elevation and precipitation were also considered in the final model. Peng *et al.* (2007) proposed a new fire susceptibility index (FSI) based on the physical concept of heat energy pre-ignition. The authors found that, the FSI increases as the day approaches to the fire day, hence, it can be a useful tool to estimate the fire risk. A web-based interactive fire detection mapping system for dynamic wildfire risk assessment has been presented by the USDA forest service (http://activefiremaps.fs.fed.us). Elvidge *et al.* (1998) show a tool for wildfire detection with Meteorological Satellite Data in remote sensing methodology. The authors utilized OES, AVHRR, and DMSP-OLS (http://www.ssd.noaa.gov) for a case study Mexico in 1996, which can be a proper tool for dynamic response for wildfire. Fire Identification, Mapping and Monitoring Algorithm (FIMMA) (Giglio *et al.* 1999) is an automated program developed by NOAA satellite information services to detect fires from advanced very high resolution radiometer (AVHRR) data from the polar-orbiting satellites (http://www.ssd.noaa.gov). In Colorado, a space imaging fire fighting tool, namely wildland fire risk assessment system (WFRAS) is developed to combat forest fire (Smith 2004). Although the tool is based on a modern technique, it lacks the integration of local resources for fire fighting. Justice *et al.* (2002) and Kaufman *et al.* (1998) utilized the Moderate Resolution Imaging Spectroradiometer (MODIS) to generate information about actively burning fires, along with the location and timing, immediate flammability, and presented in both spatial and temporal scales, but the process consumes a lot of resources.

Geographical information system can also be utilized to present the spatially distributed wildfire risk. Natural Resources Canada developed information systems using geographic information systems and remote sensing to interactively monitor and report on forest fire activity at a national scale (http://fire.cfs.nrcan.gc.ca) which is shown in Figure 2-20. Natural Resources Canada (http://cwfis.cfs.nrcan.gc.ca) also provides the interactive fire weather index, initiation indices, considering the natural factors. This system provides only the risk in macro scale, i.e. in city level, but it cannot provide the risk in more micro levels.

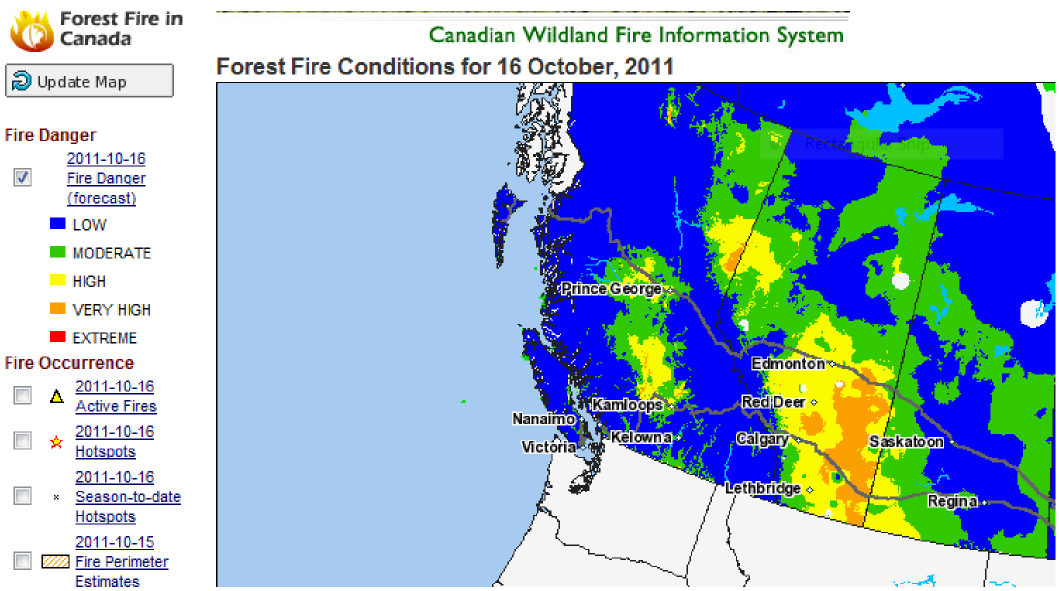


Figure 2-20: Forest fire map (http://fire.cfs.nrcan.gc.ca)

Geographical information system (GIS) can be a suitable tool, for assessing the spatially distributed risks (www.esri.com). Sun *et al.* (2007) provides a GIS-based approach for comparative analysis of potential fire risk assessment. Yin *et al.* (2005) also utilized GIS for assessing wildfire risk considering the parameters of vegetation types, altitude, slope, aspect, and settlement buffer. Zhu *et al.* (2008) utilized GIS to predict the forest fire initiation, which can also be used to estimate the regional wildfire risk. Calkin *et al.* (2011) describes primary contents of wildland fire decision support system (WFDSS) of US Forest Service, consisting of fire spread probability (fire behaviour) and rapid assessment of values at risk (resource assessment), which can be an effective tool for decision making. Lopez *et al.* (2002) presented an integrated model for wildfire risk assessment at the European scale, which combines three data sources, i.e. meteorological data, remotely sensed data and fuel maps. A fire potential index (FPI) is derived, which can be a suitable tool for identifying fire initiation probability in any area. Florida Forest Services provided a Florida wildfire risk assessment score sheet, which includes the fire fighting capability of a community very effectively (http://www.fl-dof.com and Division of Forestry 2010). However, the fire danger rating (FDR) developed by the New South Wales Government, Australia, is an early indicator of potential danger which is determined by the fire danger index (FDI). The combination of air temperature, relative humidity, wind speed and drought calculates the FDI (http://www.rfs.nsw.gov.au). Input parameters for existing fire danger and vulnerability indices have been listed in Appendix C.

Although, different methodologies exist in wildfire risk assessment, they are not always useful in terms of complexity and cost incurred. Moreover, most of them are developed to assess only the fire initiation potential, or the fire fighting potential. The lack of the presence of parameter related to human intervention for fire initiation is noted in most of the utilized methods. Application of GIS modeling with the integration of both fire initiation probability as well as the fire fighting potentials is selected as a major research need in developing a quick and reliable wildfire risk assessment tool.

Chapter 3: A COMPARATIVE STUDY ON BUILDING VULNERABILITY ASSESSMENT METHODS FOR SEISMIC RISK EVALUATION

3.1 GENERAL

Hill and Rossetto (2008) presented a comparison between different damage scales and damage definitions in different seismic loss estimation models. This chapter extends their method to compare various regional seismic vulnerability assessment techniques for buildings.

In this chapter, a comparison of existing seismic vulnerability assessment techniques for buildings is carried out to evaluate their suitability for use in seismic risk assessment. The methods considered are: 'Hybrid' vulnerability assessment method, FEMA 154 (Rapid Visual Screening), Euro Code 8, New Zealand guideline, Modified Turkish method and NRC guidelines. A scoring system is proposed to select the suitable vulnerability assessment technique to be utilized for Kelowna city, Canada. The ranking considers general description of vulnerability, building response factors, variance in output, applicability and ease of use, which are identified as the key characteristics required for vulnerability scales used in seismic risk evaluation. A sensitivity analysis has been carried out for the different methods with regard to different weighting criteria. Several multi-criteria decision making tools including AHP and TOPSIS have also been utilized to find-out the suitable alternatives for seismic vulnerability assessment of buildings. It was observed that the 'Hybrid' (which includes the local site specific issues as well as the results from non destructive testing and experimental data) method adequately satisfies all the criteria necessary for their use in seismic risk assessment. Furthermore, to highlight the utility of the different vulnerability assessment methods, a case study for 20,000 buildings in the Kelowna city has been conducted considering the shear waves and the associated damages for an earthquake provided in the code (NBCC 2005). Vulnerability maps of the study area using different methods have been integrated into a GIS (geographical information system) framework for visualization. Modified Turkish Method is not considered in the case study, as it is only applicable to the reinforced concrete (RC) structures.

3.2 PROPOSED SCORING SYSTEM TO RANK DIFFERENT VULNERABILITY ASSESSMENT METHODOLOGIES

The term seismic vulnerability is defined as the susceptibility of a population of buildings to undergo damage due to seismic ground motion (Hill and Rossetto 2008; FEMA 1999). Existing vulnerability assessment methods vary with different assumptions, e.g. quantification of seismic hazard, building vulnerability assessment, and building type (Bertogg *et al.* 2002). The region-wide seismic vulnerability assessment framework is an essential tool for governments and decision makers to optimally allocate resources and mitigate consequences of earthquakes (Tesfamariam and Saatcioglu 2008).

Three different criteria (general description, physical vulnerable parameters and description of output) have been considered to rank different vulnerability assessment methods. A performance scoring system is developed following Hill and Rossetto (2008) to rank the vulnerability assessment methodologies according to these criteria. The scoring system is shown in Table 3-1, which consists of 3 main criteria with 17 sub-criteria. The system aims to eliminate most of the subjectivity involved in the ranking of different scales. Since some subjectivity remains in respect to assigning categories, scoring results are only used as a qualitative indication of performance or reliability.

To provide a clear indication of each methodology's performance or reliability, an affirmative statement (where 3 or more observations are available) is given as 3 points, a moderate statement (2 observations are available) is given as 2, an unsatisfactory statement as zero point, whereas the method partially fulfills the requirement (only one observation is available) is given 1 point. For the sub-criteria, considering quantity of data, the scoring is based on the Table 3-2. The total score of criteria is calculated by summing up the scores assigned to the respective sub-criteria. To select the suitable alternative for seismic vulnerability assessment technique, the hierarchy of the proposed multi-criteria problem is depicted in Figure 3-1.

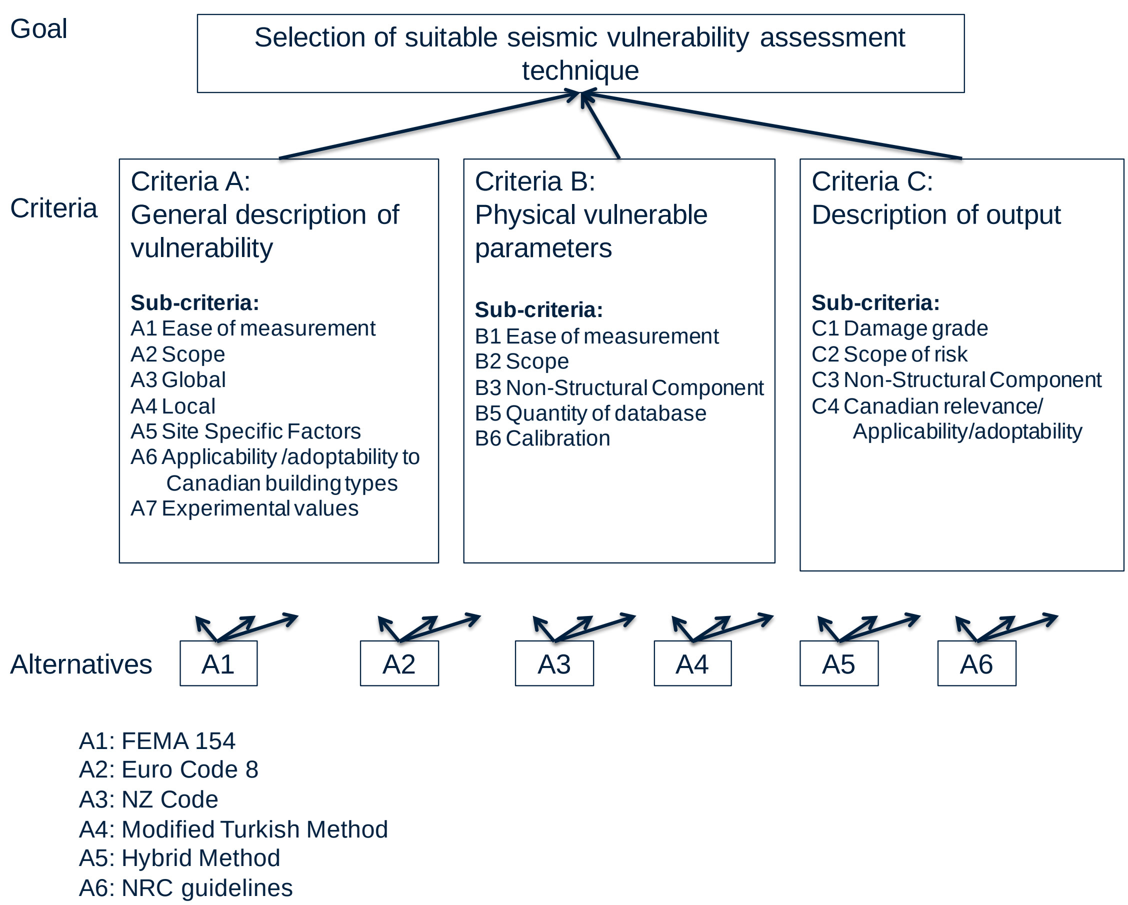


Figure 3-1: Hierarchy of the proposed problem

Table 3-1: Important characteristics of seismic vulnerability assessment methods (after Hill and Rossetto 2008)

Criteria A: General Description of Vulnerability	Definition
A1 Ease of measurement	Clearly distinguishable states and easily applicable to buildings.
A2 Scope	Wide range of building types.
A3 Global	Global vulnerability component.
A4 Local	Local vulnerability components.
A5 Site Specific Factors	Site specific factors.
A6 Applicability /adoptability to Canadian building types	Relevancy to Canadian building types.
A7 Experimental values	Consideration of experimental values from laboratory testing and NDT.
Criteria B:Physical Vulnerable Parameters	
B1 Ease of measurement	Can the parameter be straightforwardly measured from analytical results or from populations of buildings?
B2 Scope	Wide range of variability in parameters.
B3 Non-Structural Component	Non-Structural vulnerable parameters.
B4 Canadian relevance/ Applicability /adoptability to different building types	How relevant are the descriptions of the parameters to different building types
B5 Quantity of database	Sources and quantity of data.
B6 Calibration	Experimental/ analytical/ judgment.
Criteria C: Description of Output	Definition
C1 Damage grade	Defined damage grade.
C2 Scope of risk	Wide range of risk variances.
C3 Non-Structural Component	Impact of non-structural vulnerable parameters.
C4 Canadian relevance/ Applicability /adoptability	Relevancy to Canadian situation.

Table 3-2: Definition of 'significant', 'moderate', 'minimum' or 'unsatisfactory' in quantifying categories (after Hill and Rossetto 2008)

Condition	Definition	Score
Unsatisfactory	Not minimum or unspecified	0
Minimum	If the guideline meets the minimum requirement for the criteria	1
Moderate	2 observations are available for any criteria	2
Significant	3 or more observations available for any criteria	3

Criteria A of the scoring system deals with the basic input description of vulnerability assessment tools, i.e. ease of measurement, range of building types covered, site specific factors, including local and global aspects. This is important for the people working in the field. In criteria B, mostly physical measurable vulnerability factors have been considered, which is very useful for analyzing the structural behaviour. It deals with the scope of vulnerable parameters, quantity of database, applicability of tools as well as non-structural components of the structures. However, criteria C of the proposed scoring system deals with the association of the output factors, which encompasses the well defined damage grades, risk variances, impact of non-structural components as well as the applicability to Canadian context.

Table 3-3 summarizes individual scores for the six vulnerability assessment methods and different performance criteria A (Table 3-3a), B (Table 3-3b) and C (Table 3-3c). Table 3-3a shows the individual scores for various vulnerability assessment methods for criteria A. Here the proposed Hybrid method, NRC Guidelines and FEMA 154 show higher scores than the other methods. In Table 3-3b, individual scores have been calculated for criteria B. Here, the Hybrid method, NRC Guidelines, FEMA 154 and NZ Code score higher, whereas the modified Turkish method and the Euro Code 8 have lower scores. The individual scores for the criteria C have been presented in Table 3-3c. Due to the presence of Canadian preference, the NRC Guidelines scored as the highest. The proposed Hybrid method also scored higher due to the versatile character in the input variables.

Table 3-3a: Individual scores for various vulnerability assessment methods for different proposed criteria (for criteria A)

Sub-criteria	FEMA 154	Euro Code	NZ Code	Modified Turkish	Hybrid	NRCC Guidelines
	Points (Y/extent/N)=(3/1/0)					
	Criteria A: General Description of Vulnerability					
A1 Ease of measurement	3	1	1	1	3	2
A2 Scope	3	3	3	0	3	3
A3 Global	1	3	3	1	3	1
A4 Local	3	1	3	1	3	3
A5 Site Specific Factors	3	1	1	1	3	3
A6 Applicability /adoptability to Canadian building types	3	1	2	0	3	3
A7 Experimental values	0	0	0	0	3	2
Sum	16	10	13	4	21	17

Table 3-3b: Individual scores for various vulnerability assessment methods for different proposed criteria (for criteria B)

Sub-criteria	FEMA 154	Euro Code	NZ Code	Modified Turkish	Hybrid	NRCC Guidelines
	Points (Y/extent/N)=(3/1/0)					
	Criteria B : Physical Vulnerable Parameters					
B1 Ease of measurement	2	0	0	0	0	2
B2 Scope	1	1	1	1	3	2
B3 Non-Structural Component	0	1	1	0	3	3
B4 Canadian relevance/ Applicability /adoptability to different building types	2	1	1	0	3	3
B5 Quantity of database	1	3	3	3	3	3
B6 Calibration	1	1	1	1	3	2
Sum	7	7	7	5	15	15

Table 3-3c: Individual scores for various vulnerability assessment methods for different proposed criteria (for criteria C)

Sub-criteria	FEMA 154	Euro Code	NZ Code	Modified Turkish	Hybrid	NRCC Guidelines
	Points (Y/extent/N)=(3/1/0)					
	Criteria C: Description of Output					
C1 Damage grade	3	1	1	3	3	1
C2 Scope of risk	1	1	3	1	3	2
C3 Non-Structural Component	1	1	1	0	3	3
C4 Canadian relevance/ Applicability /adoptability	3	0	2	0	1	3
Sum	8	3	7	4	10	9

3.3 MULTI CRITERIA DECISION ANALYSIS FOR SELECTION OF SUITABLE SEISMIC VULNERABILITY ASSESSMENT TOOL

Two Multi criteria decision making (MCDM) tools, TOPSIS (Technique for Order preference by Similarity to Ideal Situation) and AHP (Analytical Hierarchy Process), are utilized to rank the suitable approach among the selected vulnerability assessment tools i.e. FEMA 154, Euro Code 8, New Zealand guideline, Modified Turkish Method, Hybrid Method and finally NRC guidelines. The AHP is a decision-aiding method developed by Saaty (1980). The main goal of AHP is to quantify the relative priorities for a given set of alternatives on a ratio scale, based on the judgment of the decision-maker, and stresses the significance of the perceptive judgments of a decision maker as well as the consistency of the comparison of alternatives in the decision-making process (Saaty 1990). It was intended to compare the vulnerability assessment methodologies to select a proper tool for assessing the seismic risk for a group of buildings. Three criteria were considered for comparing different assessment tools. The general description of vulnerability, physical vulnerable parameter and the description of outputs are denoted as the criteria A, B and C respectively. The AHP pair wise comparison carried out according to the scales provided in Table A1-1 of Appendix A1. The calculations are also summarized in Table A1-2 through Table A1-4.

To check the efficiency of the proposed scoring method, another MCDM technique called TOPSIS has been employed. In this study entropy method (Hwang and Yoon, 1981) is utilized to determine the weights of a given set of criteria and TOPSIS was employed to determine performance ratings of the selected alternatives. Hwang and Yoon (1981) described the TOPSIS concept as the ideal and anti-ideal solutions, with reference to the positive and negative ideal solutions respectively. The TOPSIS method defines an index called similarity (or relative closeness) to rank the alternatives based on the distance (or similarity) of their evaluated score from the ideal solution in a MCDM problem. TOPSIS selects the alternative which is closest to the ideal solution and farthest from negative ideal alternative (Olson 2004). The weighted normalized matrix has been formed with the default weight assigned as (A=0.33, B=0.33 and C=0.34). The detailed procedure is shown in Appendix A2.

However, the vulnerability assessment ranking reflects how appropriate the method is for the use in seismic risk assessment (Hill and Rossetto 2008). A sensitivity analysis has therefore been carried-out to assess the influence of category weighting on the final score. The final rankings of the competing alternatives are highly dependent on the weights attached to the main criteria. Small variations in the relative weights may result in a major change in the final ranking. The objective is to assure whether a few alteration in the judgment evaluations can lead to significant modifications in the final ranking or not. The categories are weighted according to different scenarios as depicted in Table 3-4.

Table 3-4: Weighting scenarios (after Hill and Rossetto 2008)

Weighting scenarios for scoring system	Criteria			Description
	A	B	C	
I	33.33%	33.33%	33.33%	Default.
II	50%	25%	25%	To highlight scales more suited for in-field measurement.
III	25%	50%	25%	To highlight scales more suited for analysis of structures.
IV	25%	25%	50%	To highlight scales more suited for decision makers.
AHP	9%	17%	74%	
TOPSIS	33 %	33%	34%	

The overall result is shown in Table 3-5, where it is evident that, the Hybrid method and the NRC method are the best alternatives, however, there is a little variation in the ranking in case of Turkish method. The proposed scoring system is a general tool for comparing the vulnerability assessment methods in the context of ease of use and applicability. Although it cannot accommodate all the parameters, it qualitatively gives a better indication of the suitable seismic vulnerability assessment method for buildings.

Table 3-5: Overall results of the sensitivity analysis

Seismic Vulnerability Assessment Techniques	Ranks					
	AHP	TOPSIS	Scenario I	Scenario II	Scenario III	Scenario IV
FEMA 154	4	3	3	3	2	2
Euro Code 8	6	5	5	5	4	4
NZ Code	3	4	4	4	3	3
Turkish	5	6	6	6	5	4
Hybrid Method	1	1	1	1	1	1
NRC Guidelines	2	2	2	2	1	1

3.4 CASE STUDY FOR THE CITY OF KELOWNA, CANADA

A case study for the 20,000 buildings in the City of Kelowna is conducted to find the utilities of the above mentioned vulnerability assessment methods. The overall soil of the study area is derived from the lower and middle Jurassic class rocks (http://gsc.nrcan.gc.ca). As the Modified Turkish method only considers the reinforced concrete buildings, it can not be applied for a general case study, like Kelowna, where, other types of buildings are present. Hence, for this case study Hybrid' vulnerability assessment method, FEMA 154 (Rapid Visual Screening), Euro Code 8, New Zealand guideline, and NRC guidelines have been considered to check the applicability.

3.4.1 Development of grids

The building database for the Kelowna city is developed with the help of Google Maps (http://maps.google.com/). Furthermore, grids of different resolutions have been generated with the help of ArcGIS®. 9.3.1 tool (www.esri.com). A 5 km × 5 km grid has been developed to assess the vulnerability in a macro scale. However, 1 km × 1 km and 0.5 km × 0.5 km grids have also been developed to check the sensitivity of the analysis in different resolutions. Figure 3-2 shows the grid maps of the Kelowna city in different resolutions.

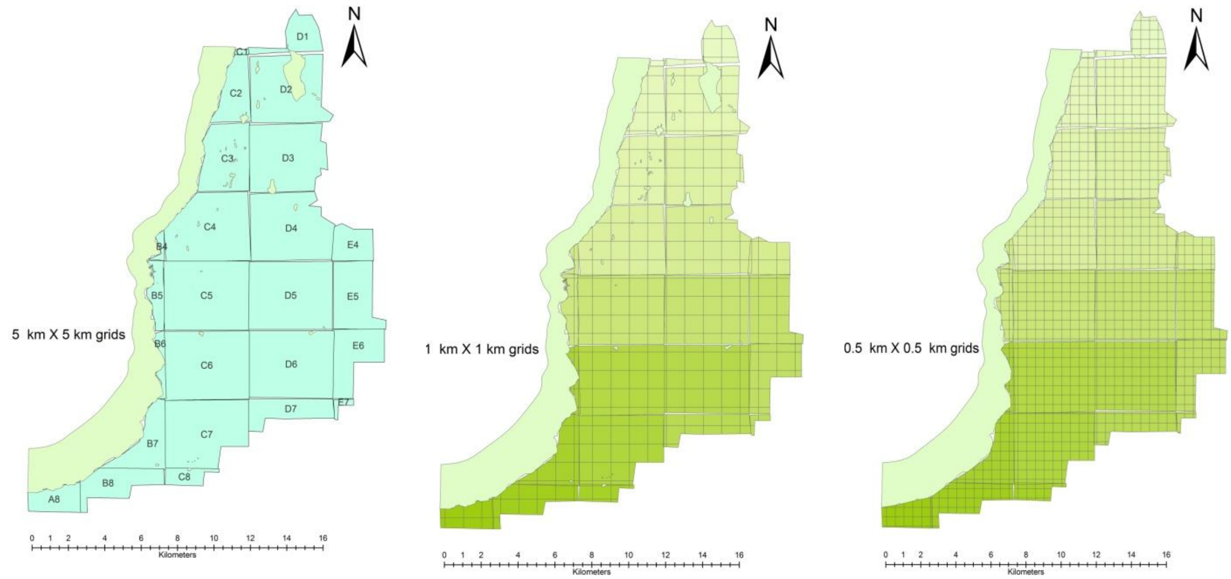


Figure 3-2: Grid maps of the City of Kelowna in different resolutions

3.4.2 Vulnerability assessment

The study reveals that, about 8% buildings within the city are made of reinforced cement concrete. The rest are timber buildings. Figure 3-3 shows the existing vulnerability factors within the city. From the study, it was found that, 48% buildings of the Kelowna city have the plan irregularities. Another major vulnerability factor found in Kelowna is the non-structural components of buildings (18%). However, very few Kelowna buildings have also the pounding possibility and vertical irregularities, most of which are located in downtown area.

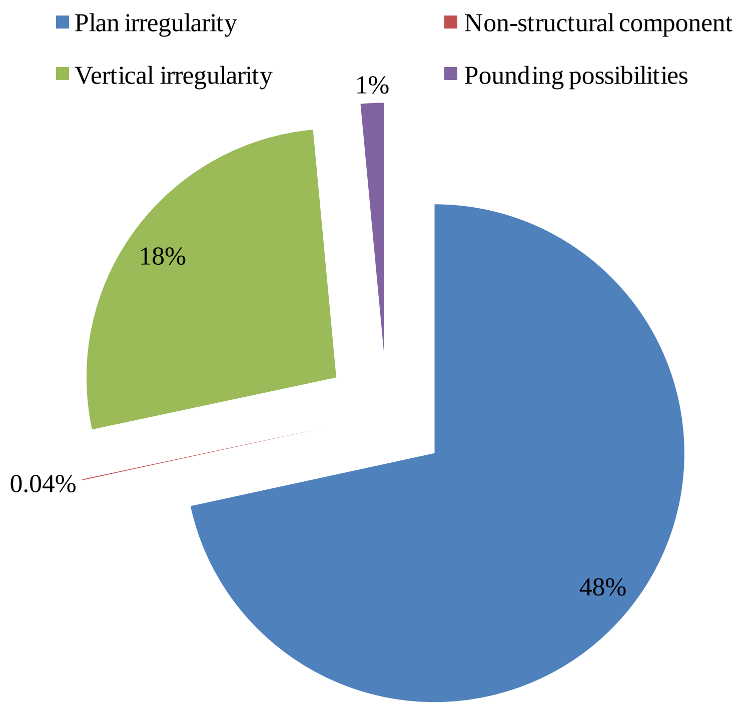


Figure 3-3: Presence of vulnerability factors in Kelowna city, Canada

Figure 3-4 shows the results from different seismic vulnerability techniques for the city. This chapter reveals that, the proposed Hybrid method, the New Zealand guideline as well as the NRC guidelines (NRCC 1993) has more segregation in risk classes, which will be a suitable benchmark for the decision making. Assessing with the Hybrid method, the Kelowna case study finds 48% of the buildings in moderate vulnerability state, whereas 52% of the buildings were assessed as low vulnerable buildings. However, for mapping purpose, the grids are assigned to a single vulnerability score (Cockburn and Tesfamariam 2011). Buildings under each vulnerability state are converted to percentage within a grid. After that with the help of weights assigned to each vulnerable state (e.g. Low = 0.10, Moderate =0.75 and High = 0.90), the overall vulnerability state is obtained. A sample calculation is shown in Table 3-6 for a 0.5 km × 0.5 km grid.

The spatial distribution of the vulnerable area assessed with 'Hybrid' method has been integrated with GIS interface in 0.5 km × 0.5 km grid resolution which is depicted in Figure 3-5. From the case study, it is clearly evident that, the downtown area is more vulnerable to seismic hazard, compared to other areas in Kelowna.

Table 3-6: Sample seismic vulnerability assessment calculation for a 0.5 km × 0.5 km grid (after Cockburn and Tesfamariam 2011)

Grid ID	Building Type		Seismic Vulnerability		Overall Vulnerability State
	Wooden	Concrete	Low	Medium	
11	0.84%	99.16%	46.67%	53.33%	Moderate

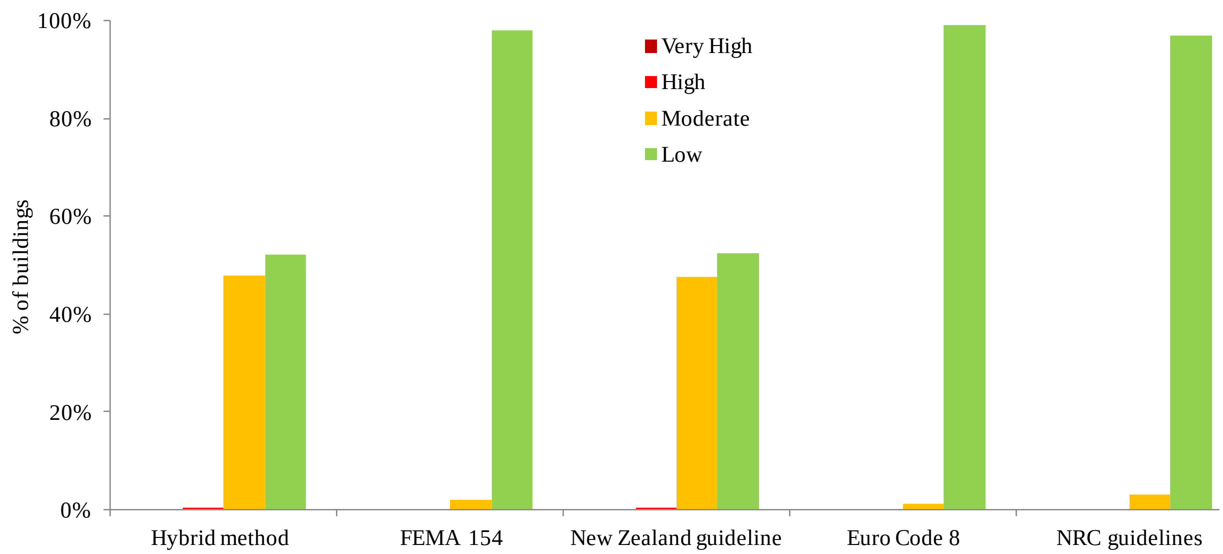


Figure 3-4: Vulnerability assessment result for the City of Kelowna

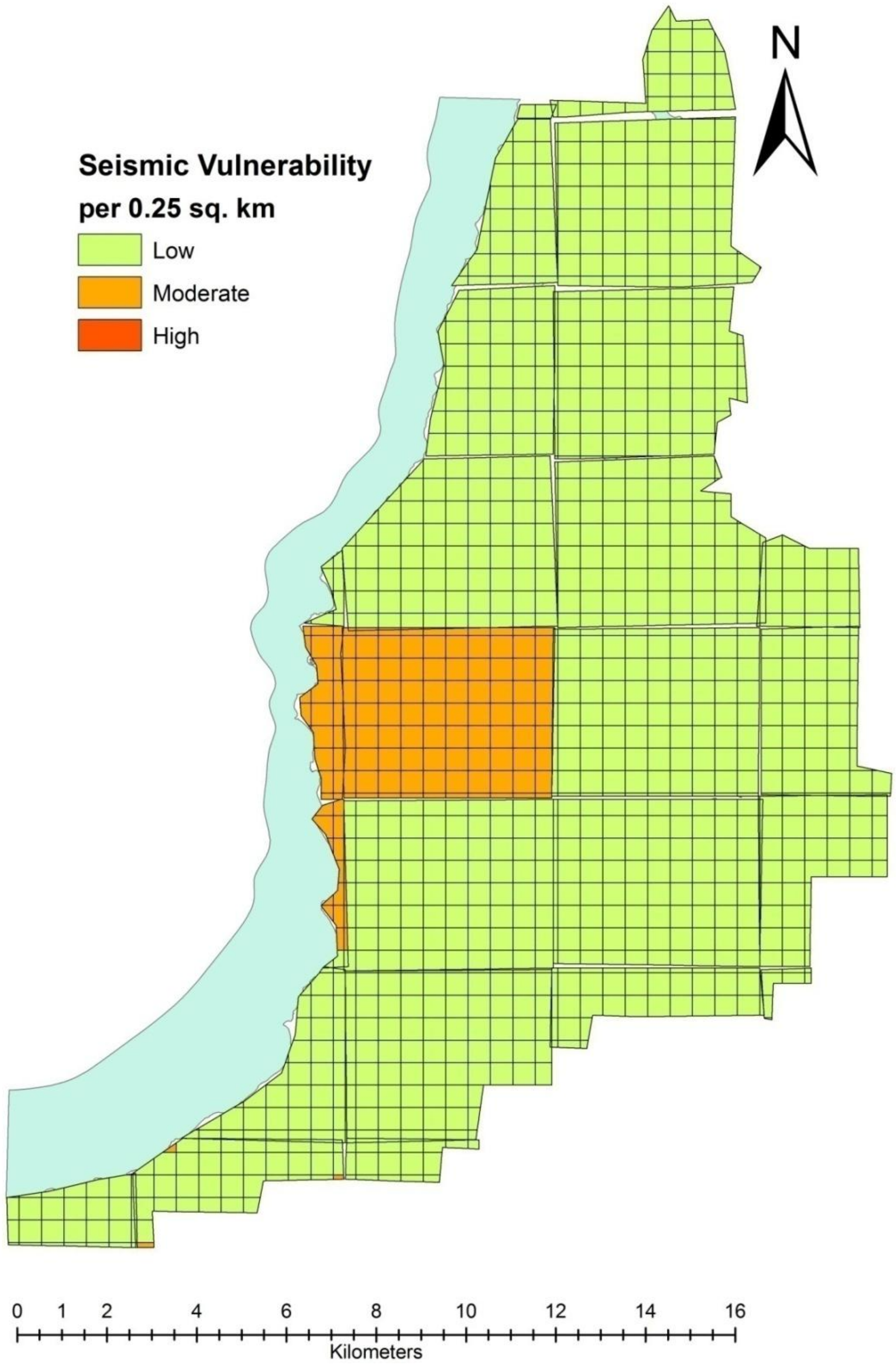


Figure 3-5: Distribution of seismic vulnerability of buildings (per 0.25 km^2) in Kelowna

3.5 SUMMARY

This chapter proposes an innovative ranking method for seismic vulnerability assessment techniques, based on several multi-criteria decision analyses. The chapter reveals that the proposed Hybrid method is one of the most suitable alternatives for the seismic vulnerability assessment of buildings. However, in case of Kelowna city, 48% buildings were found to be moderately vulnerable to seismic hazard, most of which are situated in the Kelowna downtown area. This assessment might provide the basis for conducting seismic damage estimation for the city. As the least grid spacing recommended for the seismic damage assessment tool utilized in this thesis is 0.5 km, the 0.5 km ×0.5 km grids can be applied as a reasonable resolution for further multiple hazard risk assessment for the city.

Chapter 4: GIS-BASED SEISMIC DAMAGE ESTIMATION

4.1 GENERAL

Due to the limitation of the readily available budget and efforts to implement seismic disaster reduction actions, the knowledge of what will happen if a seismic event occurs is vital for the earthquake prone cities (www.oyo.co.jp). This will facilitate to set priorities within the limited resources. The seismic damage estimation can serve as a starting point for an effective seismic risk reduction program. This chapter presents the results of a regional seismic risk assessment study carried out for the City of Kelowna, B.C. Ground shaking intensity in the area was developed utilizing the seismic source zones defined by the Geological Survey of Canada and the expert opinions from local experts. Building inventories were compiled by aggregating data from municipal databases as well as side-walk surveys and survey through Google maps. In this chapter, a GIS-based RADIUS (GBR) guideline is developed to investigate the probable damage estimation for different seismic scenarios, where damage distributions are quantified and mapped over 0.5 km × 0.5 km grids. The assessment reveals that an earthquake with M_w8.5 in the Cascadia zone may damage 62 buildings within the city. In order to aid the emergency response planning, three more scenarios (M_w4.5, M_w5.5 and M_w6.0 located just beneath the lower left corner of the city) are simulated with the proposed method. It was further found for the extreme case, about 1,361 buildings can be damaged for an earthquake scenario of M_w6.0 beneath the city, where the number of casualty can be as high as 39 (as most of the collapsed buildings are wooden buildings). In this chapter, the damage assessment with M_w8.5 in Cascadia zone is considered as the optimistic scenario within the region.

This chapter further shows damage assessment for the major road network. The assessment results, in addition, show that the downtown area of the city is expected to suffer highest amount of damage, which in turn may produce the highest amount of economic loss, because of the economic activities of the area.

The main tasks of this study were

- considering ground motion amplification due to local soil conditions,
- classifying and assessing the vulnerability of the Kelowna building inventory,
- selecting damage factors suitable to Canadian construction,
- assessing the "worst" case scenario as well as the "optimistic" scenario, and
- mapping the damage states in GIS.

4.2 GBR METHODOLOGY

Figure 4-1 shows the overall procedure for the proposed GBR method. After compilation of the different data, the database goes under the quality inspection phase. With the approval from the quality inspection, the whole database is subjected under a GIS query analysis to formulate the input data for RADIUS (Okazaki 2000). Result from the RADIUS analysis is shown in GIS maps, to show the spatial distributions of the seismic damage states.

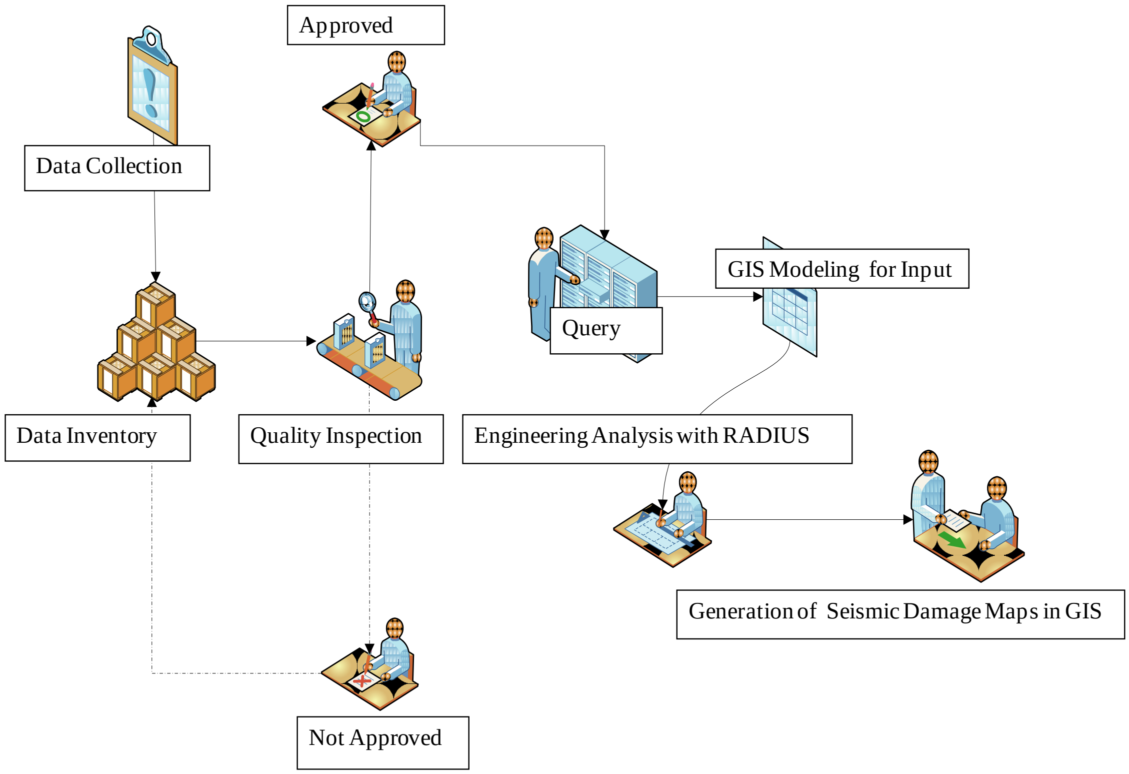


Figure 4-1: Work flow diagram of the GBR methodology

The general outline of the RADIUS method is summarized in Figure 4-2. Scenario earthquake, ground condition, demographic data and mean damage ratio are the most important input parameter for earthquake damage estimation. Zoning of the area, building classification, lifeline inventory and the soil condition are the also major input data for the tool.

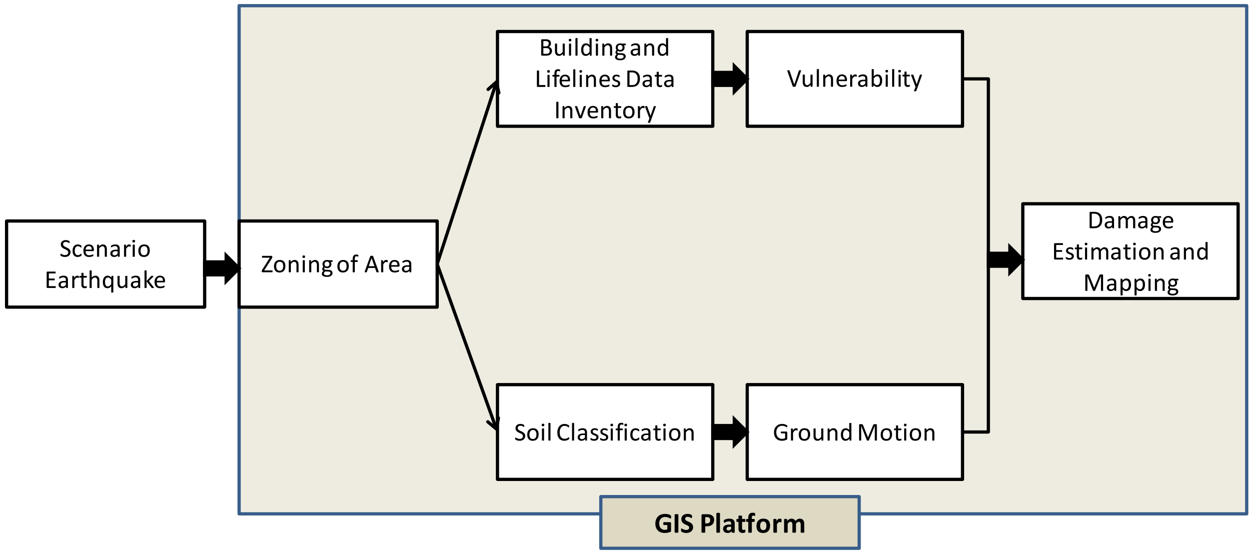


Figure 4-2: General flow of earthquake damage estimation in proposed GBR method (after RADIUS 2000)

4.2.1 Zoning of area

Damage estimation is generally carried out by subdividing the study area; hence seismic damage estimation is often called seismic micro-zoning. In the first step of the proposed methodology, the study area should be divided into equal sized square grids. The block/grid is a set of Excel cells that defines the study area in RADIUS Program. The user needs to create a uniformly spaced grid or block (normally 0.5 to 5 km) over the target region (RADIUS 2000). The grid size varies depending on the size of the study area as well as the scale of the study (local or regional). Figure 4-3 shows a sample zoning of area in RADIUS (0.5 km × 0.5 km). The input values should be assigned to each of the grids so that, spatially distributed outputs can be obtained.

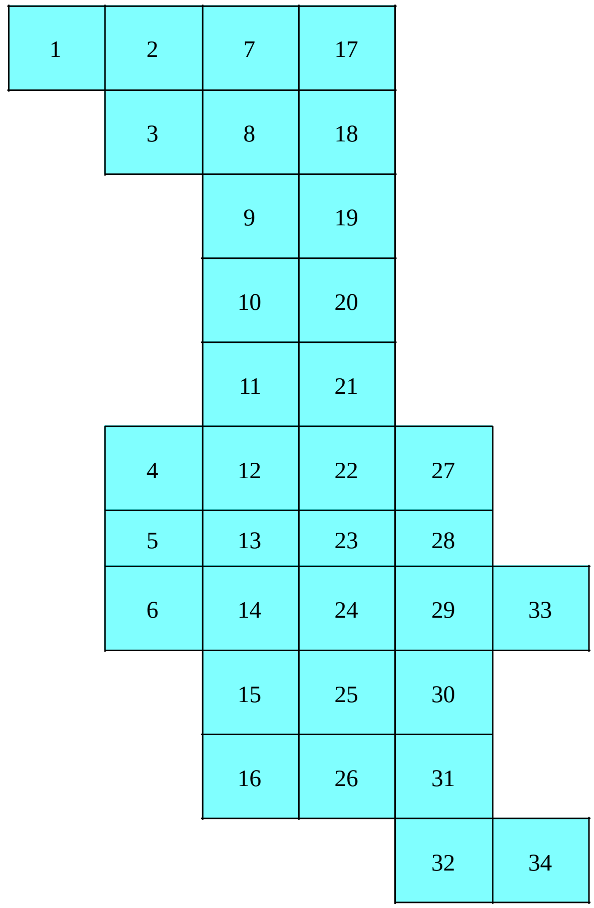


Figure 4-3: Sample grid area (0.5 km × 0.5 km) in RADIUS

4.2.2 Earthquake hazard assessment

A simplified method to evaluate ground conditions is introduced in RADIUS. The observed damage is a result of both the weakness of buildings and the soil condition of the study area. Four ground classifications based on the surface soil, namely, hard rock, soft rock, medium soil, and soft soil have been adopted in the RADIUS tool. In addition, an unknown soil type also exists for the convenience of the users. These classifications correspond to the amplification factors of each soil type, which can be changed by the user, depending on the situation. The values of amplification factors are shown in Figure 4-4 for different soil classes.

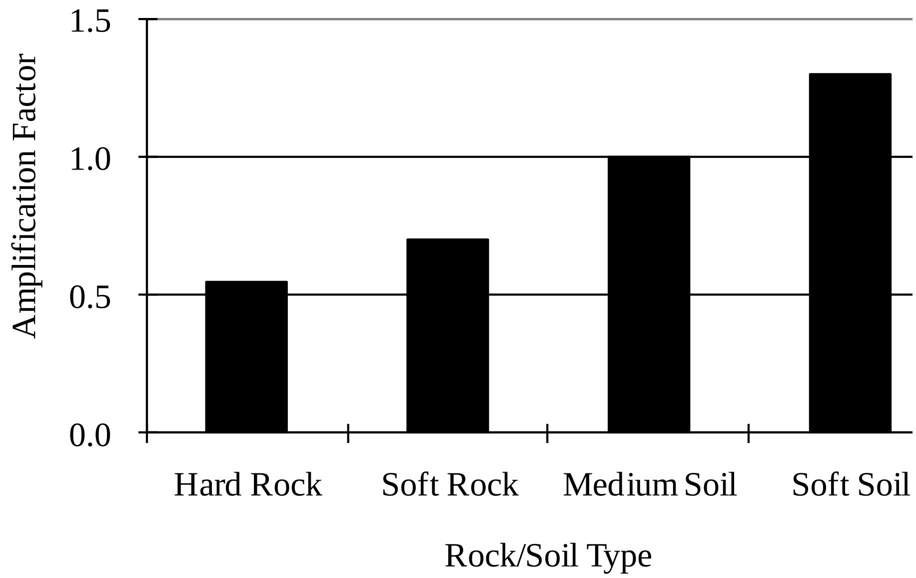


Figure 4-4: Surface ground amplification for different soil/rock types in RADIUS (after Nippon Koei and Oyo 2001)

Hard rock refers to volcanic rocks, and sedimentary rocks, which correspond to an amplification factor of 0.55. Soft rock (amplification factor = 0.7) corresponds to tertiary sand and/or mud stones and conglomerates. Medium soil refers to diluvial soil and stiff alluvial soil etc., which corresponds to an amplification factor for of 1.0 as a standard. Whereas, soft soil" corresponds to soft alluvial soil, reclaimed land and landfill etc. The amplification factor for this type of soil is set to 1.30. For unknown soil types, an amplification factor of 1.0 is used. However, the value of all the amplification factors can be calibrated by users. For a particular city, some soil types can be found homogeneously spread over a wide area while other soil types are distributed over narrow areas such as old river courses. A 1 km to 0.5 km grid spacing is recommended to capture the scenario in an efficient way for a city like Kelowna.

The reoccurrence of a past damaging earthquake or an active fault earthquake is normally adopted in case of a scenario earthquake selection.

Kappos *et al.* (2008) defined scenario earthquake as a particular seismic event which has a probability of exceeding higher, equal, or lower than the code specified design earthquake for a particular area. Unlike the seismic risk analysis, a comprehensive description of consequences is provided considering the occurrence of a particular seismic event in the scenario based analysis. Although hypothetical earthquakes can be used as the scenario earthquake, it should be validated from a seismological point of view. However, the historical earthquakes provided in the RADIUS tool are helpful for deciding scenario earthquake input parameters e.g. location, depth, magnitude and occurrence time of the earthquake. It is necessary to specify the time of occurrence for the scenario earthquake, as the casualty count depends on whether the earthquake occurs during the night or day.

The seismic intensity scale is the most commonly used index to specify the level of ground shaking and/or effect within a study area. Although there are various formulas, MMI (Modified Mercalli Intensity) for seismic intensity scale is adopted in the tool derived from popular empirical formula. PGA is also adopted in the tool for the convenience of design engineers and calculated by one of three most popular attenuation formulas shown in Table 4-1 and converted to MMI using the empirical formula of Trifunac and Brady (1975) which is shown in Figure 4-5.

Table 4-1: Attenuation equations utilized in RADIUS (after RADIUS 2000)

Equation	Source	Attenuation Equation
1	Joyner & Boore - 1981	PGA=10^(0.249*M-Log(D)-0.00255*D-1.02, D=(E^2+7.3^2)^0.5
2	Campbell - 1981	PGA=0.0185*EXP(1.28*M)*D^(-1.75), D=E+0.147*EXP(0.732*M)
3	Fukushima & Tanaka - 1990	PGA=(10^(0.41*M - LOG10 (R + 0.032 * 10^(0.41*M)) - 0.0034*R + 1.30))/980

Note:
E-----Epicentral distance, R----Hypocentral distance, M= Earthquake Magnitude

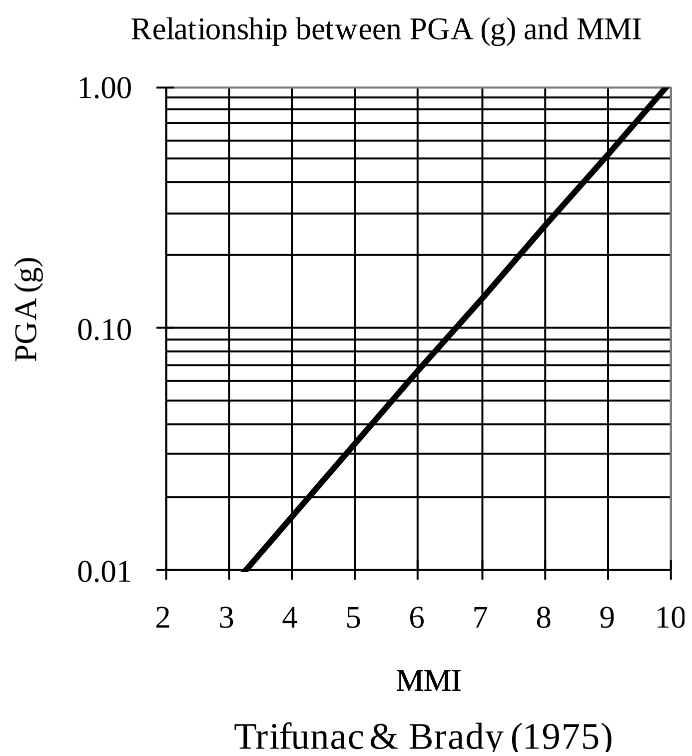


Figure 4-5: Attenuation equations and relationships utilized in RADIUS (after Nippon Koei and Oyo 2001)

4.2.3 Collection of existing building inventory

RADIUS methodology (RADIUS 2000) provides 10 different building classifications based on building materials, construction type, building age, story or height and usage, etc. These classes have been derived from the HAZUS building classifications (FEMA 2004) such as, residential (RES1, RES2, RES3 and RES4), educational (EDU1 and EDU2), medical (MED1 and MED2), commercial (COM) and industrial (IND). The tool provides fragility functions for each building category. Classifications of building types used in RADIUS for Kelowna case study are described in Table 4-2.

4.2.4 Vulnerability assessment and damage estimation

Vulnerability functions utilized for each building type can be derived from past events. The user inputs the percentage of each building type for each grid area. Mesh weights, defined as the relative density of buildings should be specified for each grid. Thus, combining all the factors with the calculated seismic intensity distribution, building damage can be estimated.

The tool can also be utilized for lifeline damage estimation, e.g. roads (local and highway), bridges, tunnels, electrical and telecommunication supply (towers and sub-stations), water supply and sewage (trunk and distribution lines, pumping stations and treatment plants), reservoirs, dams and tanks, and gasoline stations, but the damage to contents or business interruption cannot be estimated. Vulnerability curves show the relationship between mean damage rate and seismic hazard (MMI or PGA). The vulnerability curves for building and lifeline damages are normally based on MMI (RADIUS 2000). Hazard is generated as PGA in RADIUS tool, which is transformed to MMI, using an empirical conversion relationship given by Trifunac and Brady (1970). Onur *et al*. (2005) proposed mean damage factors (MDF) for major classes of buildings for the British Columbia. Damage ratios for MMI V and IV have been adopted in this method from the RADIUS tool. The modified figure is shown in Figure 4-6. In this study, WLFLR and CFCWHR refer to wooden and concrete buildings respectively. From the figure, it is obvious that the concrete buildings (heavier mass) suffer more damage in any seismic event compared to wooden structures. The percentage of MDF is multiplied with the number of building within a block to measure the total number of damaged buildings (RADIUS 2000).

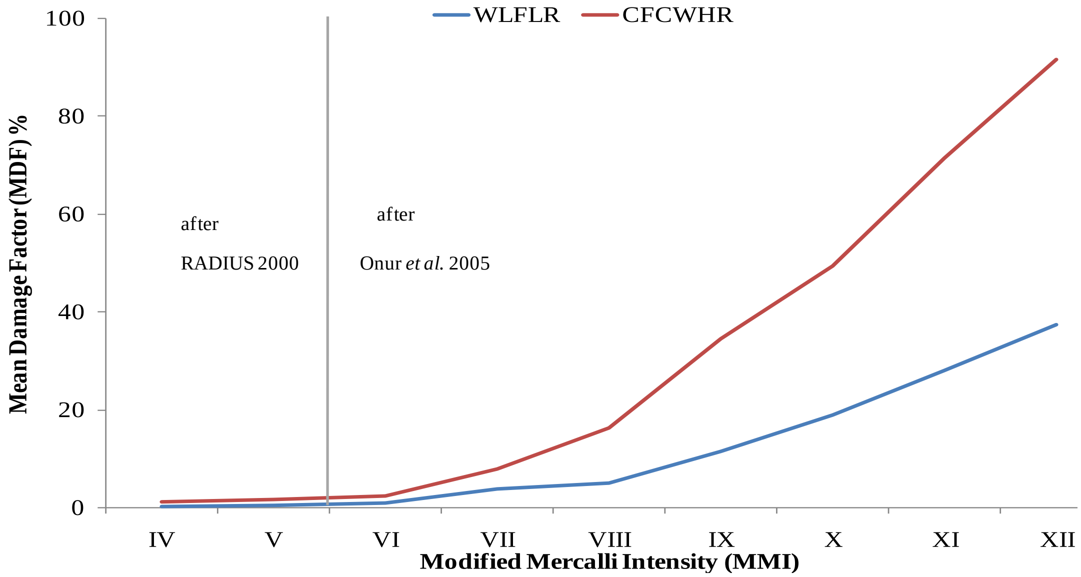


Figure 4-6: Mean damage factors (MDF) for wooden (WLFLR) and concrete (CFCWHR) buildings in Vancouver, Canada (after Onur et al. 2005 and RADIUS 2000)

Table 4-2: RADIUS building class definition (after RADIUS 2000)

RADIUS building class	Structural type	Definition
RES1	Wood	Informal construction: mainly slums, row housing etc. made from unfired bricks, mud mortar, loosely tied walls and roofs
RES2	Wood	Substandard construction, not complying with the local building code provisions (height up to 3 stories).
RES3	RC	URM-RC composite construction: old, deteriorated construction, not complying with the latest building code provisions (height 4 - 6 stories).
RES4	RC	Engineered RC construction: newly constructed multi-story buildings, for residential and commercial purposes.
EDU1	Wood	School buildings, up to 2 storeys: generally, the percentage of this type of building should be very low.
EDU2	RC	School buildings, greater than 2 storeys: office buildings should also be included in this class; generally, the percentage of this type of buildings should be very low.
MED1	Wood	Low to medium rise hospitals: generally, the percentage of this type of building should be very low.
MED2	RC	High rise hospitals: generally, the percentage of this type of building should be very low.
COM	Wood	Shopping centers.
IND	Wood	Industrial facilities

4.2.5 Loss of lives

The RADIUS tool assesses the losses to human life in the form of injuries (both moderate and severe) and deaths, caused by a particular seismic event. The seismic casualty estimation methodology is derived from historical earthquake experiences worldwide, and used in the RADIUS tool (RADIUS 2000). Since casualties and injuries caused by the seismic events are the main social damage parameters, their reduction should be the main objective of the community in disaster planning and preparedness (UNISDR 1999). Casualties can be calculated from the number of damaged and collapsed buildings. The number of people residing inside buildings during the earthquake is essential for casualty and injury estimations which are normally not the same during day and night time. In RADIUS, the number of day inhabitants and night inhabitants are calculated individually for each type of building classification. The day time (6 AM to 6 PM) and night time (6 PM to 6 AM) definitions can be changed by the user.

With all of these considerations in mind, the proposed GBR methodology is developed for the reduction of deaths and suffering caused by seismic hazards in vulnerable communities. The main features of the method can be highlighted as follows:

- Compilation of the GIS-based inventory of a city.
- Development of sound damage estimates for an appropriate scenario-based contingency plan of a city.
- Best possible use of existing information and local expertise.
- Incorporation of representatives of the various stakeholders throughout the project.
- Set up of the environment that will allow the instant start of the implementation of the prepared risk management plans.

4.3 ILLUSTRATIVE EXAMPLES

In this section two different case studies are presented for the implementation of RADIUS projects. The first case study is based on the 1978 Thessaloniki (Greece) Earthquake (Kappos *et al.* 2008). It is intended to compare the RADIUS results with a past earthquake scenario, which would validate the utility of RADIUS. In case of the second case study, the RADIUS project is implemented for the City of Kelowna, B.C. to estimate the probable damage states for different seismic scenarios. This result can be utilized for the development of a scenario based contingency plan for the city.

4.3.1 Applicability of RADIUS for Greece: The 1978 Thessaloniki (Greece) Earthquake (M_W=6.5)

Kappos *et al.* (2008) reported the seismic damage estimation methodologies for Greece in both reinforced concrete and masonry buildings. The major earthquake occurred in Thessaloniki in June 1978 with a focal depth estimated to be between 6 and 11 km and an epicentre at a distance of about 30 km NE of the city, a magnitude of Mw 6.5 is considered for this validation case study (Theodulidis *et al.* 2006). For the sake of the study, the local soil amplification factor was assigned as 1 (RADIUS 1999). The maximum PGA was found to be 0.15 g, which caused a total of 47 deaths, 37 of them due to the collapse of a 9-storey R/C building, a limited number of partial collapses, and slight to moderate damage to a large number of buildings with a repair cost equal to 1.6% the cost of replacing the existing building stock (Stylianidis *et al.* 2002). With all these parameters taken into consideration, a RADIUS simulation is conducted. Figure 4-7 shows the study area defined by Kappos *et al.* (2008) and the 0.5 km × 0.5 km blocks for the RADIUS case study.

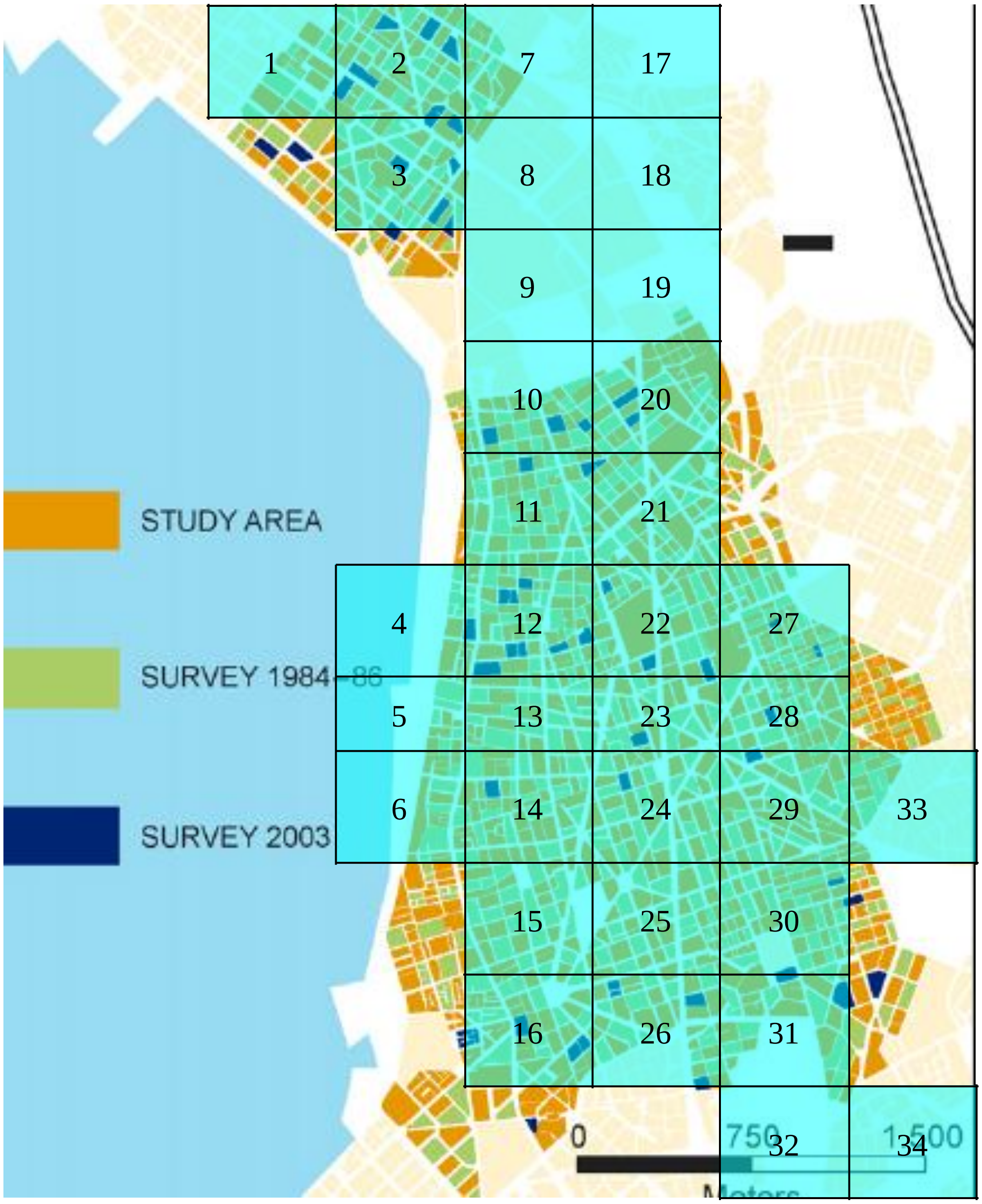


Figure 4-7: Case study area, denoted by 0.5 km × 0.5 km blocks (after Kappos et al. 2008)

The city had 1,000,000 inhabitants and 19,000 buildings (Kappos *et al.* 2008). The study utilized the fragility curves adopted by Kappos *et al.* (2008) in terms of PGA. For the current GBR methodology, the PGA was converted to MMI with the help of the equation of Trifunac and Brady (1975).

The results of the case study with the proposed GBR method are shown in Table 4-3. From the analysis, it is found that, about 309 buildings would be damaged for a same magnitude of earthquake of Thessaloniki in June 1978. The probable causalities are reported as 54, which is comparable with the real scenario (47 deaths). Figure 4-8 and Figure 4-9 shows the probable spatial distributions of damaged buildings as well as causalities, which is comparable with the previous case study conducted by Kappos *et al.* (2008).

Table 4-3: Results of the Thessaloniki case study with proposed GBR method

Area ID	Soil Type	PGA (g)	Damaged Building Count	Injury (Severe and Moderate)	Death
1	1	0.0	8	34	1
2	2	0.1	11	64	3
3	1	0.0	8	34	1
4	1	0.0	8	43	2
5	1	0.0	8	34	1
6	1	0.0	8	42	2
7	1	0.0	11	46	1
8	1	0.0	11	57	3
9	1	0.0	11	46	1
10	1	0.0	11	57	3
11	1	0.0	11	45	1
12	1	0.0	11	57	3
13	1	0.0	11	45	1
14	1	0.0	11	57	3
15	1	0.0	11	45	1
16	1	0.0	11	56	3
17	1	0.0	11	46	1
18	1	0.0	11	58	3
19	1	0.0	11	46	1
20	1	0.0	11	57	3
21	1	0.0	11	45	1
22	1	0.0	11	57	3
23	1	0.0	11	45	1
24	1	0.0	11	57	3
25	1	0.0	11	45	1
26	1	0.0	11	57	3
27	1	0.0	5	23	0
28	1	0.0	5	29	1
29	1	0.0	5	23	0
30	1	0.0	5	28	1
31	1	0.0	5	23	0
32	1	0.0	5	28	1
33	1	0.0	5	23	0
34	1	0.0	5	28	1

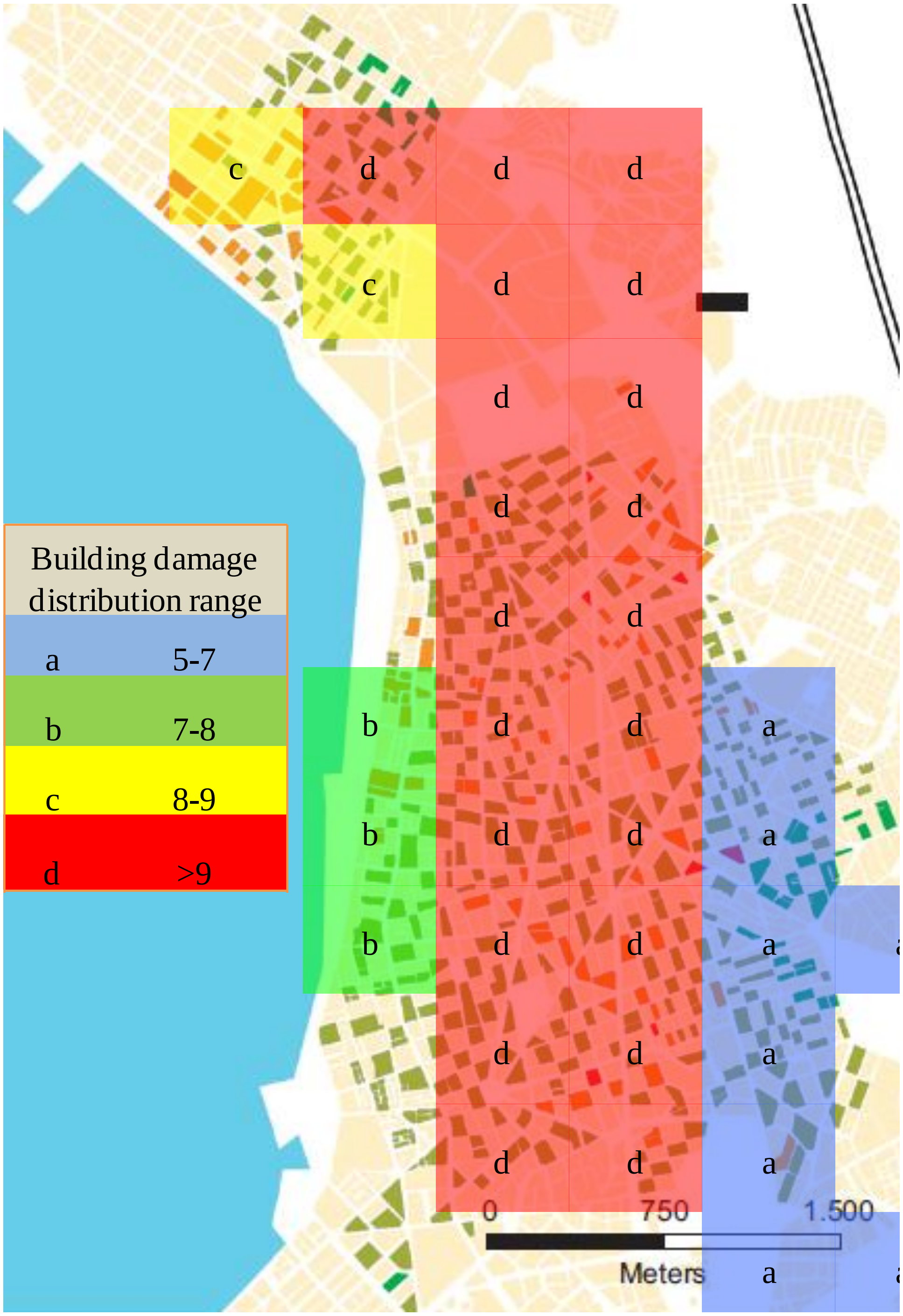


Figure 4-8: Building damage distribution (per 0.25 km^2) with proposed GBR method for the 1978 Thessaloniki (Greece) earthquake (ranges shown as number of damaged buildings)

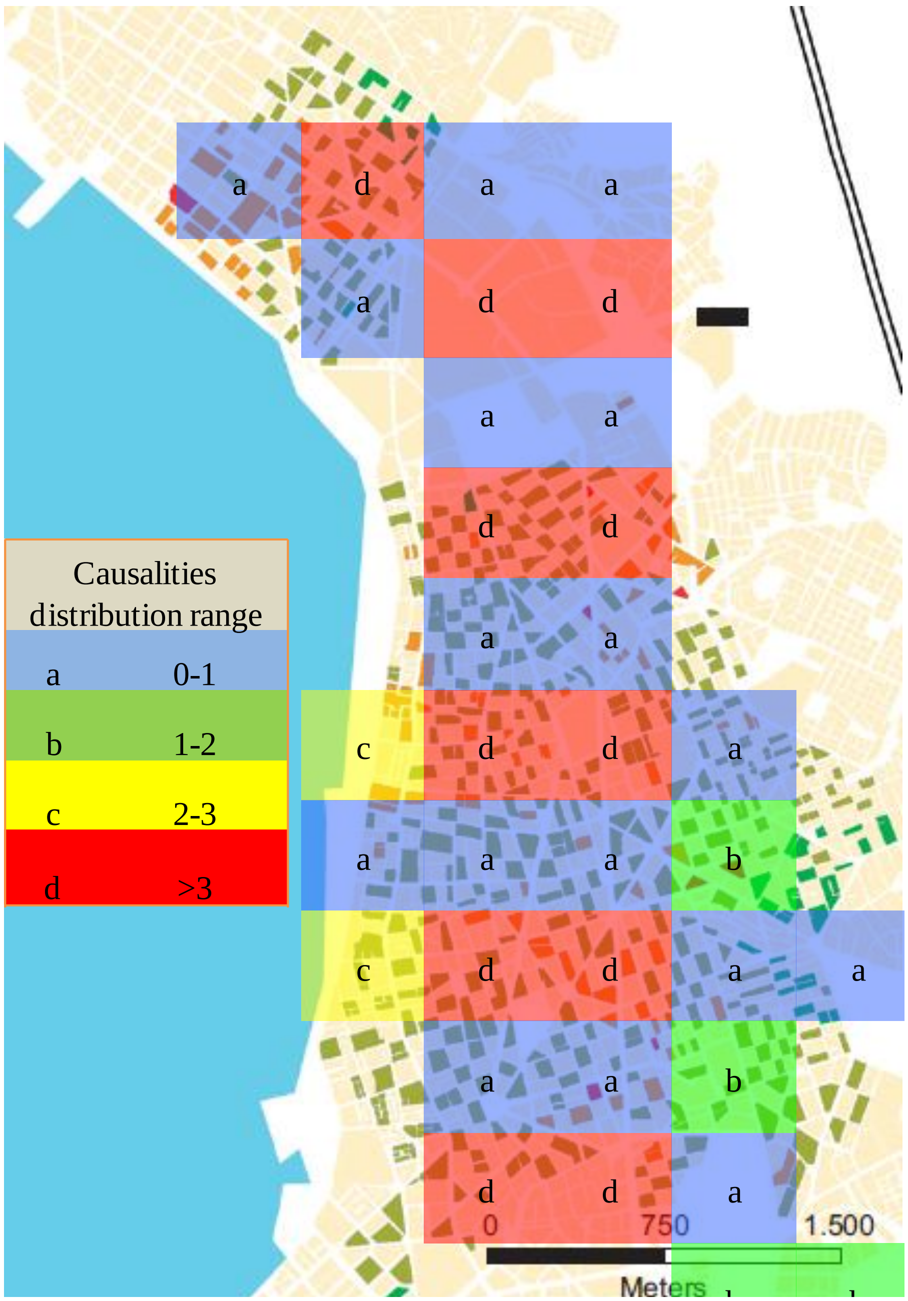


Figure 4-9: Distribution of causalities (per 0.25 km^2) with the proposed method (ranges shown as number of causalities)

The comparison of the simulation with the real earthquake scenario is shown in Table 4-4, where the simulation gives about the same result from the real time earthquake.

Table 4-4: Comparison between real earthquake scenarios with the RADIUS results

Topic	Kappos *et al.* 2008	RADIUS Result
Focal Distance	6~11 km	10 km
Highest PGA recorded	~0.15 g	~0.1 g
Casualties (Death)	47	54

4.3.2 Case study for the City of Kelowna, BC

A case study for the seismic damage estimation of the City of Kelowna, Canada was conducted with the proposed methodology. According to Canadian disaster database, an increase over 300% in the number of natural disasters was reported in the last few decades (PSC 2007). The city was selected as the case study for the proposed GBR methodology, to check its applicability. The spatial representation of the probable impacts can be an essential tool for the decision makers for the future development planning of the city as well (Beck *et al.* 2009). Records of historical earthquakes within the region were obtained from the Canadian seismicity database (http://earthquakescanada.nrcan.gc.ca), which showed the necessity of the assessment.

4.3.2.1 Zoning of the study area

The whole area of the city is divided into 1407 cells on 0.5 km × 0.5 km grids. The occupancy classes (industrial, commercial or residential) of buildings in Kelowna are depicted in Figure 4-10, which is utilized as to generate the basic input data for RADIUS tool. For lifelines seismic damage estimation, in this chapter, only the major road network (482 km) has been taken into account.

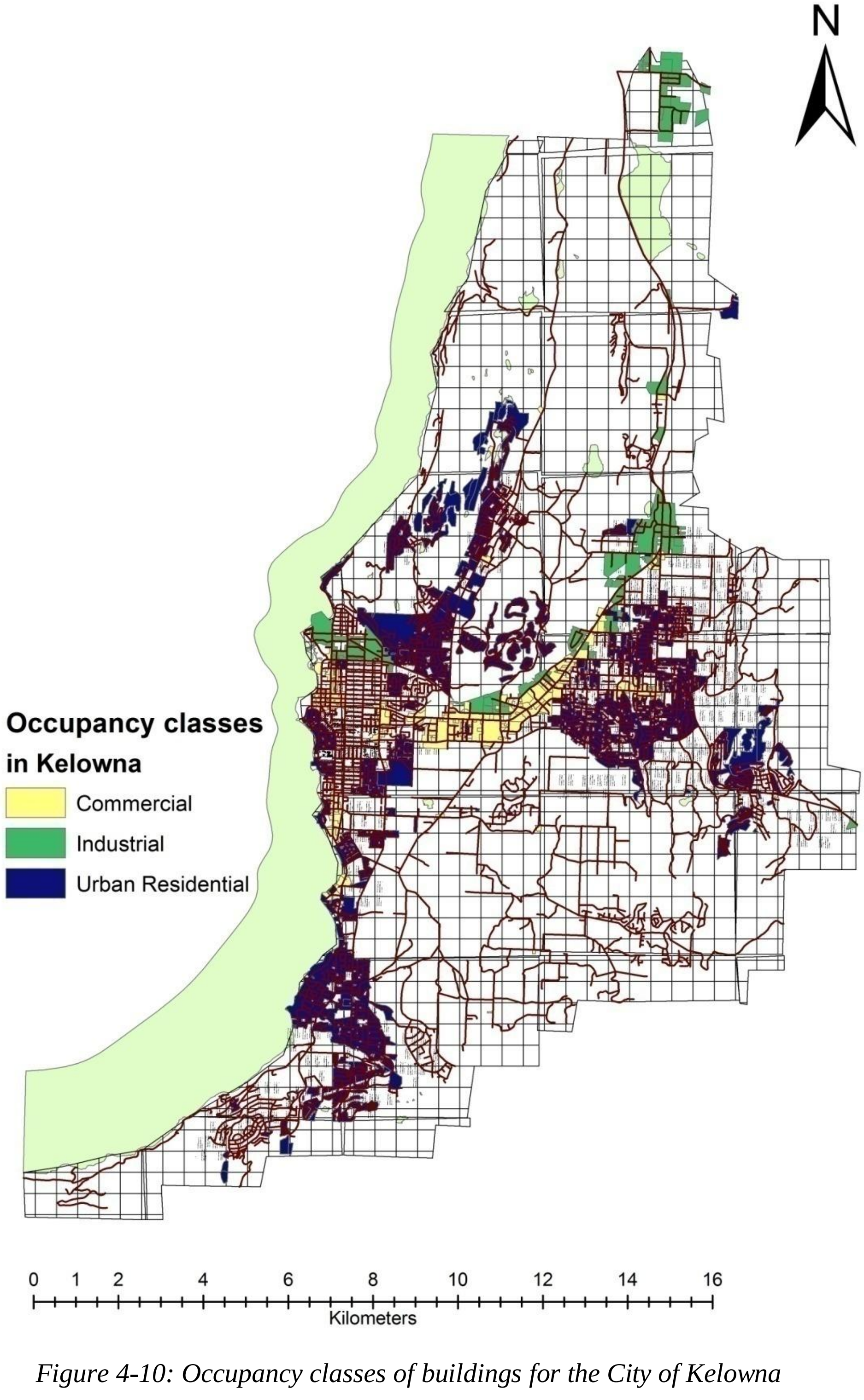


Figure 4-10: Occupancy classes of buildings for the City of Kelowna

4.3.2.2 Soil class selection

The soil class is a major attribute for seismic risk assessment, as it attenuates the peak ground acceleration (PGA) of the study area. The soil class for the City of Kelowna is selected from the Geological Survey of Canada website. The overall soil of the study area is derived from the lower and middle Jurassic class rocks (http://gsc.nrcan.gc.ca). However, for the sake of the detailed seismic damage estimation, a more comprehensive classification is needed; hence a local survey for the soil classification was conducted with the expert consultation.

From local expert consultation and the past studies (Church 1981 and Gough *et al*. 1994), a soil classification map is developed according to Table 4-5. An elevation contour map has been utilized to select the hilly areas within the city. The map is developed for the grid analysis in RADIUS, which requires a single soil class for each 0.5 km × 0.5 km grid, which is not necessarily the fact in actual case. Hence, the applicability of the developed soil map is limited to the proposed framework only. The classification is shown in Figure 4-11, which shows the downtown area of the City of Kelowna falls under soft soil class, which might come from the recent sediments, designated by the red color. From the expert opinion, about a 2 km strip of downtown area from the Okanagan lake shore was assigned as soft soil (designated as deep red color), due to the recent deposits of the area. The green area is mainly composed of rocks (hard and soft), where the orange color areas cover the medium soil types.

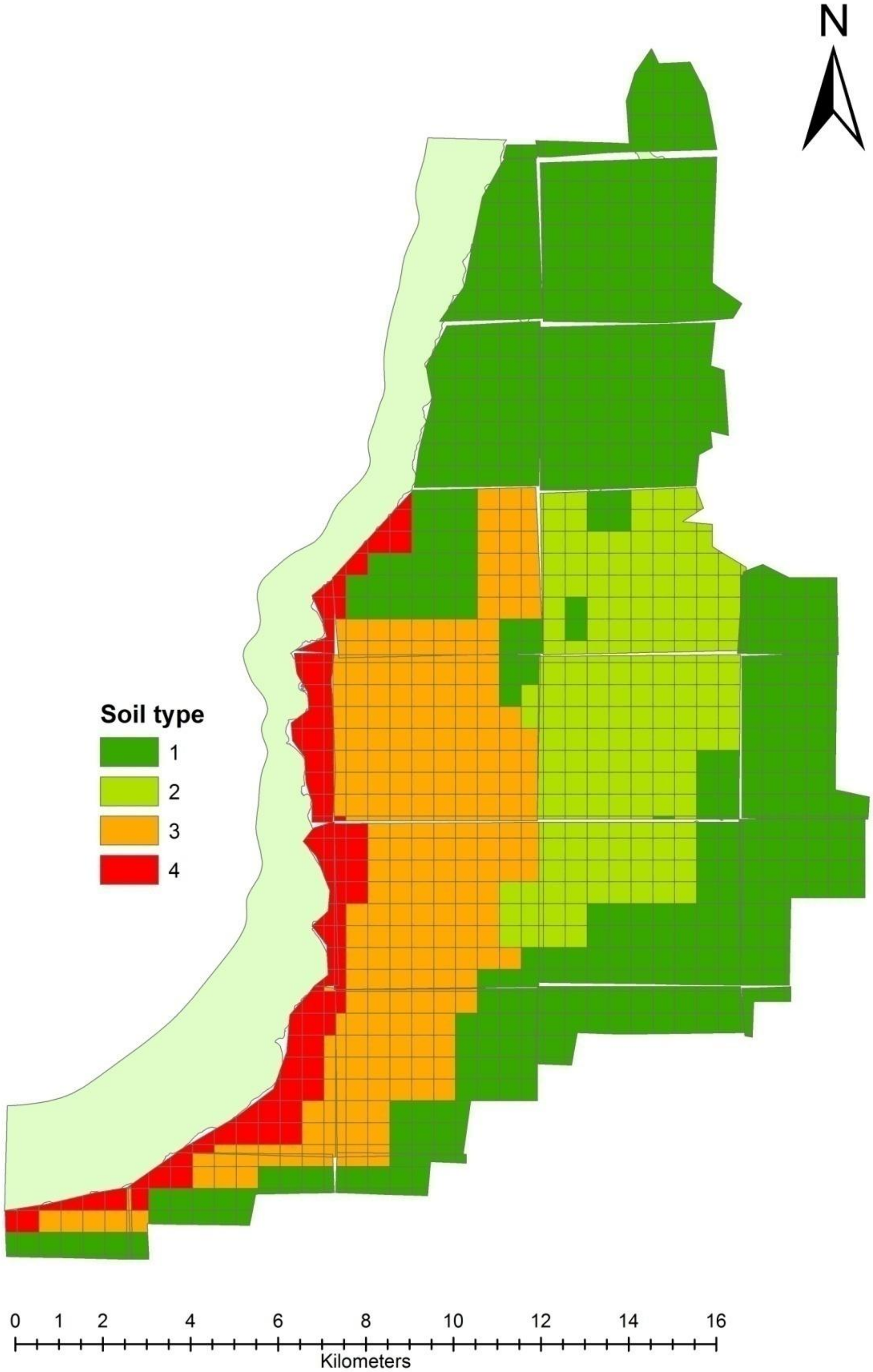


Figure 4-11: Soil classification of the City of Kelowna (from expert opinion, applicable only to the proposed GBR method)

Table 4-5: Soil classification (after UNISDR 1999)

Soil Class Code	Description	Amplification Factor	SPT N Value (From Expert Opinion)
0	Unknown	1.00	-
1	Hard Rock	0.55	NA
2	Soft Rock	0.70	25-50
3	Medium Soil	1.00	10-25
4	Soft Soil	1.30	<10

4.3.2.3 Seismic fault zone selection

The oceanic Juan de Fuca plate, situated in the west of Vancouver Island, and extending from the north tip of the Island to northern California, is moving towards North America at about 2 to 5 cm/year, which is known as the Cascadia Subduction Zone (http://www.usgs.gov). Geological evidence describes that every 300-800 years, huge subduction earthquakes use to strike this area (http://earthquakescanada.nrcan.gc.ca). Onur *et al.* (2005) described that the maximum probable seismic event can be greater than M_w8.0 in Vancouver area. Whereas Satake *et al.* (1996) predicted the maximum seismic event as high as M_w9.0 for the Cascadia Subduction zone. An earthquake of M_w8.5 in the Cascadia Subduction (20 km depth) zone is considered for the scenario case study for City of Kelowna. The inputs for the scenario earthquake are shown in Table 4-6 for the City of Kelowna.

Table 4-6: Scenario earthquake for the City of Kelowna

Scenario earthquake of *Mw* 8.5 in the Cascadia Subduction zone	
Occurrence Time	2 AM
Earthquake Magnitude (M_w)	8.5
Ref. Grid	Grid ID 2 (Lower left corner of the city)
Earthquake Direction relative to Ref. Grid	North East
Earthquake Distance (km) from Ref. Grid	271

4.3.2.4 Compilation of the GIS-based inventory for the City of Kelowna

A rapid visual survey was conducted with the help of Google map for the study. Some physical surveys were also conducted to validate the work.

The base map developed for the City of Kelowna is shown in Figure 4-12, where Figure 4-13 shows the distribution of buildings by height. The study depicts that 91% of the buildings within the city are low rise (1 to 3 storeys) building, which are mainly timber structures. The remaining 9% buildings are mainly made of timber or reinforced concrete, which are either medium (3-7 storeys) or high rise (>7 storeys) buildings.

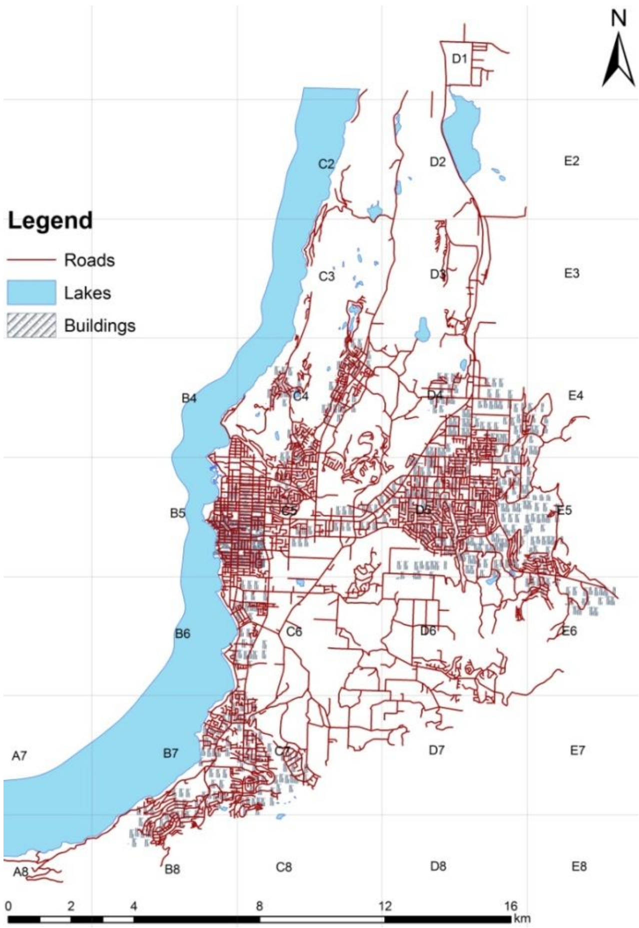


Figure 4-12: Base map of the City of Kelowna

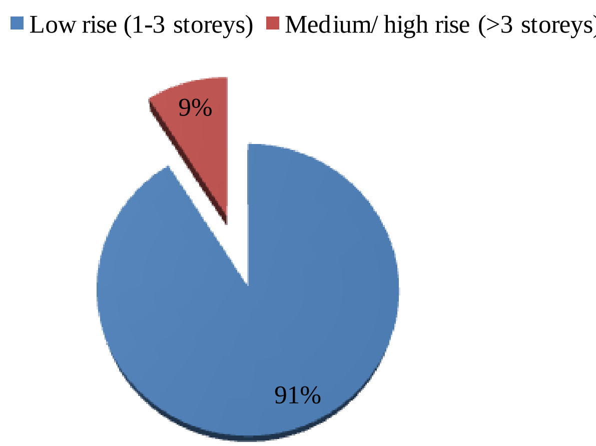


Figure 4-13: Distribution of buildings by height

4.3.2.5 Mean damage factors considered for the building classes of the study area

The mean damage factors (MDFs) are incorporated from a study done by Onur *et al.* (2005), which was developed for the City of Vancouver, British Columbia. In this study, the predominant building types are wooden light-frame low-rise residential (WLFR) buildings which include three storey apartment buildings, having the lowest MDFs, about 5% for MMI VIII. Other common building types are the concrete high-rises, majority of which are CFCWHR (Concrete frame with concrete walls high rise) and have MDFs of about 11% for MMI VIII.

Damage factors for MMI IV and MMI V have been incorporated from RADIUS (RADIUS 2000) to evaluate the seismic risk for the City of Kelowna which is shown in Table 4-7.

Table 4-7: Mean damage factors (MDF) for major classes of buildings of Kelowna (after Onur et al. 2005 and RADIUS 2000)

Material	Building type	MDF (%) for MMI								
		IV	V	VI	VII	VIII	IX	X	XI	XII
Wood	WLFLR	0.2	0.4	1	3.8	4.9	11.6	18.9	28.1	37.4
Concrete	CFCWHR	0.8	1	1.1	4	11.3	22.9	30.4	43.2	54.2

Note: MMI, Modified Mercalli intensity.

4.3.2.6 Sample grid calculation

To check the applicability of RADIUS, a sample grid calculation is presented in this section. The basic input data for the grid is shown in Table 4-8.

Table 4-8: Basic input data for the sample grid

Total Buildings	% of Buildings		Number of Buildings		Local Soil Type
	Wooden	RC	Wooden	RC	
122	85%	15%	104	18	4

With an earthquake scenario of M*w*8.5 in Cascadia zone (271 km), for local soil type 4, peak ground acceleration (PGA) is calculated as 0.03g with the attenuation equation of Fukushima & Tanaka (1990), which is converted to MMI (Modified Mercalli Intensity) V, using the conversion equation given by Trifunac and Brady (1975). The building damage of the particular grid is then calculated with the mean damage factors, described in Table 4-7.

Mean damage factors assigned to wooden and concrete buildings are 0.4 % and 1% respectively for MMI = V (RADIUS 2000). The total calculation for number of building damage is shown in Table 4-9. The number of total damaged building has been found as 0.60 per 0.25 km^2, which is shown as a yellow color (range of 0-1) in GIS map depicted in Figure 4-14.

Table 4-9: Damage output for the sample grid

Number of Buildings		MDF (%) for MMI =V		Number of Damaged Buildings		Total Number of Damaged Building
Wooden	RC	Wooden	RC	Wooden	RC	
104	18	0.4	1	0.41	0.18	0.60

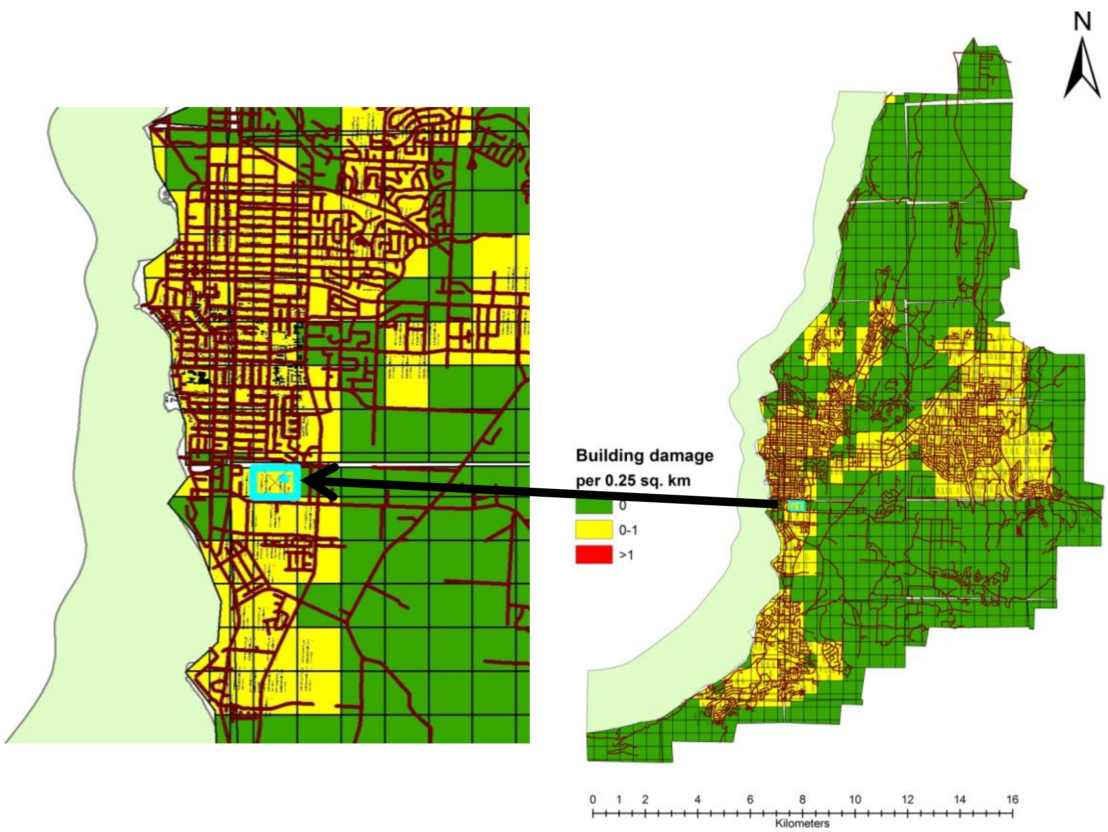


Figure 4-14: Damage estimation result of the sample grid

4.3.2.7 Outcomes and discussion

The proposed GBR method is unique compared to the current RADIUS procedure in terms of spatial representation of the damage states. Through the proposed methodology, the relative risk can be determined for each of the analyzed grid by estimating physical damage of buildings and lifelines for a particular seismic scenario. This section presents the estimation of physical damage to buildings and lifelines for each of the 0.5 km × 0.5 km grids within Kelowna city for different earthquake scenarios.

Cardona and Hurtado (2000) define the physical damage to buildings and lifelines, and the number of causalities and injuries as hard seismic risk, whereas the seismic hazard potential and the soft soil area are regarded as the soft seismic index. This thesis focuses on both. The study showed that about 2 km strip of downtown area from the Okanagan lake shore was assigned as soft soil area. The seismic hazard of the area is depicted as the Modified Mercalli Intensity (MMI) of each grid for the particular seismic event.

The proposed GBR methodology provides a suitable tool to assess the seismic vulnerability in relatively fast and convenient way. From the seismic damage estimation case study, the following conclusions can be drawn for a M_w8.5 scenario earthquake in Cascadia Subduction:

- Even though, the soil classification system is limited for the proposed method, the study reveals, Kelowna downtown area is situated on the recent deposits, which amplifies the ground accelerations for seismic events. The distribution of Modified Mercalli Intensity (MMI) within the city has been found to be in a range of III to V. Distribution of MMI V has been found mostly in the Kelowna downtown area, resulted from the soft soil assigned.

- Number of damaged buildings might be as high as 62. As most of the damaged buildings are wooden structures, only 13 people may suffer severe injury for the particular seismic event

- About 1 km road network of the city might suffer major damage, most of which are placed in the Kelowna downtown area.

- From the spatial analysis in GIS, it can be stated that, the downtown area of the City of Kelowna is more susceptible to seismic damage, compared to other areas, which may turn to a huge economic loss.

In Figure 4-15, the MMI distribution for the particular scenario is plotted on the GIS map using an appropriate color and size scale. In addition to the density and type of building classes, the soil type and distance from the earthquake source also play vital roles in building damage (RADIUS 2000). For the particular scenario earthquake with M_w8.5, the expected damage of the buildings and corresponding injuries are shown in Figure 4-16, where, a damage value less than 1 refers to the partial damage of the buildings. It is interesting to observe that, the distributions of damaged buildings are predicted more in downtown area. It is evident from the study that the majority of the buildings within Kelowna downtown would suffer more damage for a particular scenario earthquake of M_w8.5 in Cascadia fault zone. The distribution of injured people depicted in Figure 4-17 would help the emergency operations of the first responders.

The damage prediction in this study is of course, related to the severity of the seismic event (Kappos *et al.* 2008), i.e. the depth, distance, magnitude of seismic event. To facilitate the emergency response planning, 3 more scenarios are simulated with the proposed method. The Okanagan Valley is mostly a north-south trending tectonic lineament which is over 300 km in length located in south-central BC and northern Washington (Brown 2010), and having a major west dipping slope forming the western boundary of the Okanagan Highlands. Due to lack of adequate information, it was difficult to predict the probable seismic activity from the Okanagan

Valley fault. Hence, a default seismic scenario of magnitude 6.0, located just beneath the city is considered (http://www.adpc.net/.../CDMP). Moreover, a magnitude 6.0 earthquake located just beneath the city (15 km below) produces an average MMI of VII which in turns make the average peak ground acceleration (PGA) of 0.13g (Trifunac and Brady 1975),which complies with the National Building Code of Canada (NBCC 2005).

However, to check the sensitivity of the method, another two seismic events (M_w5.5 and M_w4.5) are considered (Olshansky *et al.* 2003). The detailed damage estimation results of these 3 different earthquake scenarios are depicted in Appendix B. The results show that the M_w6 earthquake produces higher seismic intensity and subsequent damage (1361 building damage with 39 causalities). However, the damage assessment with M_w8.5 in Cascadia zone is selected as the most probable case of seismic event within the region Onur *et al.* (2005), which can be utilized in preparation of a scenario-based contingency plan for seismic hazard.

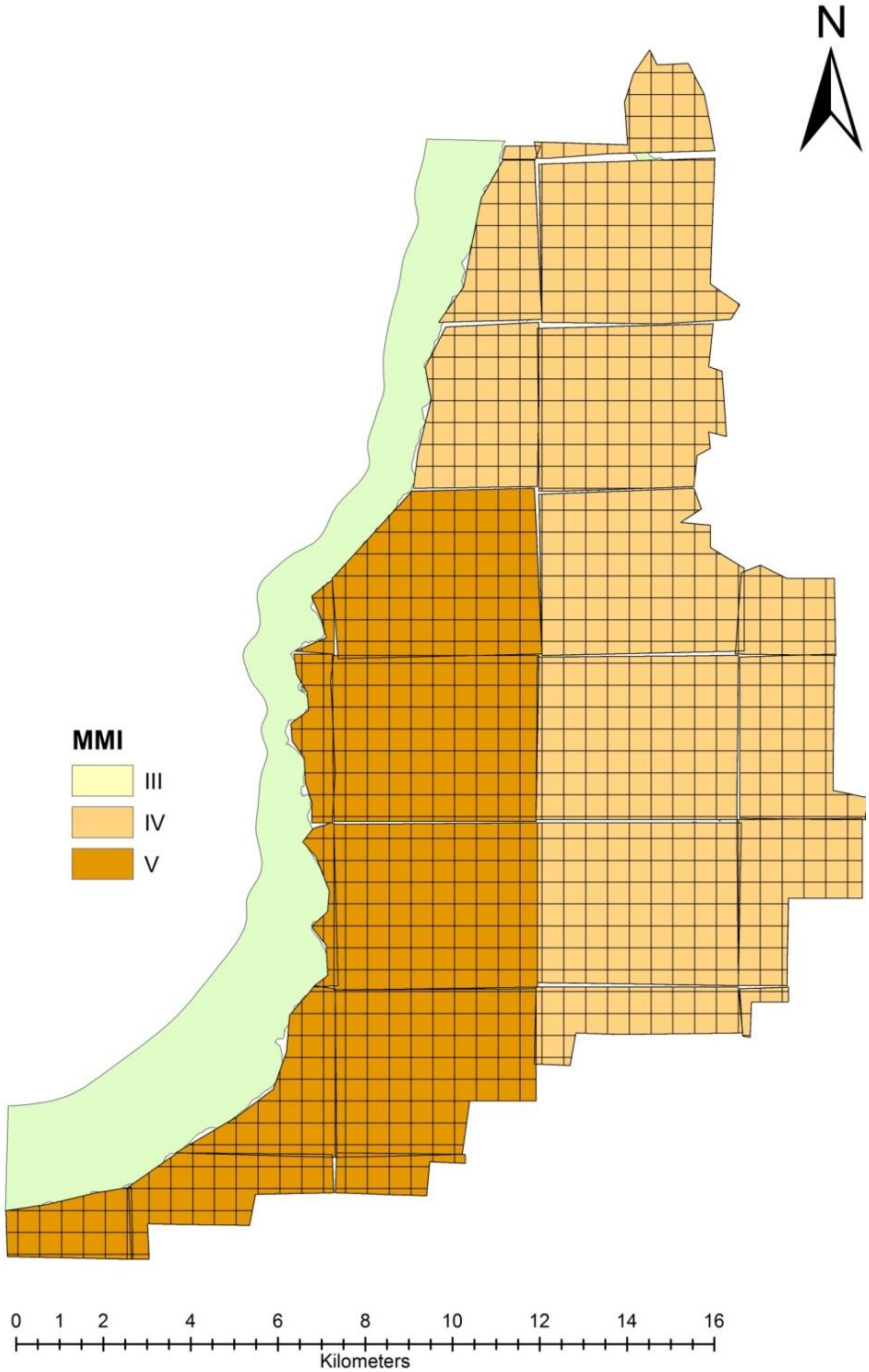


Figure 4-15: Modified Mercalli intensity (MMI) distributions for Mw8.5 scenario earthquake in Cascadia zone (distance 271 km)

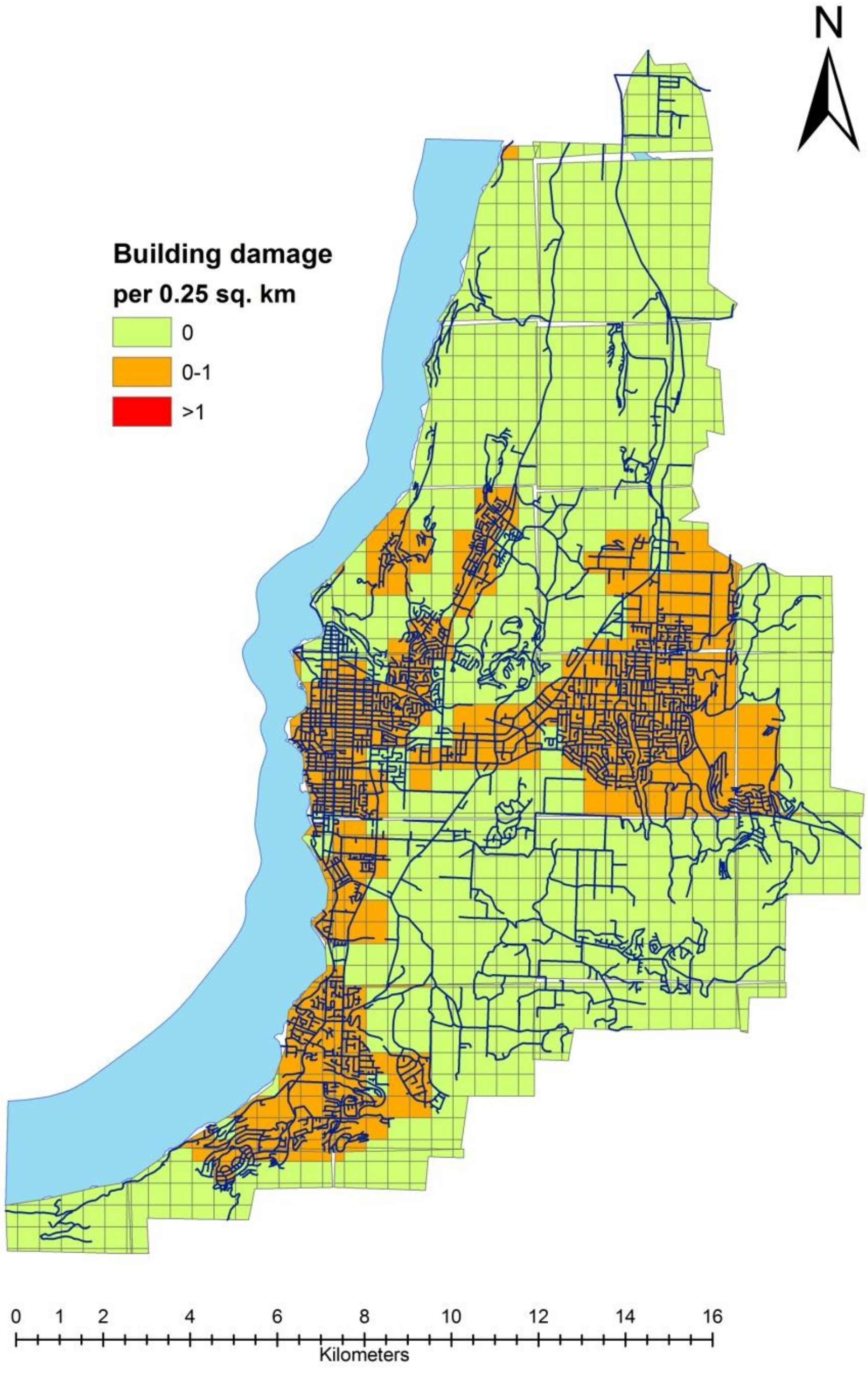


Figure 4-16: Distribution of damaged buildings (per 0.25 km^2) for Mw8.5 scenario earthquake in Cascadia zone (distance 271 km)

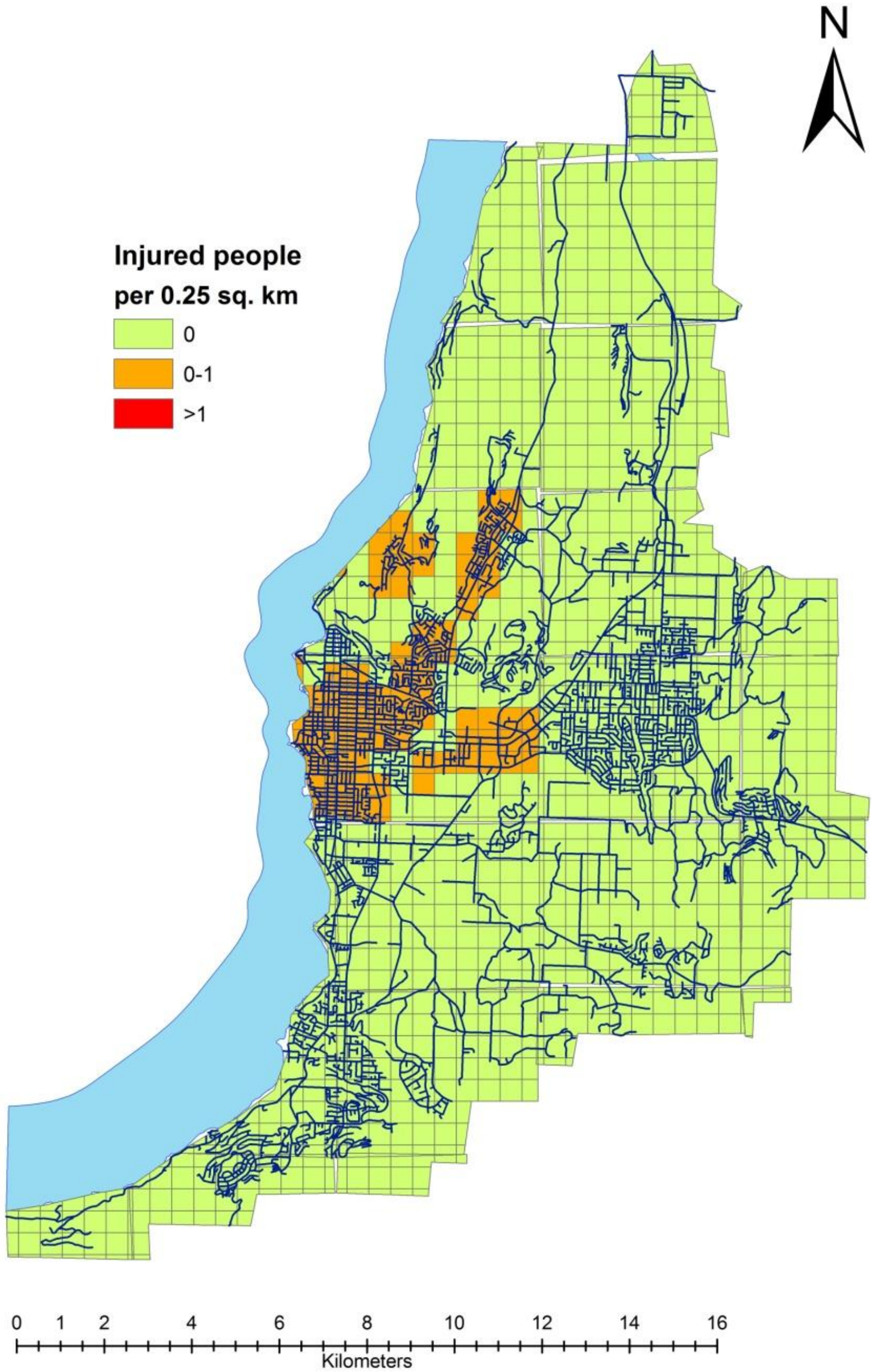


Figure 4-17: Distribution of injured people (per 0.25 km^2) for Mw8.5 scenario earthquake in Cascadia zone (distance 271 km)

The risky areas denoted by the red colors can be a benchmark for the further damage assessment of infrastructure and lifelines. For example, the road networks are assessed with the help of the mean damage factors in Figure 4-18, which is suggested in the RADIUS (UNISDR 1999, RADIUS 2000) software. The average MMI for the different blocks is derived from the scenario earthquake for the case study. Finally, the damage states for different blocks are shown in GIS map. Figure 4-19 shows the distribution of damaged major road network for the scenario earthquake (*Mw* 8.5), where, the low and the moderate damaged areas are denoted by the yellow color and orange color respectively, whereas the red color areas are selected as the probable risky areas. From this case study, it can be said that the highly risky areas for the road network are mostly in downtown area. This can be used as a benchmark for the decision makers to prioritize the development work as well as to select the alternative safe routes in case of a future seismic disaster. The vulnerability of other utilities and lifelines can also be determined in the same manner with the help of proposed GBR method.

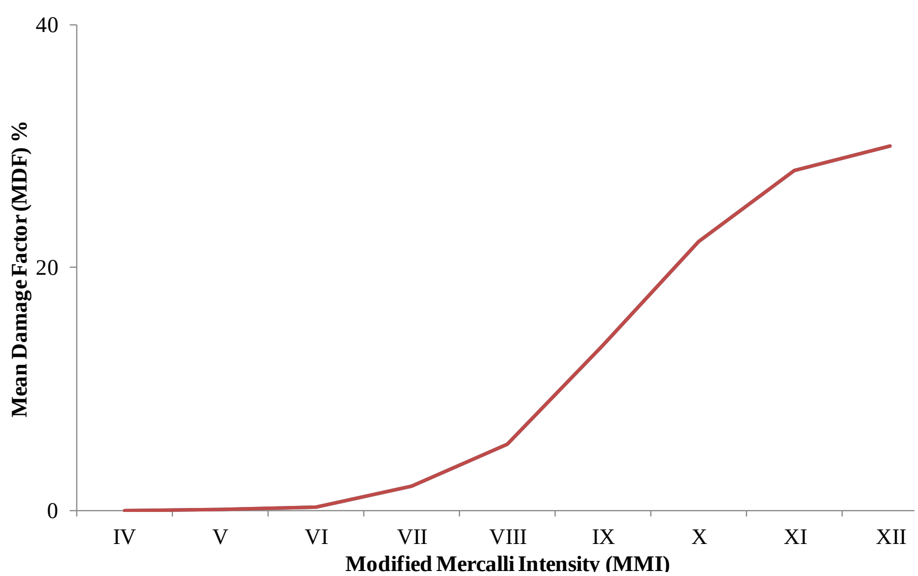


Figure 4-18: Mean damage factors major road network (after UNISDR 1999)

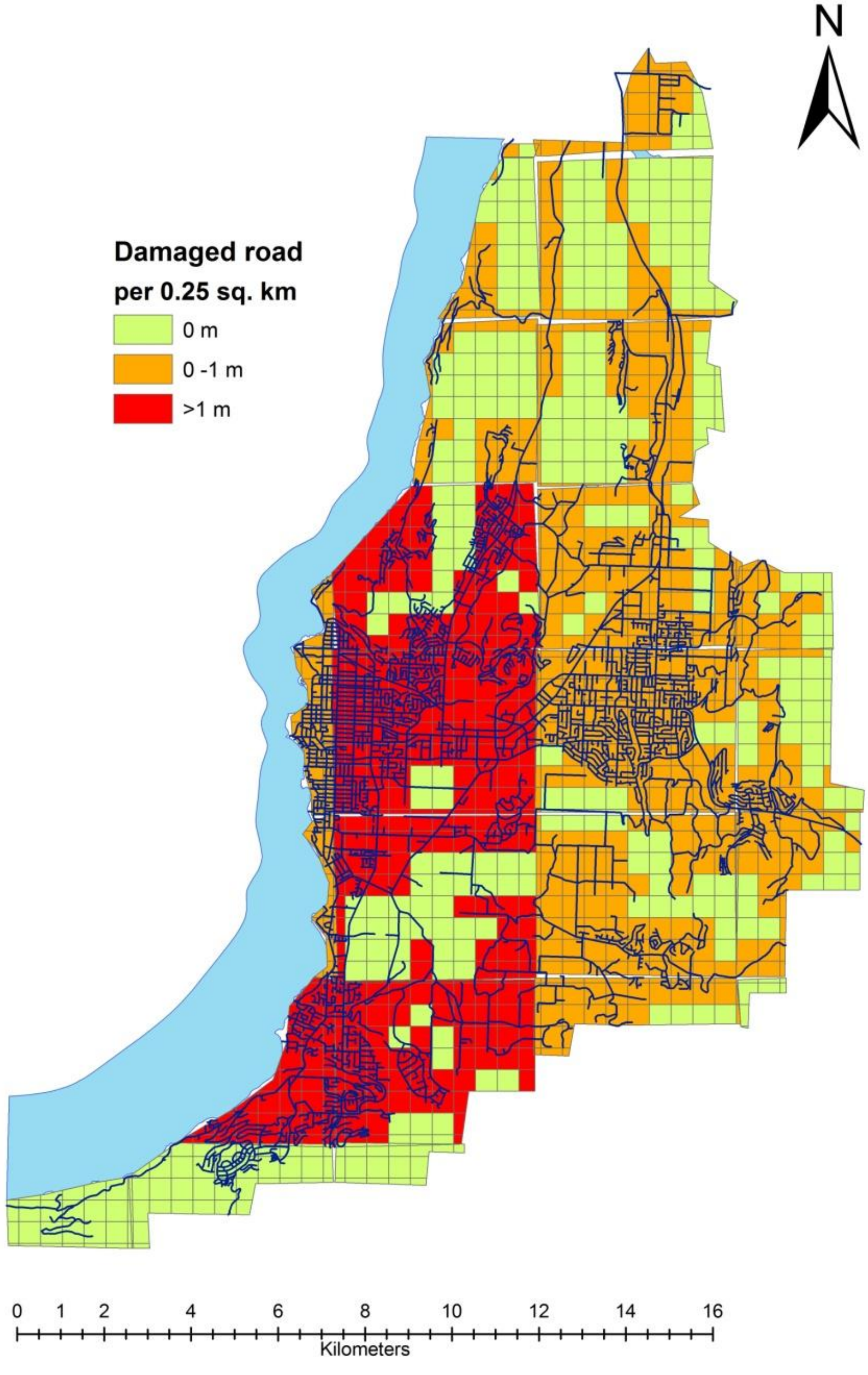


Figure 4-19: Damaged road network (per 0.25 km^2) for M_w8.5 scenario earthquake in Cascadia zone (distance 271 km)

4.4 SUMMARY

To assess the probable loss of a scenario earthquake, a GIS-based RADIUS methodology is proposed in this chapter, which might help the decision makers to prioritize the risky areas in terms of probable damage and casualty losses. The Kelowna case study reveals that, for a Mw 8.5 earthquake, located in Cascadia region, the number of building damage will be as high as 62. As most of the damaged buildings are wooden structures, less numbers of injured people have been found (13 injuries). However, it also reveals that, the Kelowna downtown is more susceptible to seismic damage, compared to other areas, which provides a benchmark for development of a scenario-based contingency plan for the city.

Chapter 5: GIS-BASED WILDFIRE RISK ASSESSMENT

5.1 GENERAL

In addition to seismic vulnerability and damage assessment, the study also focuses on the wildfire risk assessment for the City of Kelowna; due to the frequency of devastating wildfires within the region (http://www.gov.bc.ca). In extreme cases, multiple hazards may occur at the same time, which makes the rationale for conducting this study. This chapter summarizes results of a semi qualitative wildfire risk assessment study for the City of Kelowna. A GIS-based framework is proposed and a case study is performed to evaluate the risk of each of the 1,407 0.5 km × 0.5 km grids for the city. In addition to natural factors, existing vulnerabilities of the community are considered to generate the framework. The inventories for the analysis were compiled by aggregating data from municipal database as well as from the literature. The study found that 26% area of the city of Kelowna fall under the high risk category, whereas 12% area fall under moderate risk category and 63% of the total area fall under low risk category for a wildfire hazard. The estimated risk distributions have been mapped on each grid with the help of GIS. The wildfire risk assessment, along with the seismic risk assessment will facilitate the decision makers to identify the potential risky areas for multiple hazards, which might lead to the development of a proper multiple hazard emergency management plans for the city.

5.2 GIS-BASED WILDFIRE RISK ASSESSMENT

Figure 5-1 shows the overall procedure for the proposed wildfire risk assessment method. After compilation, the database goes under the quantitative assessment phase, where the wildfire initiation probability index and vegetation vulnerability index are calculated.

Finally, a qualitative analysis is conducted to assess the wildfire initiation risk using a risk matrix. After analyzing, the results could be shown in GIS maps, to show the spatial distributions of the wildfire risk states.

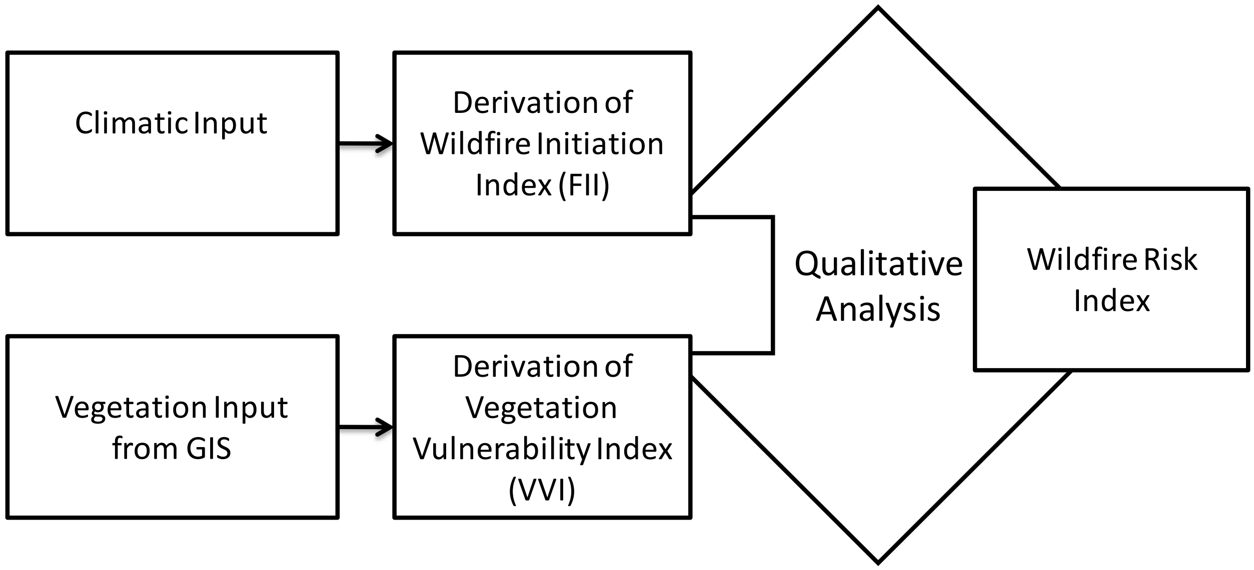


Figure 5-1: Proposed wildfire risk assessment methodology

5.2.1 Proposed fire initiation index (FII)

The fire danger rating (FDR) is an early indicator of potential danger, which is expressed as the fire initiation index (FII) in this section. The trends of the changes in FII due to environmental factors are derived from the software, FDR calculator developed by the Bureau of Meteorology, Australia (www.bom.gov.au), Alan Richert (http://www.zfps.co.za/fdi-calculator.html) and New South Wales Government, Australia (http://www.rfs.nsw.gov.au). The calculation procedure combines air temperature, relative humidity, wind speed and possibility of drought. Dry Bulb Temperature of Air (DBT) is measured by the ordinary thermometer, which is nothing but the atmospheric temperature (http://www.brighthub.com/). The fire initiation probability increases with the increase of DBT.

The ratio of the actual amount of water vapour in the air to the amount it could hold when saturated expressed as a percentage is called the relative humidity (RH) (http://www.bom.gov.au/). The effect of RH is inversely proportional to the FDR. The wind speed is also a vital dynamic factor for the wildfire spread. Higher prevailing wind speed increases the potential of fire initiation and spread. In the FDR calculator, the wind speed should be input in km per hour unit. Finally, the drought factor, or the precipitation factor is also an important factor in FDR calculation. If the number of days since the last rain is not known, a default value of 10 should be the input. The amount of precipitation has the reverse effect on FDR calculation.

For developing a simple equation for FII, a number of hypothetical observations are made in FDR calculator and corresponding FII are calculated. The trends of the changes in FII have been adopted from the Bureau of Meteorology, Australia (http://www.bom.gov.au/). After that a linear regression analysis is conducted to derive a simple equation as Equation 5-1.

$$FII = 25 + 1.002 * (T) - 0.17 * (RH) + 0.133 * (WS) - 0.127 * (RF) \quad \text{Equation 5-1}$$

where, T = Maximum dry bulb temperature of an area (^{o}C), RH = Relative humidity of the study area (%), WS = Average wind speed (km/hr), RF= Average rainfall (mm).

The changes of the different variables are depicted in Figure 5-2, where it is evident that the FII is largely influenced by the dry bulb temperature on an area. Dry bulb temperature and wind have the positive correlation with the FII, whereas the relative humidity and the rainfall have the negative correlation with the proposed index for fire initiation.

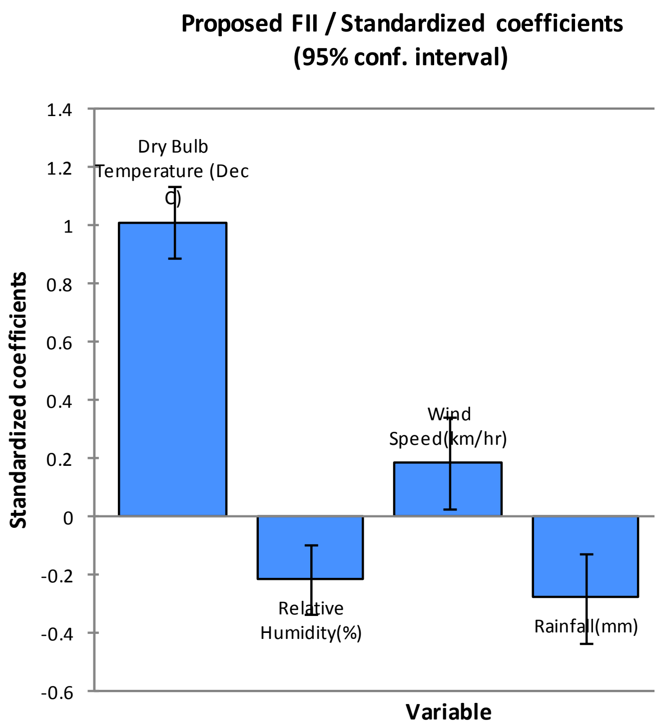


Figure 5-2: Changes of variables in FII

The output risk scale ranges from 1 to 100 (www.bom.gov.au). An FII of 1 (Low-Moderate) refers to the fact that fire would not burn, or would burn so slowly that it would be easily controlled, that the probability of initiation is low, whereas an FII in excess of 100 (Catastrophic) means uncontrollable fire event, and the initiation probability is very extreme. Table 5-1 shows the risk scales utilized in the current study for fire initiation probability.

Table 5-1: Fire initiation probability (after www.bom.gov.au)

Fire Initiation Probability	FII
Low	0-11
Moderate	12-24
High	25-49
Very High	50-74
Extreme	75-99
Very Extreme	More than 100

5.2.2 Vegetation vulnerability index (VVI)

In this section vegetation vulnerability indices are adopted from the City of Kelowna 'Fuel Management Strategy' study (www.kelowna.ca). The City of Kelowna has conducted a forest cover inventory and a landscape level vegetation vulnerability assessment to cope with the prevailing wildfire threat. The vegetation vulnerability index (VVI) is found as a linguistic term e.g. low, moderate high, very high etc. for different area of the city following the city's fuel hazard ranking score sheet (http://www.kelowna.ca). The goal of this score sheet is to provide a standardized vegetation vulnerability ranking system that accounts for the risk of potential wildfire behavior. The major parameter considered in the calculation of the vegetation vulnerability were the fuel characteristics that influence rate of spread, crown fire potential and fire intensity. Finally, the overall vegetation vulnerability index (VVI) is mapped over a 0.5 km × 0.5 km grids.

5.2.3 Proposed risk matrix

A risk matrix is proposed to assess the final wildfire initiation risk of a community in qualitative approach after National Wildfire Coordination Group, USA (http://www.nwcg.gov/). Figure 5-3 depicts the risk matrix for the proposed framework. Probability of initiation of fire (FII) is depicted in the row of the matrix, whereas the wildfire vulnerability index (VVI) is shown in the column of the matrix. From this matrix, any assessor can estimate the risk qualitatively.

VVI \ FII	Low	Moderate	High	Very High	Extreme	Very Extreme
Low	Low	Low	Moderate	Moderate	High	High
Moderate	Low	Moderate	High	High	High	Very High
High	Moderate	High	High	Very High	Very High	Very High
Very High	High	Very High	Very High	Very High	Extreme	Extreme
Extreme	Very High	Very High	Very High	Extreme	Extreme	Catastrophic

Figure 5-3: Proposed risk matrix (after http://www.nwcg.gov/)

5.2.4 Fire vulnerability index (FVI) for pre-positioning of future fire stations

In this chapter, a fire vulnerability index is also developed for any kind of urban fires, which might be initiated due to seismic event or wildfire spread. This index will help the decision makers to find the probable locations for future fire stations. For fire vulnerability index (FVI), mainly the fire fighting resources of community are considered. Table 5-2 shows the maximum score assigned for different parameters. The scores were compiled from the Florida Wildfire Risk Assessment Score sheet (www.fl-dof.com) and expert judgment which is shown in Appendix C.

Table 5-2: Assigned scores for fire vulnerability index (FVI) (after www.fl-dof.com)

Parameters	Maximum Assigned Score
Accessibility	60
Vegetation	50
Building Construction Type	35
Fire Protection	32
Utilities	11
Additional Factors	50

The accessibility parameter includes the road length, road width, cul-de-sec and presence of street signs. The vegetation parameter can be found from the length and the type of the vegetation as well as the presence of other fuel sources. The type of vegetation on and within 300 feet of the property is an essential factor in its vulnerability to wildfire (Division of Forestry 2010). Roof material, siding materials and skirting are included in building construction type parameter. A wooden building is considered more susceptible to fire than a concrete building. For fire protection parameter, proximity to the helicopter dip spots (lake, ponds and canals), proximity to fire stations as well as the density of pressurized water hydrants within a grid have been considered. The underground utilities have been considered as the safe factors in the score sheet. The number of facilities has also the reverse effect on the score. If the number of facilities is more than 100, the score will be as low as zero.

With summing up of all the parameters, a fire vulnerability index can be found. The ranges of vulnerability index are shown in Table 5-3.

Table 5-3: Assigned ranges for fire vulnerability index (FVI) (after www.fl-dof.com)

Fire Vulnerability Index (FVI)	Point Range
Low	less than 50
Moderate	50-74
High	75-99
Very High	100-120
Extreme	more than 120

5.2.4.1 GIS modeling

The input variables for the vulnerability index are modeled in geographical information system (GIS) with the help of ArcGIS®. 9.3.1 (www.esri.com). It increases the computational capability as well as the accuracy. The distance from the fire station can be shown by a buffer analysis for a specified distance. A GIS model is shown in Figure 5-4, where 5 km buffering is assigned to fulltime fire stations and 3 km to the paid on call (POC) fire stations.

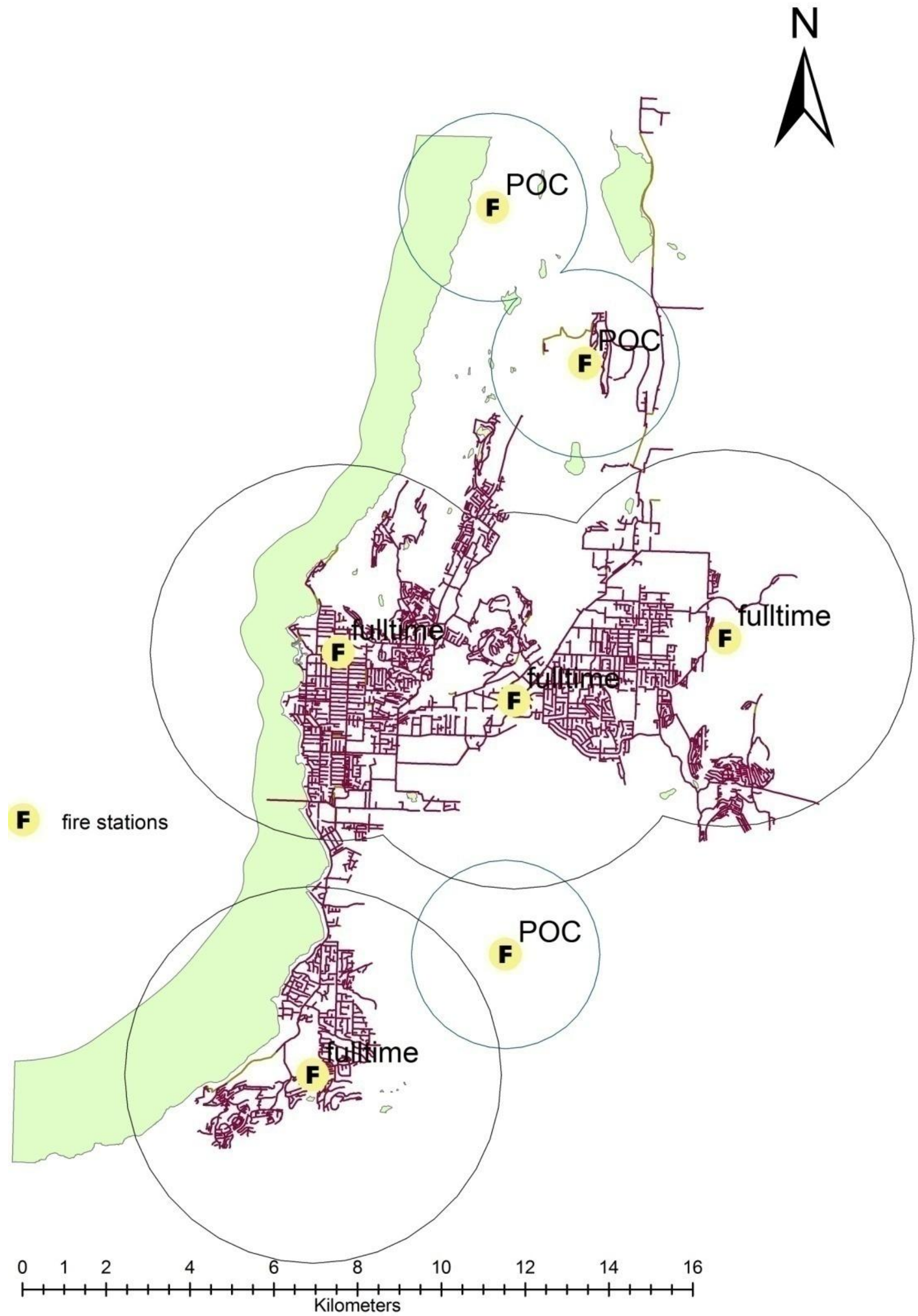


Figure 5-4: Buffering of fire stations in Kelowna city

For the other input variables, such as vegetation inventories, utilities, fire hydrant distributions, building distributions etc. are modeled in the GIS interface. Finally, the vulnerability scenario can be presented in GIS mapping interface in block by block basis (0.5 km × 0.5 km, 1,407 grids).

5.3 CASE STUDY FOR THE CITY OF KELOWNA, BC

Canadian communities are exposed to noteworthy and growing risks from natural disasters. According to Canadian Disaster Database, an increase over 300% in the number of natural disasters is reported in the last few decades (PSC 2007). The City of Kelowna in British Columbia is one of most vulnerable cities exposed to natural hazards in Canada particularly to wildfire hazard. Hence, risk assessment for wildfire has become essential for developing an effective emergency management plan for the city. The spatial representation of the probable impacts can be an essential tool for the decision makers for the future development planning of the city as well (Beck *et al.* 2009). The city is selected as the case study for the proposed GIS-based methodology, to check its applicability.

The British Columbia province is primarily subjected to wildfire risk. Table 5-4 shows the 10 year long trend or pattern on wildfire history in British Columbia. On average 1784 wildfires occur every year in British Columbia (http://bcwildfire.ca), of which about 44% is caused by human interventions and the rest by natural factors.

On August 16, in 2003, the City of Kelowna suffered a big wildfire event, named as “2003 Okanagan Mountain Park Fire”, which caused a lot of disruptions to the city. About 25,912 hectares area was burned, whereas 239 homes were lost and 30,000 people had to be evacuated. Almost 60 fire departments, 1,400 armed forces troops and 1,000 forest fire fighters took part in controlling the fire, but were largely helpless in stopping the disaster. This event makes the rationale for the study (http://www.kelowna.ca/CM/page129.aspx).

Table 5-4: History of wildfire in British Columbia (after http://bcwildfire.ca)

Year	Total Fires	Total Loss (Hectares)	Total Loss (millions)	Average Loss (Hectares per Fire)
2009	3064	247,419	$382.1	80.8
2008	2026	13,240	$82.1	6.5
2007	1606	29,440	$98.8	18.3
2006	2570	139,265	$159.0	54.2
2005	976	34,588	$47.2	35.4
2004	2394	220,518	$164.6	92.1
2003	2473	265,053	$371.2	107.2
2002	1783	8,539	$37.8	4.8
2001	1266	9,677	$53.8	7.6
2000	1539	17,673	$51.5	11.5
1999	1208	11,581	$21.1	9.6
Average	1784	74,957	$108.7	34.7

5.3.1 Selection of fire initiation probability input

The month of August has been selected as the fire season for the City of Kelowna (http://bcwildfire.ca/). The average wind speed is considered as the 9.26 km per hour for the particular month (http://www.kelowna.com/climate/). Dry bulb temperature of air (DBT) and precipitation is selected from Table 5-5. Whereas, relative humidity is derived from weather data for Kelowna city (http://kelowna.weatherstats.ca) depicted in Figure 5-5.

Table 5-5: Weather data for the City of Kelowna in 2011 (after www.weather.com)

Month	Avg. High Temperature	Avg. Precipitation
Jan	30°F	1.20 in.
Feb	37°F	0.90 in.
Mar	48°F	0.90 in.
Apr	59°F	1.00 in.
May	68°F	1.50 in.
Jun	75°F	1.50 in.
Jul	81°F	1.30 in.
Aug	81°F	1.30 in.

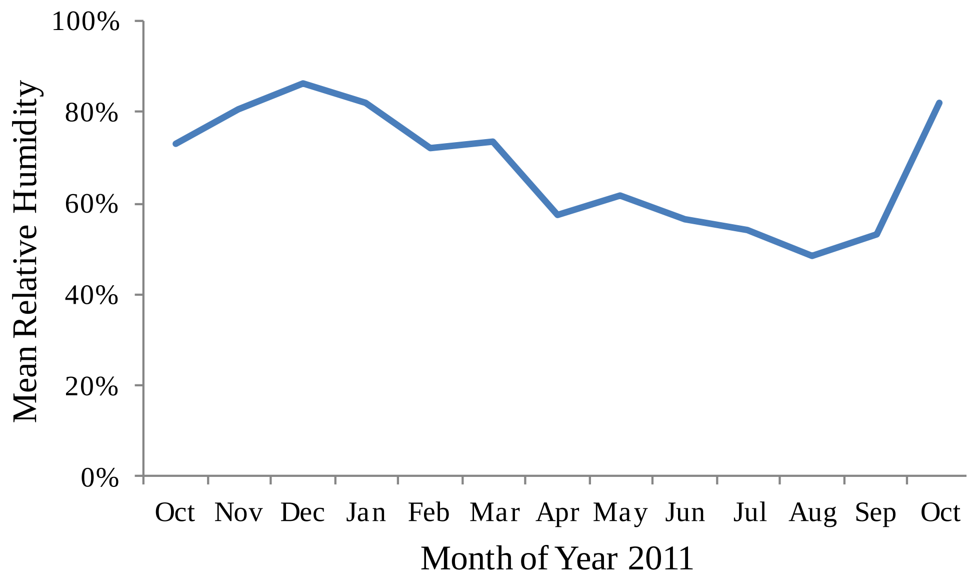


Figure 5-5: Humidity of City of Kelowna in 2011 (after http://kelowna.weatherstats.ca)

The climatic input parameters for calculating FDR for the City of Kelowna in August, 2011 are shown in Table 5-6. Utilizing the proposed fire initiation index described in Equation 5-1, the FII value is calculated as 41, which corresponds to a high probability of fire initiation for the city.

Table 5-6 : Input for FDR calculation for the City of Kelowna in August 2011

Parameters	Value
Relative Humidity	50%
Dry Bulb Temperature	28^{o}C
Rainfall	33 mm
Wind Speed	9.26 km per hour

5.3.2 Vegetation vulnerability index (VVI)

For vegetation vulnerability, a map has been developed with the acquired vegetation vulnerability data from the City of Kelowna database (www.kelowna.ca). Figure 5-6 shows the vegetation vulnerability maps, where, it is evident that, the most of the hilly areas of Kelowna city is vulnerable to wildfire hazard.

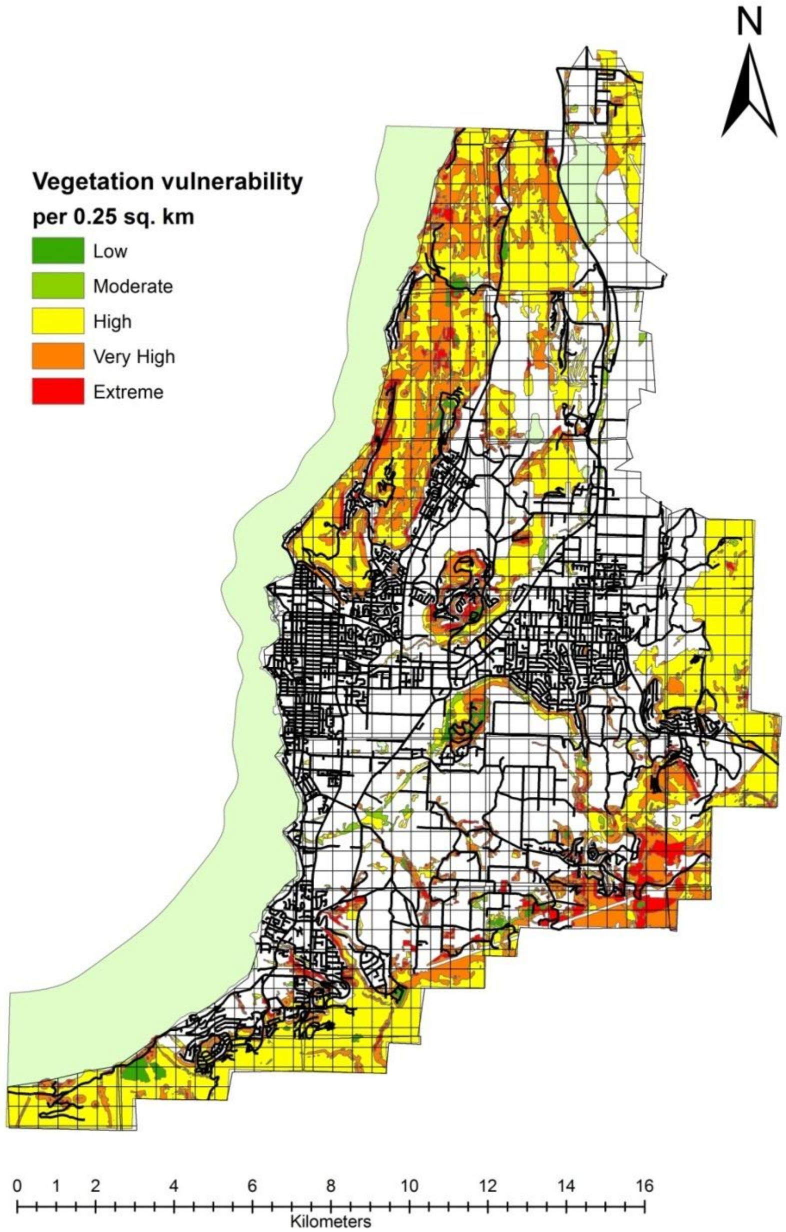


Figure 5-6: Vegetation vulnerability in City of Kelowna (after www.kelowna.ca)

5.3.3 Results and discussions

The proposed framework can be utilized to facilitate the management decisions in several ways. Fire protection zones can be refined based on the proposed risk map. Areas with moderate to high fire risk can be allowed to burn with defensible manners (Olson 2004). The proposed risk map can also be useful to evaluate the resource allocation in fire management systems.

The result of the case study is depicted in Figure 5-7. The spatial distribution of the risk within the city is depicted in Figure 5-8 in GIS maps over a 0.5 km × 0.5 km grid. The case study reveals that, 26 %, 12% and 63% area in Kelowna are assessed to be in a high, moderate and low risk category, respectively.

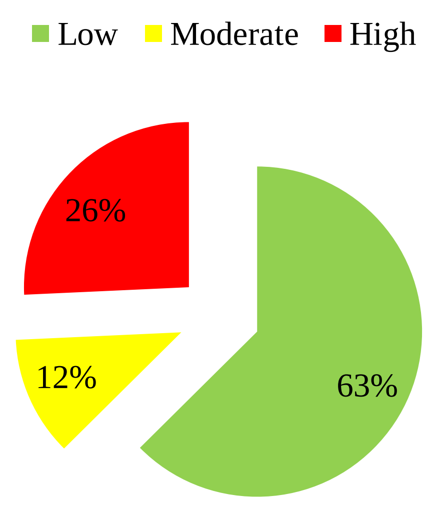


Figure 5-7: Percentages of grids or blocks under different wildfire risk statements

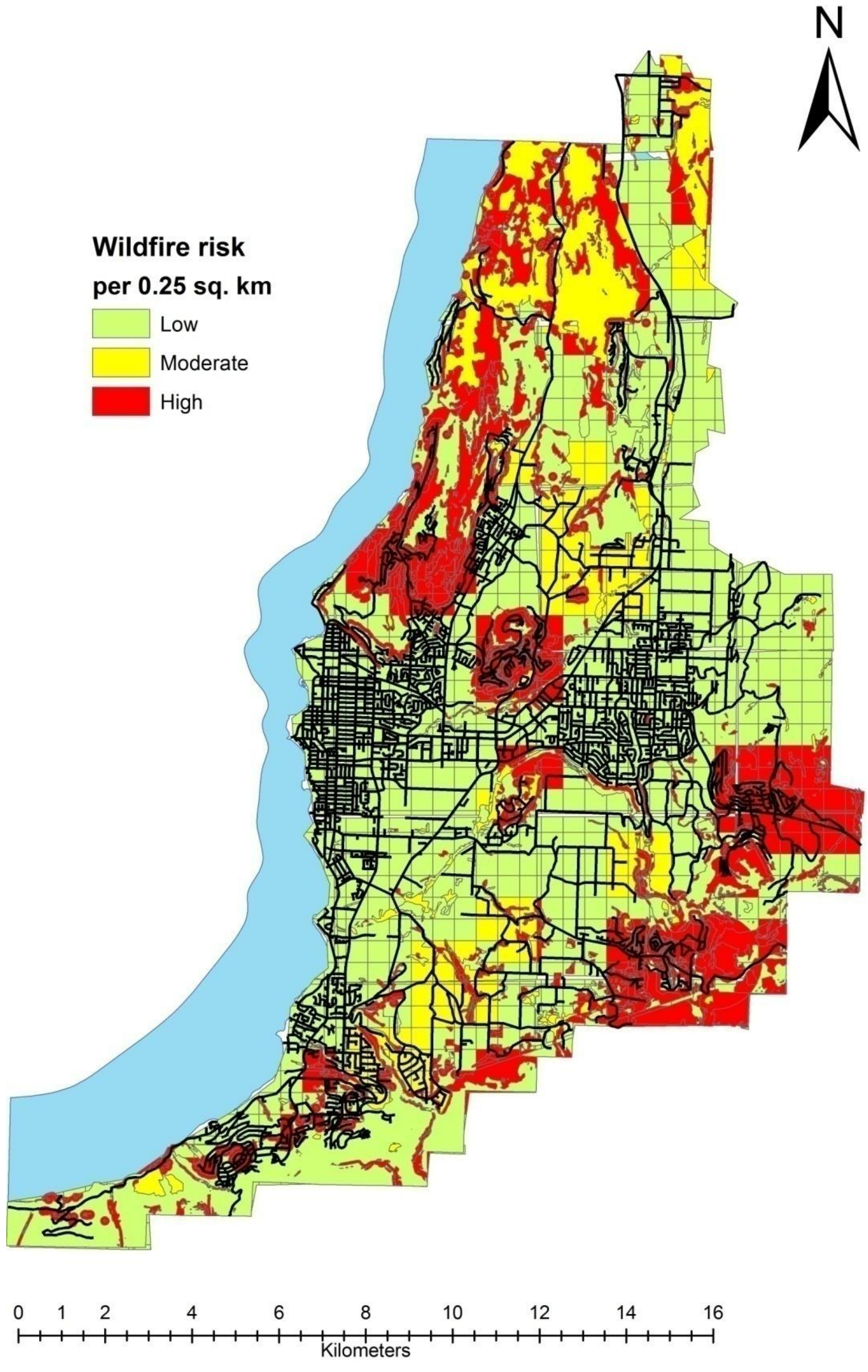


Figure 5-8: Distribution of wildfire risk within the City of Kelowna

5.3.3.1 Pre-positioning of future fire stations with the help of fire vulnerability index (FVI)

In addition to the known facts about the role of weather and fuels in determining wildfire behaviour (Prestemon *et al.* 2010), this chapter suggests that any improvement in fire fighting capabilities will be more successful in reducing the severity of future fires in an urban area. Overall fire vulnerability index is mapped over 0.5 km × 0.5 km grids, which is applicable to any kind of urban fire response. Figure 5-9 shows the vulnerable areas for the City of Kelowna for any kind of urban fire. For calculating fire vulnerability index, GIS is utilized to measure the input parameters for each of the grids. Input values have been adopted from the City of Kelowna database (www.kelowna.ca). With the help of the vulnerability assessment score sheet (after www.fl-dof.com) provided in Appendix C, FVI values for different grids have been measured and mapped over 0.5 km × 0.5 km grids. A sample calculation procedure for a grid is shown in Table 5-7 and Table 5-8. For the particular sample grid, the FVI value was found as 50, which corresponds to a moderate vulnerability of the grid for an urban fire. The FVI map can be useful for the pre-positioning of the future fire stations of an urban area.

Table 5-7: Input variables of a sample grid for fire vulnerability index (FVI) calculation

Input Variable	Description
Road Inventory (km)	116
Vegetation Types	Low
Fuel	YES
Roof Material	Wooden
Siding	Wooden
Distance from nearest Helicopter Dip Spots (km Distance)	0.5
Structural Fire Protection (Distance from nearest Fire Stations)	2.2
Pressurized Hydrants per sq km	23
Facilities (per sq. km)	3

Table 5-8: FVI and corresponding vulnerability for the sample grid

Fire vulnerability index(FVI)	Vulnerability state
50	Moderate

The risky areas denoted by the orange and red colors can be a benchmark for the future decisions and emergency planning for the city. Moreover, the study can be utilized for the decision on pre-positioning of future fire stations within the city. In Figure 5-9, the fire station coverage is determined with a buffer analysis, where 5 km and 3 km buffers are assigned to fulltime fire stations and paid on call fire stations respectively (from the expert opinion). It is evident that there is an urgent need for fire stations in red color grids, that don't have adequate fire station coverage. There is also an urgent need to convert all the existing paid on call service-based fire stations to fully staffed fire stations. However, expert judgements can be incorporated within the model (Vadrevu *et al.* 2010). This would help the decision makers to develop a decision matrix that would identify important causative factors of fire ignitions.

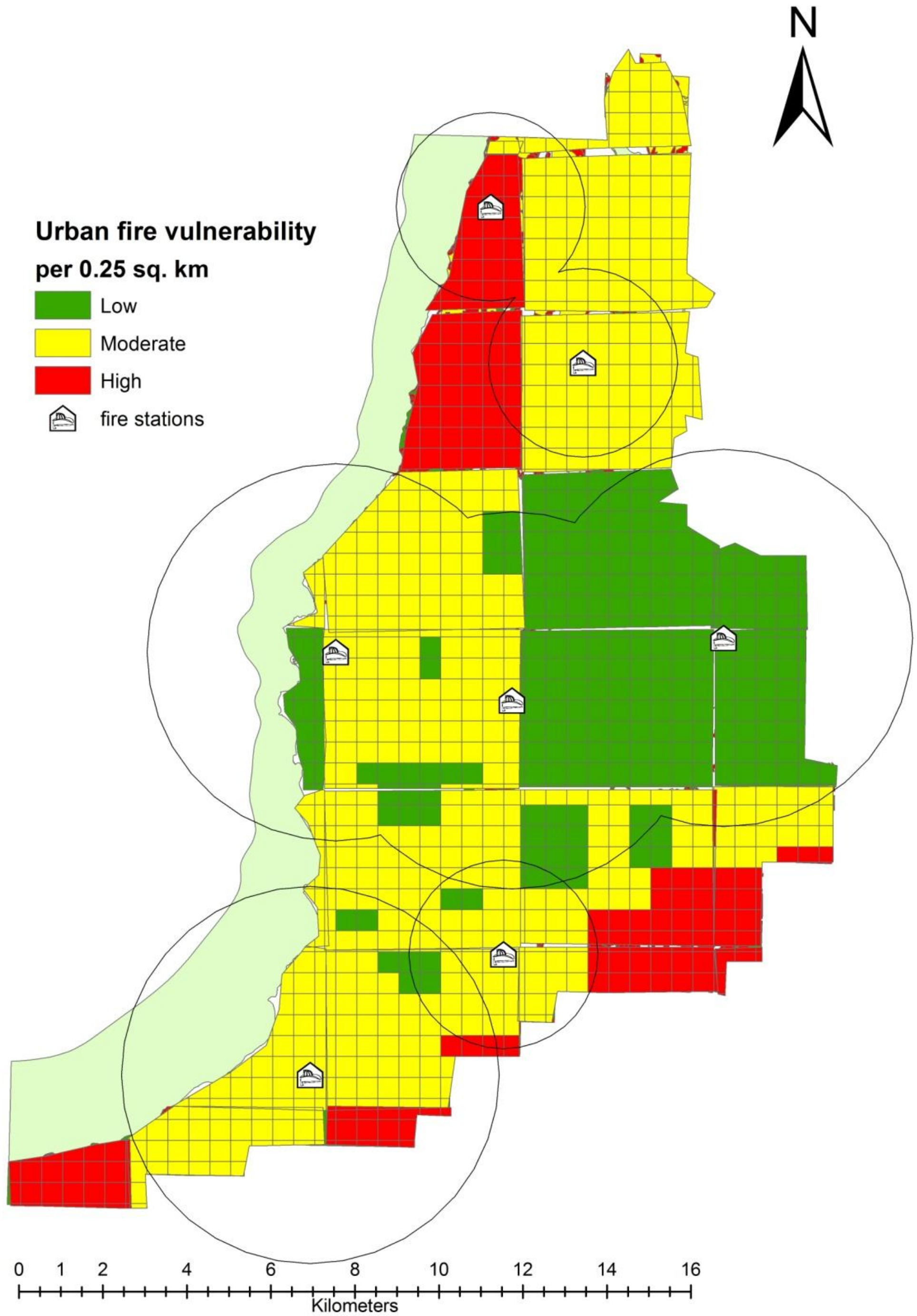


Figure 5-9: Fire station coverage

5.4 SUMMARY

This chapter adopted the GIS-based evaluation approach to assess the wildfire risk considering both the wildfire initiation probability as well as the vulnerability which might make the situation more devastating. To check the applicability of the proposed method, a case study for the City of Kelowna has been conducted. The chapter reveals that, 26 %, 12% and 63% area in Kelowna are assessed to be in a high, moderate and low risk category, respectively for wildfire hazard. Besides, for pre-positioning of the future fire stations, a GIS-based fire vulnerability index is proposed, which is mapped over a 0.5 km × 0.5 km grids. The method considers the existing fire fighting inventories of the community to assess the index. This case study captures the areas to be prioritized for the future up-gradation and extension of the fire stations.

Chapter 6: CONCLUSIONS

6.1 SUMMARY

Although, proposed multiple hazard risk assessment provides the rough estimates of the probable damage, it can be utilized in various ways. Through this assessment, the potential extent of damage and the vulnerable points of the city are highlighted, which can be a starting point for an effective multiple hazard risk reduction plan. This thesis proposes a GIS-based multiple hazard risk assessment methodology for assisting decision makers in resource/fund allocation for emergency response. The decision on choosing the most risky area of a city, which needs immediate concern, has a huge societal and financial impact. A ranking methodology was developed for this purpose considering the existing seismic vulnerability assessment techniques along with due attention to their economic and social importance. This proposed prioritization technique will certainly help the engineers and decision makers in selecting the suitable tool for seismic vulnerability assessment for a particular area. To assess the probable loss of a scenario earthquake, a GIS-based RADIUS methodology is developed. This method will help the decision makers to prioritize the risky areas in terms of probable damage and casualty losses. Finally, a GIS-based wildfire risk assessment tool is developed to facilitate the development of a multiple hazard risk management plan.

This thesis explores the possibility of utilizing different methodologies for multiple hazard risk assessment, particularly for seismic hazard and wildfire hazard. This study provides literature review on various vulnerability and risk assessment techniques and comparative analysis of various techniques are also presented.

This study demonstrates a case study of multiple hazard risk assessment for the City of Kelowna. GIS modeling is utilized for accuracy and quick assessment of the risk. Finally, a systematic approach is demonstrated for risk assessment of the particular area.

6.2 LIMITATIONS OF THE STUDY

The main limitations of the current study are

- For the seismic vulnerability assessment, only the pre-earthquake assessment techniques are taken into account, which may not describe the whole system.

- RADIUS fragility functions generalize both the RC and Masonry buildings, which may not be the appropriate in real time case studies. The structural type developed some uncertainty by simplifying all the buildings into major 2 types (wooden and reinforced cement concrete buildings). The occupancy classes also have similar kind of uncertainty. This caused the buildings within a certain type, to react in the same manner for a particular seismic activity, whereas certain buildings have unique features and do not follow the same damage pattern. The estimation of inhabitants for the individual blocks has also impact on uncertainty; it has been estimated in accordance with the building size, which may not be always accurate. Moreover, the census variables have been derived from the Statistics Canada 2006 census data which leads the seismic damage estimation projected for the year 2006. The current estimated values may change due to the steady increase in overall population. Assigning the building inventory with the actual current inhabitants would improve the quality of the results. The values can be updated easily with the proposed GIS-based model. Moreover, more detailed soil classification should be assigned for the study.

- The effect of lightning is one of the major natural factors for wildfires initiation, which is not considered in the study. Also the equation developed for fire initiation index is valid for grid size up to 5 km^2.

- In case of wildfire risk assessment for the City of Kelowna, some of the recently burned areas should be treated as safer areas, as it may take a while to grow the plantation in those particular areas. Updated vegetation database should be considered to overcome this limitation.

6.3 CONCLUSIONS

This study has identified important characteristics that should be taken into account to select a suitable seismic vulnerability assessment method for buildings. A scoring system was developed for the qualitative review of various vulnerability assessment techniques and a particular attention was given to potential use in Canada. It was found that a vulnerability assessment technique termed as "Hybrid" method i.e. combination of FEMA 310 and IITK GSDMA captures to a greater extent the characteristics that a suitable vulnerability assessment method should possess. The NRC guidelines follows the building categories of Canada, however, it lacks the detailed assessment. Moreover, the comparison between different vulnerability scales has been developed within the study, which can be an appropriate tool for the assessor to translate the vulnerability in a proper way. In seismic risk assessment, many sources of data may be used to estimate the building vulnerability, amongst which is the past earthquake damage survey data. Existence of various vulnerability assessment approaches, raises concern over worldwide to have a simplistic effective vulnerability assessment tool.

The proposed "Hybrid" method provides a suitable basis for the interpretation of vulnerability of buildings for both developing countries as well as developed countries.

The proposed methodologies for seismic damage estimation can yield the guidelines for engineers in designing the future extension and retrofit of the existing infrastructure. Although the developed seismic damage assessment methodology entails some uncertainty coming from both the natural heterogeneity of the database and other uncertainties, it proposes a very effective tool to visualize the risk within a specific area. It will also guide the engineers to develop an effective scenario based seismic hazard emergency plan and a robust decision support tool for the city. The risk assessment methodology can be applied to other cities with very little modifications, which leads to development of a simplistic framework for multiple hazard risk assessment in a scientific manner.

The proposed methodologies for wildfire risk assessment can yield the guidelines for the decision makers in designing the future extension and retrofit of the existing infrastructure.

It will also guide the fire service authorities to develop an effective scenario based wildfire emergency plan and a robust decision support tool for the City of Kelowna. However, the proposed risk assessment methodology can be applied to other cities with very little modifications, which leads to development of a simplistic framework for wildfire risk assessment in a scientific manner. Based on the results obtained from both seismic and wildfire risk assessments, the following conclusions are drawn:

- The developed ranking system for the seismic vulnerability assessment techniques shows that, the proposed Hybrid method outranks the other methods in all perspectives.

- From the case study, it was found that, the Hybrid method has the better variances in risk statement, which can be a better state for the decision makers. The New Zealand Guidelines as well as the NRC Guidelines are also found to perform better in the developed ranking system. In case of the case study of the City of Kelowna, most of the seismically vulnerable buildings are found in the downtown area.
- For scenario of M_w6.0 earthquake under the city, 1361 buildings may be subjected to complete damage among the 20,000 buildings. In this scenario, the number of casualty can be as high as 39. The distribution of MMI can be a benchmark for micro-zonation of the city. For the scenario of M_w8.5 earthquake, located in Cascadia Subduction region, the level of damage states found to be less (62 building damage, with 13 injuries), due to the distance of the source. However, from the spatial analysis in GIS, it can be stated that, the downtown area of the City of Kelowna is more susceptible to seismic damage, compared to other areas, which may turn to a huge economic loss.
- For the wildfire risk assessment, an equation has been developed to predict the probability of wildfire initiation within a region, considering the natural factors. The study developed a GIS-based semi qualitative risk assessment methodology, which combines both the fire initiation probability as well as the vulnerabilities within the community. A case study for the City of Kelowna is conducted. The case study reveals that 26 %, 12% and 63% area in Kelowna are assessed to be in a high, moderate and low risk category. Moreover, the study presents an urgent need for fire stations for some selected blocks within the City of Kelowna, conducting a fire vulnerability assessment for any urban fire.

6.4 RECOMMENDATIONS FOR FUTURE RESEARCH

The current study only focuses on the pre seismic vulnerability assessment tools. The future study may emphasis on conducting some case studies both for pre and post seismic vulnerability assessment in developed as well as in developing countries to generate a validated uniform seismic vulnerability assessment tools.

The identified risky areas from the seismic damage estimation can be undergone to deeper level of vulnerability assessment. An intensive vulnerability assessment may be conducted for the critical infrastructure as well.

The study was conducted with a basic soil map of the area. A proper seismic micro-zonation can be obtained with the actual updated soil map within the area.

The proposed methodology for wildfire risk assessment will guide the fire service authorities to develop an effective scenario based wildfire emergency plan and a robust decision support tool for the City of Kelowna. The pre-positioning of fire service facilities can be determined from the spatially distributed risk. Although the methodology is developed considering the local factors of the City of Kelowna, it can also be applied to other cities with very little modifications, which leads to development of a simplistic framework for wildfire risk assessment in a scientific manner.

The proposed methodologies for multi hazard assessment can yield the guidelines for the decision makers in designing the future extension and retrofit of the existing infrastructure. Moreover, with the help of the generated scenario, guideline for developing a scenario-based contingency plan can also be proposed.

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APPENDICES

Appendix A1: Calculations for AHP

Table A1-1: Pair-wise comparison scale for AHP preferences (after Saaty 1980)

Numerical value	Verbal judgment of preferences	Explanation
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
8	Very, very strong	
7	Very strong or demonstrated	An activity is favored very strongly over another; its dominance demonstrated in practice
6	Strong plus	
5	Strong importance	Experience and judgment strongly favor one activity over another
4	Moderate plus	
3	Moderate importance	Experience and judgment slightly favor one activity over another
2	Weak or slight	
1	Equal importance	Two activities contribute equally to the objective

Table A1-2: Attribute comparison matrix for the AHP

	A	B	C	multiplication^(1/n)	Normalized value
A	1	0.33	0.2	0.40	0.09
B	3	1	0.14	0.75	0.17
C	5	7	1	3.27	0.73
				Sum 4.43	

Table A1-3a: Pair-wise comparison matrix for the alternatives for criteria A

	FEMA 154	Euro Code 8	NZ Code	Tur kish	Hybrid Method	NRC Guidelines (NRCC)	multiplicati on^(1/n)	Normalize d value
FEMA 154	1.0	3.0	3.0	3.0	0.3	0.3	1.25	0.13
Euro Code 8	0.3	1.0	5.0	3.0	0.2	0.2	0.76	0.08
NZ Code	0.3	0.2	1.0	3.0	0.3	0.3	0.53	0.05
Turkish	0.3	0.3	0.3	1.0	0.1	0.1	0.30	0.03
Hybrid Method	3.0	5.0	7.0	7.0	1.0	3.0	3.60	0.40
NRC Guidelines (NRCC)	3.0	5.0	7.0	7.0	0.3	1.0	2.50	0.28

Table A1-3b: Pair-wise comparison for criteria B

	FEMA 154	Euro Code 8	NZ Code	Turkish	Hybrid Method	NRC Guidelines (NRCC)
FEMA 154	1.0	1.0	1.0	3.0	0.2	0.2
Euro Code 8	1.0	1.0	0.3	3.0	0.1	0.2
NZ Code	1.0	3.0	1.0	5.0	1.0	1.0
Turkish	0.3	0.3	0.2	1.0	0.1	0.2
Hybrid Method	5.0	7.0	7.0	7.0	1.0	1.0
NRC Guidelines (NRCC)	5.0	5.0	5.0	5.0	1.0	1.0

Table A1-3c: Pair-wise comparison for criteria C

	FEMA 154	Euro Code 8	NZ Code	Turkish	Hybrid Method	NRC Guidelines (NRCC)
FEMA 154	1.0	3.0	1.0	1.0	1.0	1.0
Euro Code 8	0.3	1.0	0.3	0.3	0.1	0.2
NZ Code	1.0	3.0	1.0	1.0	1.0	1.0
Turkish	1.0	3.0	1.0	1.0	1.0	1.0
Hybrid Method	1.0	7.0	1.0	1.0	1.0	1.0
NRC Guidelines (NRCC)	1.0	5.0	1.0	1.0	1.0	1.0

Table A1-4: Final AHP ranking

Alternatives	Criteria				
	A	B	C	Weighted sum	Rank
FEMA 154	0.13	0.08	0.13	0.13	4.00
Euro Code 8	0.09	0.06	0.04	0.04	6.00
NZ Code	0.06	0.18	0.13	0.14	3.00
Turkish	0.03	0.03	0.13	0.11	5.00
Hybrid Method	0.41	0.39	0.16	0.22	1.00
NRC Guidelines (NRCC)	0.28	0.33	0.15	0.19	2.00

Appendix A2: Calculations for TOPSIS

First of all, the normalized decision matrix was developed, which is shown in B1. This step converts various attribute dimensions into non-dimensional attributes, and thus allows comparisons across criteria. The normalization has been done using:

$$r_{ij} = x_{ij}/ (\Sigma x^2_{ij}) \quad \text{for } i = 1, \ldots, m;\ j = 1, \ldots, n \qquad [1]$$

Where, $x_{ij}$is the score of option i with respect to criterion j.

Table A2-1: Normalized decision matrix for TOPSIS

Alternatives		**Criteria**	
	A	B	C
FEMA 154	0.46	0.33	0.35
Euro Code 8	0.29	0.33	0.13
NZ Code	0.37	0.33	0.30
Turkish	0.12	0.23	0.17
Hybrid Method	0.61	0.70	0.44
NRC Guidelines (NRCC)	0.41	0.37	0.74

Then the weighted normalized matrix has been formed. The weight has been derived from the entropy method (A=0.33, B=0.33 and C=0.34) and the weighted normalized matrix is shown in Table B2.

Table A2-2: Weighted normalized matrix

Alternatives	**Criteria**		
	A	B	C
FEMA 154	0.15	0.11	0.12
Euro Code 8	0.09	0.11	0.05
NZ Code	0.12	0.11	0.11
Turkish	0.04	0.08	0.06
Hybrid Method	0.19	0.23	0.15
NRC Guidelines (NRCC)	0.13	0.13	0.26

Then the ideal and negative ideal solutions have been determined as follows:

Ideal solution: $A^* = \{ v_1^*, \ldots, v_n^* \}$, where $v_j^* = \{ \max (v_{ij}) \text{ if } j \in J ; \ \min (v_{ij}) \text{ if } j \in J' \}$

Negative ideal solution: $A' = \{ v_1', \ldots, v_n' \}$,

where $v' = \{ \min (v_{ij}) \text{ if } j \in J ; \ \max (v_{ij}) \text{ if } j \in J' \}$

If J is the set of benefit attributes or criteria (more is better) and J' be the set of negative attributes or criteria (less is better). After that the separation measures for each alternative has been calculated as follows:

The separation from the ideal alternative is calculated as equation [2]

$$S_i^* = [\Sigma (v_j^* - v_{ij})^2]^{½} \qquad i = 1, \ldots, m \qquad [2]$$

Similarly, the separation from the negative ideal alternative is shown in Equation [3]

$$S'_i = [\Sigma (v_j' - v_{ij})^2]^{½} \qquad i = 1, \ldots, m \qquad [3]$$

Table A2-3: Relative closeness in TOPSIS analysis

Alternatives	Positive Ideal Solution (S*)	Negative Ideal Solution (S-)	Relative Closeness (C*)
FEMA 154	0.19	0.14	0.42
Euro Code 8	0.27	0.06	0.19
NZ Code	0.21	0.11	0.34
Turkish	0.30	0.02	0.05
Hybrid Method	0.11	0.24	0.69
NRC Guidelines (NRCC)	0.13	0.24	0.65

The relative closeness to the ideal solution C_i^* is calculated with the following Equation:

$$C_i^* = S'_i / (S_i^* + S'_i) \ ,0 \quad < C_i^* < 1 \qquad [4]$$

Appendix B: RADIUS results

Table B1: RADIUS building classes

Building Classes Explanation (RADIUS)	
RES1	Informal construction - mainly slums, row housing etc. made from unfired bricks, mud mortar, loosely tied walls and roofs.
RES2	Wooden composite construction - sub-standard construction, not complying with the local code provisions. Height up to 3 stories. Also found in Un-Reinforced Masonry and Reinforced Concrete building.
RES3	URM-RC composite construction - old, deteriorated construction, not complying with The latest code provisions. Height 4 - 6 stories.
RES4	Engineered RC construction - newly constructed multi-storey buildings, for residential and commercial purposes.
EDU1	School buildings, up to 2 stories, usually percentage should be very small
EDU2	School buildings, greater than 2 stories, usually percentage should be very small
MED1	Low to medium rise hospitals, usually percentage should be very small
MED2	High rise hospitals, usually percentage should be very small
COM	Shopping Centers
IND	Industrial facilities, both low and high risk

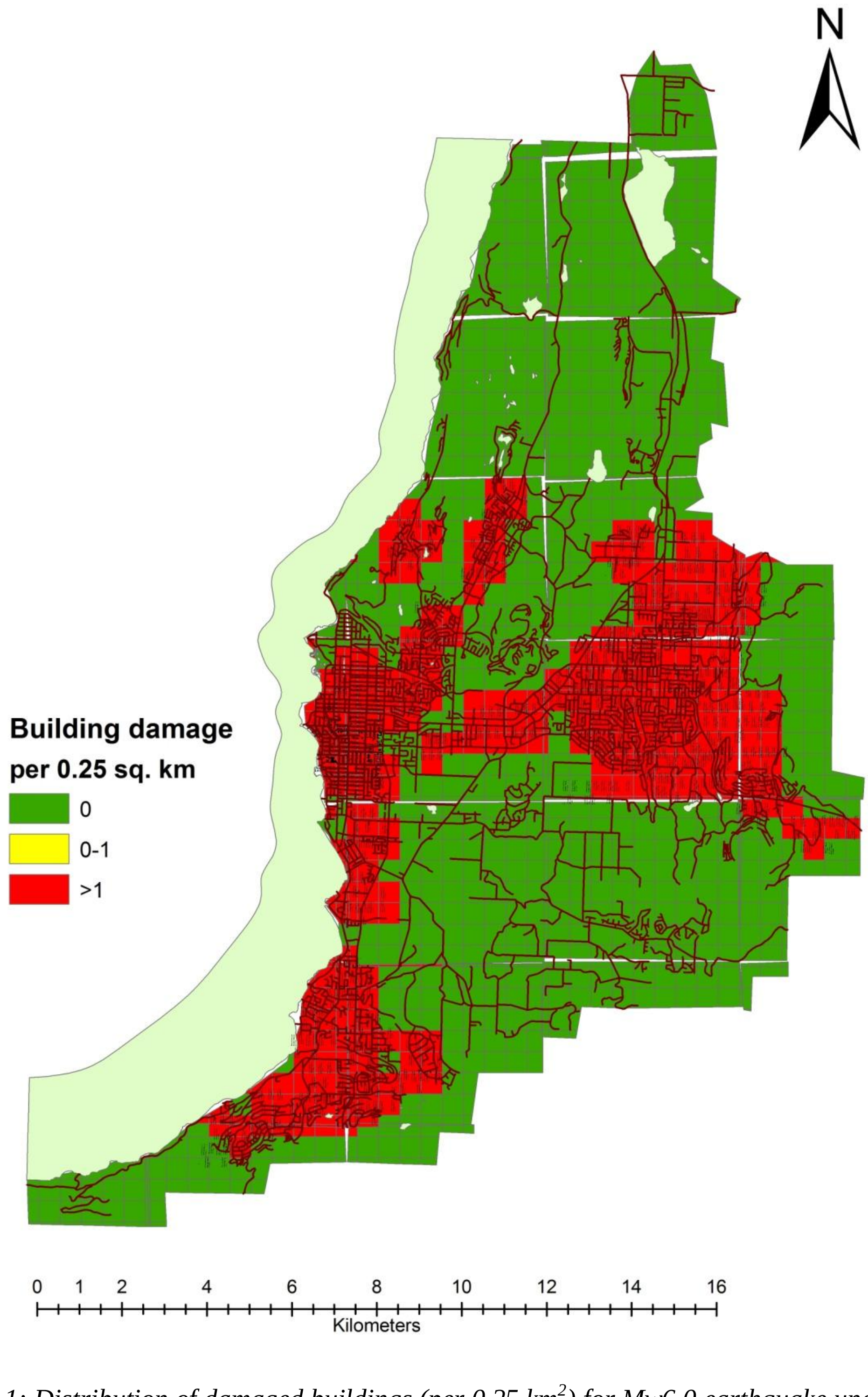

Figure B-1: Distribution of damaged buildings (per 0.25 km^2) for Mw6.0 earthquake under the city (distance = 0 km)

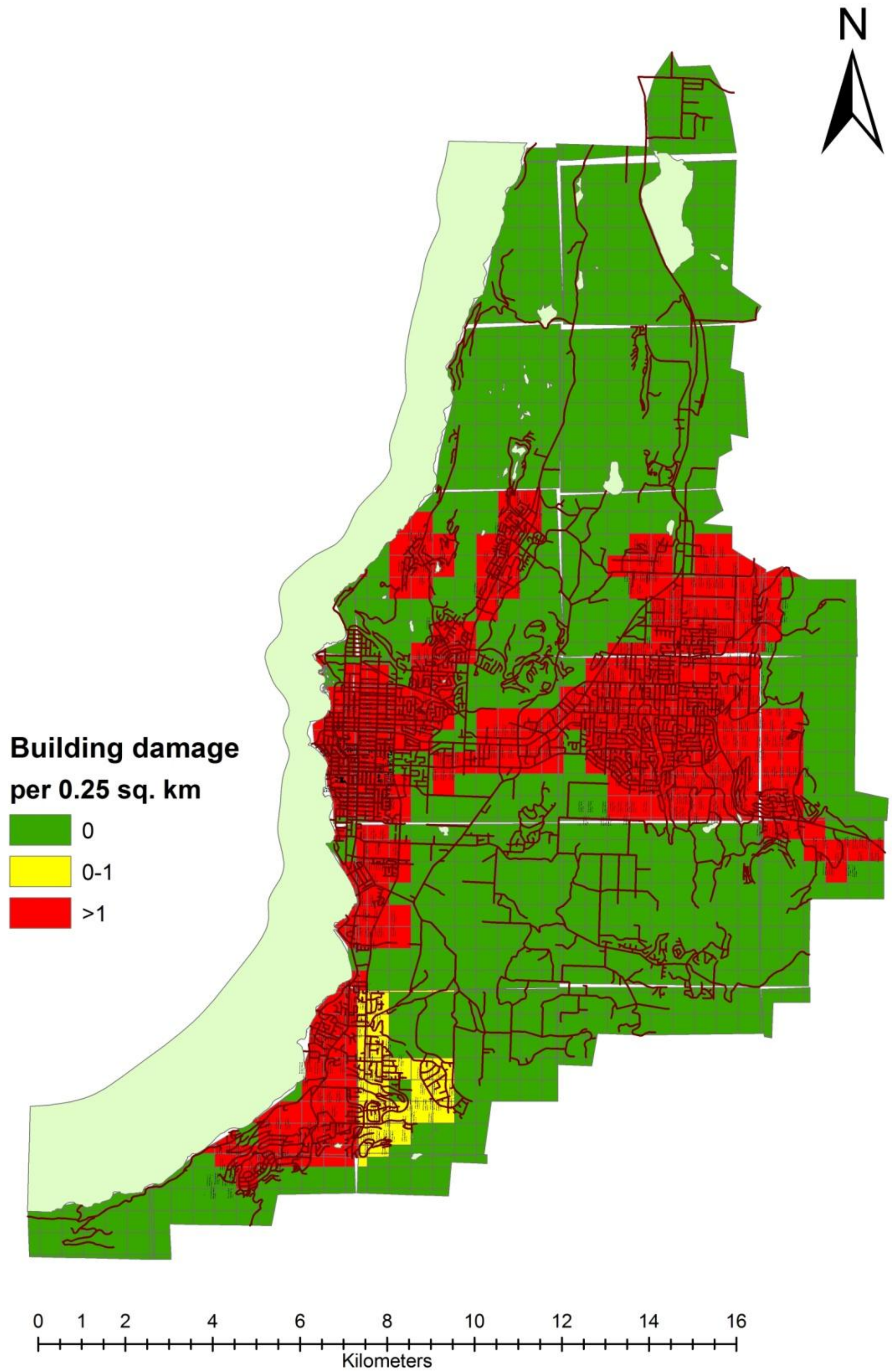

Figure B-2: Distribution of damaged buildings (per 0.25 km^2) for Mw5.5 earthquake under the city (distance = 0 km)

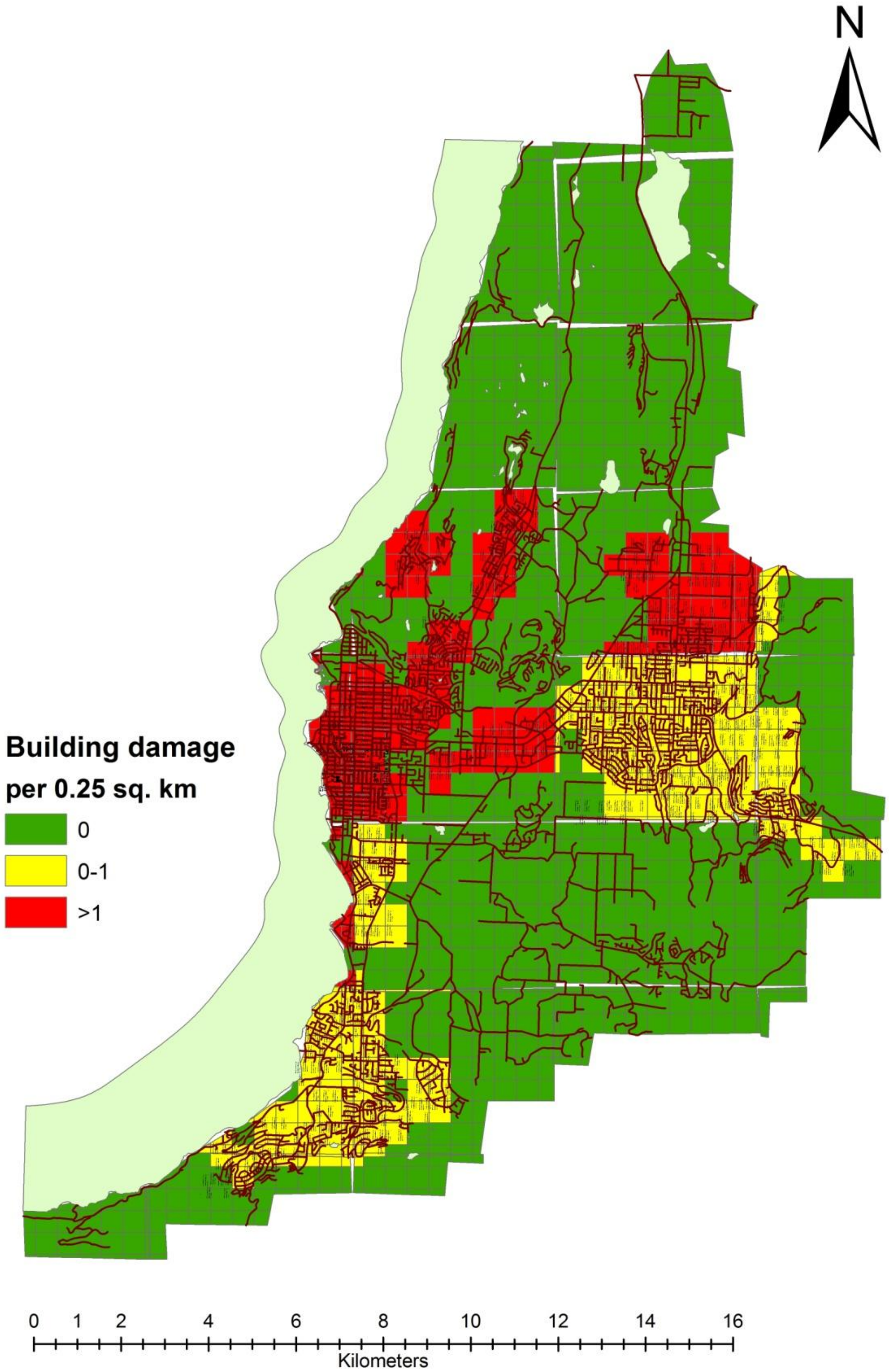

Figure B-3: Distribution of damaged buildings (per 0.25 km^2) for Mw4.5 earthquake under the city (distance = 0 km)

Appendix C: Input parameters for existing fire danger and vulnerability indices

Table C1: Different wildfire risk assessment tools

System	Developed/ Proposed By	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
Fire weather index system	Forest Service, British Columbia, http://bcwildfire.ca	Y	Y	Y	Y	Y	-	-	-	-	-	-	-	-	-	-	-	-	Maps
National fire danger rating system	USDA forest services (http://www.fs.fed.us) (http://www.wrh.noaa.gov), National Wildfire Coordinating Group (2002)	Y	Y	Y	Y	Y	Y	-	-	-	-	-	-	-	-	-	-	-	Maps
Canadian forest fire danger rating system	Lawson and Armitage (2008), http://fire.ak.blm.gov http://www.srd.alberta.ca	Y	Y	Y	Y	Y	-	Y	-	-	-	-	-	-	-	-	-	-	Maps
Canadian Wildland Fire Information System	http://cwfis.cfs.nrcan.gc.ca	Y	Y	Y	Y	Y	-	Y	-	-	-	-	-	-	-	-	-	-	Interactive Maps
Interface wildfire threats rating in British Columbia	First Nations' Emergency Services, British Columbia, http://www.fness.bc.ca	Y	Y	Y	Y	Y	Y	-	-	-	-	-	-	-	-	-	-	-	Score (55-130)
National fire danger rating system	The New Jersey Forest Fire Service (http://www.nj.gov)	Y	-	-	-	-	-	-	Y	-	-	-	-	-	-	-	-	-	Maps

A wildfire threat rating system for the McGregor model forest	Hawkes *et al.* (1997), http://www.mcgregor.bc.ca	Y	-	-	-	-	Y	-	Y	Y	-	-	Y	Y	Y	Y	-	-	Scores and GIS Maps
Wildfire danger rating system	Gem County Fire District (http://gcfd1.com/)	Y	-	-	-	-	Y	-	-	-	Y	Y	Y	Y	-	-	-	-	Linguistic Values and flags
Wildfire hazard severity rating checklist for Arizona homes and communities	University of Arizona, DeGomez (2011)	Y	-	-	-	-	Y	-	-	-	Y	-	Y	-	-	-	Y	Y	Scores (49-84)
GVWD wildfire risk management system	The Greater Vancouver Water District (GVWD), Ohlson *et al.* (2003), http://www.fire.uni-freiburg.de	Y	Y	Y	Y	Y	Y	Y	-	Y	-	-	-	-	-	-	-	-	GIS Overlay Maps
Fire danger index	New South Wales Government, Australia, http://www.rfs.nsw.gov.au And Zululand Fire Protection Services, http://www.zfps.co.za	-	Y	Y	Y	Y	-	-	-	-	-	-	-	-	-	-	-	-	Black box, Scores (0-100)
Wildfire risk assessment score sheet	Florida Forest Service , Division of Forestry (2010)	Y	-	-	-	-	-	-	-	-	Y	-	Y	Y	Y	-	Y	Y	Scores (50-120)
Florida fire danger index	Florida Forest Service, http://www.fl-dof.com	Y	Y	Y	Y	Y	-	Y	-	-	-	-	-	-	-	-	-	-	Black box, Score (1-5) and Maps

"Y": Considered, "-": Not Considered

Annotation Used:

Parameters	**Annotation**	**Parameters**	**Annotation**
Fuel or vegetation Type	A	Building Materials	J
Relative Humidity	B	Escape Routes	K
Temperature	C	Accessibility	L
Drought	D	Proximity to Water Sources	M
Wind Speed	E	Fire History	N
Topography and Landscape	F	Human Factors	O
Supplementary weather elements(e.g. Lightening, Air quality etc.)	G	Available Fire Protections	P
Automated Weather Stations	H	Utilities	Q
GIS	I	Output Type	R

Table C2: Fire vulnerability assessment score sheet (after www.fl-dof.com)

Vulnerable Parameters	Score
A. ACCESSIBILITY	
1. Ingress and Egress	
Two or more roads in/out	0
One road in/out (entrance and exit is the same)	7
2. Road Width	
Road width is >24 feet	0
Road width is > 20 feet and < 24 feet	2
Road width is < 20 feet	4
3. Road Accessibility	
Hard surface all-weather road with drivable shoulders	0
Hard surface road without drivable shoulders	2
Graded dirt road	3
Non-maintained dirt road	5
4. Secondary Road Terminus	
Majority of dead end roads <= 300 feet long	0
Majority of dead end roads > 300 feet long	3
5. Cul-de-sac Turnarounds	
Outside radius >50 feet	0
Outside radius < 50 feet	3
6. Street Signs	
Present with non-combustible materials	0
Present with combustible materials	3
Not Present	5
B. V E G E T A T I O N	
1. Vegetation Types	
Low fire hazards (with recent fire history)	5
— grasses to 3 feet tall (except cogon grass)	
— blowy leaves	
— hardwood swamps	
— palmetto/gall berry less than 3 feet	
Medium fire hazards (With recent fire history)	10

— cypress swamp	
— palmetto/gall berry 3-6 feet	
— grasses over 6 feet tall/cogon grass	
— sand pine scrub less than 6 feet tall	
— dense pine 20-60 feet tall	
High fire hazards (Very few recent fire history)	20
— palmetto/gall berry 3 to 6 feet with dense pine over story*	
— palmetto/gall berry greater than 6 feet	
— sand pine scrub over 6 feet	
Extreme fire hazards (No recent history)	25
— palmetto/gall berry over 6 feet with dense pine over story*	
— sand pine scrub with dense pine over story*	
* Pine canopy must have at least 75% crown closure to be considered dense pine	
2. Defensible Space (average for subdivision structures adjacent to wildland fuels)	
More than 100 feet	0
Between 30 and 100 feet	10
Less than 30 feet	25

C. BUILDING CONSTRUCTION

1. Roof Material	
> 75% of homes have Class A asphalt or fiberglass shingles, slate, or clay tiles, cement, concrete or metal roofing or terra-cotta tiles	0
50-75% of homes have Class A asphalt or fiberglass shingles, slate, or clay tiles, cement, concrete or metal roofing or terra-cotta tiles	10
< 50% of homes have Class A asphalt or fiberglass shingles, slate, or clay tiles, cement, concrete or metal roofing or terra-cotta tiles	15
2. Soffits/Siding	
> 75% of homes have non-combustible or fire-resistant siding and soffits	0
50-74% of homes have non-combustible or fire-resistant siding and soffits	5
< 50% of homes have non-combustible or fire-resistant siding and soffits	10
3. Skirting (skip if not applicable)	
> 75% of homes have skirting underneath raised floors/decks	0
50-74% of homes have skirting underneath	5
< 50% of homes have skirting underneath	10

D. FIRE PROTECTION	
1. Helicopter Dip Spots (min 4’ water depth year round/45’ radius obstruction clearance/75’ approach clearance in at least one dire c t i o n)	
Under 2 minute turnaround (< 1 mile)	0
Within 4 minute turnaround (1-2 miles)	2
Within 6 minute turnaround (2-3 miles)	4
Beyond 6 minute turnaround (greater than 3 miles) or unavailable	7
2. Structural Fire Protection	
5 miles or less from staffed fire department	0
More than 5 miles from staffed fire department	5
3. Water Supply	
a. Pressurized hydrants	
500 gallons per minute hydrants available < 1000 foot spacing (municipal)	0
< 500 gallons per minute hydrants available	5
No pressurized hydrants available	10
b. Other water sources	
*NOTE: If a pressurized system is available, skip this section	
Dry hydrants available year round within subdivision	0
Other accessible draft sources (min. 3000 gal) exist within subdivision	1
Draft or pressure sources available within 5 miles via all weather roads	3
No draft or pressure sources available within 5 miles	10
E. U T I L I T I E S	
1. Gas (skip if not applicable)	
Underground/clearly marked	0
Underground/not marked	3
Above ground/clearly marked with a 30 foot cleared perimeter	1
Above ground/not marked	3
2. Electric	
Underground/clearly marked	0
Underground/not marked	3
Overhead with a 20 foot wide maintained right of way	1
Overhead with right of way not maintained	5
3. Septic Tank/Drain Field Systems (skip if not applicable)	

Present and clearly marked	1
Present, not clearly marked	3

F. ADDITIONAL RATING FACTORS *

1. Large adjacent areas of wildland with accumulated wildland fuels and no prescribed burning program for fuel management	0-10
2. Homeowner association lacks the organizational structure for a sustained fire Prevention and mitigation effort.	0-5
3. Extensive canal or ditch system makes cross country access to fires difficult	0-10
4. Closeness of adjacent structures may contribute to fire spread from structure to structure	0-5
5. Less than 2/3 of the lots have been developed - undeveloped lots covered with wildland fuels, making stopping spread of the fire through the subdivision difficult	0-10
6. History of wildfire occurrence is higher than surrounding areas due to lightning, arson, debris burning etc.	0-10