Earthquake Vulnerability and Critical Infrastructure Inventory of Metro Vancouver

SolSchools International, 2015

Prepared by The Critical Infrastructure Analysts

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Disclaimer:
This report was created by undergraduate students to fulfill course requirements at Simon Fraser University and should not be interpreted as expert opinion. The Critical Infrastructure Analysts is not a real company.

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1.0 INTRODUCTION

Urban earthquake vulnerability has increased over the years due to the complexities in urban environments (Duzgun *et al*., 2011). It is essential to have a clear view on how vulnerable our surrounding environment is during an earthquake in order to conduct some targeted preparedness plans. This study will be conducted by The Critical Infrastructure Analysts for Metro Vancouver. Through a diligent literature review, critical infrastructure will be defined and located, and the most vulnerable regions within Metro Vancouver to a major magnitude 9.0 megathrust earthquake will be delineated. Various ESRI ArcGIS software will be employed to construct an inventory of critical infrastructure and a weighted multi-criteria analysis of the most and least vulnerable regions. Data varying from socio-economic factors to geophysical features and various public infrastructures will all be included in this analysis to obtain a greater understanding of human and physical vulnerabilities in the region.

Our scenario is a worst-case event involving an M9.0 megathrust earthquake. With that said, due to the unpredictable nature of earthquakes (Geller, 1997), this study is not a simulation; rather, this is an assessment of what critical infrastructure is at risk of being damaged or destroyed. This report will serve as a tool for different groups to preview their situation. From the economic perspective, it will indicate which areas are at greater risk of losses in the event of an earthquake; from the political perspective, it will help to guide the provincial government in preparing a quick response when the earthquake happens and it can also help to facilitate infrastructure improvements; from the social perspective, it will provide some information for the general public with regards to evacuation shelters and potentially vulnerable areas.

The following section will provide a background to megathrust earthquakes and their relevance to Metro Vancouver, as well as provide a definition of critical infrastructure.

1.1 STUDY AREA

The study area, Metro Vancouver, is a major metropolitan area in southwestern British Columbia located at the Fraser River delta (Figure 1). With a total population of 2.4 million people in 2012, according to Statistics Canada, the Vancouver area contains 22 municipalities; the largest cities in the region are Vancouver, Surrey, Burnaby, and Richmond. This region has a variety of different geographic features and land types, such as mountains, reclaimed land, and deposited silt from the Fraser River, all of which present challenges in determining vulnerable areas, especially with regards to the danger of soil liquefaction and landslides. Additionally, the region is physically bordered by the Coastal Mountains to the North and Northeast and by the Georgia Strait to the west. Point Roberts, in the United States, is not included in this study.

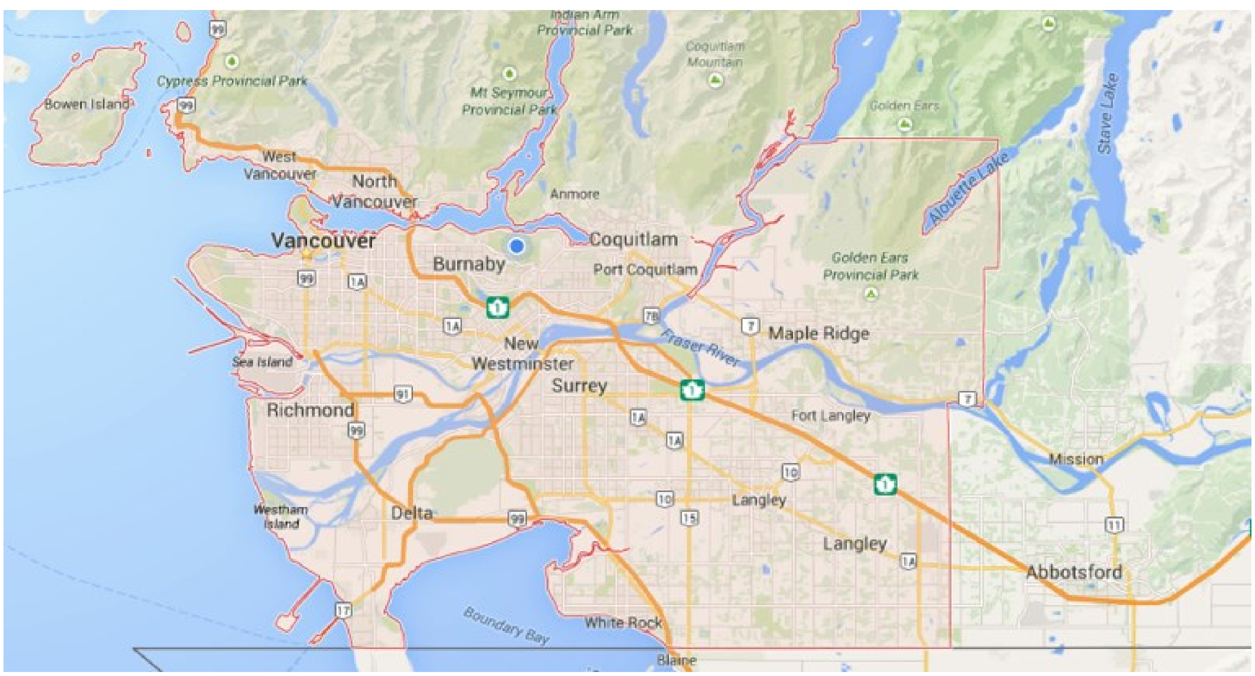

Figure 1. Metro Vancouver; the study area stretches from Bowen Island in the west to Maple Ridge and Langley in the east (Google Maps, 2015).

2.0 LITERATURE REVIEW

2.1 Megathrust Earthquakes

Earthquakes are part of the earth's natural tectonic processes; because of the movement of tectonic plates, stress builds up where these plates meet at faults or plate boundaries. Earthquakes occur when two plates suddenly move past each other, relieving the stress that had built up.

Subduction zones are areas where a dense oceanic plate subducts, or is pushed under the less dense continental plate (Stern, 2002). Due to irregularities in rock formations and friction, these plates often become locked together (Stern, 2002). When the strain overcomes friction, the two plates move quickly and violently past each other, causing what is known as a megathrust earthquake (Stern, 2002). Subduction zones have been the source of the largest earthquakes in recorded history; the 1960 Chile earthquake (M9.5), 1964 Alaska earthquake (M9.2), 2004 Indian Ocean earthquake (M9.1), and the 2011 Japan earthquake (M9.0) were all megathrust earthquakes (Stern, 2002). Subduction zones are found at the plate boundaries of the Pacific plate and where the Indo-Australian plate meets the Eurasian plate (figure 2).

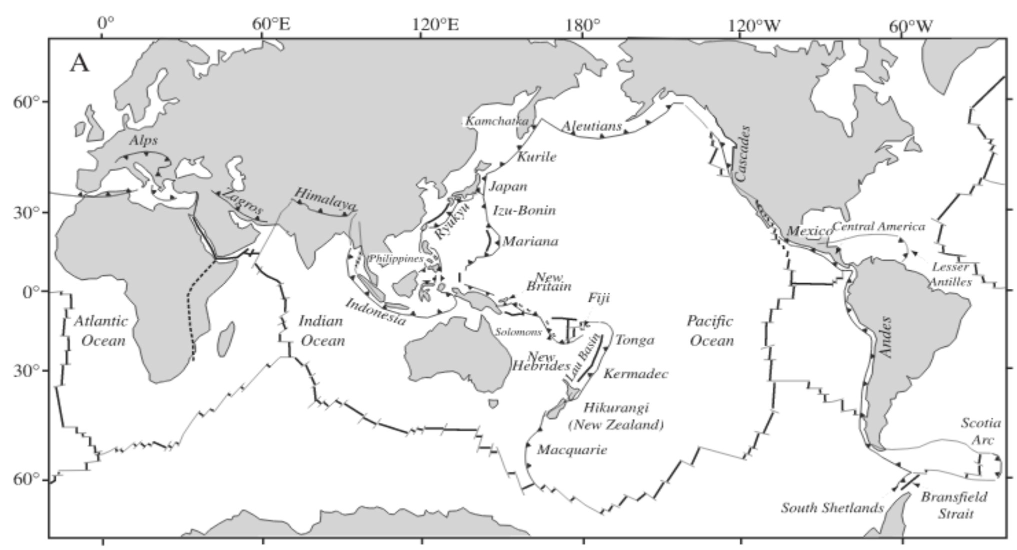

Figure 2. Subduction zones and convergent plate boundaries (Stern 2002).

2.2 Earthquakes and Metro Vancouver

Metro Vancouver sits in a seismically active region. Every year, hundreds of small earthquakes occur in and around our region. However, with the exception of, for example, the M6.8 earthquake near Seattle in 2001 and the M7.8 earthquake in Haida Gwaii in 2012, most earthquakes are too small or too far away to be felt, often falling between M2.0 and M4.0.

Metro Vancouver is situated near a convergent plate boundary called the Cascadia Subduction Zone. This 1000 km fault line extends offshore from southern British Columbia down to northern California, and it is where the oceanic Juan de Fuca plate subducts underneath the continental North American plate (figure 3).

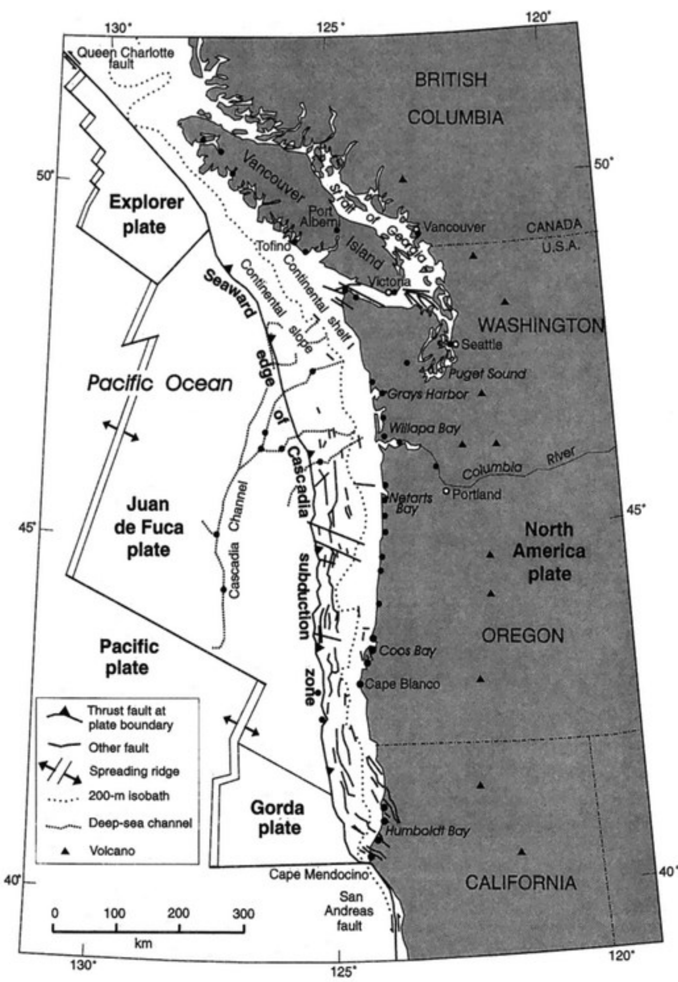

Figure 3. Location of the Cascadia Subduction Zone and the Juan de Fuca, North America, and Pacific plates (Clague, 1997).

Unlike subduction zones around the world which have produced large and very destructive earthquakes in recent memory, the Cascadia Subduction Zone has not produced a major earthquake in recorded North American history. As a result, until the 1980s, many scientists assumed that Cascadia did not produce large earthquakes (Clague, 1997). Recent research suggests that the plate boundary is similar to other major subduction zones around the world which have produced large earthquakes, and that the Juan de Fuca and the North American plate are locked and are accumulating stress, meaning that in the future, this subduction zone could produce a large earthquake with a magnitude around M9 (Heaton & Hartzell, 1987; Rogers, 1988). Additionally, while written records do not show any occurrence of major earthquakes, evidence of large subduction earthquakes can be found in the geological record. Examination of buried soils on the Washington coast by Atwater and Yamaguchi (1991) showed a layer of soil covered by a large layer of mud, with well-preserved plant material still present in the soil layer, which suggested a sudden rise in the sea level too large to be explained by non-seismic processes. Also, tsunami records from Japan show an occurrence of a large tsunami with no local accompanying earthquake in early 1700. This, along with examination of tree rings and carbon dating in the buried soil samples in Washington, suggests that the last major subduction earthquake occurred in January of 1700 (Satake *et al*., 1996). Recently, studies have suggested that the risk of the next big earthquake hitting Cascadia could be as high as 37% (Goldfinger *et al*., 2012), with a magnitude comparable to the 2004 Indian Ocean earthquake or the 2011 Japan earthquake.

Because Metro Vancouver has not experienced large earthquakes, many people are not equipped with earthquake survival packs, and many buildings, especially those that were built before modern building codes, are at risk of severe damage or collapse. However, not only older buildings are at risk of collapse. During the 2010 Chile earthquake, a 15-story apartment building fell over, despite having just been completed a year prior. Additionally, several other buildings experienced varying degrees of damage. Rojas et al. (2011) found that structures like these buildings have longer periods of motion, which makes them more susceptible to damage from long-period ground motion such as that produced by a subduction earthquake. Molnar et al. (2014) found that the soil in the Metro Vancouver area have the potential to amplify long-wavelength ground motion, posing a high risk of damage to the hundreds of long-period highrises and bridges in Metro Vancouver. This presents several problems for the effectiveness and the vulnerability of the region's critical infrastructure, especially in areas that may be prone to liquefaction or landslides. The 2010 Christchurch and the 2011 Japan earthquakes showed that liquefaction can render road networks impassable, making movement and evacuation difficult. Water distribution systems can be significantly affected by a major earthquake event, which in turn can hamper fire suppression and rescue efforts (Kuraoka & Rainer, 1996). Additionally, Port Metro Vancouver is one of the largest ports in North America. Shafieezadeh and Burden (2014) note that medium to large earthquakes can disrupt seaport operations for months after the initial earthquake event, especially if berths are damaged.

2.3 Defining Critical Infrastructure

Before any analysis can be done, it must be determined what the term "critical infrastructure" actually means and what can be considered critical infrastructure. In defining this term, we can narrow down the amount of data that needs to be looked at, and we can exclude factors that may be less critical. Public Safety Canada (2014) defines critical infrastructure as "processes, systems, facilities, technologies, networks, assets and services essential to the health, safety, security or economic well-being of Canadians and the effective functioning of government," and that should our critical infrastructure be disrupted, it would result in loss of life or severe economic damage. For the purposes of our study, we have narrowed down critical infrastructure into categories (table 1). Table 1 also presents our reasons for choosing the different categories of critical infrastructure.

Table 1. Critical Infrastructure Inventory and their Categories

Factor	Reasoning	References
Transportation		
Major road network, bridges & tunnels	Impair post-disaster evacuation, response and recovery	Chang et al., 2012; Arsik and Salman, 2013; Sun et al., 2014; Clague, 2002
Public transportation	More individuals are car-free and need transportation to remove people from risky areas	The Carfree Census Database, 2012
Utilities		
Water mains/pump stations	Water for consumption and to fight fires, potable water for residential and hospitals	Christchurch City Council, 2011; Mousavi et al. 2008; Pickett, 2008
Reservoirs/dams	Water for consumption; potential flooding	Christchurch City Council, 2011
Sewage lines/pump stations	Efficient and clean method of waste disposal; contamination risk to ground water, water reservoirs & natural bodies of water; unsanitary conditions expose citizens to major health risks	Christchurch City Council, 2011
Power lines	Catalyst of fires following an earthquake; electricity to civilians	Michigan Technological University, 2007
Emergency services		
Fire halls	Fire response, structural damage & hazardous materials	Scawthorn, 1997; Scawthorn, 2011; Mousavi et al., 2008
Hospitals	Tend to victims seeking medical attention & failure would prevent rapid care	Wang, 2014; Geohazards International, 2009; Onur et al., 2005; Providence Health Care, 2013; Pickett, 2008
Evacuation Shelters		
Schools, arenas, community centres, convention centres	More stringent building code standards to shelter displaced civilians; relief and rehabilitation shelters for communities	Johnson, 2007; APEGBC, 2006; Moteff & Parfomak, 2014; BC Ministry of Public Safety, 2009
Economic		
Airports	Stop or delay the transportation of cargo and passengers; economic damage	Shepard and Dybvig, 2003
Ports	Stop or delay the transportation of cargo and passengers; economic damage	Port Metro Vancouver Economic Impact Study, 2012; Horwich, 2000
Railways	Stop or delay the transportation of cargo and passengers; economic damage	
Oil pipelines	Environmental damage; economic damage	CAPP, 2013; Ministry of Environment
Jet fuel pipelines	Catalyst of fires following an earthquake; fuel source for the airport and port	Scawthorn, 1997

2.4 Defining Vulnerability

Vulnerability has several different definitions, depending on the context to which it is applied. The United Nations Office for Disaster Risk Reduction (2007) defines vulnerability as the "characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard." Various factors, including physical, social, and economic factors, contribute to vulnerability; building construction, public awareness, and governmental preparedness are some examples. For the purposes of our study, socio-economic and physical factors will be combined with emergency services, evacuation spaces and water pipelines to produce weighted multi-criteria evaluations.

2.4.1 Physical Vulnerabilities

The geology of Metro Vancouver makes it susceptible to landslides and liquefaction during an earthquake. Landslide and liquefaction zones are important to a vulnerability assessment because a majority of structures in Metro Vancouver may be affected by these processes. Loose bedrock on slopes will fall due to the shaking from an earthquake. Steep slopes with a large volume of loose sediment will cause the most damage during an earthquake (Valagussa *et al*., 2014). The loose bedrock may fall on major transportation routes blocking important emergency responders. It may also fall on buildings or people causing inhabitable structures or death. The steep slopes also present problems for the region's water reservoirs. The Capilano, Seymour and Coquitlam Reservoirs are the main sources of drinking water for the Metro Vancouver region and could prove necessary if potable water is inaccessible. Both Seymour and Coquitlam reservoirs have been seismically retrofitted as of 2007 and 2008 respectively, however the Cleveland Dam which holds the Capilano Reservoir has been in use since 1957 and has not been retrofitted (Metro Vancouver). This presents a major risk of flooding as the Capilano reservoir sits in the steepest watershed of the three. If the Cleveland Dam were to fail, large volumes of water would rush down toward West and

North Vancouver causing flooding and potentially large debris flows. Additionally, should landslides occur in the creeks and rivers feeding the reservoirs, the reservoirs could be damaged or have reduced capacity, while the increased turbulence in the water can have adverse effects on water quality.

Liquefaction occurs when the ground acts like a liquid due to water pressure differences in the soil. The ground moving will cause instability to any infrastructure built on top. This may cause the structure to fall causing destruction or it may become heavily damaged and unusable (Bhattacharya *et al*., 2011). Infrastructure that is built upon accumulated sediment from the Fraser River are susceptible to the effects of liquefaction; this includes highways, bridges, and emergency services that are located in cities such as Richmond and Delta. Damage to transportation networks, especially bridges, due to liquefaction can greatly impair post-disaster evacuation, response, and recovery (Clague, 2002; Chang *et al.,* 2012). Underground water and sewer mains are also susceptible to damage from the effects of liquefaction. The 2011 Christchurch earthquake destroyed 124 km of water mains and 300 km of sewage lines, leaving thousands of residents without water for weeks (Christchurch City Council, 2011). Damage to mains can hamper efforts to fight fires as well as the ability for hospitals to maintain a sanitary environment, while damage to sewers can cause severe environmental damage. Damage to natural gas lines can cause fires that can spread easily between wood-framed buildings; during the 1995 Kobe earthquake, 5500 buildings were lost to fire (Scawthorn, 1997).

Landslides and liquefaction can have major effects on transportation in and out of the region, as the major transportation corridors feeding into the city pass through areas that may be susceptible to either landslides or liquefaction; damage to these networks can have effects on the economy in addition to rescue and recovery. Landslides and liquefaction can also cause damage to the oil pipelines that cross our city, causing severe environmental damage and adverse effects to marine wildlife. In 2007, the Trans-Mountain pipeline was ruptured by road construction workers on Inlet Dr. in Burnaby. This resulted in spraying of 234,000 liters of crude oil in the surrounding area, damaging up to 50 homes and incapacitating the Barnet Highway (Ministry of Environment). The spill caused widespread environmental damage to the Burrard Inlet and wildlife by seeping into soil and storm drains that emptied out into the inlet.

Physical vulnerabilities also extend beyond landslides and liquefaction. Many of Vancouver's building stock was constructed before modern earthquake building codes were placed in effect (APEGBC, 2006), and despite efforts to seismically retrofit schools and emergency facilities, many buildings are still not up to code (BC Ministry of Education, 2015). This is especially a concern with regards to temporary evacuation shelters. Past earthquakes around the world have forced people to take shelter in schools, arenas, and convention centres (Johnson, 2007). Additionally, it is essential that all hospitals in the region remain operational post-disaster, as many people will require medical attention and the failure of just one hospital would prevent rapid care (Geohazards International, 2009). This is especially a problem in the case of St. Paul's hospital in Vancouver. In addition to it being the only hospital in the Downtown peninsula, it is also one of the oldest hospitals in the region, with some of its buildings being over a century old. According to Providence Healthcare (2013), the Burrard Building, built in 1913, has no chance of surviving a magnitude 9.0 earthquake, and its failure would also take one of the busiest emergency departments in Vancouver out of service. The failure of one hospital can place stress on every other hospital in the region, as was the case during the 1994 Northridge earthquake, damaged hospitals were forced to evacuate patients to other hospitals or set up triage in parking lots (Pickett, 2008).

2.4.2 Economic Vulnerabilities

Metro Vancouver depends heavily on trade and tourism as a source of income in this region. Port Metro Vancouver is the largest exporter in Western Canada and one of the largest ports in North America, and provides the economy of Canada with $20.3 billion from direct and indirect employment; Airports provide the economy with $1.9 billion directly and $5.3 billion indirectly (Port Metro Vancouver Economic Impact Study, 2012; Shepard and Dybvig, 2003). Port Metro Vancouver operates across automobile, breakbulk, bulk, container, and cruise ship business sectors. Destruction to airports would stop the air transportation of people and goods. Vancouver International Airport (YVR) is one of the busiest airports in North America, moving over 19 million passengers in 2014. A temporary stop in a port's daily activities will cause economic damage to British Columbia and the rest of Canada. International companies may relocate their business to other ports along the Pacific coast if the ports in Metro Vancouver remain inactive or have a drastically reduced capacity. In the 1995 Kobe Earthquake, damage to their ports resulted in a 2% drop in GDP and took them numerous years to return to the same export volume as pre-earthquake (Horwich, 2000). It may be difficult for the ports to regain international business when they have relocated elsewhere.

Metro Vancouver's transportation network is also key to the region's economy and post-disaster recovery. The region's highways provide efficient and safe movement of goods between the port and businesses (Translink, 2015), while the major highways, such as Highway 1, and railways provide physical connections between Vancouver and the rest of North America. Damage to these networks may cause companies to reconsider trade through the city due to the lack of fluid movement of goods. Canada is the fifth largest oil producing country in the world and is a major contributor to the economy of North America. Most of the oil produced in Canada is exported to the United States or across the Pacific Ocean resulting in industry revenues in excess of $56 billion

(CAPP, 2013). In order for Canada to export its oil across the Pacific, a network of oil pipelines have been constructed from the oil sands to the coast of British Columbia. The destruction of an oil pipeline is an essential economic factor that could seriously harm Canada's economy if incapacitated for an extended period of time.

2.4.3 Social Vulnerabilities

The ability of social groups to rebound and recover from natural disasters is largely dependent on socio-economic status (SES). SES is an important factor in determining human vulnerability to natural disasters (Chou *et al*., 2004). Typically, people with lower SES are "more likely to be exposed to environmental risk factors, such as lower housing quality, residential crowding, and unfavorable neighbourhood conditions" (Chou *et al*. 2004). There are a number of studies that incorporate socio-economic indicators from Census data in analyzing social vulnerability to earthquakes (Hewitt 2013; Morrow, 1999). Common factors used to measure social vulnerability include average income, age, and family composition (Chou *et al*., 2004; Morrow, 1999; Cutter *et al*., 2003). Income is often considered the most important socio-economic indicator of vulnerability. Disadvantaged populations tend to have limited resources for health care, transportation, seismically upgraded infrastructure and financial reserves. Thus, they are more negatively affected both immediately after an earthquake, and long after the disaster has settled (Morrow, 1999). Literature typically defines dependent age groups of those over 65 and under 15 years of age, as the second most at risk group to natural disasters (Walker *et al*., 2014). The elderly are more likely to require disaster-related assistance, and are hesitant to follow evacuation orders, while children require adult assistance at all times (Morrow, 1999).

2.4.4 Systemic Vulnerabilities

Traditionally natural disaster studies have only considered social and physical factors in examining overall vulnerability (Walker *et al*., 2014). However, as Walker discussed, examining the systemic vulnerabilities is important to a more detailed definition of vulnerabilities in specific regions (2014). Systemic vulnerabilities can be defined by public accessibility to emergency services such as hospitals and fire halls (Walker *et al*., 2014; Hornet *et al*., 2011). Those who are located at a greater distance from emergency services following a major earthquake have been shown to be at greater risk of negative health outcomes as their injuries remain untreated for longer periods of time (Walker *et al*., 2014; McLafferty, 2003). Road networks affect both the distance, barriers and travel time to and from facilities (Walker *et al*., 2014). Thus the quality of access to emergency facilities relies heavily on road network systems specific to regions (Walker *et al*., 2014; McLafferty, 2003).

Other factors important to post-disaster response include access to evacuation shelters as they are vitally important relief and rehabilitation centers for communities after an earthquake (Moteff & Parfomak, 2004). The BC Ministry of Public Safety currently recognizes school gymnasiums, as well as community centers and arenas as post-disaster Group Lodging Facilities (2009). Large evacuation shelters are especially important to dense city centers like Vancouver where much of the buildings were constructed before seismic building codes were upgraded in the 1970's and 1990's; therefore the probability of evacuation is high (APEGBC, 2006).

Although the Canadian government does not classify schools as critical infrastructure, they are vitally important relief and rehabilitation shelters for communities after an earthquake (Moteff & Parfomak, 2004). Schools are widespread and numerous throughout communities in Metro Vancouver, making them highly accessible after an evacuation order is given. However, many of the schools within Metro Vancouver have not been seismically upgraded, leaving them at risk of structural failure during an earthquake (BC Ministry of Education, 2015). Of the 126 high risk schools in BC, 35 are located within Vancouver and Richmond and received the highest vulnerability ranking by the Association of Professional Engineers and Geoscientists of BC (BC Ministry of Education, 2015)(Table 2).

Rating	Definition
High 1 (H1)	Most vulnerable structure; at highest risk of widespread damage or structural failure; not reparable after event. Structural and non-structural seismic upgrades required.
High 2 (H2)	Vulnerable structure; at high risk of widespread damage or structural failure; likely not reparable after event. Structural and non-structural seismic upgrades required.
High 3 (H3)	Isolated failure to building elements such as walls are expected; building likely not reparable after event. Structural and non-structural seismic upgrades required.

Table 2: Vulnerable school structure rating (BC Ministry of Education, 2014)

3. 0 DATA ACQUISITION

In our study, data collection is an important process to contribute to the output, a reliable data source can provide high quality data and reduce the biases and inaccuracy. Table 3 shows the data we used, the source where we get them from, and the data format.

Table 3: Data sources and file types for each critical infrastructure category.

Category	Description	Source	File type
Transportation	Bridges and tunnels	Metro Vancouver	.shp
	Major Road Network	Translink	.shp
	Ferries	BC Ferries	.xlsx
	Skytrain Lines	BC Data	.shp
Utilities	Water mains/Pump Stations	Metro Vancouver	.shp
	Reservoirs/Dams	Metro Vancouver	.shp
	Sewage lines/Pump Stations	Metro Vancouver	.shp
	Oil Pipelines	Kinder-Morgan	.shp
	Power Lines	SFU Data Warehouse	.shp
	Jet Fuel Pipelines	Kinder-Morgan	.shp
Emergency Services	Fire Halls	Google	.xlsx
	Hospitals	Google	.xlsx
Evacuation Shelters	Seismic Upgraded Schools	Google	.xlsx
	High 3 Risk Schools	Google	.xlsx
	High 2 Risk Schools	Google	.xlsx
	High 1 Risk Schools	Google	.xlsx
	All Schools	Google	.xlsx
	Post-Secondary Schools	Google	.xlsx
	Community centers	Google	.xlsx
	Convention centers	Google	.xlsx
Economic	Airports	Google	.xlsx
	Ports	Metro Vancouver	.xlsx
	Railways	SFU Data Warehouse	.shp
Socio economic	Population Density	CHASS Data Center	.dbf
	Age	CHASS Data Center	.dbf
	Income	CHASS Data Center	.dbf
	Education	CHASS Data Center	.dbf
	Single Parent Households	CHASS Data Center	.dbf
Physical	Soil type	Gov. of Canada Data	.shp

4. 0 METHODOLOGY

4. 1 Critical Infrastructure Inventory

The first set of map outputs for this project is a collection of critical infrastructure spatial data as defined in Table 1 for the region of Metro Vancouver. As shown earlier, infrastructure identified as critical for this project have been separated into subcategories in order to reduce the cognitive overload in the final outputs. Each subcategory shows all critical infrastructure from that sector with appropriate symbology to improve cognition. Spatial data representing all critical infrastructure identified has been acquired through multiple avenues as shown in Table 5. Publicly available data was used in conjunction with data compiled and created by us. For the Major Road network, a map provided by Translink was used to compile a list of major transportation routes which was then SQL out of a street centerline shapefile provided in the SFU Data Warehouse. Due to the lack of sufficient public data for the utilities sub category, maps provided by the Region of Metro Vancouver were georeferenced in ArcMAP to a Metro Vancouver shapefile. Once georeferenced, polyline and point shapefiles were digitized by tracing the Metro Vancouver sewer and water mains and pump stations. This process was repeated for the oil and jet fuel pipelines using maps provided by Kinder-Morgan. For the majority of our point data, excel spreadsheets were compiled using Google and Yellowpages to determine latitude and longitude coordinates for geocoding. Each excel spreadsheet was converted to CSV format and imported into ArcMAP and geocoded based on its XY coordinates.

4.2 Preparing Data for Weighted Multi-Criteria Evaluation

4.2.1 Soil Data

To examine the liquefaction potential in Metro Vancouver, soil data from the CanSIS National Soil Database were used. In this format, areas in the region were split into polygons of varying sizes, each with data categories such as soil classification, elevation, and type of deposit. Based on information from Bozorgnia & Bertero (2004), it was determined that soils created by fluvial, alluvial, or colluvial deposits are most susceptible to liquefaction. Polygons that fit this criteria were then separated from the other polygons and used to create a new shapefile containing only areas susceptible to liquefaction.

4.2.2 Distance-based Network Analyses

Calculating systemic vulnerabilities through distance-based road network analyses has been done in Walker's earthquake vulnerability analysis of Victoria, British Columbia (2014). For our study of Metro Vancouver, we used the same method to calculate travel time from hospitals and fire halls to all other areas of the region. We performed separate network analyses for hospitals and fire halls as the travel speed of their emergency vehicles varies (Table 4). Distance travelled was calculated on a minute basis to obtain a detailed analysis of the time it takes for emergency vehicles to reach all areas of Metro Vancouver (Table 4).

Table 4. Travel methods, average speed and distance travelled in 1 minute time.

Travel Method	Average Speed	Source	Distance travelled in 1 minute
Ambulance	67 km/hr	Petzall et.al, 2010	1.11 km
Fire Truck	56 km/hr	ISO, 2014	0.93 km
Walking	4.6 km/hr	Bohannon & Andrews, 2011	0.076 km

For the critical infrastructure inventory, we divided the schools into groups based off their level of vulnerability to earthquakes as defined by the BC Association of Professional Engineers in Table 3. A list of safe schools was also compiled. Schools that were constructed post 1994 are considered to be safe because engineering building codes had better knowledge of the effects of seismic ground motion at this time (BC Ministry of Education, 2014). Other safe schools include those that have completed seismic upgrading renovations in the BC Seismic School Upgrade program. Because access to safe evacuation centers like schools and arenas is important to post-disaster recovery, a distance-based network analysis was performed. We performed a walkability analysis as it is assumed that roads will be damaged after a major earthquake, and many people do not have access to personal vehicles (Table 4) (Walker *et al*., 2014).

4.2.3 Standardized Scores and Pair-Wise Comparison

Before performing the final overlays to create the multi-criteria evaluation maps, all the datasets first needed to be converted into raster. This was necessary so that a standardized scale of scores from 0 to 1 could be assigned to each unique value based on a set of criteria. The sigmoidal monotonically increasing method was used to reclass all factors to the standardized scale. Next the weights for each factor needed to be determined. We used an analytic hierarchy pair-wise comparison method to derive the weights (Table 7). This method is common within natural hazards studies as it allows for expert opinion and literature to be consulted when determining weights (Walker *et al*., 2014).

4.3 Weighted Multi-Criteria Evaluation

To delineate the most vulnerable regions of Metro Vancouver, a number of multi-criteria evaluations (MCE) were performed. A multi-criteria evaluation is a decision-making tool used in geographic information systems to perform complex multi-criteria problems, and assist in decision-making processes (Walker *et al*., 2014). MCEs are commonly used in studies examining vulnerabilities of regions to earthquakes and other natural disasters (Walker *et al*., 2014; Feizizadeh & Blaschke, 2013). MCEs are advantageous over using other methods such as boolean overlay. They provide a range of values and allow for varying degrees of tradeoff and risk to be incorporated into the results (Barredo & Bosque-Sendra, n.d.) . In contrast boolean only offers a binary result of yes or no, limiting the complexity of the analysis.

Three separate MCEs were created and then combined in a final vulnerability map for Metro Vancouver. MCEs were made for systemic vulnerabilities, social vulnerabilities, and physical vulnerabilities. This method was also used in the study of at risk regions in Victoria, BC (Walker *et al*., 2014). Separate MCEs were produced for the different themes because it is difficult to compare, for example, the vulnerability of distance to hospitals, to vulnerability of soil classes. Thus within each MCE weights could be appropriately assigned to each factor within that theme (Table 5). The MCEs were then combined in a final output where each MCE was given an equal weighting of 0.33 so that neither the social, physical or systemic vulnerability MCEs were given priority (Walker *et al*., 2014).

Table 5: Multi-criteria evaluation factors and corresponding weights. A pair-wise comparison method was used to derive the weights. Source material assisted in decision-making for weight assignment

MCE	Factor	Weight	Source
Social Vulnerability	Age 65+	0.2029	Chou et al. 2004; Cutter et al. 2003; Morrow 1999; Walker et al. 2014
	Age 0-14	0.0401	Cutter et al. 2003
	Low Income	0.4786	Chou et al, 2004; Cutter et al. 2003
	Education-no high school diploma	0.0384	Cutter et al. 2003
	Population Density	0.1679	Kuroaka & Rainer, 1996
	Single Parent Household	0.0384	Morrow, 1999
Physical Vulnerability	Soil Class	1	
Systemic Vulnerability	Network Analysis: Hospitals	0.5769	Geohazards International, 2009
	Network Analysis: Fire halls	0.342	Scawthorn, 2011
	Network Analysis: Evacuation Shelters	0.0811	Johnson, 2007

5.0 RESULTS

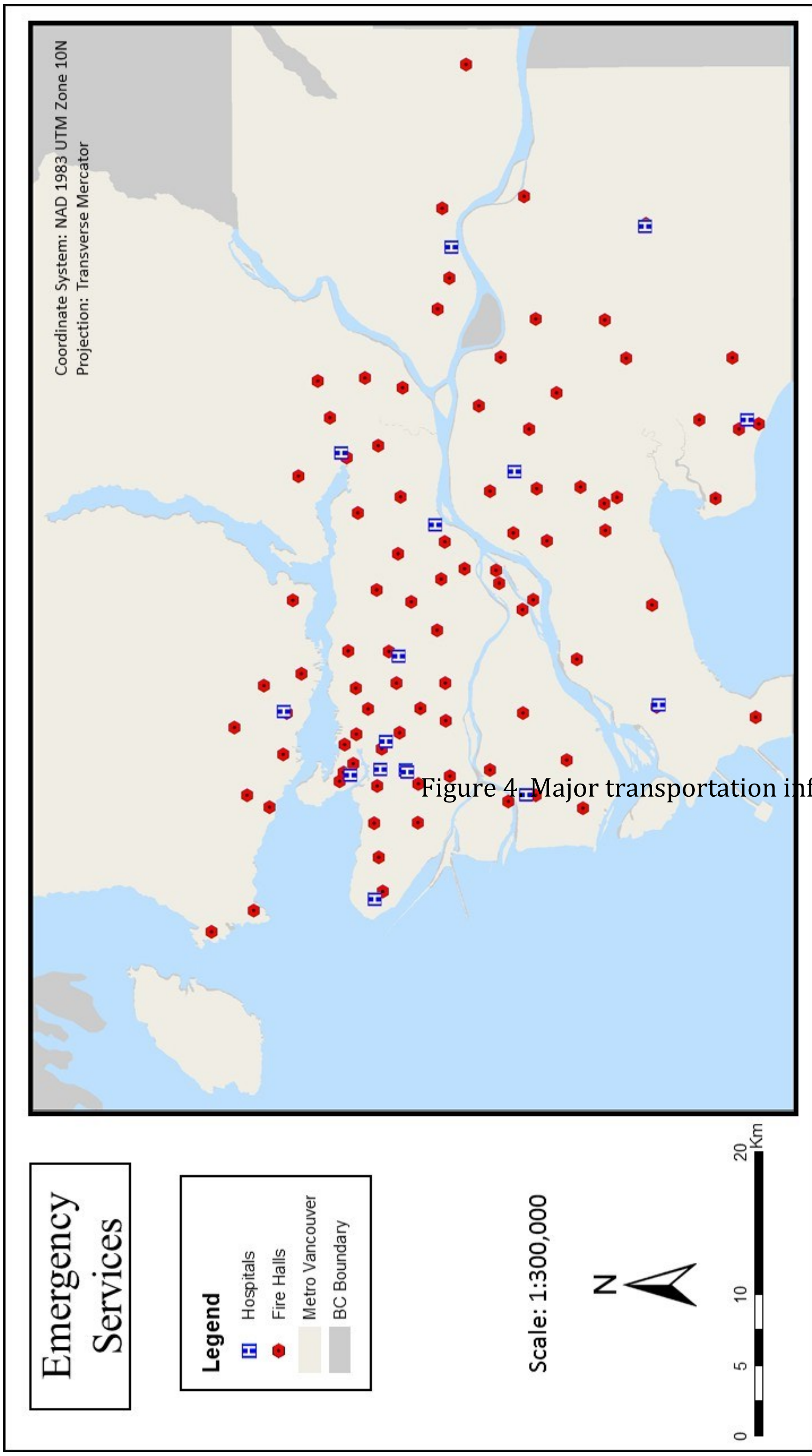

Figure 4. Major transportation infrastructure in Metro Vancouver, including ferr

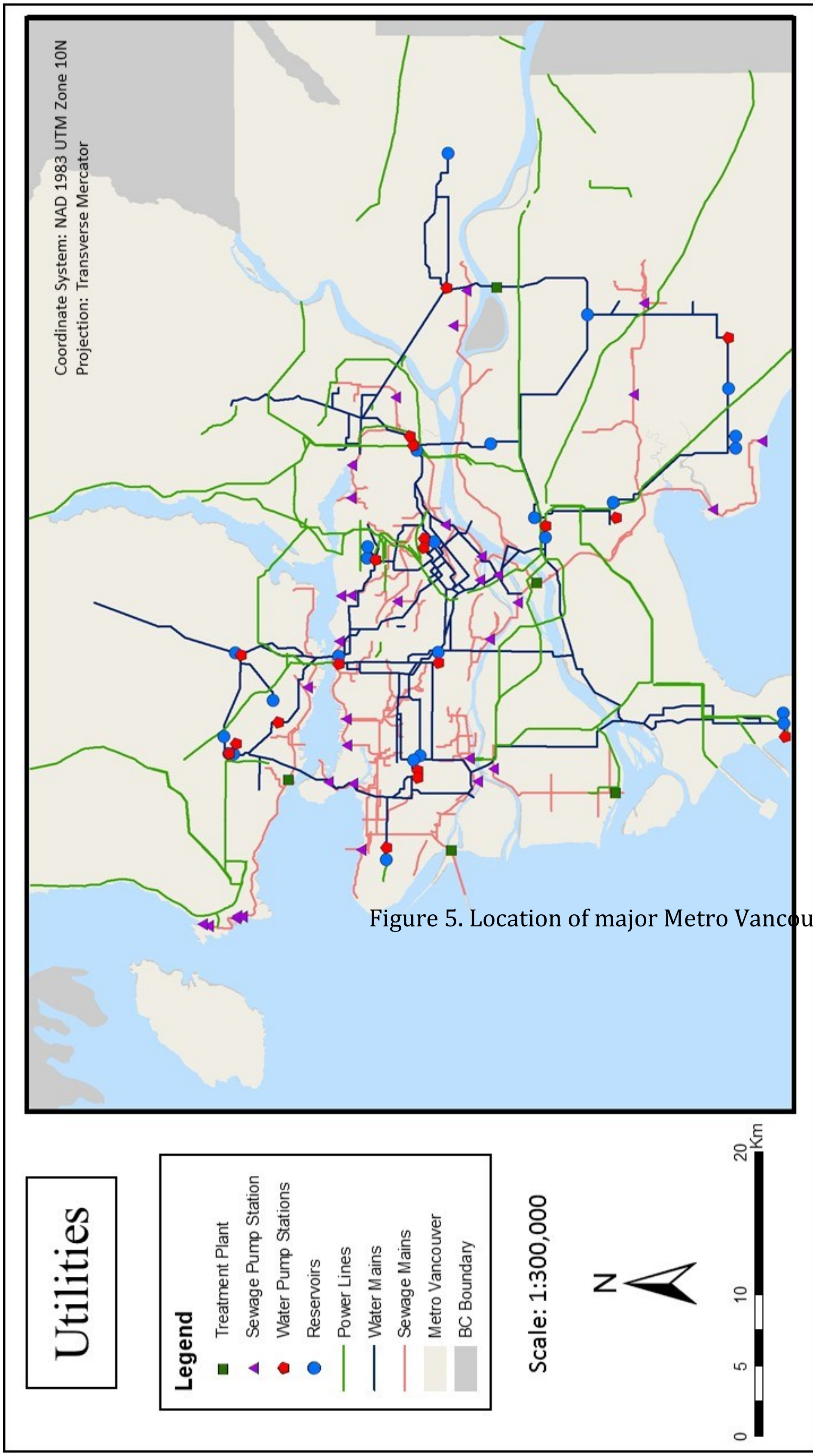

Figure 5. Location of major Metro Vancouver utilities, including reservoirs and tre

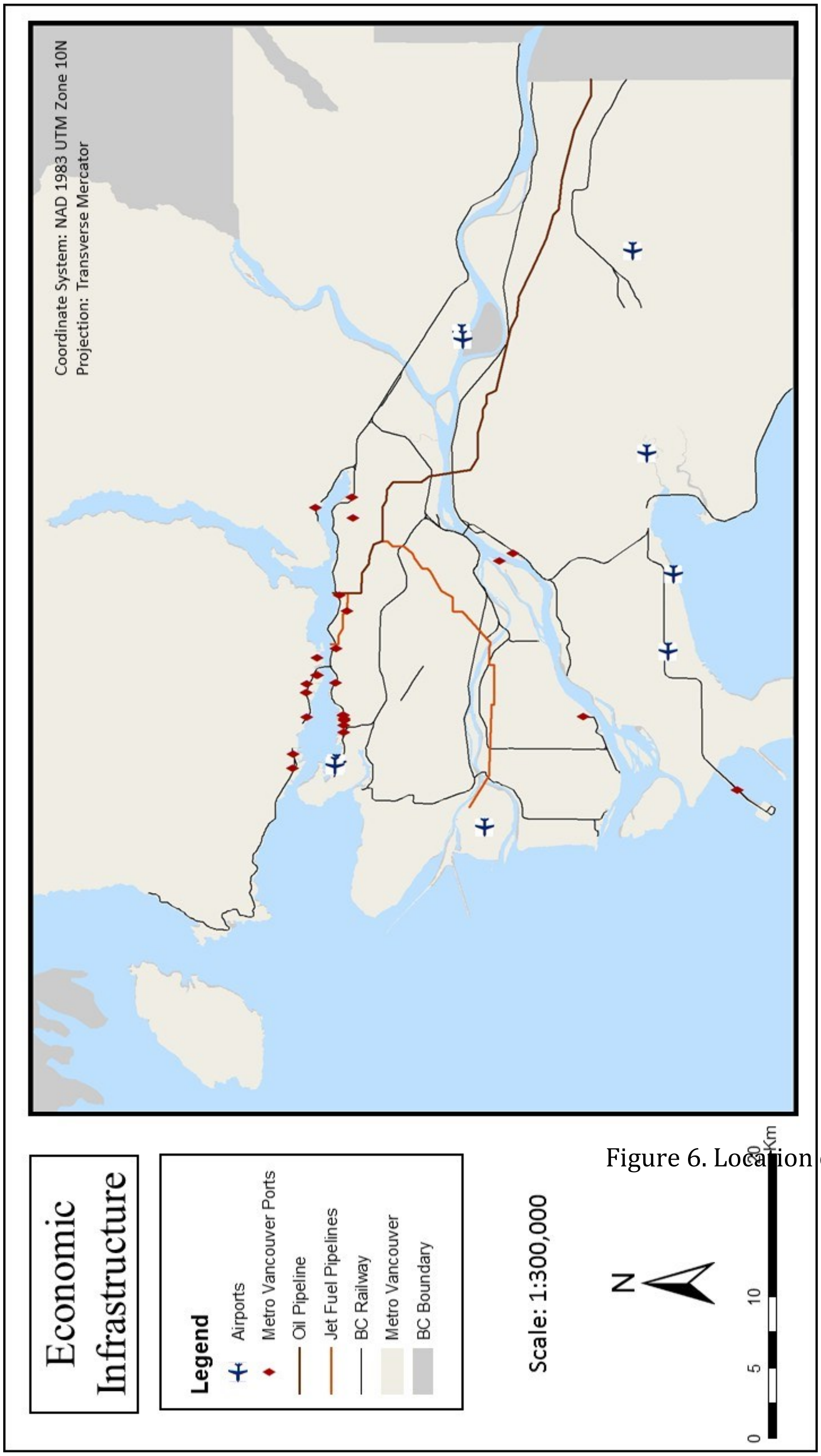

Figure 6. Location of all ports and pipelines.

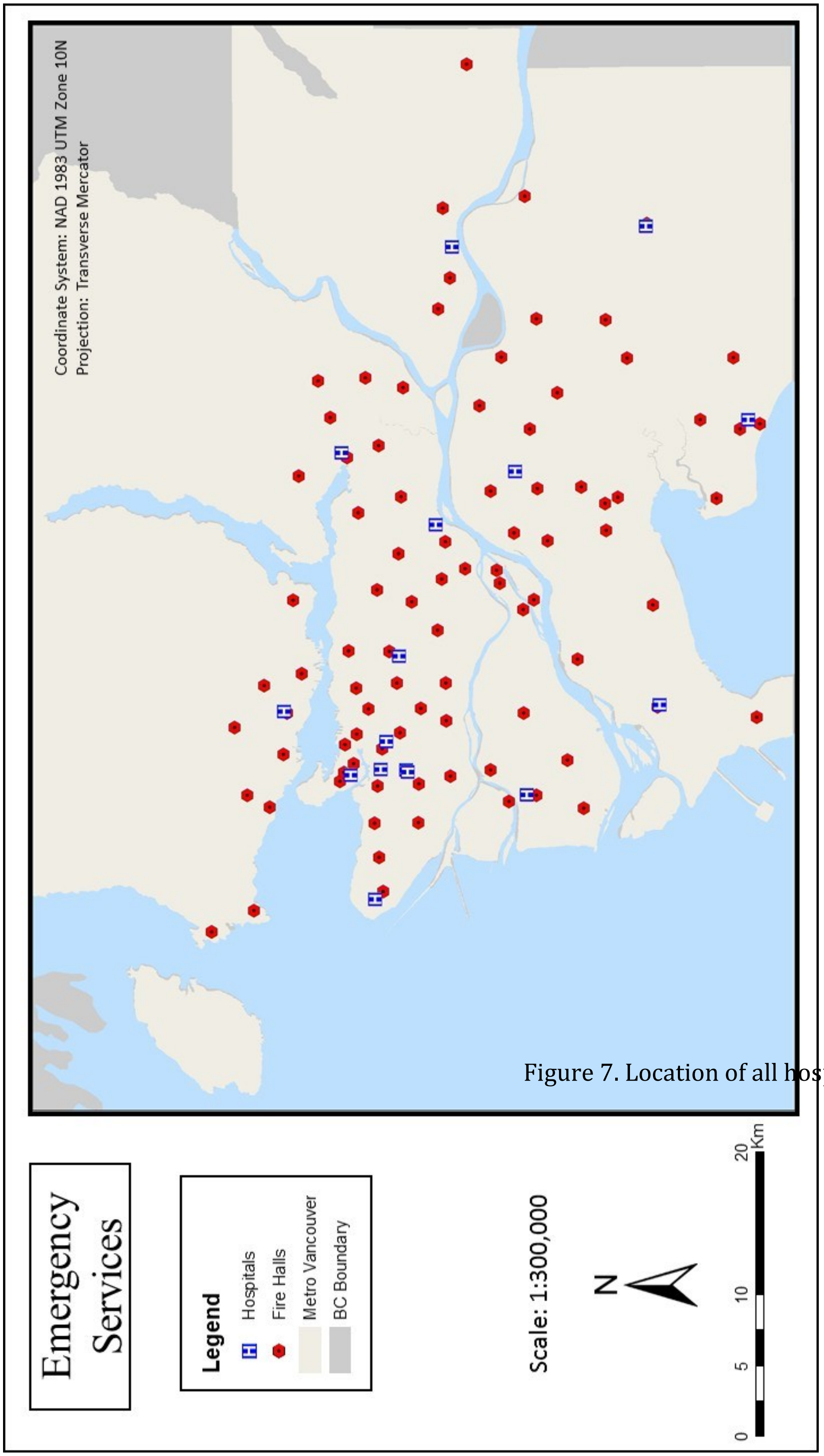

Figure 7. Location of all hospitals and fire halls in Metro Vancouver

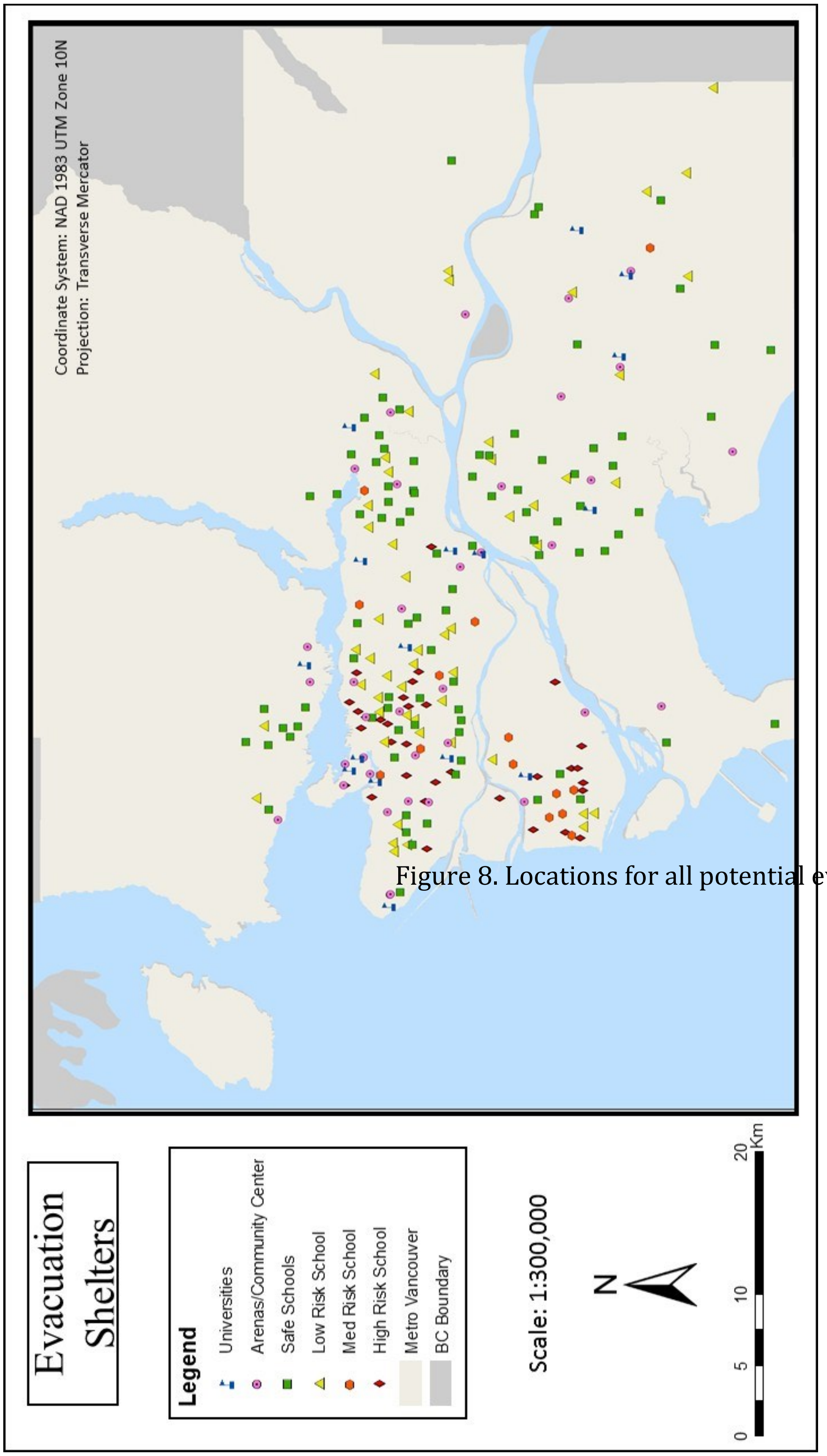

Figure 8. Locations for all potential evacuation shelters in Metro Vancouver.

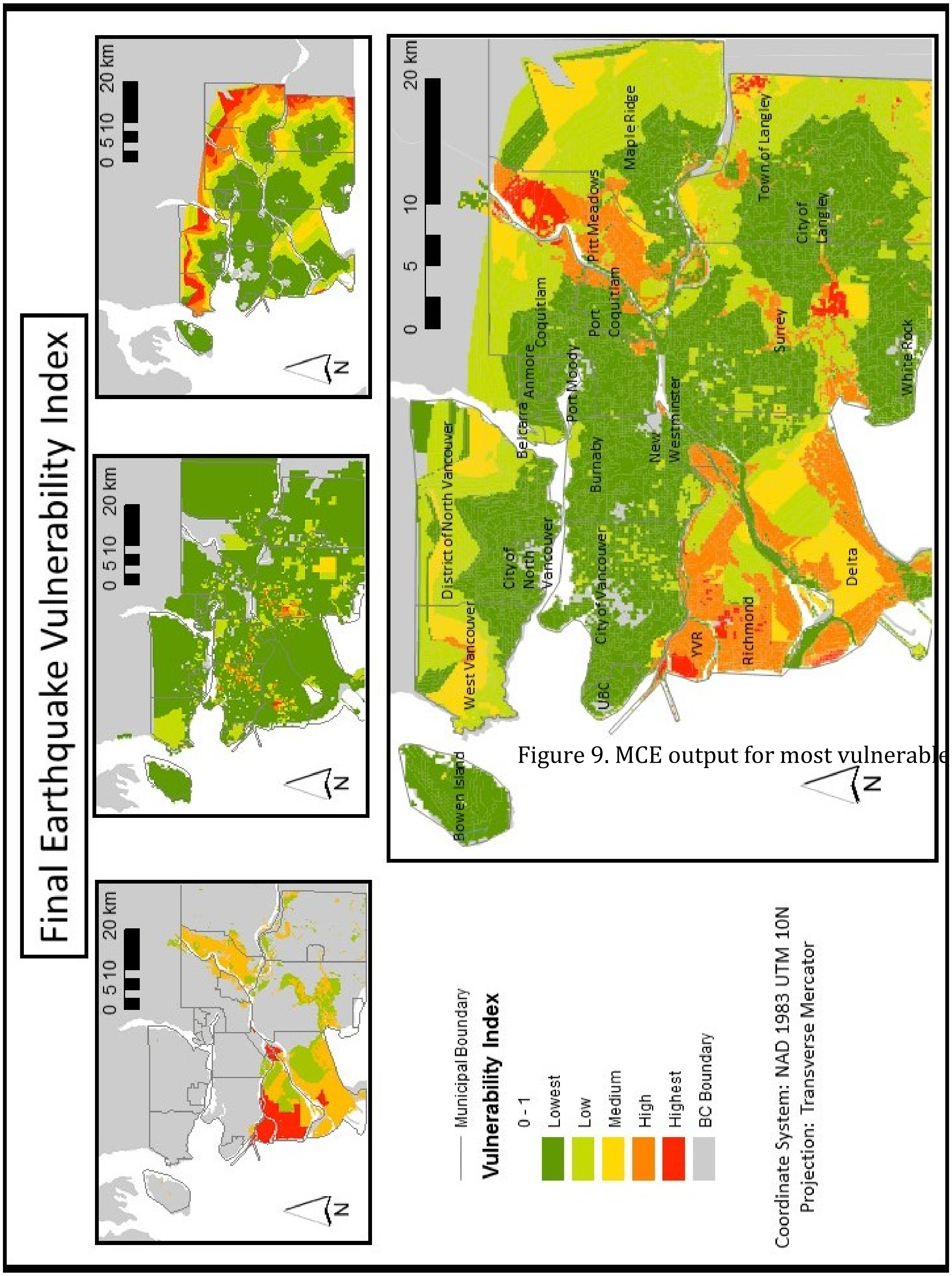

Figure 9. MCE output for most vulnerable areas in Metro Vancouve

6.0 DISCUSSION AND LIMITATIONS

As seen in our results, critical infrastructure in the cities of Richmond, Delta, and Pitt Meadows are the most vulnerable, likely due to the high risk of liquefaction occurring during an earthquake. For residents of these locations, this means that in the event of a major earthquake, evacuation routes, emergency services, and shelters may be inaccessible, while also preventing rescue personnel from accessing those communities, and the power and water supplies would most likely be taken out of service. Also note that Vancouver International Airport is located where there is a high vulnerability rating. Damage to any of the airport's facilities, such as runways and terminals, could slow recovery efforts post-disaster. On the North Shore where the communities of North Vancouver and West Vancouver are located, there is a higher risk of landslides, contributing to the higher vulnerability rating in those areas. Landslides in those areas could mean damage to the power and water facilities that are located on the North Shore.

Some limitations presented themselves in developing this vulnerability assessment. First, because of the size of the region and time constraints, we were limited in the scope of our analysis. Some factors and critical infrastructure were not included for this reason. Second, for the transportation factors, road accessibility is heavily dependent on how seriously the roads are damaged during the earthquake. As a result of that, transportation is significantly affected by the location and the magnitude of the earthquake, although we are assuming that major traffic routes are more reliable than smaller capacity roads. In reality, however, road conditions and reliability are highly variable. Third, for the census data, one major issue is that the income and education data are from 2006, which added some inaccuracies in the data analysis. Due to the uncertainty about how population distribution will change spatially over time, the older the data is, the more inaccurate it will be, which is reflected in our final outputs. Additionally, in the 2006 Census data, some dissemination areas did not provide which resulted in some holes in our socio-economic census data. Fourth, for some of the secondary geographical phenomena, there is not enough adequate data to use to produce a functional model. Some areas had incomplete or ambiguous soil data, while others were missing soil data altogether. In the case of analysing areas that were at risk of liquefaction, the data did not include land that had been artificially filled in. Finally, because there is a lack of public data for utilities in Metro Vancouver, the location of the region's utilities, such as power lines and water mains, had to be manually georeferenced using maps provided by Metro Vancouver. This process, in addition to the unknown accuracy of the provided maps, may have contributed to inaccuracies in our results.

7.0 Conclusion

The goal of this project was to determine and categorize the critical infrastructure in Metro Vancouver, to assess the vulnerability of said critical infrastructure to damage and destruction in the event of a major earthquake, to identify the vulnerability and locations of potential evacuation shelters, and to assess the vulnerability of the various socio-economic groups within Metro Vancouver. This was done using both the ESRI ArcMap and Idrisi Selva GIS software for georeferencing and to produce the multi-criteria evaluation outputs, Microsoft Excel to analyze and categorize our data, and Canada census data for our socio-economic analysis so that as many vulnerability factors could be included while also being supported by the literature. We feel that because of the thoroughness of our analysis, our results are a useful resource for the region of Metro Vancouver, both by governments and the general public. Our analysis could be improved, however, by more accurate input data, especially due to the varied geography of our region, as well as by addressing our other limitations. However, because of the region's proximity to a major fault line, as well as the significant risk of a major destructive earthquake in the future, it is important for regions like Metro Vancouver to know the vulnerabilities of their critical infrastructures and the effects a major earthquake could have. In knowing this, governments can plan a more effective response to a disaster and better educate the public in earthquake preparedness.

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