## DRAFT: Physical Exposure and Patterns of Human Settlement

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Canada is similar in geographic area to China or the United States (9,984,670 km²) but ranks 38th in terms of global population (35.1 million in 2016), with the majority of people and assets (~76%) concentrated in urban centres and sparsely settled areas situated along its southern border (Statistics Canada, 2016b).  Like many areas in the world, Canada has experienced rapid growth and development with built up-areas in urban settings nearly doubling over a 40-year period from 5,300 km² in 1975 to more than 10,880 km² in 2016 (Pesaresi et al., 2018).  Nearly half of all Canadians (15.5 million people) currently live in and around the metropolitan centres of Toronto, Windsor, Montreal, Vancouver, Calgary, Edmonton, Ottawa and Winnipeg.

The number of buildings constructed in areas exposed to damaging earthquake hazards has more than doubled over the same time period from 2 million in 1975 to nearly 4.5 million in 2016. Financial investments in residential and commercial buildings that are situated in these hazard-prone areas total more than CAD $4 trillion, nearly half the total capital stock value of Canada. The susceptibility of people and assets to earthquake hazards in these areas is concentrated primarily in older neighbourhoods in which buildings and related infrastructure either predate or do not meet current seismic safety guidelines (NBCC, 2015). These concentrated pockets of older and poorly constructed buildings also house some of the most vulnerable populations in Canada. Areas of concern in Central, Eastern and Maritime regions of Canada include urban and rural settlements along reactivated zones of crustal weakness in the St. Lawrence Valley, the northern Appalachians and the Atlantic coastal margin.  Areas of concern in western Canada include densely settled urban centers and rural-remote coastal communities in the Cascadia region of southwest British Columbia, the Queen Charlotte region of central British Columbia and the Yakutat region of northern British Columbia and the Yukon.

The following sections present results of a detailed physical exposure model that describes key characteristics of the built environment for settled areas across Canada (see Figure 3).  It includes a vector-based aggregate portfolio of more than 9.7 million residential and commercial/industrial buildings for more than 454,000 neighbourhoods across Canada; the distribution of 35.1 million people across these neighbourhood regions at three different times of day, and the estimated replacement costs for capital assets totalling ~8.3 trillion CAD$ (~6.3 trillion USD$). Our approach builds on existing best practices for the development of multi-hazard exposure models to support quantitative risk assessments at a national scale (Dell’Acqua et al., 2013; Ehrlich et al., 2013; Gunasekera et al., 2015; Yepes-Estrada et al., 2017; Pesaresi et al., 2018)), and introduces a methodology for characterizing the distribution of building construction types at the neighbourhood level based on land use typologies and available 2016 Census data for settled areas across Canada (Statistics Canada, 2016a).

## Human Settlement Areas

Settled areas delineate the presence of structures and related infrastructure which define physical characteristics of the built environment that are visible and measureable using global earth observation sensors. By definition, physical risk is concentrated within those settled areas exposed to the probable impacts and consequences of natural hazard threat(s).  For large and sparsely populated countries like Canada, the delineation of human settlement boundaries is a foundational step in the process of generating physical exposure models that are required to undertake a national risk assessment.

Earth observation and data extraction methods used to define settled areas in Canada are consistent with those described for the Global Human Settlement Layer, a multi-decadal exposure dataset developed by the European Commission Joint Research Centre (JRC) to monitor increasing susceptibility to natural hazards as part of the 2017 Atlas of the Human Planet (Pesaresi et al., 2018).  Built-up areas in urban and suburban regions of Canada were extracted from a 30m-resolution land cover classification (circa 2015) developed by Agriculture and Agri-Food Canada (Fisette et al., 2006; Agriculture and Agri-Foods Canada, 2015).  Built-up areas in sparsely populated rural and remote communities were delineated by buffering building locations derived from a 2017 collection developed by the Canadian Centre for Mapping and Earth Observation (CCMEO) branch of Natural Resource Canada’s Land and Minerals Sector (Natural Resources Canada, 2019).

Current patterns of land settlement mirror those established early in the colonial history of Canada (see Figure 3). Although population density and land use characteristics have evolved significantly over time, the backbone patterns of settlement are one of the primary drivers of earthquake susceptibility along the Saint Lawrence Valley of Quebec, and in the Cascadia region of southwest British Columbia.  In eastern Canada, the urban centres of Montreal and Quebec City are home to more than 4.9 million people with ~30% of the population exposed to ground shaking hazards capable of causing significant structural damage to older and poorly constructed buildings. In western Canada the Cascadia region of southwest British Columbia is home to 3.7 million people with more than 75% of the population living in amalgamated metropolitan centres of Metro Vancouver and the western Fraser Valley (2.5 million), and an additional 10% in the Capital region of Victoria  (368,000 people). More than 2.8 million people living in this region (78% of the population) are exposed to ground shaking hazards capable of causing significant damage in older and poorly constructed buildings (see Table 1).

### Building Inventory

Methods used to classify and analyze land use patterns vary widely across the disciplines of geography, urban planning, landscape design, sustainability and ecology (Marshall, 2005). Land use typologies provide insights on the general form and mix of occupancy classes within an individual neighbourhood (residential, commercial, industrial, civic, etc.), and are used in this study to develop context-specific mapping schemes that describe the mix of buildings that are likely to be present in terms of both structural type (wood, concrete, masonry, etc.) and age of construction.  The specific ratio of building classes for a given land use class is derived from available tax assessment data, and from detailed site-level inventories developed by visual screening techniques for representative neighbourhoods in western and eastern Canada (Onur, 2002; Ploeger et al., 2018).

A close up of a map

Description automatically generated

**Figure 3**: A physical exposure model for Canada illustrating areas of human settlement, characteristic patterns of land use and significant historic earthquakes of magnitude M6.8 and greater.

The building stock of Canada is classified using a combination of 36 structural types and 33 occupancy classes that are defined as part of the standard HAZUS methodology (FEMA, 2011).  Context-specific mapping schemes for each combination of land use, structural type and occupancy class are used to allocate a distribution of building classes that reflect the overall structural form and function of a given neighbourhood. Eight structural types represent more than 95% of the aggregate building inventory in western Canada and the Maritime provinces of eastern Canada.  As expected, the majority of these are single and multi-family residential wood frame buildings (1-3 stories), and mixtures of low and mid-rise unreinforced masonry and concrete structures that accommodate both residential and business functions.  The relative proportions of these buildings vary as a function of land use and the mix of occupancy classes at the neighbourhood level.

The distribution of building types is more varied in central portions of Canada.  Although single and multi-family wood frame structures make up more than 90% of the total inventory, there are significantly higher proportions of low and mid-rise unreinforced masonry buildings (9.3%) with lesser amounts of reinforced masonry and low-rise steel frame structures. Building classes in the far north (Nunavut) are dominated by multi-purpose wood frame and manufactured panel wall structures (96%) with lower proportions of brick masonry and steel frame buildings used for commercial and industrial purposes. Differences in the mix of building classes reflect construction practices that have been adapted to accommodate both extreme weather conditions, and the higher costs of construction materials that are shipped from manufacturing centres in southern Canada.

### Population Dynamics

Unlike other disaster types, the impacts of an earthquake event are experienced over a period of minutes, and can be repeated in aftershock sequences that can last several weeks or months.  Understanding the population dynamics of a community and the fractions of people likely to be in buildings of different types over a 24-hour period is essential for estimating injuries and fatalities at the time of an earthquake. We use a Canadian adaptation of the HAZUS and PAGER methodologies (FEMA, 2011; Jaiswal & Wald, 2014) to estimate average building populations at different times of the day based on the number, square footage and mix of functional building types for a given area. Neighbourhood-level populations are estimated for standard workday hours when people are at an office, school or other group facility (9am-5pm); for morning and evening commute hours when people are in transit (7am-9am; 5pm-7pm), and; for evening hours when the majority of people are at home (7pm-7am).

### Capital Asset Valuation

Capital asset values reflect the estimated cost to repair or replace residential and business property that may be damaged as a result of an earthquake. Estimates are based on unit construction costs ($CAD/ft2) that are derived for 33 representative structural classes using building valuation data compiled from available public sources (Moselle, 2017; Turner & Townsend, 2017; Altus Group, 2018).  The resulting assessment of total capital wealth for Canada is 8.3 trillion CAD$, consistent with 2014 global values reported in the Penn World Table (Arcadis, 2015; Feenstra et al., 2015).  These values have been adjusted with an annual growth rate of 3.1% to reflect estimated capital stock assets at the time of the 2016 census.  Capital asset valuation for each Province and Territory (see Table 1) reflects regional variations in construction costs as reported by the Canadian Consumer Price Index (Chiru et al., 2015).

Although Canada ranks 15th in the global valuation of capital wealth for developed countries (Arcadis, 2015), it has a very high potential for loss with nearly half of all capital assets (4.3 trillion CAD$) exposed to severe earthquake hazards.  Half of the exposed capital wealth is distributed across low-density residential neighbourhoods in urban and exurban settings where the number of single and multi-family homes exceeds that of all other urban land use types by a factor of 5 to 1. However, it is the concentrations of high value building assets in high-density mixed urban residential neighbourhoods and commercial-industrial precincts that pose the greatest threat in terms of both direct economic loss potential, and the cascading effects of lost revenue caused by business disruptions in the months and years following a catastrophic earthquake. This is of particular concern in major commercial hubs of Metro Vancouver, Victoria, Montreal and Quebec City; and in the surrounding urban centres of southern Vancouver Island and the Saint Lawrence Valley that support interconnected networks of both regional commerce and international trade.

More than 90% of Canada’s building stock assets are concentrated in three primary structural types.  These include single-family and larger commercial wood frame buildings (48%; 3.9 trillion CAD$); low and mid-rise unreinforced masonry buildings (30%; 2.5 trillion CAD$), and; mixed purpose concrete shear wall structures (15%; 1.3 trillion CAD$) that are common in medium and high-density residential neighbourhoods and in mixed residential and commercial high-rise business centres across Canada. Of concern are concentrations of older wood, unreinforced masonry and non-ductile concrete frame structures in areas of high seismic hazard that predate modern building performance design guidelines that were introduced into the National Building Code beginning in 1975.

## Physical and Social Vulnerability

Vulnerability and related concepts of resilience provide a measure of the intrinsic capacities of communities to withstand, recover from and adapt to both the immediate physical impacts of a hazard event, and the cascading effects of damage, injury, disruption and loss that can linger for weeks, months and years after a major disaster (United Nations, 2016).  Framed in this way, the concept of vulnerability emphasizes root causes and dynamic pressures that create unsafe conditions, thereby increasing the susceptibility of buildings, people and assets to the potential negative consequences of a hazard event. Analytic measures of physical and socioeconomic vulnerability are of particular importance in the realm of risk reduction and recovery planning. They are used to inform proactive mitigation and/or adaptation investment decisions that have a potential to directly reduce the likelihood of damage and loss, thus effectively increasing the prospects of disaster resilience over time.

### Building Performance

Physical dimensions of vulnerability emphasize performance characteristics of the built environment and are measured using a blend of engineering-based fragility and vulnerability functions. Fragility functions for buildings and critical infrastructure establish the probabilities of reaching or exceeding pre-defined damage state thresholds based on hazard intensity measures at a given location (Martins et al., 2016; Yepes-Estrada et al., 2016). A related suite of vulnerability and consequence functions are used to assess probability distributions over a range of hazard intensity levels and the ratios of damage, injury, loss and disruption that are relevant for modeling both risk reduction and recovery. The assignment of seismic design level used to assess building performance for each asset in the portfolio is based on a combination of construction year and the intensity of ground shaking assessed at a probability threshold of 2% in 50 year.

The fragility and vulnerability model used in this study relied on the capacity curves featured in HAZUS (FEMA 2011) and a selection of ground motion records for North America (REF)[[VS1]](" \l "_msocom_1) . Each capacity curve (i.e. one per building class) was used to define a single-degree-of-freedom (SDOF) oscillator, which was tested against the set of ground motion records using nonlinear time history analysis. The response (in terms of maximum displacement and acceleration) was used to compute the probability of exceeding a number of damage states (i.e. slight, moderate, extensive and complete) as defined in HAZUS. These fragility functions were converted into vulnerability functions based on the damage-to-loss model proposed by HAZUS. A thorough description of this procedure can be found in Martins and Silva (2019).

### Capacity to Withstand and Recover

Social vulnerability focuses on the question of who is most affected by the immediate impacts of a hazard event, and the underlying human and socioeconomic factors that may amplify downstream negative consequences, thereby influencing capacities for recovery and adaptation.  We analyze social vulnerability at a neighbourhood level across Canada using a modified version of the ‘hazards of place’ methodology that utilizes geo-statistical methods of analysis to detect and rank patterns of vulnerability based on a wide range of representative demographic indicators that are known to be effective in profiling complex social and economic interactions (Morrow, 1999; Cutter et al., 2000; Dwyer et al., 2004; Cox et al., 2006; Khazai et al., 2015).  Key factors for the Canadian model include the extent to which building occupants are susceptible to the impacts of a major earthquake (physical capital); demographic variables that influence the capacities of individuals and groups to cope with and recover from the direct impacts of a disaster event (social capital), and; economic variables that reflect overall agency and the relative capacity of some to take actions that minimize the downstream consequences of a disaster while forcing others to succumb or rely on social services during the recovery process (economic capital).

Numerical values for each of these variables are first transformed into a common frame of reference using linear scaling and standardization methods to ensure internal coherence.  A multivariate Principal Component Analysis (PCA) is then used to assess the strength of correlation across the full set of variables and to generate a reduced set of indicators.  Separate social vulnerability models are constructed for each of eight community archetypes defined by statistical area classification in the national census (Statistics Canada, 2016c). Outputs of these context-specific models are then amalgamated into a hierarchical national model that is used to identify who is most likely to be impacted in areas of high seismic hazard, and to assess their relative capacities to withstand, respond to and recover from the consequences of catastrophic earthquake event.