Patterns of Human Settlement and Natural Hazard Threat in Canada

M. Journeay, P. LeSueur, T. Hobbs, W. Chow and C. Wagner, *others?*

Abstract

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Part I: Patterns of Human Settlement

Settled Areas

Human settlement patterns describe the form and function of cities, towns, villages or other agglomerations of buildings where people live and work. They provide important insights into the history of development for a particular region and reflect our connection to the land. Defining the spatial extent of human settlement is important for planning and risk assessment but challenging in a landscape as vast and as sparsely populated as Canada, which ranks second in the world in terms of area (~9.9M km2) and 39th in terms of population (~ 35.15M).

Figure 1: Distribution of population centres in Canada

The majority of Canadians (~95%) live in urban centres and a connecting fabric of small and medium sized towns situated within a relatively narrow 500km wide band along the southern border with the United States, and a broad agricultural region that extends an additional 500km into the interior plains of Alberta, Saskatchewan and Manitoba (Figure 1). 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 km^2 in 1975 to more than 10,880 km^2 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.

Census blocks and corresponding dissemination areas are the smallest standard geographic unit for reporting population and dwelling statistics across Canada (Statistics Canada, 2016a). Dissemination blocks are used to count the numbers of people and permanent dwellings within an area of no less than 15 people that is spatially defined by road networks and standard administrative boundaries commonly used for community-level spatial planning. Characteristic data about the types of people (demographics), housing attributes and income profiles are then aggregated up to the corresponding dissemination area level for statistical analysis and reporting purposes. Dissemination areas represent characteristic profiles of between 400 and 600 people and vary in size from less than 1 square kilometer in dense urban settings to between 10 and 60 square kilometers in urban fringe areas. In rural and remote settings, these same statistical dissemination areas can vary from 10,000 square kilometers to several hundred thousand square kilometers in size.

Knowing where clusters of buildings and people are situated within a particular dissemination area is essential for a broad range of spatial planning activities including resource management, land development and environmental impact assessment (Statistics Canada, 2016c). It is also a requirement for assessing the susceptibility of buildings and people to the potential impacts of future disaster events which, by definition, occur at the intersection between settled areas and natural hazard footprints that can vary widely in both shape and size.

Delineating areas of human settlement is less of an issue in more densely populated urban areas where the spatial extent of development (buildings and related infrastructure) largely coincides with dissemination area boundaries. In these settings, the relative proportion of developed land to parks and open green space generally exceeds 90% of the total dissemination area. In fringing areas of suburban and/or agricultural development, the proportion of settled land can vary between 15-30% of the total dissemination area. In more sparsely populated regions, the spatial extent of human settlement ranges between 5-15% for rural areas to less than 1% of the total dissemination area in remote hinterland settings.

Measurement

This study uses a blend of analytic methods and available public domain information to measure the spatial extent and temporal evolution of built-up areas in Canada. Development footprints, which define the geographic location and spatial extend of settled areas are based on information provided by high resolution earth observation sensors and land survey data. This study builds on pioneering work of Statistics Canada in understanding the characteristics of human settlement across Canada, and more recently on studies that have focused on the dynamics and environmental impacts of urbanization in major metropolitan areas (Statistics Canada, 2003, 2006, 2010, 2011, 2016a, 2016c)

Built-up areas in urban and suburban regions of Canada are based on a 30m-resolution land cover classification (circa 2015) developed by Agriculture and Agri-Food Canada (Agriculture and Agri-Foods Canada, 2015; Fisette et al., 2006). Settled areas in sparsely populated rural and remote communities are delineated by buffering building locations derived from a 2017 land survey developed by the Canadian Centre for Mapping and Earth Observation (CanVec+ dataset: Natural Resources Canada, 2017, 2019). The distinction between urban and rural settlements is based on a threshold of 400 people per square kilometre (Statistics Canada, 2016c)

Changes in settlement patterns over time are based on results of a 250m resolution grid-based model developed as part of the Global Human Settlement Layer (GHSL); a seamless fabric of earth observation metrics tracking built-up areas and patterns of urbanization over a 40-year period (Pesaresi et al., 2016). The GHSL methodology is based on advanced machine learning and spatial data mining methods that allow seamless processing, data analytics and knowledge extraction from large and heterogenous datasets including high resolution satellite imagery, national census statistics and Open-Source geospatial information (Dijkstra et al., 2020).

Development boundaries are largely coincident in urban areas across Canada when comparing outputs of the NRCan and GHSL assessments of built-up areas, except for isolated regions of rapid growth where settlement boundaries have expanded since 2015. The biggest differences

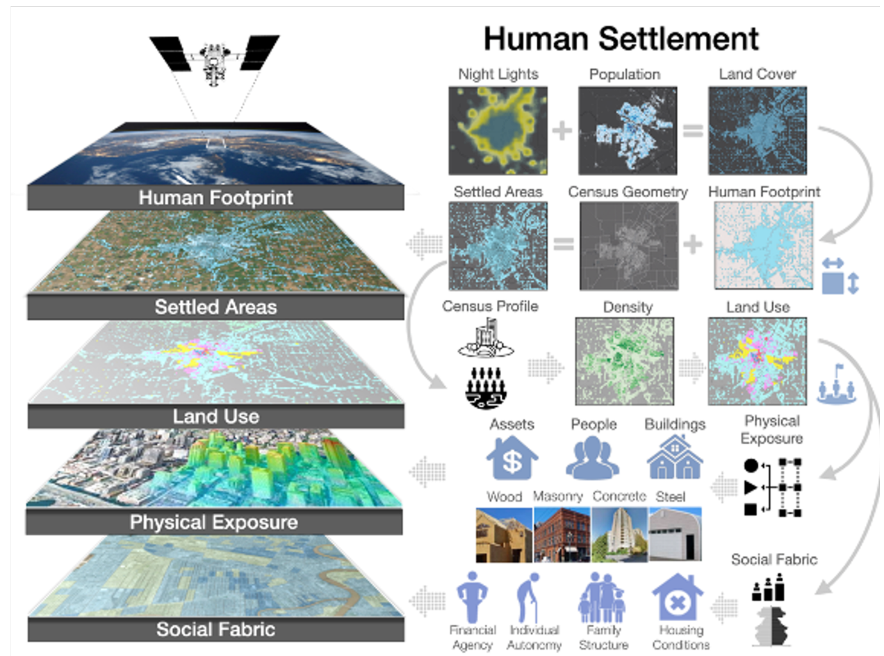


Figure 2: Methodology for defining settled areas

are in rural and remote regions, where isolated small clusters of buildings are captured in the NRCan assessment as a result of buffering surveyed building point locations but appear to be below the detection thresholds of the GHSL methodology.

A critical step in the process of developing a coherent fabric of human settlement across Canada is the spatial intersection of built-up area boundaries with the standard dissemination area geometries used in the national census to report population and housing statistics. As illustrated in Figure 2, the integration of these two layers results in a more detailed assessment of where buildings and people are likely to be situated within a particular dissemination area. We define this new layer as the NRCan Settled Area boundary and assign each polygon with a unique identification code (SAUID) that is linked to standard census administrative boundaries to allow the integration of statistical population and housing information.

Settlement areas and census dissemination regions are generally coincident in urban settings, except for the delineation of open spaces such as parks, wetlands and forest enclaves in which there are few permanent structures. Settlements in rural and remote settings are defined by isolated small clusters of buildings and people within broader census dissemination areas that can be several hundred or thousand kilometers in area. In these cases, population and dwelling counts from individual census dissemination blocks (source region) are allocated to settlement areas (target regions) using a process of dasymetric mapping, an area-based cartographic technique where statistical information is transformed from one geometry type to another.

The concentration or density of population and dwellings allocated to each settled area target zone is based on a combination of areal weighting and ancillary data that help guide the allocation process. Areal weighting is based on a percentage of the dissemination block represented by each settlement polygon. Night-time light intensity values are used as a proxy for measuring the degree of development and its spatial variation within any particular dissemination area. For this study, we use VIIRS (Visible Infrared Imaging Radiometer Suite) data collected by earth observation sensors (circa 2016) and processed by the Earth Observation Group in partnership with NOAA's National Centers for Environmental Information (Earth Observation Group, 2017). The data are filtered to exclude the effects of cloud cover and ephemeral light sources such as industrial flares and forest fire and processed at a scale of approximately 500 meters. Outputs of the dasymmetric mapping process include a suite of indicators that measure spatial extent, geographic area, density of settlement areas (people, dwellings), and the percent coverage of built-up regions within a corresponding census dissemination boundary polygon (See Table X and Appendix X for details).

Results & Intended Use

Delineation of settled areas serves several purposes. It provides important insights on cartographic patterns of land use and density in different regions across Canada that will be of interest for a variety of spatial planning functions. For example, the shape and density of built-up areas provides insights on our connection to the land and the influences of physical geography on the patterns and history of development across Canada (Figure 3). It also makes explicit the geographic overlap between human settlement and natural hazard footprints -- a requirement for quantitative risk assessments that measure characteristics of physical exposure and the susceptibility of people and assets to the expected impacts and consequences of future disaster events (See Part III).

Settlement patterns in the Cordillera region of western Canada are controlled by the physical constraints of steep mountainous terrain and the availability of land for residential development (Figure 3A). More than 3.9 million people (85% of BC population) live in clustered urban centres situated along low-lying coastal areas of the Georgia Basin (Metro Vancouver), southern Vancouver Island (Victoria), Fraser Valley (Langley-Abbotsford) and the Okanagan Lake region (Kelowna). Residential densities in these urban centres are the third highest in Canada, with an average of ~2,075 people per square kilometre. These larger urban clusters are connected by a sparse necklace of smaller settlements situated along the coast and within interior mountain valleys that serve as major transportation corridors. Concentrations of people living on low-lying river deltas and along interior mountain valleys results in high levels of susceptibility to earthquake ground shaking, tsunami and flood inundation, wildfire conflagration and slope instabilities.

In contrast, built-up areas in the Prairie provinces of western Canada (Alberta, Saskatchewan and Manitoba) reflect the relatively flat topography of the Interior Plains region, and a rectangular pattern of settlement resulting from land subdivision along lines of latitude and longitude (Figure 3B). Approximately 3.4 million people (53.5% of prairie province population) live in a handful of 6 urban centers that exceed a population of 100,000 people. In order of population size, these include

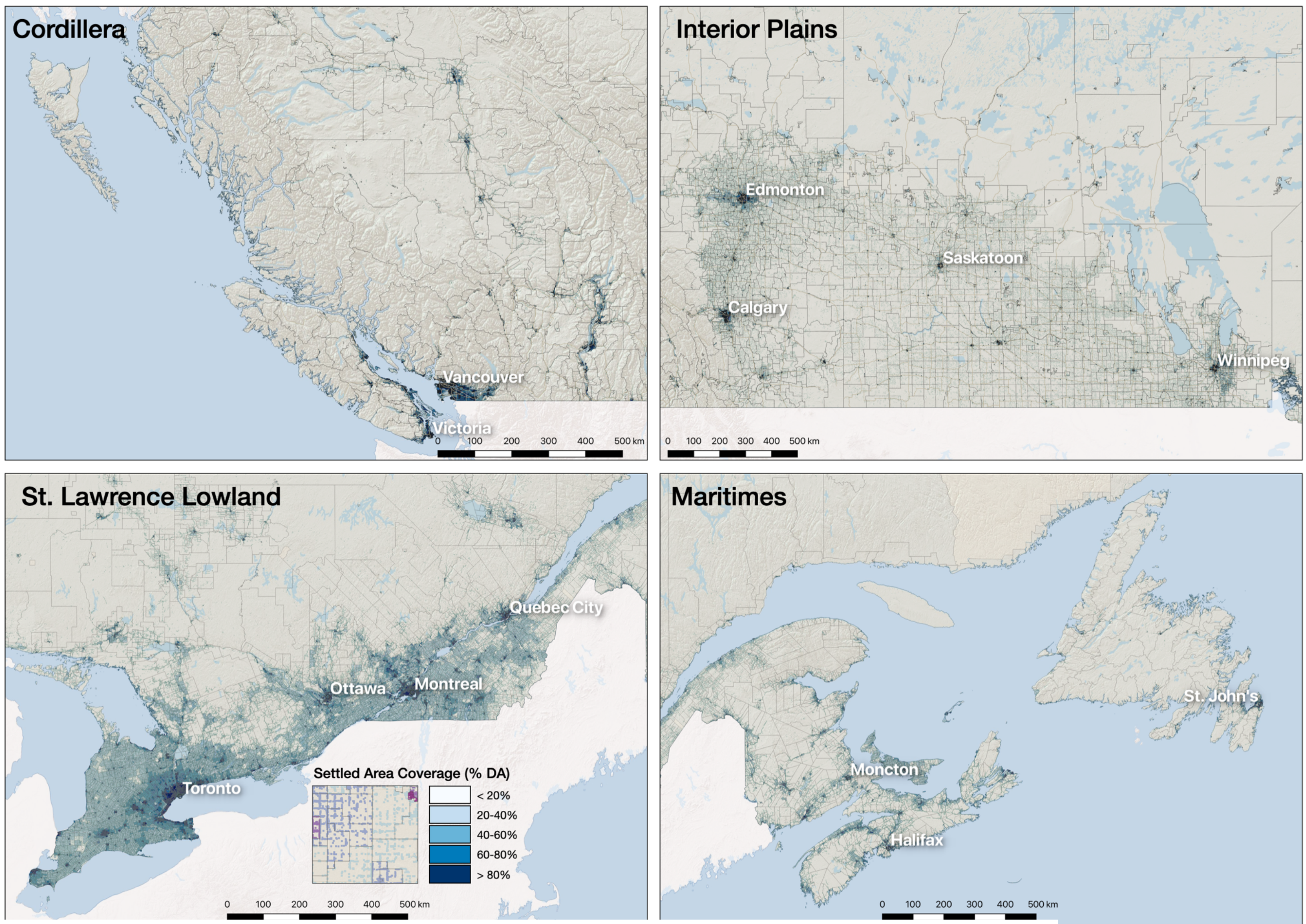


Figure 3: Patterns of human settlement across Canada. 3: Cordilleran region, 3B Interior Plains; 3C Great Lakes and St. Lawrence Lowland; 3D Maritime provinces

the cities of Calgary, Edmonton, Winnipeg, Saskatoon, Regina and Red Deer. Average residential densities in these urban areas range from ~540 people per square kilometre in Manitoba to ~240 per square kilometer in Saskatchewan. The balance of the region's population lives in small and mid-sized towns that were initially settled along transportation lines established for the movement of agricultural produce from rural farms to city centres. The distribution of these prairie farm towns reflects both the availability of water and the regular spacing of grain elevators and schools that were established early in the history of settlement (McGregor & Lehr, 2016; Vervoort, 2006). Over time, densification of these towns occurred mainly along the intersections of primary transportation routes. Average rural population densities on the prairies range between 75 people per square kilometer in Alberta to 25 people per square kilometer in Saskatchewan. Hazard threats of concern include wildfire conflagration in grassland and northern forested regions, and floods along major river systems in more densely settled areas to the south.

Patterns of settlement along the southern Ontario Peninsula are constrained by the Great Lakes of Huron, Erie and Ontario, and influenced by a patchwork of land subdivisions that reflects the vestiges of British surveying practices and more recent industrial development (Figure 3C). Township boundaries are rectilinear but were initially established along baselines with different azimuthal orientations resulting in an irregular grid pattern that has been accentuated with ongoing growth and development (Belshaw, 2018). Clustered urban centres in the Greater Toronto Area (GTA), Hamilton-Niagara Peninsula, Ottawa Valley, Kitchner-Waterloo-Barrie and London regions account for more than 9.7 million people (~90% of Ontario population), with the balance living on rural farms and in scattered industrial centres situated along major transportation corridors.

The Great Lakes region is characterized by dense patterns of development with settlement footprints generally representing more than 60% of census dissemination boundaries in the exurban fringe areas and 90-100% in urban centres. Urban residential densities are variable ranging from ~435 people per square kilometre in London to more than ~4,760 people per square kilometre in Toronto. In contrast, rural settlements to the north have an average of ~100 people per square kilometre. Hazards threats of concern in this region include flooding and earthquake ground shaking in densely populated areas to the south and a mix of wildfire and flooding to the north.

Maritime regions of eastern Canada include the eastern townships of Quebec, and Maritime provinces of New Brunswick, Nova Scotia, Prince Edward Island and Newfoundland-Labrador (Figure 3D). Development patterns in these regions reflect the influences of early colonial settlement along river systems within the St. Lawrence Valley and the establishment of clustered fishing ports scattered along the outer Atlantic coastline. Densification of these backbone settlement patterns around early centres of commerce resulted in establishment of the metropolitan areas of Montreal and Quebec City. These two urban centres account for more than 6.4 million people (~79% of Quebec population) with an average residential density of ~2,750 people per square kilometre. Smaller urban centres of the Maritime Provinces account for 2.19 million people (31% of region total) and are characterized by much lower residential densities (350-1,340 people/km2). Earthquakes and flooding are the primary hazards of concern for densely populated settlements along the St. Lawrence Valley and Appalachian region of New Brunswick along with the threat of wildfire, which increases to the North. Low-lying maritime settlements are primarily susceptible to inland flooding, and severe wind/storm surge hazards associated with hurricanes that sweep northward along the Atlantic coast.

Northern regions of Canada, including the Yukon, Northwest Territories, Nunavut and rural portions of northern Saskatchewan, Manitoba, Ontario, Quebec and Labrador encompass a vast and sparsely populated landscape. These north regions account for 76% of the landmass in Canada (~7.5M km2) with built-up areas representing only 3% (3,900 km2) of the total area. Only 1.3% of Canadians live in the far North (~450,000) with only one in ten people choosing the major cities of Whitehorse, Yellowknife and Iqaluit as home. The majority of people (~90%) live in small rural villages and towns of between 500-2,000 full-time residents, or in scattered remote communities. These settlements reflect a more intimate and direct connection to land that is influenced by primary activities such as agriculture, animal husbandry, fishing, forestry and mining. Average residential densities in concentrated villages and towns are ~60 people per square kilometre, and substantially less in hinterland areas. Although wildfire, flooding and earthquakes are of concern across the region, the overall threat is relatively low compared to other parts of Canada owing to the sparse and scattered pattern of settlement.

Urban Form and Function

Urban form is a concept used in the fields of landscape ecology, geography and community design to describe the architecture, morphology and/or internal structure of settled areas in terms of different land use types and the system functions they provide (Clifton et al., 2008; Duranton & Puga, 2015; Marshall & Gong, 2009; Miller, 2013). In landscape ecology, urban form is used more generally to describe built-up areas and their relationship to ecosystem-based land cover types (e.g., forest, rangeland, cropland, wetland etc.). The focus is on broader spatial patterns of settlement (concentrated vs. fragmented) and the associated environmental impacts of urbanization over time. In this context, urban form is equivalent to the more general concept of settled areas discussed in the preceding section and is measured primarily on the basis of shape, area and the relative densities of people and buildings.

We use the more specific concept of urban form in this study to describe the internal structure, composition and arrangement of settled areas in terms of both land use types (residential, commercial, industrial, etc.,) and the corresponding mix of building functions that provide system services such as habitation and commerce within a particular town, city or region. The focus here is on details that are relevant for community design and spatial planning. We use the concept of 'built environment' in this context to encompass engineered structures (buildings) and enveloping areas that have been developed to support human activities. The interface between built and natural elements of land cover can be sharply delineated along an enveloping zone of transition (e.g., legislated growth boundaries), feathered across a fringing transition zone with intermixing of engineered and natural features (mixed interface), or contained within a settled area where islands of vegetation occur within an area that has been developed.

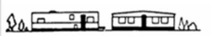
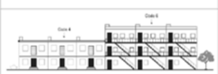
Land use patterns offer a familiar conceptual framework for characterizing the design and structure of urban and rural communities of all sizes. They are used to support growth management, spatial land use planning and sustainable community development at all levels of government. The urban form of many small and medium-sized settlements is characterized by concentric patterns of development with high-density residential and mixed-use business precincts clustered around central transportation hubs and/or historic nodes. These higher-density cores radiate outward to medium and low-density residential neighbourhoods in suburban zones and exurban fringe areas that are dominated by single family detached and multi-family low-rise buildings with supporting networks of commercial and civic facilities situated along transportation arterials. Larger metropolitan regions, particularly those whose growth patterns have been constrained by geography and/or the influences of land use policy, are characterized by polycentric patterns of development in which residential density and business functions have been amalgamated and re-distributed over time.

Understanding patterns of land use and related functionality at a given location provides important insights on the connections between people and place, the flows of goods and services and the overall resilience of human settlements in terms of social, economic and environmental sustainability (Williams, 2014). For example, the number, location and types of businesses within a community can reflect patterns of economic vitality (stocks and flows) and relative contributions to the overall ecological footprint of a surrounding region. Similarly, the number, locations and types of residential buildings reflect the influence of competing land use policies over time and can provide important insights on underlying patterns of physical and social vulnerability. This is particularly relevant in the fields of climate change adaptation and disaster resilience planning where risk is defined in terms of intrinsic capacities to manage ongoing growth and development while minimizing the uncertain future impacts and socio-economic consequences of natural system processes.

Functional Land Use

Methods used to characterize general land use patterns for each of the ~389,000 settled areas in Canada are similar to those developed for more detailed studies of land use change and the analysis of community energy and emission profiles (Clifton et al., 2008; Salter et al., 2020; Song & Knaap, 2007). The process begins with development of detailed spatial inventories that describe the number of people and occupancy classes of residential and non-residential buildings within each settled area.

Figure 5: Translation of census attributes into building occupancy classes

StatsCan Classification of Dwelling Types (estimated range of number of units)		Allocation	Average # Dwellings/ Building	Hazus Occupancy Code (range of of units)
	**Single detached house (Code 1):** A single dwelling not attached to any other dwelling or structure (except its own garage or shed). A single-detached house has open space on all sides, and has no dwellings either above it or below it. A mobile home fixed permanently to a foundation is be coded as a single-detached house.	100%	1	**RES1** (1)
	**Other single-attached house (Code 7):** A single dwelling that is attached to another building and that does not fall into any of the other categories, such as a single dwelling attached to a non-residential structure (e.g., store or church) or occasionally to another residential structure (e.g., apartment building)	100%		
	**Mobile home (Code 8):** A single dwelling designed and constructed to be transported on its own chassis and capable of being moved to a new location on short notice. It may be placed temporarily on a foundation such as blocks, posts or a prepared pad and may be covered by a skirt.	100%	1	**RES2** (1)
	**Semi detached house (Code 2):** One of two dwellings attached side by side (or back to back) to each other, but not to any other dwelling or structure (except its own garage or shed). A semi-detached dwelling has no dwellings either above it or below it and the two units together has open space on all sides.	100%	2	**RES3A** (2)
	**Apartment or flat in a duplex (Code 4):** One of two dwellings located one above the other. If duplexes are attached to triplexes or other duplexes or to other non-residential structure (e.g. a store), assign code 4 to each apartment or flat in the duplexes	100%		
	**Row house (Code 3):** One of three or more dwellings joined side by side (or occasionally side to back), such as a town house or garden home, but not having any other dwellings either above or below. If row houses are attached to high-rise buildings, each townhouse is assigned to code 3.	30%	3.5	**RES3B** (3-4)
		70%	7	**RES3C** (5-9)
	**Apartment in a building with fewer than five storeys (Code 6):** A dwelling unit attached to other dwelling units, commercial units, or other non-residential space in a building that has fewer than five storeys.	70%	15	**RES3D** (10-19)
		30%	30	**RES3E** (20-49)
	**Apartment in a building with five or more storeys (Code 5):** A dwelling unit in a high-rise apartment building which has five or more storeys.	30%		
	**Apartment in a mixed use building with five or more storeys (Code 5):** A dwelling unit in an apartment building that has five or more storeys where the first floor and/or second floor are commercial establishments.	70%	~75	**RES3F** (50+)

NAICS Classification of Business Functions (range of of codes)	Description	Hazus Occupancy Code
721110 -721214	Hotel/Motel - temporary lodging	**RES4**
721310 -721309	Institutional dormitory -group housing (military, college, etc)	**RES5**
623110 -623311	Nursing home & care facilities	**RES6**
311330 -339115; 441110-454390; 722213- 722330	Retail trade - food, auto, merchandise	**COM1**
311612 -313312; 423110-425120; 444190-493190; 531130-562119	Wholesale trade - warehouse	**COM2**
238220 -238290; 326212-335312; 442299-488410; 532111-562998; 611511-624410; 811111-813319	Service station/shop	**COM3**
221111 -238990; 312229-334612; 423990-443120; 481111-492110; 511140-562998; 611710-621910; 711310-722310; 811212-813990	Office building (professional/technical services)	**COM4**
521110 -523991	Financial institution - bank, credit union, etc.	**COM5**
622110 -622310	Hospital and specialty medical care facilities	**COM6**
339116; 621111-621999	Medical office/clinic	**COM7**
721110 -722410	Restaurant/bar	**COM8**
512131; 711110 -713990; 712110-712190; 713990	Theatre and entertainment services	**COM9**
812930	Parking garage	**COM10**
313111 -339999	Heavy industrial - factory	**IND1**
313222 -316999; 321999-326299; 332211- 339999	Light industrial - factory	**IND2**
311111 -312229; 324110- 325998	Food/Drug/Chemical factory	**IND3**
211111 -238910; 324199-335929	Metals/Mineral processing factory	**IND4**
334111 -334413	High technology factory	**IND5**
236115 -238990	Construction office	**IND6**
111110 -115310; 311119-311611; 541320-561730	Agricultural building	**AGR1**
813110 -813990	Church/Non-Profit building	**REL1**
921110 -922110; 922130-922190; 923110-928120	General service building	**GOV1**
922120, 922160	Emergency response facility (police, fire, EOC)	**GOV2**
519120; 611692-611692	Elementary/Secondary school facility	**EDU1**
611699 -611210	Colleges, Universities and Professional Schools (not including dormitory)	**EDU2**

Resulting density characteristics and functional use characteristics are then used to derive a representative typology of more general land use classes that describe the range of variability within the portfolio.

The residential component of the land use model is based on detailed population and dwelling counts provided by Statistics Canada at the census dissemination block level, and related information about dwelling type and housing characteristics reported at higher levels of aggregation (Statistics Canada, 2016a, 2016b, 2016e). Nine mutually exclusive dwelling types are identified as part of the census enumeration process, including single-detached houses, semi-detached houses, row houses, apartments or flats in a duplex, apartments in a building that has five or more storeys, apartments in a building that has fewer than five storeys, other single attached housing configurations, mobile homes and other movable dwellings (See Figure 4).

The non-residential component of the building stock is derived from location and occupancy information provided through licensed access to commercial business registries (Dun & Bradstreet, 2011; Emporis International, 2017; Scott's Directories, 2019). Business functions are based on standard code descriptions of the North American Industry Classification System (NAICS, 2017). Correlation between NAICS business functions and more generalized HAZUS occupancy codes is then used to establish the dominant business functions for each unique building point in the registry (See Figure 4). Non-residential and residential buildings are aggregated at the census dissemination block level and allocated to each settled area using dasymmetric mapping techniques described above.

Land Use Archetypes

Resulting population density and building profile statistics are used to characterize six representative archetypes of urban form that describe variable patterns of land use for all settled areas in Canada (Figure 5). Building functions for each of the 33 occupancy classes used in this study are based on a standardized North American typology developed as part of the HAZUS methodology (FEMA, 2011).

Spatial metrics that describe each archetype include overall site coverage, relative proportions of residential and non-residential buildings, the number of people and dwelling units per hectare, and the relative proportions of single and multi-family buildings. In order of physical concentration and building profile complexity, the patterns include High-Density Urban Residential (RES-HD), Medium-Density Urban Residential (RES-MD), Mixed Use Residential and Commercial (MIXED), Low-Density Urban Residential (RES-LD), Commercial and industrial (COMM-IND), and rural residential (RURAL).

High-density urban residential neighbourhoods that exceed 75 people per hectare represent 12% of all built-up areas in Canada (~330 km2) with average population density more than double minimum threshold values in larger metropolitan centres. They tend to be situated in downtown central business districts and are characterised by high concentrations of medium and high-rise buildings with large cumulative floor area resulting in an average site coverage of ~78% in most regions. The internal structure is complex with a large diversity of residential and non-residential building functions. Multi-family residential apartments and professional office buildings are the dominant occupancy types with lesser amounts of civic and industrial facilities.

Medium-density residential neighbourhoods represent 18% of the built-up area in Canada (~1,630 km2) and are characterised by population densities ranging between 35 and 75 people per hectare. They tend to be located along the periphery of established downtown business districts and/or clustered in satellite urban centres designed to accommodate the demands of increased growth and development. Building diversity is limited with high concentrations of single-family detached homes, duplexes and row houses situated on larger parcels of land with an average site coverage of ~21% in most neighbourhoods. Supporting networks of commercial retail, school and health facilities provide essential services within and between adjacent residential neighbourhoods and are often concentrated along the intersections of major transportation arterials.

Mixed-use archetypes represent 7% of the built-up area in Canada (~450 km2) and share many of the attributes of medium and high-density residential land use neighbourhoods. They are characterized by lower population density (15-35 people per hectare) and higher concentrations of commercial, civic and light industrial buildings (~34%) that reflect a wide diversity of functional services. Non-residential building footprints tend to be larger, resulting in an overall site coverage of ~28% in most settled areas. The spatial distribution of mixed-use neighbourhoods is quite varied from region to region. They can be clustered in downtown business districts, distributed along linear transition zones with high-density residential and/or industrial areas and/or scattered across larger metropolitan regions that have experienced growth and the amalgamation of smaller municipalities over time.

Figure 6: Land use typologies for national human settlement layer

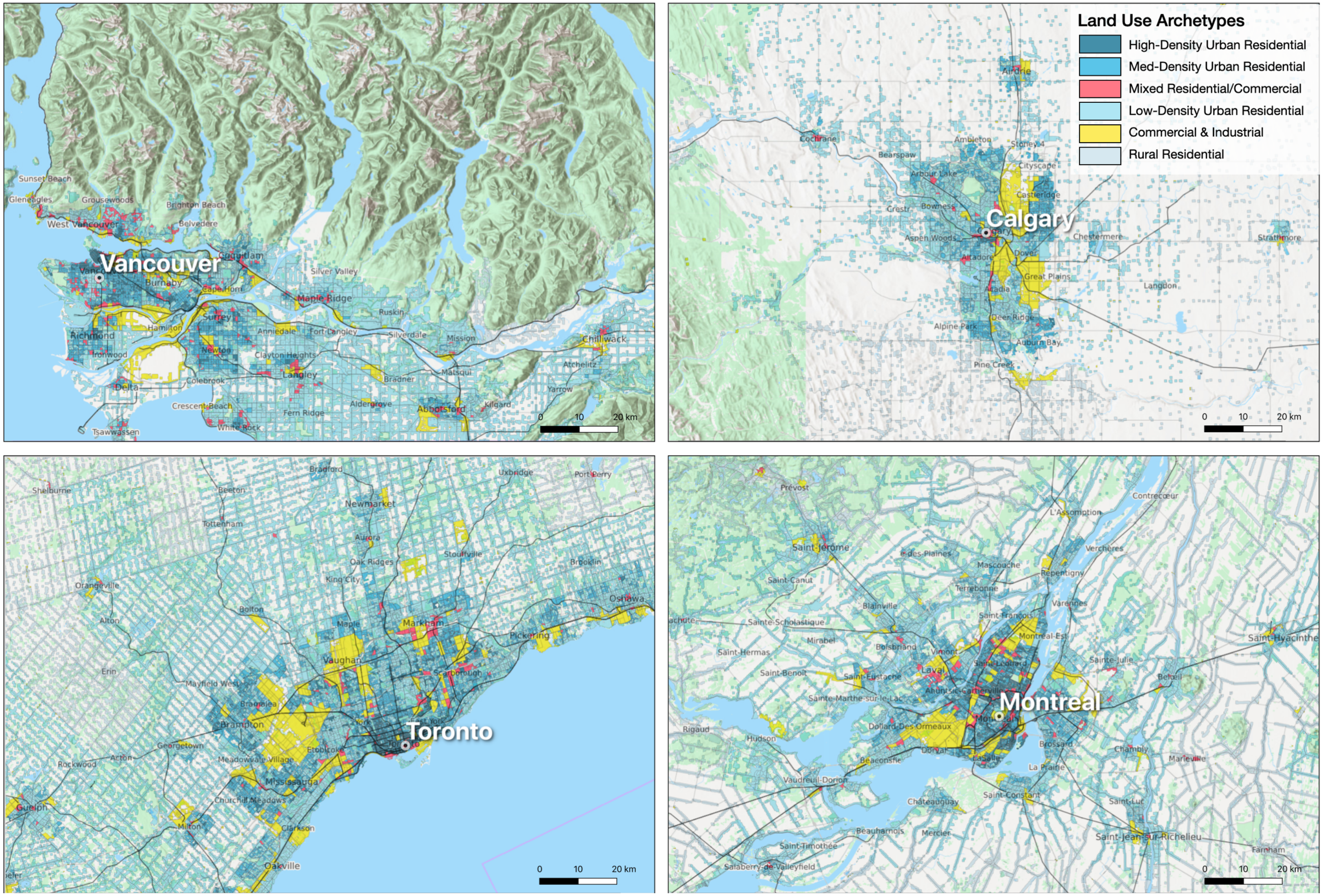


Figure 7: Land use archetypes for representative urban centres in Canada

Low-density residential neighbourhoods represent 36% of all built-up area in Canada (~40,000 km2) and are the dominant land use type in communities of all types and sizes. They are characterized by population densities that range between 2 and 10 people per hectare and tend to form a connecting fabric extending outward from urban centers to increasingly less dense suburban and exurban fringe areas. Building diversity is very low with the majority of residential structures represented by single-family detached homes (83%), duplexes and row houses (8%). Non-residential buildings are dominated by commercial retail businesses and civic facilities, including school, police, fire and health centres that serve broad catchment areas.

Commercial-Industrial neighbourhoods represent 9% of all built-up area in Canada (~8,460 km2) and are extremely variable from region to region in terms of internal structure, diversity of building types and related functional services. They are similar in composition to mixed use neighbourhoods but characterized by very low population density (<1 person/hectare) and higher concentrations of industrial warehouses and related commercial businesses situated around major transportation hubs that support the distribution of goods and services within and between interconnected supply chains. Although commercial-industrial zones can be relatively large in size, the aggregate building area is relatively small compared with surrounding open space resulting in average site coverage values that are less than a few percent in most areas across Canada.

Low-density rural residential neighbourhoods make up 19% of all built-up land (~77,210 km2) and are by far the most numerous, representing 60% of all settled areas in Canada. They are similar in composition to low-density urban residential neighbourhoods but characterized by lower population density (<1 person/hectare), smaller overall site coverage (<1%) and lower building diversity. An equally important distinction is that rural and remote residential areas are, by definition, situated in hinterland areas outside the socioeconomic influences of metropolitan centres (Statistics Canada, 2016a, 2016d). Most are defined by small clusters of buildings that are separated by vast open spaces in the interior plains of Alberta, Saskatchewan and Manitoba, along all three coastlines and within northern boreal and arctic regions of Canada. Sample land use maps for representative urban centres across Canada are illustrated in Figure 6.

Validation and ground-truthing of model outputs is based on visual comparisons between interpreted land use archetypes and observed settlement patterns using a combination of high-resolution satellite imagery and compiled land use bylaw information for representative urban areas across Canada.

Arcadia: A Case Study Example

In addition to providing important insights on general patterns of urban form and functionality, outputs of the land use classification can be used to generate a more detailed profile of the internal structure and composition of a community or region. In the following sections, we explore how outputs of the land use classification and other components of the national human settlement layer might be used to support regional planning and policy development efforts through the lens of a representative community that we will refer to as 'Arcadia'. The maps and related charts for the Arcadia region are generated using information extracted from the national human settlement layer (See Figure 7).

Arcadia is a typical medium-sized community of ~185,000 people with a downtown historic business district situated at the intersection of major road and rail transportation routes. It is characterized by a monocentric urban form with higher density residential, mixed use and commercial-industrial neighbourhoods clustered in the downtown core with a surrounding area of lower density residential neighbourhoods of varying size that become increasingly more sparsely populated toward the outer fringe. The majority of residents live in low-density neighbourhoods that are composed primarily of single-family residential homes (76%) with increasing numbers of attached duplex and row house complexes (18%) toward the city centre.

Like many communities across Canada, Arcadia is managing the pressures of increased growth and development by creating higher-density residential and mixed-use neighbourhoods around the city core and in satellite regions outside the central business district. Medium-density neighbourhoods are characterized by clusters of low-rise row house and condominium buildings that represent ~9% of the overall land use archetype in this region. The relative proportion of these multi-family buildings jumps to ~15% in high-density residential neighbourhoods, along with an equal proportion of mid-and high-rise apartment buildings surrounding the downtown core area.

Non-residential buildings are distributed throughout the community but in varying proportions depending on land use type. Commercial structures, including professional offices and retail shops make up only 3-5% of all buildings within residential neighbourhoods. The concentrations and diversity of commercial buildings increase to 20% in mixed use neighbourhoods and up to 40% in commercial-industrial precincts. These trends are accompanied by a corresponding increase in light industrial buildings and heavy industrial warehouses, which represent 20% or more of the building stock in the commercial-industrial complexes situated near major rail and road transportation hubs.

Defining land use characteristics and related building functionality for all settled areas in Canada serves several purposes. It complements existing land cover classifications (Agriculture and Agri-Foods Canada, 2015; Statistics Canada, 2016c), and provides an internally coherent national framework for understanding patterns of human settlement and the related impacts of urban growth and development on the natural environment. It also provides the capability to model a wide range of physical and socioeconomic interactions -- and interventions that might be considered to increase capacities for sustainable development in accordance with guidelines established by regional, national and/or international policy directives. Finally, understanding the details of land use and building occupancy at a neighbourhood scale provides a robust theoretical basis for inferring details about the types of engineered structures that are likely to be present, and the implications for both climate change adaptation and disaster resilience planning.

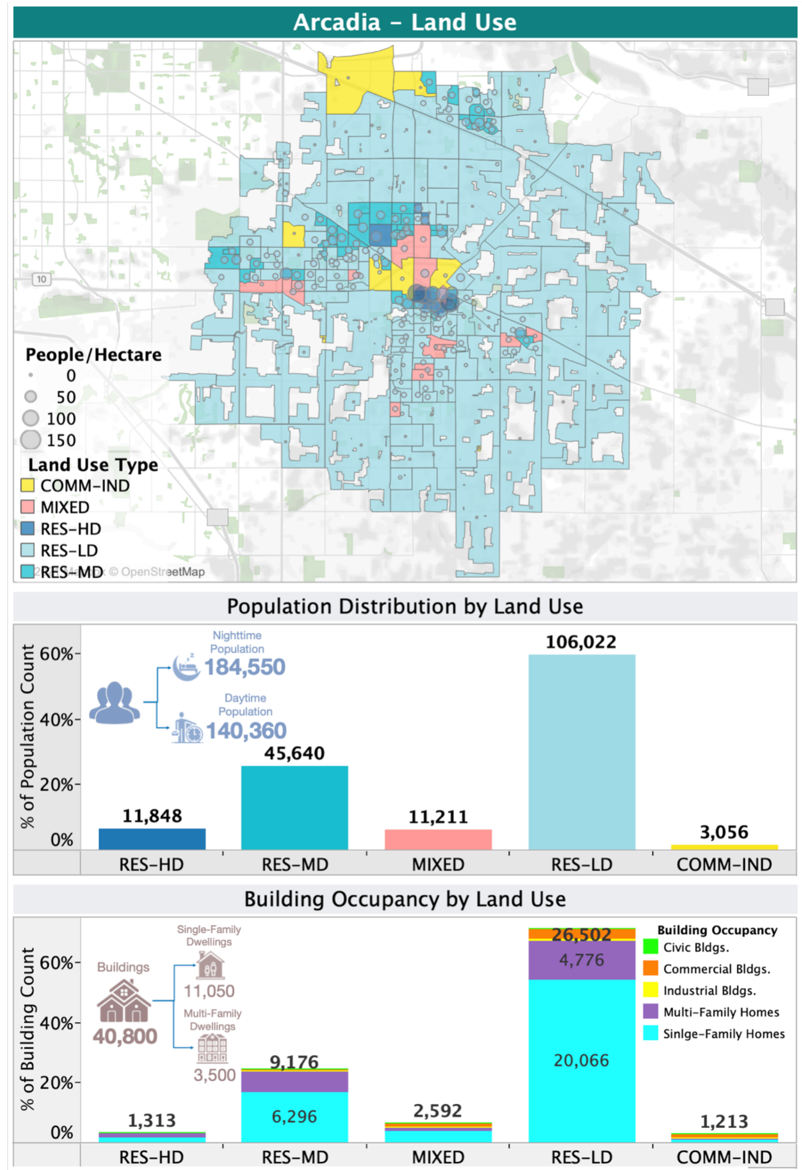


Figure 8: Settlement patterns for the reference town of Arcadia

EXPOSURE TO NATURAL HAZARDS

Physical exposure describes the construction type and age of engineered structures within a building portfolio (wood, concrete, masonry, etc.); the numbers of people who are likely to occupy these structures at different times of the day and night; and the economic value of capital assets, which includes the costs to repair and/or replace buildings and related contents in the event of a disaster. This information is used to address more specific questions about who and what are exposed to hazard threats of concern, underlying characteristics of building design and construction materials that will determine physical vulnerabilities and capacities to withstand the impacts of future hazard events, and to identify strategic opportunities for mitigation and/or adaptation.

Physical exposure models that provide detailed information on building construction materials and engineering design are in high demand but low supply owing to the time and resource investments required to compile the necessary baseline datasets. Building exposure information compiled over the years for insurance purposes is routinely used in the realm of commercial catastrophic risk modeling. However, the underlying information on building construction and engineering details for characteristic building types is proprietary and often developed using heterogenous classification schemes that hinder compilation at regional/national scales.

Public domain inventories derived from direct observation, government taxation records, and/or commercial real estate surveys generally provide address-specific location coordinates and detailed information on spatial dimensions, functional layout and asset valuation. However, they but do not always contain relevant information on construction types and lack a common set of building attributes making them difficult to compile across jurisdictional boundaries. In contrast, portfolio-based inventories derived from aggregate statistical data collected as part of Canada's national census provide a common set of attributes that are suitable for regional spatial planning. However, the baseline data lack detailed information building construction details that are required for assessing energy performance and physical vulnerabilities to natural hazard threats.

This study introduces a hybrid approach that leverages the strengths of bottom-up (site-level) and top-down (portfolio-based) methods of physical exposure modeling using publicly available information on residential and non-residential buildings in Canada. The model complements other national-level building inventories that have been developed for the United States, Australia, South America and many parts of Europe (Crowley et al., 2020; FEMA, 2011; Nadimpalli et al., 2016; Yepes-Estrada et al., 2017), and is aligned with emerging international standards established by the USGS PAGER program, the Global Earthquake Model Foundation GED4GEM, the UN Office for Disaster Risk Reduction Global Assessment Report (GAR) and the World Bank's Global Facility for Disaster Reduction and Recovery MOVER exposure model (EPI Centre, 2018; K. Jaiswal et al., 2010; K. S. Jaiswal & Wald, 2014; McGlade et al., 2019; Murnane et al., 2019; Silva et al., 2018). It is designed to support a wide range of modeling activities that inform planning and policy development in the fields of climate change adaptation and disaster resilience planning. These include the development of building energy and emission models, regional and national risk assessment models and screening tools for identifying buildings of concern for mitigation and/or adaptation planning initiatives.

The national physical exposure model for Canada builds on outputs of the land use classification outlined in previous sections. It has evolved through an iterative multi-step process of development and refinement that includes the following steps: (1) define building occupancy and construction types based on standard North American HAZUS taxonomic classification, (2) develop mapping schemes that establish the proportional mix of building typologies likely to be associated with each of the six characteristic land use archetypes, (3) allocate unique building archetypes for each settled area based on frequency distributions defined by context-specific mapping schemes that make explicit occupancy, construction type, finished floor area, number of stories and period of construction, (4) estimate the numbers of people for each building type at different times of day, and (5) estimate the capital asset value for buildings and contents based on industry standard costs for construction and/or replacement.

Procedures for each step in developing primary components of the physical exposure model are described in the following sections through the lens of

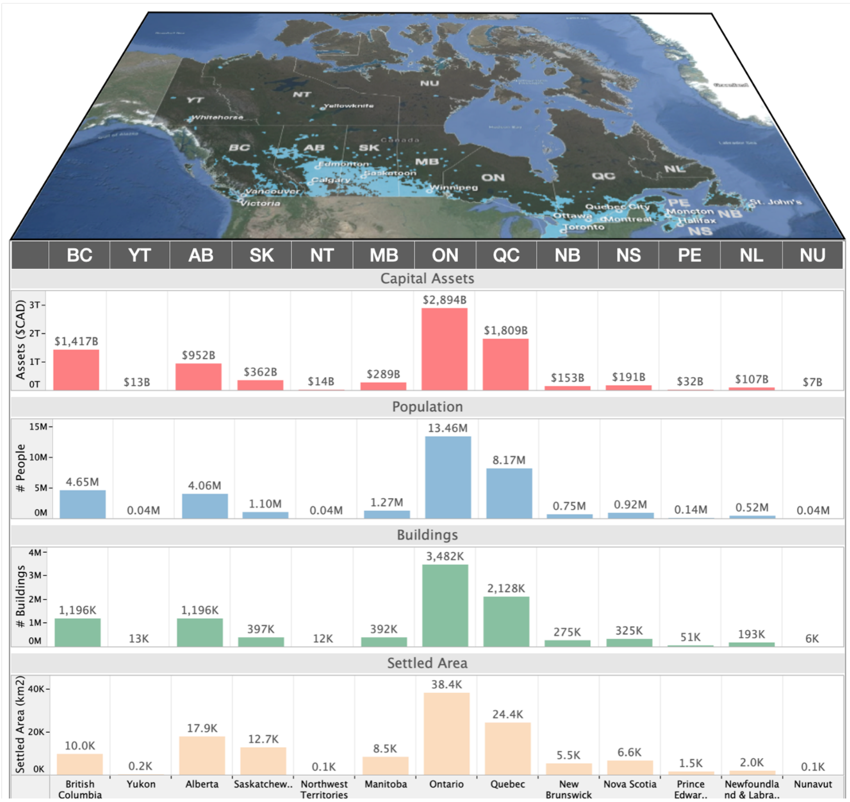


Figure 9: Distribution of physical assets in Canada

buildings, people and capital assets. As summarized in Figure 8, the model includes relevant information on the distribution of ~ 9.7 million buildings for all settled areas in Canada by occupancy and construction type, broad patterns of movement for ~35.1 building occupants during different times of day, and related capital assets (buildings and contents) with an estimated valuation of 8.24 trillion CAD$.

Buildings

Buildings constructed for permanent habitation and/or sector-wide business functions are foundational elements of the built environment. The number and types of structures define the architectural form and performance characteristics of a particular settled area and reflect both the history of development and evolution of construction practices for different regions in Canada over time.

Step 1: Taxonomic Classification

The number and types of residential buildings within each settled area is assessed based on the average number of dwelling units per structure and correlations between census dwelling type and standard HAZUS residential occupancy class definitions (See Figure 4). Dwellings in multifamily row houses and apartment complexes are proportionally allocated to corresponding HAZUS building classes based on information derived from representative site-level inventories (Journeay et al., 2015; Onur, 2002; Ploeger et al., 2018a; Ulmi et al., 2014).

Building counts for the non-residential component of the exposure model are determined on the basis of geographic coordinates for business listings that share the same physical location or street address. Building occupancy is based on correlations between NAICS functional use codes and standard HAZUS occupancy class definitions (See Figure 4). Dominant sector-level business functions are used to infer building occupancy class for those instances where there are multiple NAICS codes registered for the same physical location.

Physical characteristics of all buildings in the exposure model are classified according to engineering design attributes and related performance characteristics defined by guidelines established as part of the HAZUS North American building taxonomy standard (FEMA, 2006c, 2007, 2011). These include primary construction materials (concrete, precast, steel, masonry, wood, etc.), number of floors, lateral load resisting systems used to provide structural integrity and alignment with building code design guidelines that have evolved over time. Details of the classification for all 38 building types referenced in the national exposure model are summarized in Figure 9.

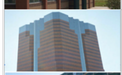
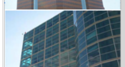
Hazus Building Taxonomy (FEMA P547)						
Model	**Construction Material**	**Typology**	**Height**	**Wall Type**	**Description**	**Design Epoch**
	Concrete	C1H	> 8 Floors	**C1:** Moment Frame	C1 buildings consist of concrete framing, either a complete system of beams and columns or columns supporting slabs without gravity beams. Lateral forces are resisted by cast-in-place moment frames that develop stiffness through rigid connections of the column and beams.	**PC**: < 1973, **LC**: 1974-1989, **MC**: 1990-2004, **HC**: 2005-present
		C1M	4-7 Floors			
		C1L	< 3 Floors			
		C2H	> 8 Floors	**C2:** Shear Wall	C2 buildings consist of concrete with flat slab or precast plank floors and concrete bearing walls. Little, if any, of the gravity loads are resisted by beams and columns. Building Type C2f has a column and beam or column and slab system that essentially carries all gravity load. Lateral loads are resisted by concrete shear walls surrounding shafts, at the building perimeter, or isolated walls placed specifically for lateral resistance.	**PC**: < 1973, **LC**: 1974-1989, **MC**: 1990-2004, **HC**: 2005-present
		C2M	4-7 Floors			
		C2L	< 3 Floors			
		C3H	> 8 Floors	**C3:** Masonry Infill	C3 is normally an older building with an essentially complete gravity frame assembly of concrete columns and floor systems. The floors can consist of a variety of concrete systems including flat plates, two-way slabs, and beam and slab. Exterior walls, and possibly some interior walls, are constructed of unreinforced masonry, tightly infilling the space between columns horizontally and between floor structural elements vertically, such that the infill interacts with the frame to form a lateral force-resisting element.	**PC**: < 1973, **LC**: 1974-1989t
		C3M	4-7 Floors			
		C3L	< 3 Floors			
	Manufactured	MH	< 2 Floors	**MH:** Light Frame	MH buildings are constructed using self-supporting steel chassis or frames that are designed to support transportation on wheels from one location to another. They are integral structures but can be designed in sections and assembled on-site. Floor and roof framing are most commonly wood-frame joists and rafters supported on wood stud walls.	**PC**: < 1973, **LC**: 1974-1989, **MC**: 1990-2004, **HC**: 2005-present
	Precast	PC1	< 3 Floors	**PC1:** Tilt-Up	PC1 buildings are constructed with concrete walls, cast on site and tilted up to form the exterior of the building. They are used for many occupancy types including warehouse, light industrial, wholesale and retail stores, and office. The majority of these buildings are one story; however, tilt-up buildings of up to three and four stories are common, and a limited number with more stories exist. Lateral forces in PC1 buildings are resisted by flexible wood or steel roof diaphragms and tilt-up concrete shear walls. Floor diaphragms are most commonly composite steel decking.	**PC**: < 1973, **LC**: 1974-1989, **MC**: 1990-2004, **HC**: 2005-present
		PC2H	> 8 Floors	**PC2:** Shear Wall	PC2 buildings include wide ranging combinations of precast and cast-in-place concrete elements. Precast members may be limited to a floor system of hollow core or T-beam construction, or may include all elements of the gravity and lateral load systems. PC2 includes concrete wall or frame buildings in which any of the horizontal or vertical elements of the lateral load system are made of precast concrete.	**PC**: < 1973, **LC**: 1974-1989, **MC**: 1990-2004, **HC**: 2005-present
		PC2M	4-7 Floors			
		PC1L	< 3 Floors			
	Reinforced Masonry	RM1M	4-7 Floors	**RM1:** Wood/Metal Diaphragm	RM1 buildings are constructed with reinforced masonry (brick cavity wall or concrete masonry unit) perimeter walls with a wood or metal deck flexible diaphragm. RM1 construction can be separated into two categories. RM1u is a multi-story structure and typically has interior CMU walls and shorter diaphragm spans, and RM1t structures are large, typically one-story buildings similar to concrete tilt-ups.	**PC**: < 1973, **LC**: 1974-1989, **MC**: 1990-2004, **HC**: 2005-present
		RM1L	< 3 Floors			
		RM2H	> 8 Floors	**RM2:** Precast Diaphragm	RM2 buildings consist of reinforced masonry walls and concrete slab floors that may be either cast-in-place or precast. This building type is often used for hotel and motels and is similar to the concrete bearing wall type C2.	**PC**: < 1973, **LC**: 1974-1989t
		RM2M	4-7 Floors			
		RM2L	< 3 Floors			
	Steel	S1H	> 8 Floors	**S1:** Moment Frame	S1 buildings are characterized by a complete frame assembly of steel beams and columns. Lateral forces are resisted by moment frames that develop stiffness through rigid connections of the beam and column created by angles, plates, and bolts, and/or welding. Floors are cast-in-place concrete slabs or metal decks infilled with concrete. Some S1 structures may have floors and roofs that act as flexible diaphragms such as wood or un-topped metal deck.	**PC**: < 1973, **LC**: 1974-1989, **MC**: 1990-2004, **HC**: 2005-present
		S1M	4-7 Floors			
		S1L	< 3 Floors			
		S2H	> 8 Floors	**S2:** Braced Frame	S2 buildings consist of a frame assembly of steel beams and columns. Lateral forces are resisted by diagonal steel members placed in selected bays. Floors are cast-in-place concrete slabs or metal decks infilled with concrete. Some S2 buildings may have floors and roofs that act as flexible diaphragms such as wood or un-topped metal deck.	**PC**: < 1973, **LC**: 1974-1989, **MC**: 1990-2004, **HC**: 2005-present
		S2M	4-7 Floors			
		S2L	< 3 Floors			
		S3	< 3 Floors	**S3:** Light Frame	S3 buildings consist of a frame assembly of flexible steel studs, joists and rafters that are used to establish a complete structural system. They are designed to support axial loads other than self-weight and the weight of attached finishes, which can include masonry veneer, metal cladding, stucco, synthetic veneers and integrated exterior insulation and finish systems	**PC**: < 1973, **LC**: 1974-1989, **MC**: 1990-2004, **HC**: 2005-present
		S4H	> 8 Floors	**S4:** Concrete Shear Wall	S4 buildings consist of an essentially complete frame assembly of steel beams and columns. The floors are concrete slabs or concrete fill over metal deck. These buildings feature a significant number of concrete walls effectively acting as shear walls, either as vertical transportation cores, isolated in selected bays, or as a perimeter wall system. The steel column and beam system may act only to carry gravity loads or may have rigid connections to act as a moment frame to form a dual system.	**PC**: < 1973, **LC**: 1974-1989, **MC**: 1990-2004, **HC**: 2005-present
		S4M	4-7 Floors			
		S4L	< 3 Floors			
		S5H	> 8 Floors	**S5:** Unreinforced Masonry Infill	S5 buildings consist of an essentially complete gravity frame assembly of steel floor beams or trusses and steel columns typical of older construction practices. The floor consists of masonry flat arches, concrete slabs or metal deck and concrete fill. Exterior walls, and possibly some interior walls, are constructed of unreinforced masonry, tightly infilling the space between columns and between beams and the floor such that the infill interacts with the frame to form a lateral force-resisting element.	**PC**: < 1973, **LC**: 1974-1989
		S5M	4-7 Floors			
		S5L	< 3 Floors			
	Unreinforced Masonry	URMM	4-7 Floors	**URM:** Unsupported	URM buildings consists of unreinforced masonry bearing walls, usually at the perimeter and usually brick masonry. The floors are typically made of wood joists and wood sheathing supported on the walls and on interior post and beam construction.	**PC**: < 1973, **LC**: 1974-1989
		URML	< 3 Floors			
	Wood	W1	< 2 Floors	**W1:** Light Frame	W1 buildings consists of one- and two-family detached dwellings of one or more stories. Floor and roof framing are most commonly wood-frame joists and rafters supported on wood stud walls. The first floor may be slab-on-grade or framed. Lateral forces in W1 buildings are resisted by wood-frame diaphragms and shear walls. W1A buildings in the US and their counterparts W2 in Canada are similar in construction detail but larger in size and characterized by 3-6 story structures that can include lower floors used for parking and/or commercial purposes and upper floors for multi-family residential dwellings. Post and beam framing often replaces bearing walls in non-residential areas. Lateral forces are primarily resisted by wood-frame diaphragms and shear walls.	**PC**: < 1973, **LC**: 1974-1989, **MC**: 1990-2004, **HC**: 2005-present
		**W2**	3-6 Floors	**W1A/W2:** Light Frame		
		W3	< 4 Floors	**W3:** Heavy Frame	W3 buildings consist of commercial, institutional, and smaller industrial buildings constructed primarily of wood framing. The first floor is most commonly slab-on-grade, but may be framed. Floor and roof framing may include wood joists, wood or steel trusses, and glulam or steel beams, with wood posts or steel columns. Lateral forces in W2 buildings are primarily resisted by wood-frame diaphragms and shear walls, sometimes in combination with isolated concrete or masonry shear walls, steel braced frames, or steel moment frames. Diaphragm spans may be significantly larger than in W1 W1A and W2 buildings.	**PC**: < 1973, **LC**: 1974-1989, **MC**: 1990-2004, **HC**: 2005-present
		W4	< 2 Floors	**W4:** Light Frame/Cripple	W4 buildings are similar in construction detail to W1 light frame structures, but distinguished by wood cripple wall frames built on irregular foundations and/or open subfloor crawl spaces. Lateral forces are resisted by wood-frame diaphragms and shear walls in structural elements above the main floor level. However, cripple wall and	**PC**: < 1973, **LC**: 1974-1989, **MC**: 1990-2004, **HC**: 2005-

Figure 10: Taxonomy for describing construction materials, height and alignment with National Building Code epochs

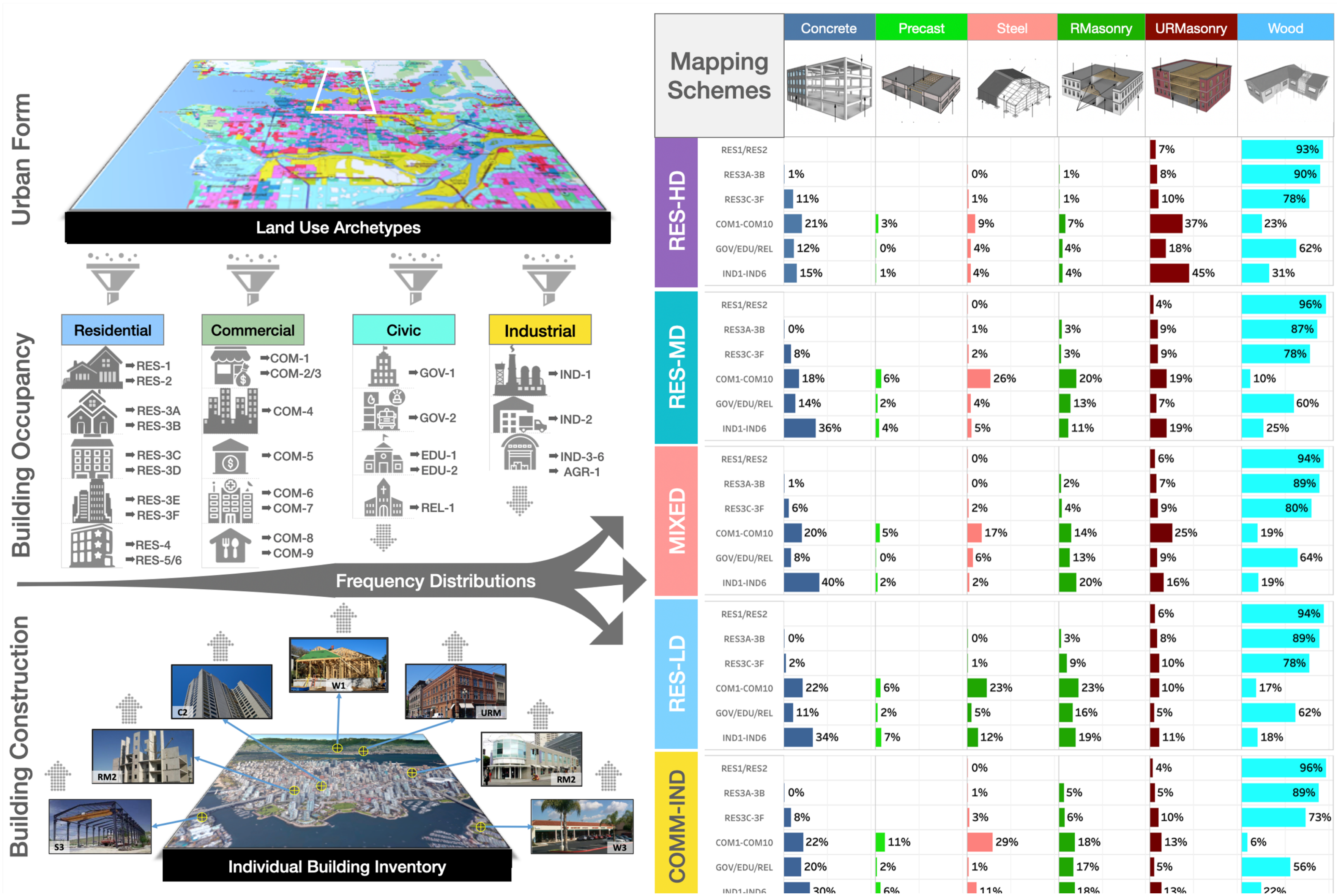


Figure 11: Mapping schemes for allocating buildings based on functional use (occupancy) and construction type

Step 2: Building Mapping Schemes

A critical step in developing a national exposure model is establishing a logical framework for inferring engineering design and performance characteristics based on available information about building occupancy (Figure 10). While there are common associations between some occupancy classes and related construction types, the degree of variability from region to region and the extent of overlap between occupancy classes can be significant, thereby ruling out simple methods of correlation. For example, medium and high-rise hotels are often constructed using reinforced masonry (RM2) or concrete shear walls (C2) with concrete slab floors that may either be cast-in-place or precast. However, these same construction types are also common for many other building occupancies, including multi-family apartment and professional office buildings in dense urban centres.

To address these uncertainties, we use available site-level inventories to establish statistical relationships between building function and construction types based on direct observation and/or windshield surveys that reflect the expert judgement of domain experts. These include a portfolio of ~130,000 individual buildings identified for urban scale risk assessment and related seismic retrofit policy initiatives in the Metro Vancouver region of southwest British Columbia (Journeay et al., 2015; Onur, 2002) and summary statistics generated from an equivalent survey of ~204,000 buildings in a corridor extending along the St. Lawrence valley from Toronto to Quebec City (Ploeger et al., 2018b). Context-specific mapping schemes are defined using spatial analytic methods to develop frequency distributions for each unique branch of the building taxonomy that make explicit relationships between general land use, building occupancy, material type, number of floors and period of construction.

Reference models for British Columbia, Ontario and Quebec provide points of reference to develop mapping schemes for adjacent regions in Western Canada and the Maritimes. Building distributions for these neighbouring regions are adjusted to reflect known variations in construction practices using general mapping schemes established for national-level exposure models that have been developed by FEMA as part of the North American HAZUS methodology (FEMA, 2006a, 2006b, 2007, 2011; The Polis Center, 2006).

There are six mapping schemes for each Province and Territory, with some regions sharing the same general patterns of building distribution. The resulting suite of 42 mapping schemes determine the proportion of building archetypes that are allocated to each settled area based on total available supply as determined from the national census and available business registries.

Step 3: Distribution of Building Archetypes

Building archetypes are allocated first on the basis of standard HAZUS occupancy class and construction typology, which determine attributes of functional use, engineering design and number of floors. For example, a single-family residential wood frame home would be classified as a RES1-W1 or RES1-W4 structure, whereas a high-rise concrete office building might be classified as a COM4-C1H, COM4-C2H or COM4-C3H structure. These higher taxonomic level designations are then subdivided into four age classes based on period of construction. Age classes (<1973; 1974-1989; 1990-2003 and 2005 to present) are defined according to frequency distribution profiles described above and cross-referenced with housing statistics collected as part of the national census, which report average period of construction for residential dwellings at the dissemination area level.

Age class designations are aligned with major revisions to safety design guidelines in the National Building Code of Canada (NBC), which address construction type and related performance characteristics for new buildings and the substantial renovation of existing buildings (Foo et al., 2001; Heidebrecht, 2003; Mitchell et al., 2010). The combination of construction type and age are the primary determinants of physical vulnerability and required inputs for assessing the risks associated with growth and development in areas exposed to natural hazard threats.

Although heterogeneous from one region to another, the distribution of buildings by construction type is characterized at a national level by five major types of structures, which together explain more 95% of the variability across Canada (See Figure 11). In order of dominance, these include light wood-frame (84%), unreinforced masonry (6%), reinforced masonry (2%), manufactured (2%) and heavy wood-frame structures (1%).

Construction types are more varied in Central Canada, where unreinforced masonry buildings of all occupancy classes make up between 10-11% of provincial-level inventories. Building construction in the far north (Nunavut) is dominated by multi-purpose wood frame and manufactured structures (86%) with lower proportions of brick masonry and steel frame buildings used for commercial and industrial purposes. Differences in the mix of building taxonomies 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.

Residential structures represent more than 90% of the total inventory of 9.7 million buildings in Canada and are dominated by single-family wood frame buildings, which represent between 80-90% of the overall mix from region to region. Unreinforced masonry homes are more common in older settlements of Central and Eastern Canada and reflect the influences of construction practices during early phases of colonial settlement (Shrive, 2012). Multi-family residential buildings are characterized by higher proportions mid- and high-rise concrete and mixed concrete/steel structures. Although classified as multi-family residential, these buildings may also accommodate mixed use commercial and civic functions, particularly in higher density urban centres. The distribution of residential 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 in these regions (~9%) and lesser amounts of reinforced masonry and low-rise steel frame structures.

Commercial buildings used in the retail, wholesale and professional service sectors represent 6.6% of the total national inventory (~634,050 structures) and encompass a diverse mix of construction types that vary in relative proportions from region to region. In western Canada, the building profile is dominated by reinforced masonry, concrete and steel structures with lesser amounts of wood, unreinforced masonry and precast construction more common in areas of commercial retail trade. In central and eastern Canada, the relative proportions of unreinforced masonry buildings in older historic business precincts increases significantly. Concrete and steel construction predominate in dense urban centres with higher proportions of multi-story professional service buildings. Higher concentrations of concrete, precast and steel occur in the wholesale trade sector, while retail trade areas are characterized by higher concentrations of wood and unreinforced masonry.

Industrial buildings represent ~1% of the total building inventory (~97.730 structures) and are dominated by concrete, reinforced masonry, wood and unreinforced masonry construction with lesser but significant amounts of steel and precast. Construction types are aligned with building functionality with higher proportions of concrete and reinforced masonry used in heavy industrial building classes in western and eastern Canada, and mixtures of concrete and wood dominating in Central Canada and the Maritimes. Factory buildings are characterized by higher proportions of unreinforced masonry and brittle concrete structures across most regions of the country, particularly in older industrial complexes where this type of construction is most common. Agricultural areas are dominated by heavy frame wood, unreinforced masonry and to a lesser extent light and heavy frame steel construction with higher concentrations of wood in Westerns and Central Canada.

Civic buildings, including schools, government facilities and non-profit community centres represent less than 1% of the total inventory (~61,660 structures). Wood, concrete and steel are the most common construction types in the educational sector, except in older settlements where there are significant concentrations of unreinforced masonry buildings. Government and non-profit buildings are more diverse and characterized by higher concentrations of reinforced masonry construction. As with all other building classes, the proportional mix of civic buildings varies across the country, often reflecting the history of development for a particular region.

The time period of building construction and/or significant renovation provides important insights on both development history and underlying patterns of physical vulnerability that will influence capacities to withstand the effects of natural hazard perils such as earthquake ground shaking, flood inundation, wildfire intensity and severe wind. More than 44% of all buildings in the Canadian inventory (~4.3M structures) are older than 1974 and predate the introduction of modern safety design codes for earthquakes and other related natural hazards (Figure 12). Nearly one quarter of the inventory (~2.3M structures) was constructed during a period of rapid growth and development between 1974 and 1989 with and additional 18.5% in the period between 1990-2004 (~1.8M structures) and 13% in the period between 2005 and 2016 (~1.3M structures).

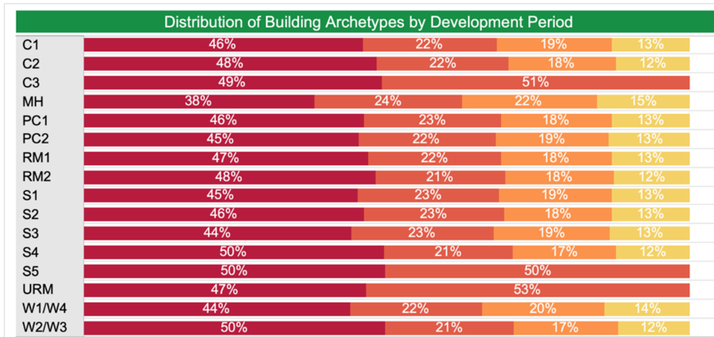
Development period statistics for specific construction types mirror the overall national trends, with the notable exception of unreinforced masonry (URM) and older concrete and steel structures built with load bearing walls of unreinforced masonry construction (C3 and S5, respectively), which have largely been phased out of new construction or subjected to stringent building code requirements due to extreme vulnerability to earthquake ground shaking hazards (Fathi-Fazl et al., 2018). Nonetheless, it is estimated that there are still nearly 730,00 of these vulnerable building types in Canada, which represent almost 8% of the total building inventory.

People

Census data provide a detailed snapshot of residential populations at regular survey intervals and yield important insights into underlying socioeconomic and demographic trends that are driving evolving patterns of community development in Canada. While essential in tracking overall population dynamics, census data do not provide enough resolution to capture the daily flow of people within a given region that is required for earthquake risk modeling. National-level assessments that make use of anonymous site-level mobile phone data to track population dynamics resulting from day-to-day activities are emerging in the public domain (Deville et al., 2014), but are not yet available for use in Canada. In the interim, we use an adaptation of the HAZUS, PAGER and FEMA P-58 methodologies (FEMA, 2011; Hamburger et al., 2018; K. Jaiswal & Wald, 2008; K. S. Jaiswal & Wald, 2014) to estimate average building populations at different times of the day.

Step 4: Population Dynamics

Allocating people to buildings at different times of day is based on a combination of occupancy class, housing characteristics and building area. The number of nighttime occupants for residential buildings is estimated by multiplying the average number of full-time residents per dwelling by



	Pre-1974	1974-1989	1990-2004	2005-Present	Total	% Total
C1	10,374	4,972	4,266	2,914	22,526	0.2%
C2	41,649	18,840	15,183	10,579	86,251	0.9%
C3	37,353	38,587			75,940	0.8%
MH	73,349	46,753	42,597	29,571	192,270	2.0%
PC1	13,661	6,719	5,386	3,823	29,589	0.3%
PC2	4,501	2,222	1,844	1,336	9,903	0.1%
RM1	96,175	44,766	37,321	26,363	204,625	2.1%
RM2	3,185	1,422	1,192	827	6,626	0.1%
S1	15,678	8,117	6,422	4,491	34,708	0.4%
S2	13,265	6,588	5,103	3,680	28,636	0.3%
S3	5,742	3,051	2,489	1,718	13,000	0.1%
S4	16,813	7,190	5,813	4,115	33,931	0.4%
S5	19,926	20,203			40,129	0.4%
URM	286,491	327,426			613,917	6.4%
W1/W4	3,587,511	1,771,615	1,637,441	1,156,420	8,152,987	84%
W2/W3	59,870	25,573	20,718	14,199	120,360	1.2%
Total	**4,285,543**	**2,334,044**	**1,785,775**	**1,260,036**	**9,665,398**	
% Total	**44.3%**	**24.1%**	**18.5%**	**13.0%**		

Figure 13: Distribution of buildings by age of construction

the average number of dwellings per building for each of the 8 private household and 3 group occupancy classes in the HAZUS taxonomy (See Figure 4). The numbers of residential occupants during standard workday hours (9am-5pm) and during commuting hours when people are in transit (7am-9am; 5pm-7pm) are estimated as a proportion of the total nighttime population (FEMA, 2011).

The numbers of non-residential occupants in commercial, industrial and civic buildings are estimated by multiplying the corresponding average number of people per 1,000 square feet by the total finished building area for each of the specific HAZUS occupancy classes (See Table X). Occupancy values for different times of day and night are based on guidelines established as part of the FEMA P58 methodology (Hamburger et al., 2018). Average building area estimates are based on information collected as part of Canada’s national survey of commercial and institutional energy use (SCIEU; Natural Resources Canada, 2014), site-level building inventories compiled from taxation records for the Metro Vancouver region (Journeay et al., 2015) and FEMA P58 building inventory guidelines. Regional variabilities in the number of dwellings for residential buildings and total finished area of non-residential buildings are accounted for by adjusting the aggregate number of nighttime occupants by small fractions up or down to match the total number of full-time residents reported at the census subdivision level.

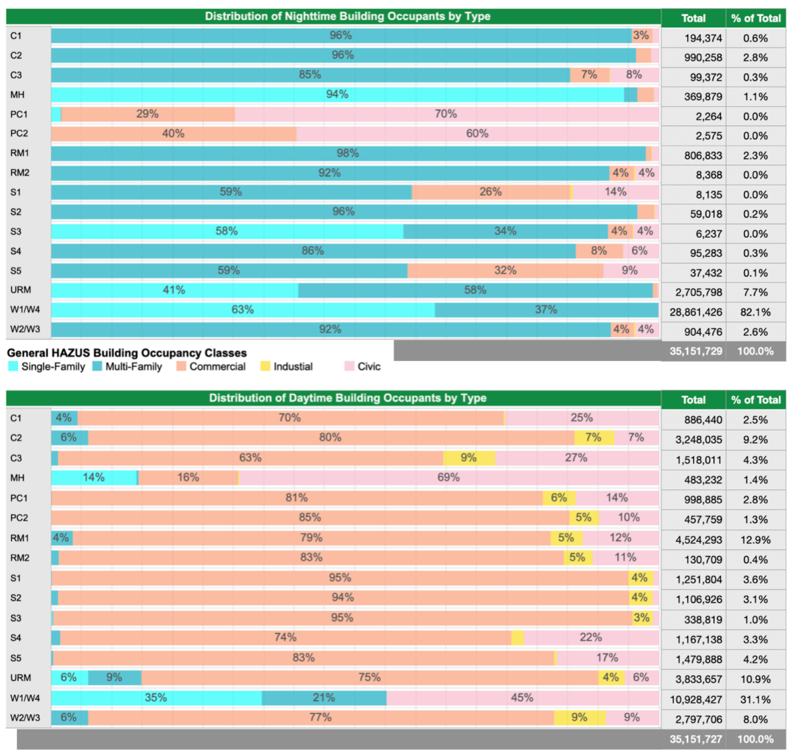


Figure 13: Distribution of building population by occupancy type

Understanding the population dynamics of a community and the fractions of people likely to be in buildings of different types and ages over a 24-hour period is essential for estimating the likelihood of injuries and fatalities in the event of a disaster. This is particularly relevant for rapid onset disasters such as earthquakes, tsunamis, and landslides where there is not sufficient advanced warning for people to take shelter and/or evacuate the area according to public safety protocols. For example, an earthquake event that occurs at night or in the early morning hours will have a very different outcome than an equivalent event that occurs during rush hour or when large numbers of people are concentrated in offices, schools and other types of civic, commercial and industrial facilities that involve group interaction.

The distribution of building occupants at different times of day are summarized at a national level in Figure 13. As expected, nighttime populations are concentrated primarily in single-family homes of light wood-frame construction (including manufactured buildings) and in multi-family duplex and multi-story residential buildings of heavier wood frame construction, which together make up ~86% of the total distribution. An additional ~8% of the population are housed in unreinforced masonry homes and multi-story buildings with the remaining ~6% of the population distributed in mid- and high-rise apartment complexes of concrete and reinforced masonry construction. The model also takes into account those people who occupy non-residential buildings as part of shift work during nighttime hours. However, the total number of nighttime workers is small by comparison (< 1%) and concentrated primarily in commercial and civic building of precast concrete, mixed steel and concrete construction.

The profile of building occupancy during daytime hours is considerably more diverse with only ~20% of the population in residential structures during normal conditions. These include those not in the workforce, and those who are either self-employed or who work from a home office. More than half of the daytime population (~53%) regularly work in commercial structures of various types and sizes with the majority of these people concentrated in buildings of mixed steel, unreinforced masonry, reinforced masonry, precast and concrete construction. Daytime occupancy in civic buildings, which include schools, government and related community facilities represents ~22% of the overall profile with the majority of people working in multi-story buildings of heavy wood frame, concrete and unreinforced masonry construction. Those employed in the industrial sector (~3.5% of daytime population) work primarily in low-rise heavy wood-frame, older concrete and unreinforced masonry buildings that reflect historic patterns of development situated around marine and ground-based transportation hubs.

Although national-level statistics help identify general patterns of building occupancy for different parts of the country, it is the spatial distribution of people and their patterns of movement during the day and night that are of particular relevance for urban planning (building, transportation and energy infrastructure systems), and for assessing the potential impacts of sudden onset disaster events. These patterns are relatively straightforward in monocentric urban regions of all sizes that are characterized by a small number of business precincts centrally located in the downtown area and/or around major transportation hubs.

Figure 14 illustrates patterns of nighttime occupancy in the region surrounding the city of Calgary, which is characterized by a relatively small cluster of high-density residential neighbourhoods in the downtown core surrounded by a broad region of older low-density single-family residential neighbourhoods with well-defined areas of higher density suburban neighbourhoods situated around the outer fringes of the metropolitan region. Building occupancy profiles generally mirror the national trend but are skewed more toward medium density neighbourhoods with higher concentrations of multi-family duplex, row house and apartment building complexes.

These patterns are dramatically reversed in the region during daytime and commuting hours, when the majority of residents travel into the downtown core and/or to adjacent commercial/industrial centres for work, school and other purposes. In addition to the regular flow of people into the city during the day, there is a significant redistribution of occupants from wood-frame residential buildings in the evening to a much more diverse building portfolio of older concrete, masonry, precast and mixed steel construction during workday hours. Spatial patterns are more complex in larger polycentric urban centres that have evolved through the aggregation of adjacent municipalities over time. Nonetheless, underlying profiles of building occupancy that make evident the locations of vulnerable buildings and affected people are still evident at a smaller scale

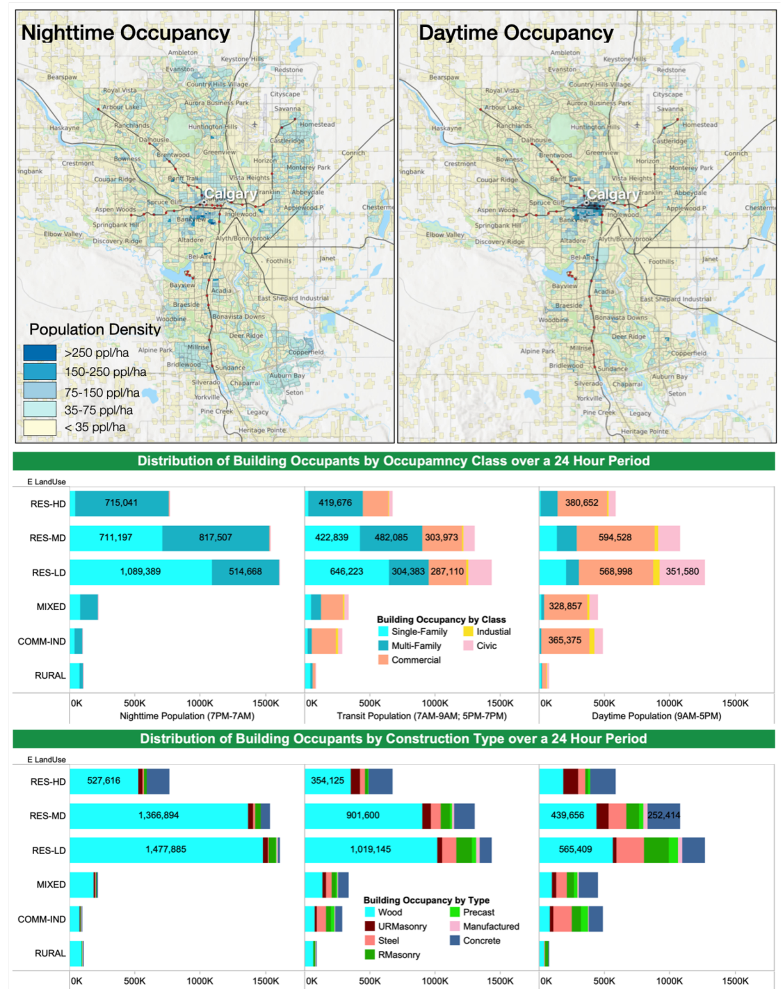


Figure 14: Population dynamics during daytime and nighttime hours in the city of Calgary

and important to understand in the context of emergency management and disaster risk reduction planning.

It is worth mentioning that the general patterns described above reflect normal conditions of building occupancy that have been severely disrupted as a result of public health measures that were introduced early in 2020 to limit the spread of the Covid-19 virus in schools, public facilities and a wide range of commercial/industrial sectors. It is clear that these measures are re-shaping existing patterns of building occupancy and may have a lasting influence on both where people choose to live and how they participate in the workforce.

Capital Assets

Capital assets are physical pieces of property that have a financial value representing an investment and/or a production cost used to generate revenue. For purposes of characterizing physical exposure, capital assets are defined in terms of the costs to construct, repair or replace the structural envelope of a building (foundation, load-bearing walls, roof, etc.,), non-structural components of the building (ceilings, mechanical equipment, fixtures, etc.) and ordinary building contents including personal belongings or commercial merchandise.

In this context, financial value reflects only physical assets at a particular location. It does not include infrastructure costs, the value of land on which these assets are situated or related influences of market forces that are more familiar in the context of residential and/or commercial real estate transactions. Valuation estimates based on total insured value (TIV) are compiled by the property and casualty insurance sector and used by private sector catastrophic risk and actuarial models. However, this information is typically not available for use in the public domain. Insured values also often include an escalation factor that accounts for inflation of labour and material costs over time. These factors are used as a baseline to estimate additional costs that may be incurred by a surge in demand and corresponding supply shortages caused by a disaster event or other disruptive market forces.

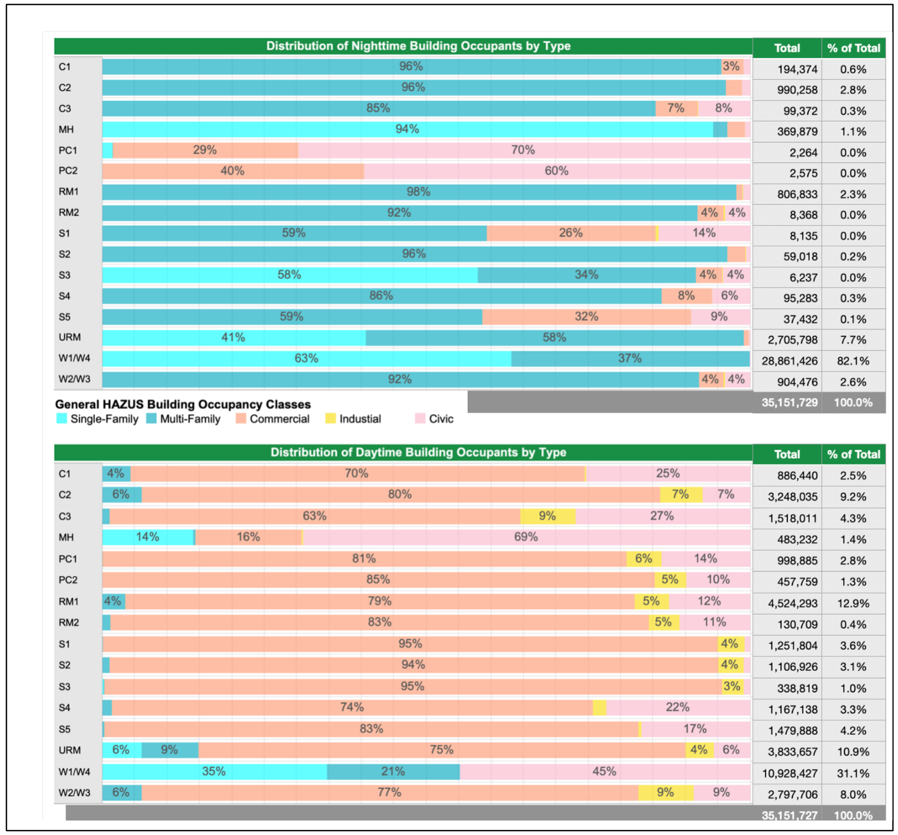


Figure 15: Distribution of financial assets by construction type

Step 5: Asset Valuation

Asset valuation used in this study is based on industry standard construction costs (CAD$/ft2) for reference building archetypes in 11 census metropolitan areas across Canada (Altus Group, 2018, 2020; Moselle, 2017; Turner & Townsend, 2017), and regional variations reported as part of the Canadian Consumer Price Index (Chiru et al., 2015). Industry cost estimates are reported in 2020 Canadian dollars (CAD$) at three levels for each region (low, medium and high), reflecting both quality of construction and market variations. Replacement costs are estimated by multiplying regional unit costs per square foot by the corresponding finished floor area for each unique building archetype in the exposure model. Separate cost tables are used for each Province and Territory taking into account variations between urban and rural areas to reflect regional market influences of larger metropolitan regions.

The resulting assessment of total capital wealth for Canada is 8.24 trillion CAD$, consistent with national summary values reported by global surveys and statistical profiles compiled as part of the Penn World Table (Arcadis, 2015; Feenstra et al., 2015). The distribution patterns of capital asset values by construction type and occupancy class mirrors general trends in the national building profile with a few notable exceptions (See Figure 15).

For example, single- and multi-family residential wood frame homes of all types represent more than 84% of the national inventory in terms of building number yet account for only ~52% of the total capital asset value (4.28T CAD$). Conversely, buildings of concrete or reinforced masonry construction represent only ~4% of the national inventory in number, but account for ~12.5% of the total capital asset value (1.03T CAD$). These differences reflect higher concentrations of capital asset wealth within commercial, industrial and civic buildings, which are characterized by larger overall building area and higher construction costs per square foot.

Physical Exposure of Arcadia

National profiles of physical exposure outlined above are based on detailed assessments carried out for each of the ~390,000 settled areas in Canada. They document statistical trends and spatial distributions of buildings, people and capital assets that help explain both the composition and regional variability of the built environment at a regional scale. As illustrated using representative information for the municipality of 'Arcadia' (introduced in Section X), these same profiles can provide important insights on the internal structure and functional dynamics of urban systems at the scale of individual communities.

Arcadia has a total building inventory of 40,800 buildings and shares many of the same characteristics of other monocentric urban centres of its size across Canada (See Figure 16). The age profile of buildings reflects a history of rapid growth and development beginning in the early 1900's with the

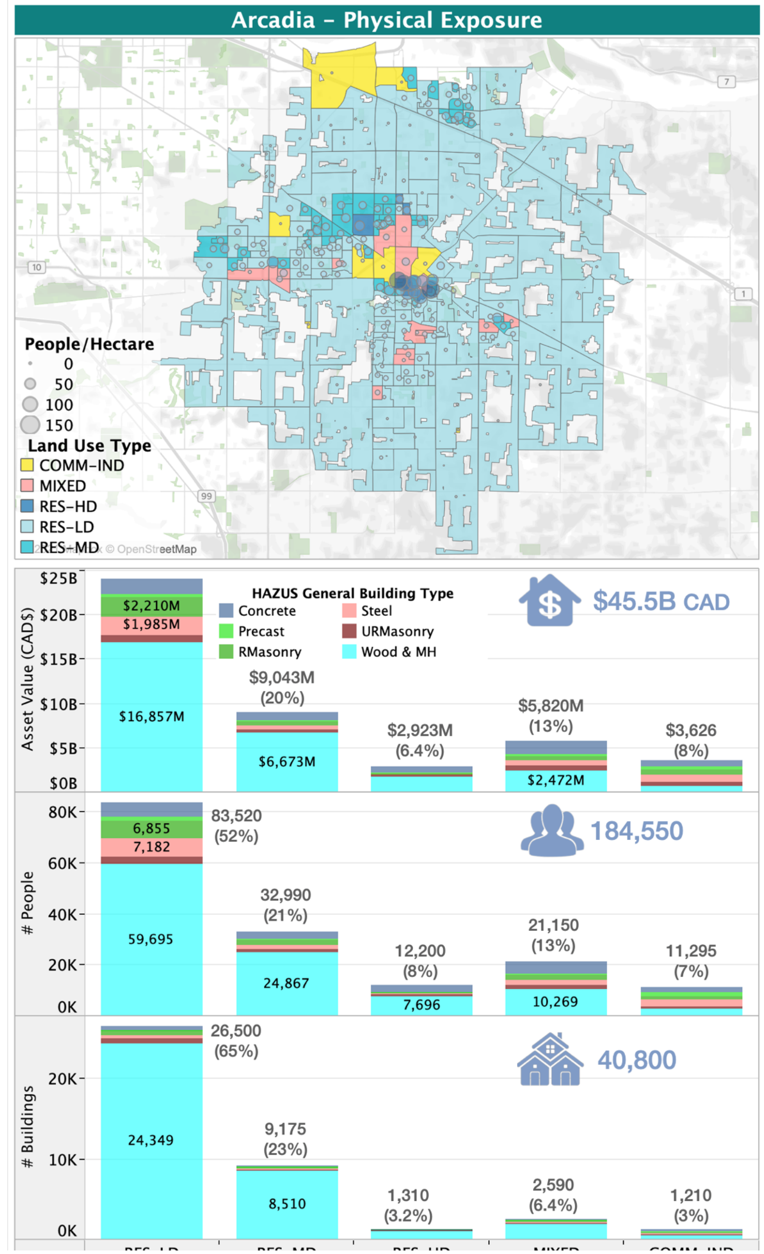


Figure 16: Physical exposure for the reference community of Arcadia

expansion of low-density residential neighbourhoods around the urban fringe representing more than ~65% of the total building inventory. However, there are concentrations of older unreinforced masonry, concrete and mixed steel buildings clustered in mixed use and industrial neighbourhoods around the historic downtown business district and in surrounding single family residential areas.

Single family wood-frame homes represent ~90% of the overall building profile with multi-story and larger heavy wood-frame construction more common in higher density residential and mixed-use land use types. Commercial and industrial neighbourhoods are characterized by a more diverse mix of construction types with nearly equal proportions of reinforced masonry, concrete, precast and mixed steel construction. Although a relatively small proportion of the overall inventory, these buildings are concentrated around major ground and rail transportation hubs surrounding the downtown business district, and on the outskirts of the city.

Daytime building occupancy profiles reflect a major re-distribution of people in the community during work hours, with nearly half the population spending the day in higher density commercial buildings of diverse construction types across all land use types. As with many older communities, the concentration of unreinforced masonry and older concrete structures in the historic downtown areas increase intrinsic vulnerabilities to earthquake ground shaking and related potential for injury and loss in the event of a disaster.

Patterns of land use and associated building profiles also have a direct influence on how capital asset wealth is distributed within the community. Although single family wood frame homes contribute more than 30% to the overall capital asset profile ($45.5B CAD$), there is a broad spatial distribution throughout the community. The majority of investment capital in fixed assets is concentrated in multi-story apartment buildings, commercial retail outlets, professional office buildings and industrial facilities in and around the downtown business district. Understanding the spatial distribution of capital assets in a community and the concentration of buildings that are essential for generating revenue in the business sectors are critical when assessing the potential impacts and downstream consequences of natural hazard threats in terms of both immediate financial losses and the compounding effects of lost revenue during the recovery process.

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