DRR PATHWAYS: RISK DYNAMICS MODELLING

Exploring how seismic risk may change over time due to urban growth and development

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RISK DYNAMICS MODELLING

UBC SCHOOL OF COMMUNITY AND REGIONAL PLANNING

Our team partnered with Metro Vancouver and Natural Resources Canada (NRCan) to better understand how seismic risk may change in Metro Vancouver over the coming decades, focusing on the effect of anticipated changes in population and the built environment. We drew on Metro Vancouver's long-range population and housing forecasts and NRCan's loss model results for different earthquake scenarios to develop a simplified Risk Dynamics Model for the region. The approach entails several methodological innovations:

It uses neighbourhoods as the basic unit of analysis;

- Each spatial unit is matched to a neighbourhood archetype, where archetypes have been empirically defined for Metro Vancouver;
- Future urban conditions are modeled by transitioning spatial units from one neighbourhood archetype to another, using empirically derived transition probabilities;
- Fragility curves are developed for each neighborhood archetype, relating ground motion to the probability of different population displacement rates;
- Expected future losses (in terms of population displacement) are estimated by applying these neighbourhood fragility curves to future urban conditions.

Results include future earthquake population displacement projections for a scenario earthquake. For this study, we used an earthquake scenario centred on the Georgia Strait with a magnitude of 7.3, generated by Natural Resources Canada. The earthquake associated with this scenario causes shaking at Vancouver City Hall which has a 0.06% (not 6%) annual probability of exceedance, based on the National Seismic Hazard Model.

What is Risk Dynamics Modelling?

Risk dynamics pertains to how the potential for disaster losses in an urban area may change over decadal timeframes. Disaster risk will transform over time in relation to factors such as population growth, land use change, new construction, building code improvements, etc. Over time, overall risk may increase or decrease, some types of losses may become more prominent, and the locations of risk "hotspots" may shift. Efforts to anticipate future risk must consider not only shifts in numerous individual factors but also their interactions.

Why is This Work Important?

Cities are continually changing. Similar natural hazard events can cause different degrees and patterns of loss if they strike at different moments in a city's history (Chang et al. 2012, 2019; Olshansky 2001). Loss model results for today's conditions may present an inaccurate and even misleading portrayal of potential losses in future years. If disaster mitigation policies and plans made without accounting for future risk increases, for example, they may be unduly conservative and skewed in the direction of current-day conditions. Anticipating future risk trends and patterns can help to identify and better characterize the effectiveness of different risk reduction strategies.

BACKGROUND

Metro Vancouver is a rapidly growing and changing region, and it can be expected that its seismic risk is also very dynamic. From 2006 to 2041, regional population has been forecasted to grow from 2.2 to 3.4 million (+55%), and total dwelling units from 0.85 to 1.42 million (+68%) (RGS 2013). The 2011 Regional Growth Strategy identifies numerous priority issues, including responding to climate change impacts and natural hazard risks, especially earthquakes, floods, and slope instability (RGS 2020). One study found that for a M7.3 Georgia

Strait scenario earthquake, estimated human casualties would have been similar in 1971 and 2006, but the population in significantly damaged buildings (who would be at risk of displacement from their homes) increased by some 60% for the region as a whole, and more than doubled in some of the fastest-growing municipalities (Chang et al. 2012). A related study compared Metro Vancouver earthquake loss estimates for 2006 with 2041, exploring three stylized land-use cases; results indicated that displaced population results could vary by as much as 47% (Chang et al. 2019). These studies made assumptions about changes in the built environment at risk, however, and did not actually model its evolution.

Models proposed for estimating future urban disaster risk have emphasized various factors. Some have focused simply on exposure, anticipating built-up area in the highest flood zones (Sarica et al. 2021) or highest expected shaking areas (Sarica et al. 2020). Others have modeled building vulnerability, considering effects such as structural aging, building code improvements, and new technologies in relation to hurricanes (Jain and Davidson 2007). For flood hazard, models have considered climate change as well as how urbanization and population growth would influence changes in impervious surface area and aging flood control infrastructure (Salman et al. 2018). For earthquake hazard, Hung et al. (2013) developed a building inventory change model based on shifting land uses, while Navarro et al. (2020) focused on urban renewal and sprawl dynamics. Chang et al. (2019) examined three alternative future development scenarios – status quo, compact, and sprawled development – for the same projected level of population increase, modeling the implications for earthquake and flood risk.

There remains considerable variation in relation to key methodological questions. Units of analysis range from individual buildings to urban grid cells and census tracts. The mechanisms of urban dynamics have been captured mainly through modeling changes in land use and/or building stock characteristics that affect physical vulnerability. Several of the studies that emphasized urban growth dynamics have adopted cellular automata (CA) modeling approaches. CA models comprise spatial units (cells) that have certain attributes or states at a given point in time, and that change states over time according to specified transition rules that relate in part to the states of surrounding cells, simulating processes such as urban sprawl (Liu et al. 2021). In terms of empirical grounding, a common approach is to use historic trends in the case study city to establish parameters such as rates of change or transition rules, on the basis of which future trends are projected. Some transition rules are constrained by information from existing land use plans.

Research Questions

Our goal for this project was to establish a simplified process to estimate future earthquake impacts to support policymakers within the Metro Vancouver region. We identified three research questions to help guide the project:

1. How has the built environment in Metro Vancouver been changing over the past decade?
2. How do we expect the built environment in Metro Vancouver neighbourhoods to change in the future?
3. What do these changes mean for future risk?

METHODOLOGY

To determine how the built environment in Metro Vancouver has changed over the past decade, we first need to establish a 'baseline' set of neighbourhood archetypes using the 2016 Canadian Census at the census dissemination area (DA) scale. Then, using the archetypes established for the baseline data, 'historic' archetypes can be determined using 2006 census data. Finally, with archetypes for these two time periods established, we can determine the likelihood that a given neighbourhood changes archetype in the future.

Growth projection data provided by Metro Vancouver allow us to estimate future population, employment, and household numbers for 2035 and 2050 at the Traffic Analysis Zone (TAZ) scale. However, as TAZ and DA boundaries do not align, some additional work is required to appropriately assign neighbourhood archetypes to our 2016 baseline and future projections.

Finally, we estimate future earthquake impacts by importing baseline earthquake scenario data from Natural Resources Canada and apply these to our projected future neighbourhood archetypes.

This process is summarized below in Figure 1 and discussed in more detail in the following sections.

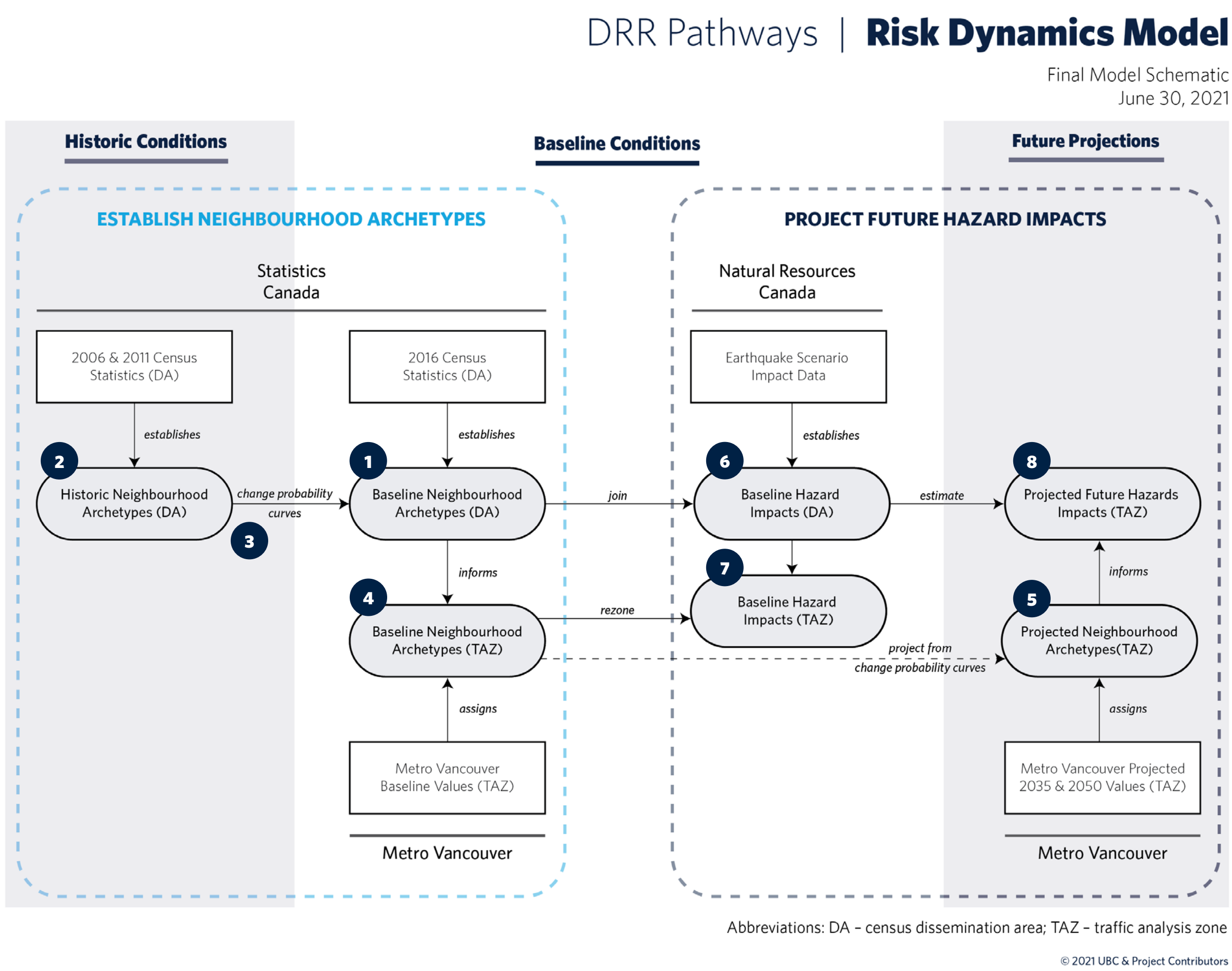

Figure 1: *The Risk Dynamics Model for Metro Vancouver Future Hazard Impact Projections*

Step 1: Establish Baseline Neighbourhood Archetypes for Census DAs

A cluster analysis was performed using data from the 2016 census for the 3,448 dissemination areas (DAs) within our study area. Five parameters were selected for the analysis:

- **Dwelling density:**
  The total number of occupied private dwelling units within a DA divided by the total area of the DA minus area occupied by major water bodies.

- **Proportion of single-detached dwelling units:**
  The total number of occupied private dwelling units assessed as "single detached" by Statistics Canada, divided by the total number of dwelling units within the DA by structural type of dwelling.

- **Proportion of apartment dwelling units:**
  The total number of occupied private dwelling units assessed as "apartment buildings with five or more storeys," divided by the total number of dwelling units within the DA by structural type of dwelling.

- **Proportion of other multifamily dwelling units:**
  The total number of occupied private dwelling units not contained by the previous two parameters, divided by the total number of dwelling units within the DA by structural type of dwelling.

- **Proportion of buildings constructed in 1980 or earlier:**
  The total number of occupied private dwelling units constructed in 1980 or prior, divided by the total number of occupied dwelling units by period of construction.

Pseudo F-scores were calculated to help assess optimal cluster sizes, which indicated that an optimal value likely fell between 3 and 8 clusters (Figure 2). We performed a spatial cluster analysis for these cluster sizes and produced i) a statistical assessment, ii) two multivariate box plots, and iii) a cluster analysis map for each analysis for manual review.

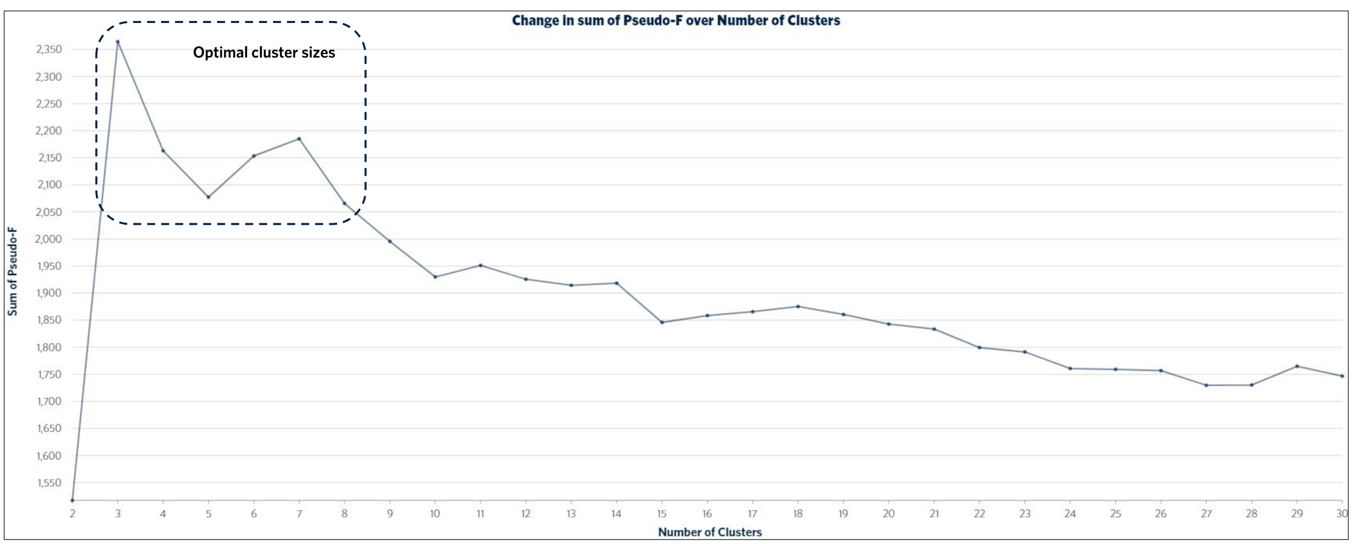

Figure 2: *Selection of optimal number of clusters using Pseudo-F Scores*

The statistical assessments provided information about the mean, standard deviation, minimum, and maximum values for each parameter for each of the six cluster analyses. Statistical significance was determined using R^2

values. The statistical outputs for the seven-cluster analysis are shown in Table 1, where all five statistical parameters were found to be significant, with R^2 values ranging between 0.64 and 0.88.

Table 1: *Cluster analysis assessment of parameter significance for seven-cluster analysis*

Variable	*Mean*	*SD.*	*Min*	*Max*	*R^2*
% Apartment dwelling units	8.260467	22.817002	0.000000	100.000000	0.884014
% Single detached dwelling units	39.310118	31.699087	0.000000	100.000000	0.860254
% Other multifamily dwelling units	51.994381	30.356647	0.000000	100.000000	0.829110
Dwelling density	2879.024427	4385.234595	0.000000	50527.011719	0.752024
% Older dwellings dwelling units	46.139798	27.833461	0.000000	100.000000	0.635097

We visually inspected the two box plots for each analysis to better understand how the five parameters manifested across the different clusters and to assign appropriate names to each cluster based on how these parameters were structured within the clusters. Box plot examples for the seven-cluster analysis are shown in Figure 3 and Figure 4, below.

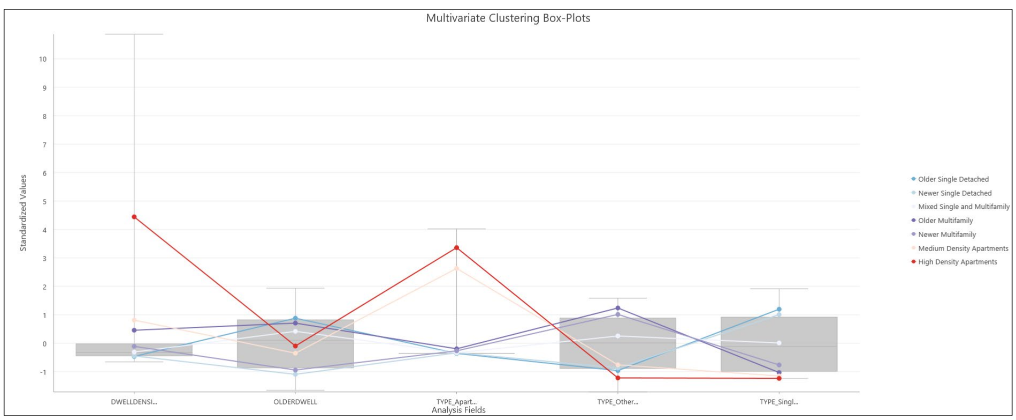

Figure 3: *Box plot with mean lines for each parameter with assigned cluster names*

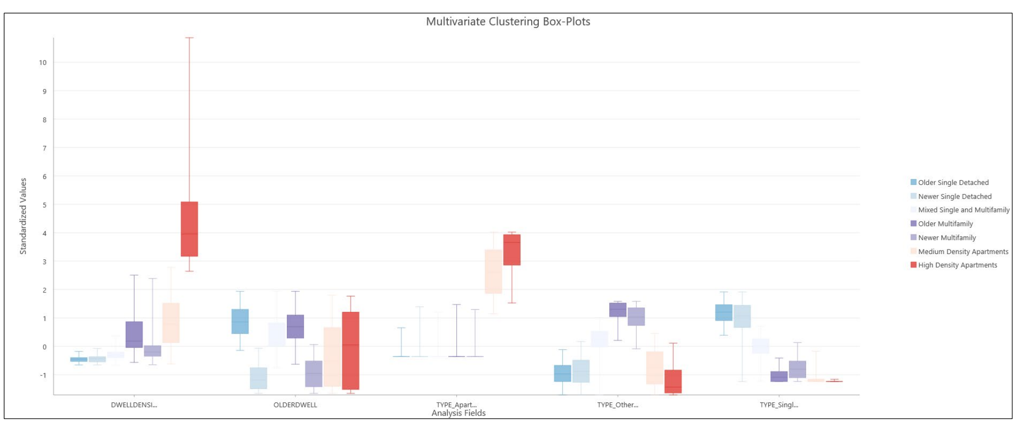

Figure 4: *Box plots for individual parameters within each cluster with assigned cluster names*

Finally, the cluster values were mapped in ArcGIS Pro at the dissemination area (DA) level for the Metro Vancouver region to help us better understand the spatial distribution of each cluster for each analysis.

Upon review of all six cluster analyses, the seven-cluster analysis was selected to represent the 2016 baseline neighbourhood archetypes for our study region, with the seven clusters matching the following categories:

1. **Older single detached:**
   A neighbourhood of predominantly single-detached dwellings built largely prior to 1980

2. **Newer single detached:**
   A neighbourhood of predominantly single-detached dwellings build largely since 1980

3. **Mixed single and multifamily:**
   A neighbourhood mixed between single-detached and other multifamily dwellings

4. **Older multifamily:**
   A neighbourhood of predominantly multifamily dwellings built largely before 1980

5. **Newer multifamily:**
   A neighbourhood of predominantly multifamily dwellings built largely after 1980

6. **Medium density apartments:**
   A neighbourhood of predominantly medium-density apartments of at least five storeys

7. **High density apartments:**
   A neighbourhood of predominantly high-density apartments of at least five storeys

We then assigned a neighbourhood archetype to each DA within the study are using the cluster ID values generated by the cluster analysis, as shown in Figure 5.

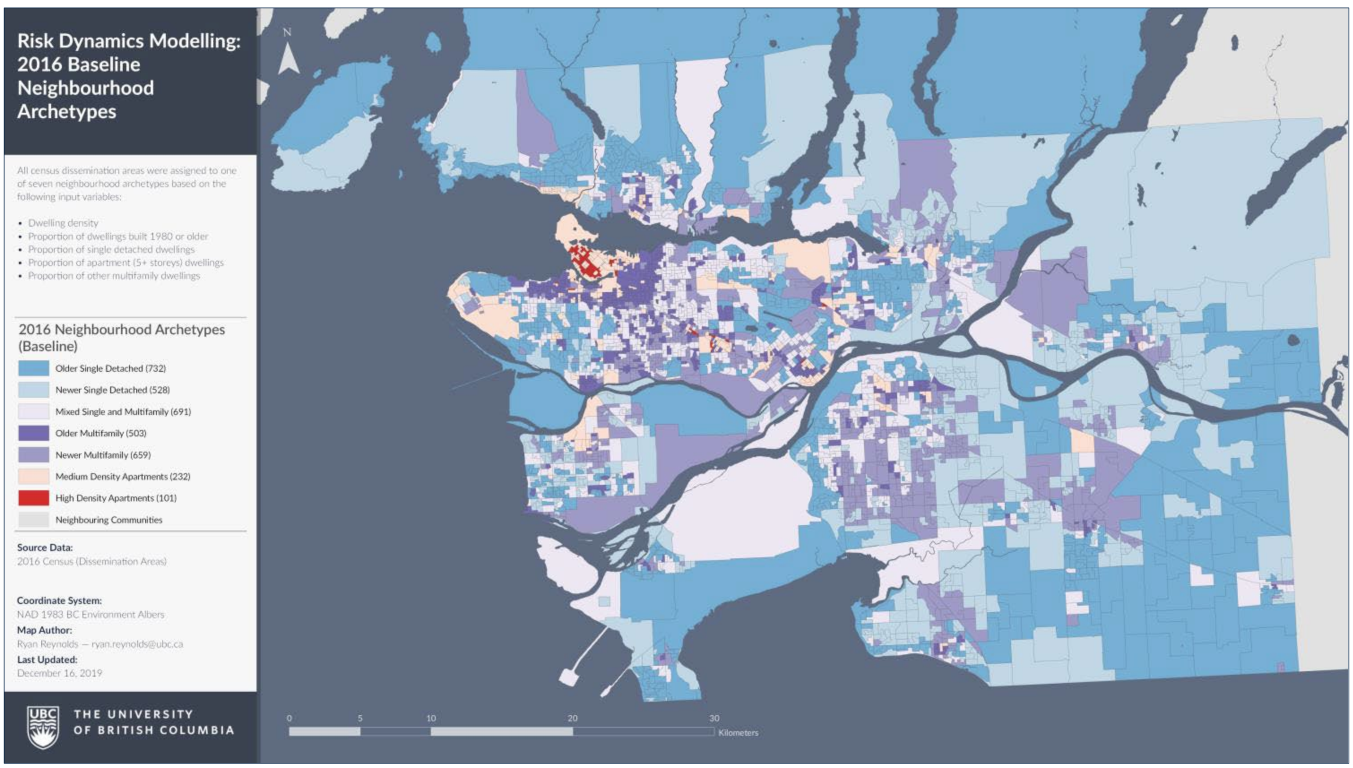

Figure 5: *Map showing the cluster distributions for the seven-cluster analysis with assigned cluster names*

Step 2: Establish Historic Archetypes for 2006 Dissemination Areas

Assigning neighbourhood archetypes to the historic 2006 census dataset was accomplished using a similarity analysis based on Gower's General Coefficient of Similarity (Gower, 1971). For each DA in the historic 2006 dataset, the similarity analysis identifies the DA from the baseline 2016 dataset that is most similar across the five provided parameters and assigns that DA's neighbourhood archetype to the 2006 DA. We calculate similarity using the equation:

$$S_{x,y} = \frac{\sum_{k=1}^{n} 1 - (abs(x_k - y_k)/r_k)}{n}$$

Equation 1: *Neighbourhood Archetype Similarity Equation*

where $S_{x,y}$ is the similarity between the same DA for time periods x and y, x_k and y_k are the k^{th} parameters for the respective time periods, r_k is the range of the k^{th} parameter for the baseline dataset, and n is the total number of parameters used for the comparison. The Python script performing the calculation excludes parameters with missing data and performs the calculations using any remaining parameters.

You can compare the 2016 baseline archetypes determined using the cluster analysis to the historic 2006 neighbourhood archetypes assigned using the similarity analysis in Figure 6.

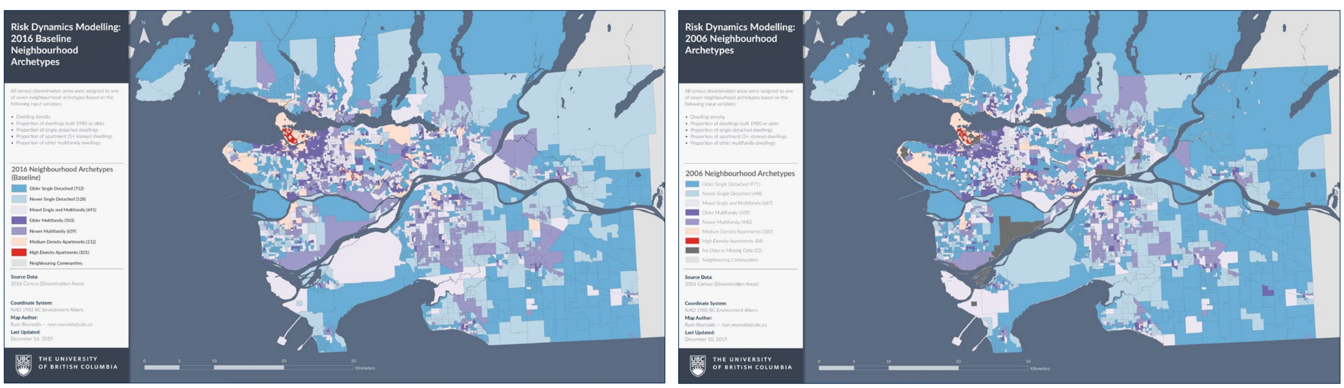

Figure 6: *2016 Baseline Neighbourhood Archetypes from Cluster Analysis (left), and 2006 Neighbourhood Archetypes Assigned using Similarity Analysis (right)*

Step 3: Calculate 2006–2016 Change Probability Curves

Next, we determined those dissemination areas that changed archetypes between 2006 and 2016. In total, 717 of the 3,449 census dissemination areas changed archetypes between 2006 and 2016. For each historic archetype, we determined how often they become any of the other six archetypes to establish a set of change probabilities, according to their rates of population growth, specifically: i) no growth (< 5%), ii) low growth (5%–100%), and iii) high growth (> 100%). This matrix is shown in Table 2:

Table 2: *Neighbourhood Archetypes Change Probabilities Matrix*

Original Archetype	*Growth Pattern*	*Older Detached*	*Newer Detached*	*Mixed*	*Older Multifamily*	*Newer Multifamily*	*Medium Density*	*High Density*
Older Detached	No Growth	35.69%	15.29%	18.04%	13.33%	9.80%	5.49%	2.35%
	Low Growth	24.70%	10.67%	26.83%	17.38%	15.70%	3.20%	1.52%
	High Growth	8.70%	21.74%	17.39%	4.35%	39.13%	8.70%	0.00%
Newer Detached	No Growth	27.19%	23.10%	14.91%	10.23%	19.01%	4.39%	1.17%
	Low Growth	20.12%	16.08%	26.90%	12.34%	20.73%	3.34%	0.51%
	High Growth	27.91%	20.93%	18.60%	9.30%	20.93%	2.33%	0.00%
Mixed	No Growth	4.88%	14.63%	17.07%	21.95%	21.95%	12.20%	7.32%
	Low Growth	14.29%	5.19%	14.29%	22.08%	28.57%	7.79%	7.79%
	High Growth	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%
Older Multifamily	No Growth	37.50%	3.57%	16.07%	19.64%	12.50%	8.93%	1.79%
	Low Growth	37.06%	6.9%	28.67%	16.78%	6.29%	4.20%	0.00%
	High Growth	40.00%	0.00%	10.00%	0.00%	10.00%	40.00%	0.00%
Newer Multifamily	No Growth	17.72%	29.11%	12.66%	3.80%	29.11%	6.33%	1.27%
	Low Growth	11.49%	25.68%	13.51%	10.81%	30.41%	5.41%	2.70%
	High Growth	0.00%	12.50%	25.00%	12.50%	37.50%	12.50%	0.00%
Medium Density	No Growth	9.30%	4.65%	12.79%	30.23%	20.93%	15.12%	6.98%
	Low Growth	3.88%	.88%	8.53%	38.76%	16.28%	19.38%	9.30%
	High Growth	0.00%	7.69%	7.69%	15.38%	7.69%	38.46%	23.08%
High Density	No Growth	5.26%	7.89%	2.63%	26.32%	2.63%	28.95%	26.32%
	Low Growth	4.69%	20.31%	3.13%	17.19%	17.19%	9.38%	28.13%
	High Growth	25.00%	0.00%	0.0%	25.00%	25.00%	25.00%	0.00%

Step 4: Establish Baseline Neighbourhood Archetypes for TAZs

Metro Vancouver's Growth Projection data is limited to estimated population, employment, and household numbers for 2016, 2035, and 2050 at the Traffic Analysis Zone (TAZ) level. As this data does not include information about the built environment and TAZ boundaries do not align with DA boundaries, we could not perform a cluster or similarity analysis to establish archetypes at this scale.

Instead, we intersected the 2016 baseline archetypes layer with the TAZ projections layer then used an areal weighted interpolation (Prener, 2020) to determine the archetype make-up of each TAZ unit. Figure 7 shows the 2016 baseline archetypes (at the dissemination area scale) and the 1,561 interpolated traffic analysis area regions side-by-side for comparison.

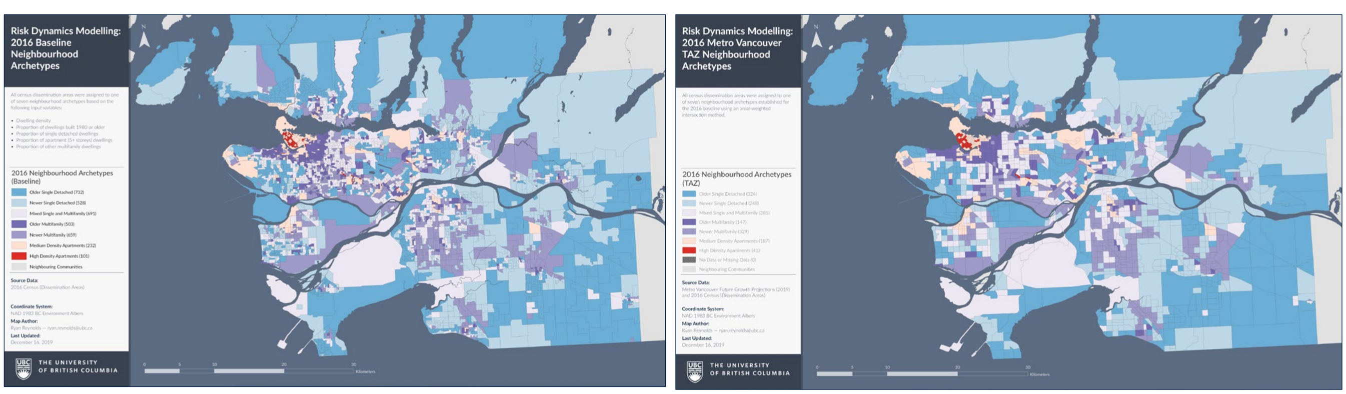

Figure 7: *2016 Baseline Neighbourhood Archetypes for Dissemination Areas(left), and 2016 Baseline Neighbourhood Archetypes Assigned to TAZs using Areal Weighted Interpolation (right)*

Step 5: Project Future Neighbourhood Archetypes for TAZs

We estimated neighbourhood archetypes for 2035 at the TAZ scale by applying the change probability curves created in Step 3 to the 2016 baseline neighbourhood archetypes created in Step 4.

Figure 8 shows the 2016 baseline archetypes (at the dissemination area scale) and the 1,561 interpolated traffic analysis area regions side-by-side for comparison. In total, 106 of the 1,562 census dissemination areas changed archetypes between 2016 and 2035 at the TAZ scale.

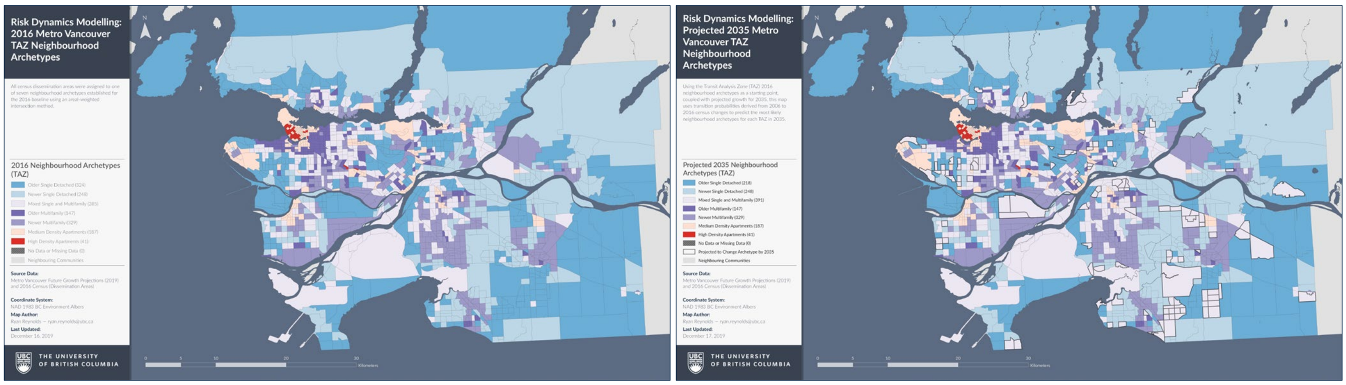

Figure 8: *2016 Baseline Neighbourhood Archetypes (TAZ) Assigned using Areal Weighted Interpolation (left), and Projected 2035 Neighbourhood Archetypes (TAZ) with Changed Areas Marked (right)*

Step 6: Establish Baseline Hazard Impacts for Census DAs

Baseline hazard impacts were provided by NRCan at the Settlement Area (SA) level, which are the occupied built-up areas located within a dissemination area. NRCan's earthquake scenarios provide several impact assessments and we explored persons displaced (for 3, 30, 90, 180, and 360 days), as well as the number of Yellow and Red tagged buildings. For this study we will focus on the population displaced for more than 3 days as our impact metric. We linked the earthquake impact data for each SA to its corresponding DA as shown in Figure 9, below. Night-time population estimates were used to calculate displaced populations.

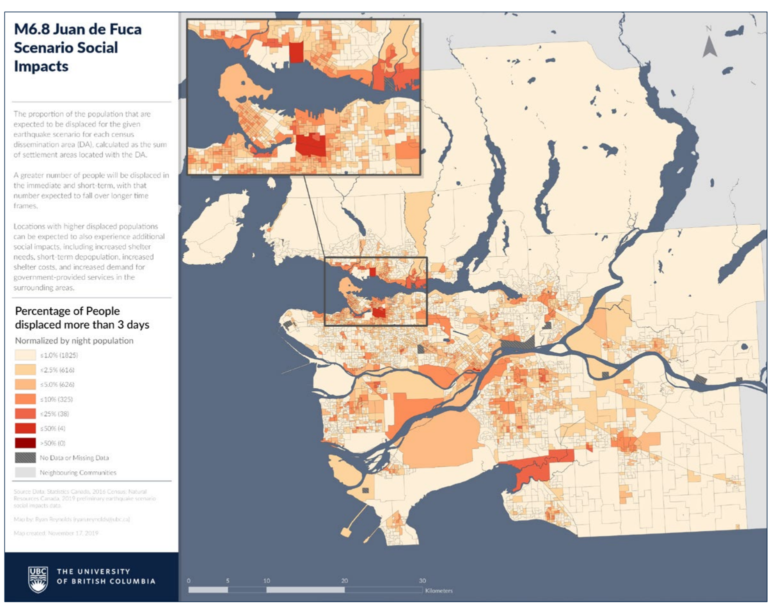

Figure 9: *Percentage of People Displaced more than 3 days – M6.8 Juan de Fuca Scenario*

Step 7: Establish Baseline Hazard Impacts for TAZs

Our model of hazard impacts estimates losses on the basis of neighbourhood fragility curves, which are conceptually analogous to building fragility curves but developed at the neighbourhood scale. Fragility curves depict a probabilistic relationship between some hazard input parameter and some metric of loss. Our neighbourhood fragility curves indicate the relationship between peak ground acceleration (PGA) and population displacement, or the percent of residents who would be displaced from their homes for more than 3 days. The curves are developed for each of the neighbourhood archetypes developed in Step 1; examples for the “older multifamily” and “newer multifamily” neighbourhood types are compared in Figure 10. The neighbourhood fragility curves are developed empirically, with each datapoint being a DA, and its associated PGA and % displaced data obtained from NRCan’s modeled scenario estimates.

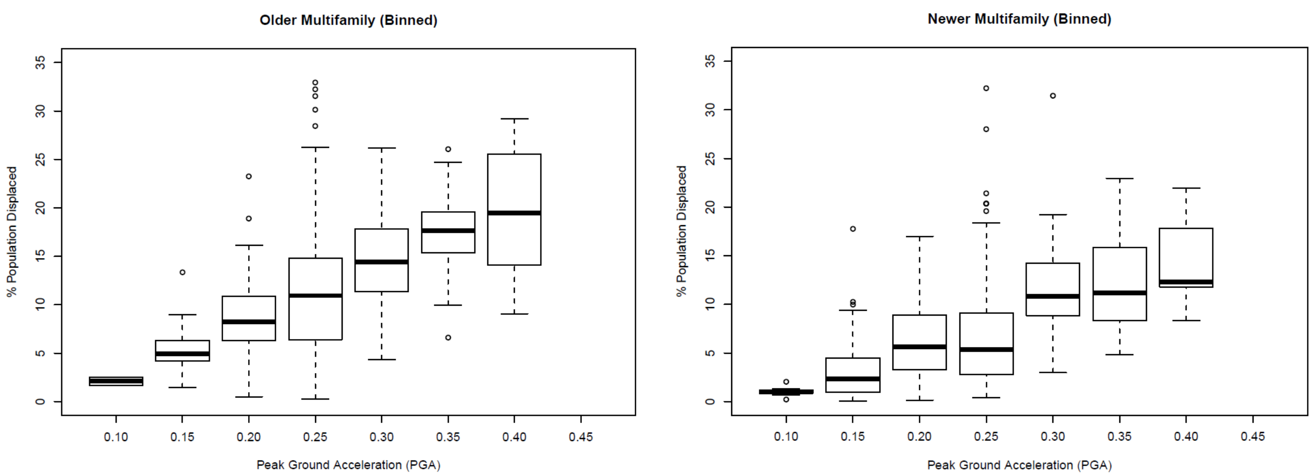

Figure 10: *Peak Ground Acceleration (PGA) vs. % Population Displacement for two Neighborhood Archetypes, Older Multifamily (left) and Newer Multifamily (right)*

Step 8: Estimate Future Hazard Impacts for TAZs

Finally, we estimated the hazard impacts for a hypothetical future earthquake occurring in 2035. Displaced population results were obtained by applying the neighbourhood fragility curves (Step 7) to the urban development projection for the year 2035 (Step 5) by TAZ. Figure 11 and Table 3 compare the estimated displaced populations in 2016 and 2035 for the same M7.3 earthquake scenario. Displaced population is anticipated to grow by 43,000 people to 176,000.

Table 3: *Population Displacement Results, 2016 vs. 2035*

	2016	***2035***	***Change***
Population[1]	2,580,000	3,370,000	787,000
Displaced Population[1,2]	133,000	176,000	43,000
	5.15%	5.22%	

[1] 25 of 35 Metro Vancouver municipalities.
[2] M7.3 Georgia Strait earthquake scenario.

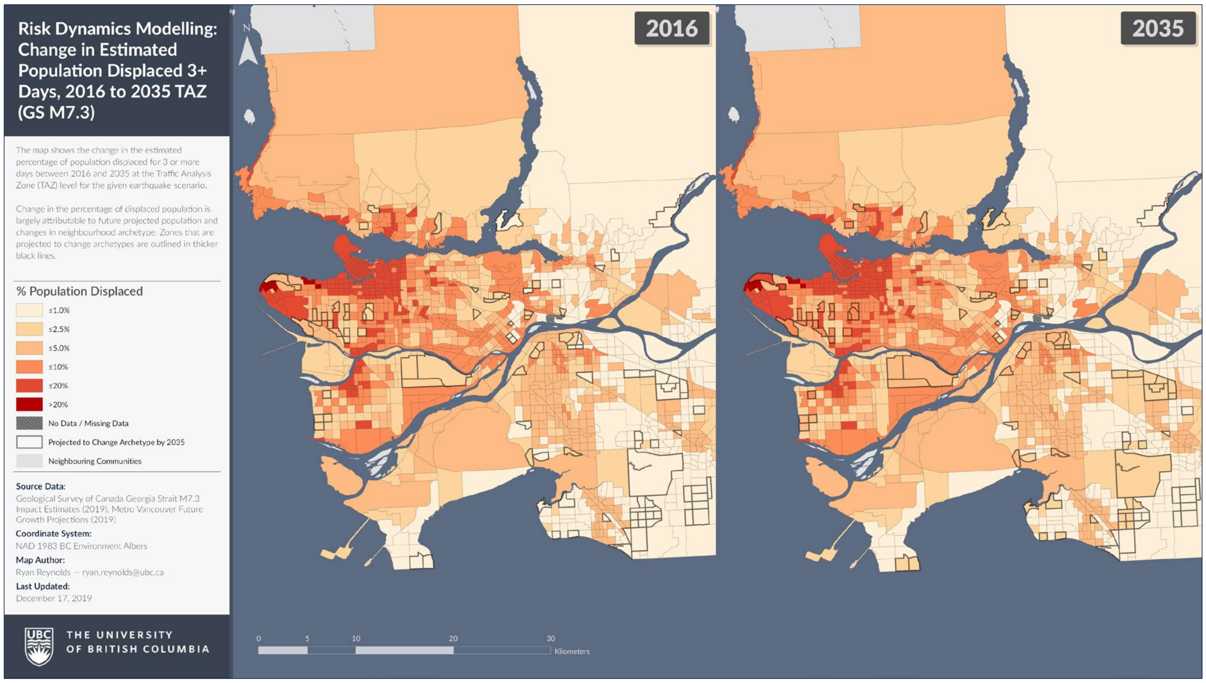

Figure 11: *Comparison of Population Displacements for 2016 and 2035 at the Traffic Analysis Zone Scale*

FUTURE ENHANCEMENTS

There are several possibilities for future improvements to this work. Of particular interest are potential refinements to the model itself, including:

- Neighbourhood archetypes
- Transition matrix
- Displacement model
- Probabilistic implementation
- Sensitivity analysis
- Other impact variables

It may also be interesting to explore this concept in other ways:

- Other time periods (e.g., 2050)
- Other earthquake scenarios
- Other hazard scenarios
- Other future population or density scenarios
- Overall trends.

LINKS TO DISASTER RISK REDUCTION PATHWAYS

This work links to three aspects of disaster risk reduction identified by the DRR Pathways Steering Committee:

Emergency Response Planning

Identifying areas of increased population displacement in the event of a future earthquake can allow emergency planners and responders to better plan for significant large-scale responses in these areas. This may include having additional staff and resources on hand to assist with temporary or long-term housing or directing affected households to available social services.

Disaster Risk Reduction Policies

Understanding how neighbourhoods change over time, and the implications related to earthquake impacts, can help planners identify areas of potential future risk that could be mitigated through planning and policy changes.

Citations

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APPENDIX A: MODEL INPUTS

We used the following data sources to establish our neighbourhood archetypes, baseline and future earthquake impact assessments:

Dataset	Source	Release Date	Licensing	Link
2006 Census	Statistics Canada	March 13, 2007	Statistics Canada Open License	2006 Census of Population
2016 Census	Statistics Canada	November 27, 2017	Statistics Canada Open License	2016 Census Program
Georgia Strait M7.3 Earthquake Scenario	Geological Survey of Canada, Natural Resources Canada	December 11, 2019	Licensed to UBC	*None*
Metro Vancouver 2035 & 2050 Growth Projections	Metro Vancouver	July 10, 2019	Licensed to UBC and Pathways Partners	*None*

APPENDIX B: PROJECT DELIVERABLES

We are sharing the following data layers, documents, and maps with our DRR Pathways partners and the public:

Dataset	Release Date	Licensing	Notes
Risk Dynamics ArcGIS Geodatabase	June 30, 2021	DRR Pathways Partners	*None*
Neighbourhood Archetypes Maps for City of Vancouver	June 30, 2021	Public	*A map for each of the 14 indicators in* `.png` *and* `.pdf` *formats*
Georgia Strait M7.3 Earthquake Scenario Maps for City of Vancouver	June 30, 2021	Public	*A map for each of the 14 indicators in* `.png` *and* `.pdf` *formats*
Projected Earthquake Impact Maps for City of Vancouver, 2035	June 30, 2021	Public	*A map for each of the 14 indicators in* `.png` *and* `.pdf` *formats*