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# Mapping current and future flood exposure using a 5-metre flood model and climate change projections

Connor Darlington[1], Jonathan Raikes[1,2], Daniel Henstra[3], Jason Thistlethwaite[1], Emma K. Raven[4]

[1]School of Environment, Enterprise and Development, University of Waterloo, Waterloo, Ontario, N2L 3G1, Canada
[2]Sustainability Research Centre, University of the Sunshine Coast, Sippy Downs, Queensland, 4556, Australia
[3]Department of Political Science, University of Waterloo, Waterloo, Ontario, N2L 3G1, Canada
[4]JBA Risk Management, Broughton, Skipton, BD23 3FD, United Kingdom

*Correspondence to*: Jonathan Raikes (jonathan.raikes@research.usc.edu.au)

**Abstract.** Local stakeholders need information about areas exposed to potential flooding to manage increasing disaster risk. Moderate and large-scale flood hazard mapping is often produced at a low spatial resolution, typically using only one source of flooding (e.g., riverine), and it often fails to include climate change. This article assesses flood hazard exposure in the City of Vancouver, Canada, using flood mapping produced by flood risk science experts JBA Risk Management, which represented baseline exposure at 5-metre spatial resolution and incorporated climate change-adjusted values based on different greenhouse gas emission scenarios. The article identifies areas of both current and future flood exposure in the built environment, differentiating between sources of flooding (fluvial, pluvial, storm surge), climate change scenarios, and return periods. The case study demonstrates the utility of a flood model with a moderate resolution for informing planning, policy development, and public education. Without recent engineered or regulatory mapping available in all areas across Canada, this model provides a mechanism for identifying possible present and future flood risk at a higher resolution than is available at Canada-wide coverage.

**Keywords.** Flood hazard mapping; flood risk management; exposure; climate change; flood modelling

**Plain Text Summary.** The impacts of climate change on local floods require precise maps that clearly demarcate changes to flood exposure; however, most maps lack important considerations that make their utility in policy and decision-making difficult. This article presents a new approach to identifying current and projected flood exposure using a 5-metre model. The results highlight advancements in the mapping of flood exposure with implications for flood risk management.

## 1.0 Introduction

The exposure of people and infrastructure to flood hazards is increasing globally due to factors such as population growth, development in flood-prone areas, and more frequent and intense extreme weather caused by climate change (Field et al., 2012; UNDRR, 2022). Moreover, it is expected that all major types of flooding, including fluvial

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(riverine), pluvial (rainfall) and storm surge (coastal) will intensify as the climate changes (Alfieri et al., 2016; Arnell & Gosling, 2016; Hirabayashi et al., 2021; Muis et al., 2016; IPCC, 2019; Winsemius et al., 2016).

Coastal cities are especially susceptible to flooding, due to their dense populations, socio-economic development, impervious surfaces, and proximity to major hydrological features such as lakes and oceans (Hallegatte et al., 2013; Lincke et al., 2022; McDermott, 2022; Neumann et al., 2015). Managing flood risk in coastal cities requires adopting actions that reduce the vulnerability of people and property to current flood hazards, but also anticipating the likely scope and extent of future flooding. Flood hazard modeling and mapping that uses climate scenarios to estimate future flood exposure enables coastal cities to better support flood risk management, inform land use planning, organize emergency management, and increase public awareness (Dransch et al., 2010; Handmer, 2013; Henstra, 2016; Porter & Demeritt, 2012).

Despite the importance of flood hazard mapping for flood risk management, few studies have mapped community exposure to multiple flood types and used future climate scenarios to assess changes to exposure (Cea & Costabile, 2022). Modeling techniques to estimate flooding under different climate scenarios vary considerably in existing scholarship, and the quality and granularity of local and regional flood maps are also highly variable (Cea & Costabile, 2022; Costabile et al., 2015; de Moel et al., 2009; Henstra et al., 2019; Mudashiru et al., 2021). These limitations underscore the need to develop flood hazard models and maps that capture flood exposure accurately and at a resolution that is useful for planning and decision-making.

This paper presents the results of a flood model that was used to produce flood hazard maps under various climate change scenarios for the City of Vancouver, Canada. Using a 5-metre resolution baseline and climate change-adjusted flood data produced by flood risk science experts at JBA Risk Management (JBA), we determined areas of existing building exposure to multiple flood types and return periods, as well as new exposure based on climate change scenarios for 2050 and 2080. The findings demonstrate the utility of local and regional flood exposure analysis using different climate change scenarios, which offers guidance for local planners, policy- and decision-makers, and other stakeholders to recognize areas of current and future flood risk and enact measures to manage this risk.

The paper begins by reviewing current scholarship on flood hazard mapping to distinguish different methodologies, assess their applicability in Canada and beyond, and identify knowledge gaps. It then describes the flood hazard mapping approach used in this study and its application in Vancouver. The third section reports the study's main findings. The paper concludes with a broader discussion on the strengths and limitations of the method, directions for its use in local and regional planning, and areas for future research.

## 2.0 Literature Review: Flood Hazard Mapping Methodologies

Scholarship on flood hazard mapping has been increasing for decades. Early approaches to flood hazard modeling were incapable of incorporating long-term climate projections and variations to hydrological processes (Batista, 2018).

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More contemporary approaches rely on computer modeling and mapping that can apply scenario-based projections of climate change and precipitation (Mudashiru et al., 2021; Teng et al., 2017). This section reviews current scholarship on methodologies for modeling flood exposure and its application in Canada with climate change.

### 2.1 Modeling Flood Exposure

There are three main methodologies for producing flood hazard maps, which include physical modeling, physically-based modeling, and empirical modeling (Mudashiru et al., 2021; Teng et al., 2017). Physical models map flood hazards using field measurements and observations of hydrological features, such as the velocity and flow of a meandering river (Mubialiwo et al., 2022; Paquier et al., 2017). Physical models produce the most accurate and highest resolution picture of flood hazards (e.g., 1-metre), but the on-site measurement and testing requirements are onerous, time-consuming, and costly, such that these models are typically limited to a small spatial coverage (Bellos, 2012).

Physically-based models simulate real-world hydrological processes to identify areas that could be inundated under various conditions (e.g., extreme weather, riverine flow patterns) (Mudashiru et al., 2021). These models reduce the need for field observations, which are instead simulated in a lab, enabling researchers to extrapolate field observations to cover a larger area in less time. However, the accuracy of these maps is sometimes challenged by critics who question assumptions about the hydrological processes that have not been fully tested in the field (Costabile et al., 2015; Mark et al., 2004).

Empirical modeling is a more recent development in flood hazard assessment that typically combines satellite imagery, remote sensing, machine learning, artificial intelligence, and geographic information systems to predict areas exposed to flood inundation (Devia et al., 2015). This approach has become more common in conventional flood hazard mapping because it can produce maps with large spatial coverage, it is less onerous and more efficient than physical and physically-based models from a cost-benefit perspective, and it is capable of incorporating environmental changes such as those associated with climate change (Jehanzaib et al., 2022; Mosavi et al., 2018; Mudashiru et al., 2021). However, empirical models typically produce lower-resolution maps (e.g., 30-metre or lower) and make broader assumptions about physical conditions than physical and physically-based models (Avand et al., 2022; Li et al., 2013; Woznicki et al., 2019).

Physically-based maps producing high levels of accuracy tend to be costly and require significant resources and time, whereas empirical models are less accurate but require less resources and can be deployed at a broader scale. Policymakers must assess these trade-offs when determining which maps should be generated for specific locations and audiences. For example, small and remote communities might lack the financial capacity to conduct physical modeling, so a cost-efficient, multiple return period model might be desirable, as it can map hazard exposure and incorporate climate change projections at a moderate resolution that is sufficient for planning and decision-making. For this reason, this study used a physically-based modeling approach as a sensible middle ground and starting point. The next section describes the evolution of flood mapping in Canada and how maps are used in flood risk management.

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**Modeling Canada's Flood Exposure Under Climate Change Scenarios**

Despite the value of flood hazard maps for land use planners, emergency managers, and other stakeholders, several factors limit their utility in practice. In particular, many existing flood hazard maps lack high-resolution data, fail to represent multiple sources of flooding (e.g., fluvial, pluvial, and storm surges), and neglect to incorporate the influence of climate change on flood exposure (Cea & Costabile, 2022; de Moel et al., 2009; Teng et al., 2017). Moreover, the variable accuracy and reliability of flood hazard maps produced through different modeling approaches, often with different assumptions and using coarse resolution data, as well as the technical and financial requirements to produce higher-quality maps, often hinders their availability and effective use by non-expert stakeholders, such as planners and policymakers (Dransch et al., 2010; Hagemeier-Klose & Wagner, 2009; Pralle, 2019; Wing et al., 2018).

Flood hazard mapping in Canada is highly variable, due in part to the country's large geographic area and diverse topography (Elshorbagy et al., 2018). Flood mapping is a provincial and territorial responsibility, with some provinces and territories performing mapping in-house, while others contract flood mapping to private industry (Natural Resources Canada, 2022a). Because provincial governments have primary responsibility for flood hazard mapping, there is a patchwork of coverage and map availability across Canada. Further, despite recent data initiatives to compile flood data (Natural Resources Canada, 2023), there is no national, high-resolution physical modeling for all of Canada.

There have been several major intergovernmental initiatives to improve and expand flood hazard mapping in Canada. First, in 1976 the Government of Canada collaborated with provincial governments to launch the Flood Damage Reduction Program (FDRP), which aimed to identify areas with high flood exposure as the basis for implementing actions that would reduce future flood losses (Bruce, 1976). According to Watt (1995), the central objective of the FDRP was to direct development away from designated flood risk areas. Although the program was effective in mapping large swaths of flood exposure throughout the country, it ended in 1998, leaving provincial and territorial governments to maintain and disseminate flood hazard maps. Today, many flood hazard maps are outdated and publicly inaccessible, limiting their usefulness for local planners, policymakers, and other stakeholders to pursue flood risk management actions (Henstra et al., 2019).

The second major Canadian flood hazard mapping initiative began with the National Disaster Mitigation Program (NDMP), a $200 million initiative launched in 2015 that aimed to fund provincial and territorial efforts to reduce flood risk, including through mapping (Public Safety Canada, 2021). Between 2015 and 2019, the NDMP funded more than 130 flood hazard mapping projects across the country (Public Safety Canada, 2019). Moreover, during this period the Government of Canada also published a series of documents intended to advance flood mapping activities, which set out guidelines for aspects such as flood damage estimation, geomatics, hydrologic and hydraulic procedures, and LiDAR (Public Safety Canada, 2022). Finally, the intergovernmental emphasis on flood mapping was extended in 2021 with the launch of the Flood Hazard Identification and Mapping Program, a $63 million initiative to support provincial and territorial efforts to undertake flood hazard assessments, map flood hazard areas, and disseminate flood hazard information to the public (Natural Resources Canada, 2022).

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Despite these initiatives, which produce local flood hazard products, there are significant gaps in flood mapping coverage across Canada, and the dominant focus of nearly all regulatory flood mapping is fluvial (riverine) flooding. To date, physically-based flood hazard modeling has been relatively unavailable in Canada, particularly modeling that includes widespread coverage, captures multiple sources of flooding, and accounts for climate change (MMM Group Limited, 2014). However, a few commercial risk modeling companies offer solutions with national or near-national coverage that include areas not otherwise mapped in Canada. To accomplish such large-scale modeling, considerable climate modeling, hydraulic modeling, data collection, and computational resources are required. Such models can be a useful source of flood intelligence as computational and physically-based modeling improve in accuracy with advancements in data availability and computational resources.

Against this backdrop, we present here an assessment of flood exposure using JBA's physically-based flood hazard model at a 5-metre resolution that includes multiple flood types—fluvial, pluvial and storm surge—and estimates future changes due to climate change based on the Representative Concentration Pathways (RCP) 4.5 and 8.5 climate scenarios. We apply this model using a case study of the City of Vancouver, British Columbia, which faces risks from all three flood types. This study illustrates a practical application of physically-based modeling for the purposes of generic flood exposure assessment and flood risk planning.

## 3.0 Methods

This section describes the methods used to harness the physically-based flood hazard model and its application to the City of Vancouver. It includes an overview of the study area and research methods that were used to assess the current and projected changes to local flood exposure based on climate change scenarios, multiple sources of flooding, and time horizons.

### 3.1 Study Area

The scope of this assessment was limited to the JBA Canada 5-metre Baseline and Climate Change Flood Map study site for the Vancouver area (JBA Risk Management Limited, 2022). This dataset contained fluvial, pluvial, and storm surge flood hazard data under non-climate change (NCC) and climate change states, specifically RCP 4.5 and RCP 8.5 climate scenarios for 2050 and 2080 (Figure 1). The flood hazard data was produced by JBA and shared with the University of Waterloo research team for the Vancouver metropolitan area. This area delineates 117 contiguous census tracts in the city from the 2016 census open census tract boundary file (Statistics Canada, 2019).

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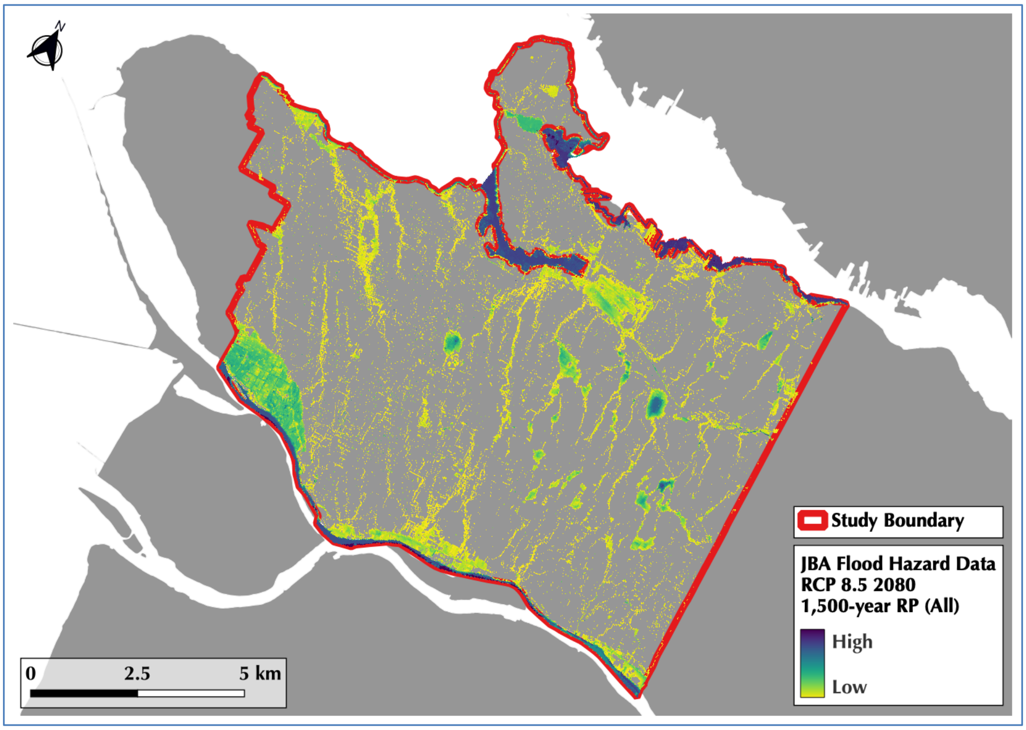


**Figure 1: Study Boundary of the JBA (2022) flood hazard data for Vancouver, British Columbia using RCP 8.5, 2080 climate conditions at the 1,500-year return period to show the broadest flood coverage observed in the study site. The flood mechanisms mapped include all three of the JBA-included sources: fluvial, pluvial, and storm surge flooding. Low and high values indicate different relative depths of water from each of the flood mechanisms individually. Other map data includes the Statistics Canada (2022) Provinces and Territories boundary file of Canada.**

Figure 1 provides an outline of the study area, along with the JBA flood hazard data at the most extreme climate state and return period available for mapping, the RCP 8.5 to 2080 scenario at the 1,500-year return period. This was done for illustrative purposes to indicate the extent of flooding within the study region. The flood modeling in Vancouver can further be broken down by flood mechanism. Figure 2 illustrates the three sources of flooding at the non-climate change (NCC) state and at the 1,500-year return period, utilized for illustrative purposes.

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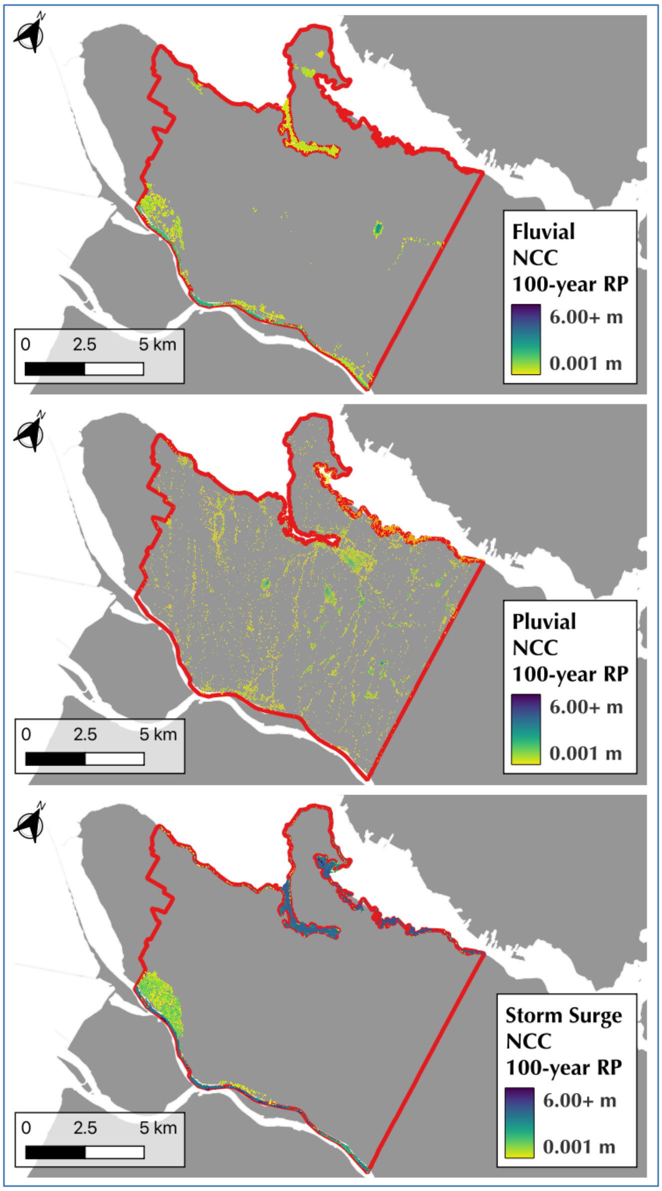


**Figure 2: JBA (2022) fluvial, pluvial, and storm surge flood hazard modeling at the 100-year return period non-climate change state. Other map data includes the Statistics Canada (2022) Provinces and Territories boundary file of Canada.**

The study area illustrated in Figure 1 and Figure 2 are used for the remainder of the assessment. An example exposure data set provided by Microsoft (2019) was incorporated to indicate the types of analysis that could be conducted using the JBA data.

**3.2 Research Methods**

This study is based on JBA's Canada 5-metre Baseline and Climate Change Flood Map data (and Canada-wide flood hazard 30m data), obtained through a data sharing agreement with the University of Waterloo. In brief, the pluvial and small river modelling captured flooding using rainfall inputs from Environment and Climate Change Canada. An infiltration coefficient was applied to remove the proportion of rainfall that would infiltrate the ground, and the rest of the rainfall was hydrodynamically routed across the digital terrain model using JBA's in-house 2-dimensional hydrodynamic flood model, JFlow (see Lamb et al., 2009). For the river flood maps, a regional flood frequency analysis was used. At a series of locations along the river network, design flow depths (representing the depth of water associated with a specific return period flood) were derived using statistical analysis of flood peak gauge data extrapolated from the Water Survey of Canada's HYDAT database (Environment and Climate Change Canada, 2018). The depths were used as inputs to JFlow to hydrodynamically spread flood water across the floodplain to create and estimate of flood depths and extents. Coastal maps were based on a statistical analysis of sea-level extremes alongside a surge and tide model. GIS horizontal projection modelling was then applied to determine the extent and depth of coastal flooding from these sea-level extremes across the inland terrain data.

For climate-related flood mapping, JBA adjusted the input hydrology to reflect anticipated changes. By comparing the statistical differences between the baseline and the future precipitation, 'change factors' were calculated to quantify the measure of change. These change factors were then applied to the baseline hydrology to create a new set of future rainfall inputs. The new inputs were run in JFlow to map future flood extents and depths. To calculate 'change factors' for fluvial flooding, future projections of rainfall and temperature were obtained from the Climate Atlas (Prairie Climate Centre, 2022). Using JBA's baseline fluvial models in combination with these future climate conditions, future estimates of river flow extremes were established. The difference between the baseline and future river flow statistics provided 'change factors', which were used in a similar way as the pluvial change factors to calculate new future hydrographs. These were also modelled in JFlow to map new fluvial flood extents and depths under climate change. For the coastal climate change estimates, sea-level rise information was obtained from the Canadian Extreme Water Level Adaptation Tool (Zhai et al., 2023) and future sea-level extremes were used to map future coastal flooding.

Access to the 5-metre baseline and climate change flood map data was intended to pilot and explore the benefits of higher resolution local flood hazard maps compared to the Canada-wide resolution which is traditionally 30-metre resolution. The data were provided as a series of raster files, with each file reflecting a return period, flood mechanism, and climate state. For example, one raster file consisted of the 100-year return period, fluvial-sourced, NCC flood hazard estimation. JBA data include three main sources of flooding: (1) fluvial, (2) pluvial, and (3) storm surge flooding, each at seven different return periods (Table 1).

**Table 1: Flood Hazard Data Provided by JBA**

| Return Period | Annual Exceedance Probability (AEP) |
|---|---|
| 20 | 0.05000 |

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| | |
|---|---|
| 50 | 0.02000 |
| 75 | 0.01333 |
| 100 | 0.01000 |
| 200 | 0.00500 |
| 500 | 0.00200 |
| 1500 | 0.00067 |

Additionally, JBA developed climate change flood hazard estimations at the RCP 4.5 and RCP 8.5 scenarios. Two separate time periods of assessment were used in this study: 2021 to 2050 and 2050 to 2080. This means that there was a total of five different climate scenarios, including NCC state based on 2020-2021 modeled data and four climate altered scenarios (Table 2).

**Table 2: Climate Scenarios Used in the Analysis**

| Climate State | Epoch | Time Period |
|---|---|---|
| NCC | 2021 | 2021 |
| RCP 4.5 | 2050 | 2021 to 2050 |
| RCP 4.5 | 2080 | 2051 to 2080 |
| RCP 8.5 | 2050 | 2021 to 2050 |
| RCP.8.5 | 2080 | 2051 to2080 |

To establish a workflow for rapidly comparing flood hazard exposure from the various JBA flood model estimates, an example exposure dataset was constructed using the open-sourced Microsoft Canadian Building Footprints (MCBF) dataset (Microsoft, 2019). This dataset contains roughly 11.8 million computer-generated building footprints across Canada using deep learning, computer vision, and Artificial Intelligence techniques rooted in image recognition.

MCBF data were downloaded from the Microsoft Github repository, specifically for British Columbia. The data were decompressed, then imported into QGIS in its raw geojson file format. To extract a sample of the MCBF data relevant to the study area, the Clip algorithm was used in QGIS using study boundary file, as shown in Figure 3. This resulted in 103,935 individual building polygons for the Vancouver study area.

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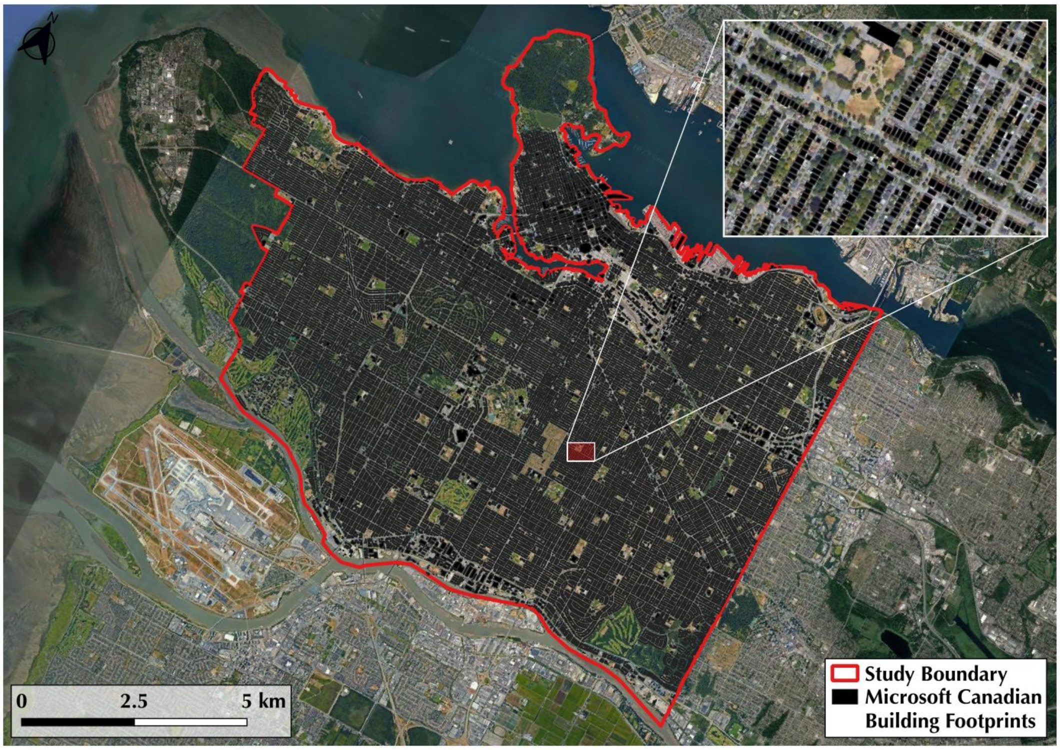


**Figure 3: Study boundary with Microsoft Canadian Building Footprint data (n=103,935). Other map data: Google Satellite Imagery ©2023, TerraMetrics ©2023**

To assess flood exposure across numerous flood hazard scenarios, a Python script was developed which combined the MCBF polygon file with each of the JBA flood scenarios and return periods. Since there were five climate scenarios (CS), three flood mechanisms (FM), and seven return periods (RP), each building was assigned 105 flood depth values (21 per climate scenario):

$$Flood\ hazard\ scenarios = N_{CS}\ x\ N_{FM}\ x\ N_{RP}$$
$$Flood\ hazard\ scenarios = 5\ x\ 3\ x\ 7$$
$$Flood\ hazard\ scenarios = 105$$

To start, the MCBF building polygon dataset was opened as a *geopandas* file in Python. Then, a systematic loop was implemented which: (1) imported one of the flood hazard files using the *rasterio* package, and (2) computed summary statistics of the hazard files using the *rasterstats* zonal statistics function for each building. This procedure was repeated for each of the 105 flood hazard files, summarizing the hazard data at each building polygon. For this assessment, the maximum depth was chosen as the metric for determining exposure, such that buildings were assigned the maximum flood hazard depth for each return period intersecting a given building polygon. If any portion of a building was implicated by flood hazard data, the maximum value of flood depth was assigned.

For each climate state scenario, flood water depths were associated with each flood mechanism and return period for each address. To illustrate, Table 3 provides the different flood hazard sampling for the NCC scenario. The same information provided in Table 3 also applied to the different RCP and time scenarios illustrated in Table 2.

**Table 3: Example CS-FM-RP Level Data at Each Location**

| Item | Climate State | Flood Mechanism | Return Period |
|---|---|---|---|
| 1-7 | NCC | Fluvial | 20 |
| | | | 50 |
| | | | 75 |
| | | | 100 |
| | | | 200 |
| | | | 500 |
| | | | 1500 |
| 8-14 | NCC | Pluvial | 20 |
| | | | 50 |
| | | | 75 |
| | | | 100 |
| | | | 200 |
| | | | 500 |
| | | | 1500 |
| 15-21 | NCC | Storm Surge | 20 |
| | | | 50 |
| | | | 75 |
| | | | 100 |
| | | | 200 |
| | | | 500 |
| | | | 1500 |

The result of this analysis was a building file that contained an associated maximum flood depth at each return period for each flood mechanism and climate state.

For this assessment, a flood depth value greater than zero indicated that a given asset was ‘exposed’ at the corresponding return period, however, it is important to note that greater depths of water are associated with a higher likelihood of damage or loss. To account for this, three exposure metrics were computed:

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1. any building with a flood depth greater than 0 m (any exposure),
2. any building with a flood depth greater than or equal to 0.3 m (moderate exposure),
3. any building with a flood depth greater than or equal to 0.6 m (severe exposure).

These heights approximate 1 foot (0.3048 m) and 2 feet (0.6096 m) first floor elevation (FFE), which are reasonable building FFE's in various contexts across Canada for residential structures. These different depths account for differences in first floor elevation and doorstep height across the study area. These factors, along with other property-level considerations or broader flood defense considerations, may differentiate risk and whether floodwaters would enter a home and cause damage. From this assessment, an evaluation of individual return period event exposure and the suite of return period exposure was taken to determine where new flood exposure might occur because of climate change. The results of this process are described below.

## 4.0 Results

Overall, there were 103,935 building footprints identified in the study area. Of these, 16,820 (16.2%) were identified as exposed to flooding at the 100-year return period in the NCC condition from *any* flood type or combination of flood types. For moderate exposure – that which is greater than or equal to 0.3m – there were 11,050 (10.6%) buildings identified in the study boundary. For severe exposure – that which is greater than or equal to 0.6m – there were 6,840 (6.6%) buildings identified in the study boundary. Table 4 provides a detailed breakdown of exposure by flood type for the NCC state at the 100-year return period.

**Table 4: Breakdown of FM of Exposure for the NCC state, 100-Year RP Flood Hazard**

| **Flood Mechanism(s)** | **n Exposed (Any)** | **% of Exposure (Any)** | **n Exposed (Moderate)** | **% of Exposure (Moderate)** | **n Exposed (Severe)** | **% of Exposure (Severe)** |
|---|---|---|---|---|---|---|
| Fluvial | 118 | 0.7 % | 73 | 0.7 % | 34 | 0.5 % |
| Pluvial | 16,252 | 96.6 % | 10,629 | 96.2 % | 6,585 | 96.3 % |
| Storm Surge | 182 | 1.1 % | 214 | 1.9 % | 175 | 2.6 % |
| Fluvial and Pluvial | 71 | 0.4 % | 41 | 0.4 % | 10 | 0.1 % |
| Fluvial and Storm Surge | 124 | 0.7 % | 68 | 0.6 % | 22 | 0.3 % |
| Pluvial and Storm Surge | 45 | 0.3 % | 21 | 0.2 % | 13 | 0.2 % |
| All Three Mechanisms | 28 | 0.2 % | 4 | 0 % | 1 | 0 % |
| TOTAL | 16,820 | 100 % | 11,050 | 100 % | 6,840 | 100 % |

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For all types of exposure in Vancouver, the overwhelming majority occured due to pluvial flooding. Of the 16,820 buildings with any exposure to flooding, 16,252 (96.6%) occurred from pluvial only sourcing. The same general distribution of exposure by flood mechanism occurred across any, moderate and severe exposure types, with pluvial being the dominant source; however, there was slightly higher proportions of severe exposure occurring from storm surge compared to estimates when using exposure at any depth.

It is worth noting that pluvial flooding involves a greater degree of uncertainty, in part due to the complexity of incorporating human-generated subsurface drainage infrastructures and waterways. Though the results indicated that pluvial flooding was the primary driver of exposure in Vancouver, this may not be true in other settings where fluvial or storm surge flooding are the drivers of exposure. Figure 4 (top) and Figure 4 (bottom) show the same Southlands region of Vancouver with fluvial and storm surge flooding, showing that though both are impacted, storm surge appears to lead to more severe exposure than fluvial flooding. This differentiation is important for determining flooding that is more likely to cause structural damage due to greater water depths.

When different climate change scenarios are factored in, flood hazard exposure can differ. Table 5, Table 6, and Table 7 provide a detailed breakdown of the different exposures for the 100-year return period under each climate scenario for any exposure, moderate exposure, and severe exposure, respectively. For all three exposure levels, the total number of building footprints exposed increased in each climate change scenario. For example, using any exposure, the total number of buildings increased from 16,820 to 18,163 (7.98%) for the RCP 8.5 (2050) climate change state. Interestingly, this exposure is similar in magnitude for the RCP 8.5 (2080) scenario, which estimated 18,156 MCBF, a 7.94% increase. Also of interest is that the total number of exposed properties at any depth decreased from RCP 4.5 (2050) to RCP 4.5 (2080), though both showed an estimated increase from the baseline of 16,820. It is generally accepted that RCP 8.5 is more reflective of the projected climate state than RCP 4.5. The same general distributions of flood exposure occured by flood type, with pluvial-sourced flooding the dominant flood type leading to exposure in the study area of Vancouver.

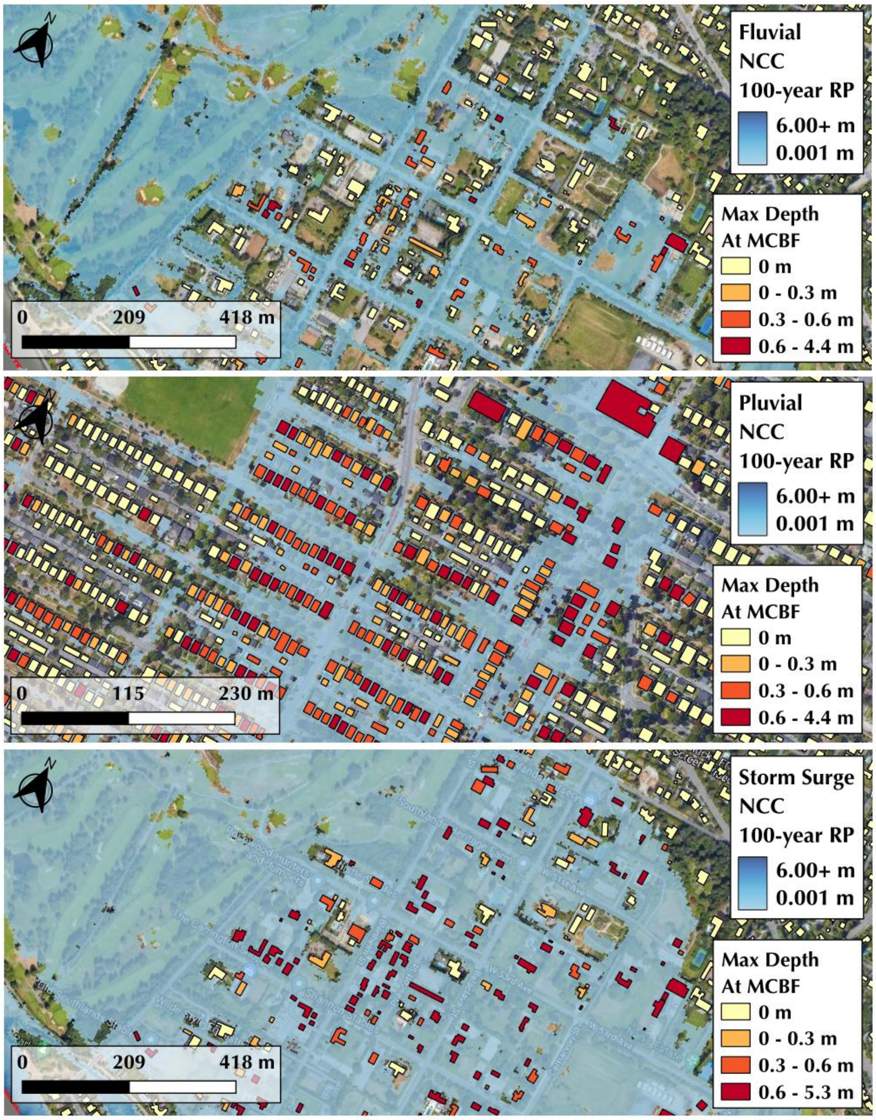


**Figure 4: Flood exposure from fluvial, pluvial, and storm surge flooding for any exposure (> 0m), moderate exposure (>= 0.3m), and severe exposure (>=0.6m) in the Southlands of Vancouver (top and bottom) and northeastern reaches of the Arbutus Ridge Neighbourhood in Vancouver (middle). Other map data: Google Satellite Imagery ©2023, CNES / Airbus, Maxar Technologies ©2023**

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**Table 5: Breakdown of Any Exposure by FM for the Various Climate States at the 100-Year RP Flood Hazard**

| **Flood Mechanism(s)** | **n Exposed (NCC)** | **% of Exposure (NCC)** | **n Exposed (RCP 4.5, 2050)** | **% of Exposure (RCP 4.5, 2050)** | **n Exposed (RCP 8.5, 2050)** | **% of Exposure (RCP 8.5, 2050)** | **n Exposed (RCP 4.5, 2080)** | **% of Exposure (RCP 4.5, 2080)** | **n Exposed (RCP 8.5, 2080)** | **% of Exposure (RCP 8.5, 2080)** |
|---|---|---|---|---|---|---|---|---|---|---|
| Fluvial | 118 | 0.7 % | 133 | 0.8 % | 151 | 0.8 % | 124 | 0.7 % | 143 | 0.8 % |
| Pluvial | 16,252 | 96.6 % | 16,767 | 96.2 % | 17,451 | 96.1 % | 16,543 | 95.8 % | 17,390 | 95.8 % |
| Storm Surge | 182 | 1.1 % | 212 | 1.2 % | 205 | 1.1 % | 235 | 1.4 % | 235 | 1.3 % |
| Fluvial and Pluvial | 71 | 0.4 % | 47 | 0.3 % | 76 | 0.4 % | 44 | 0.3 % | 57 | 0.3 % |
| Fluvial and Storm Surge | 124 | 0.7 % | 142 | 0.8 % | 160 | 0.9 % | 142 | 0.8 % | 171 | 0.9 % |
| Pluvial and Storm Surge | 45 | 0.3 % | 97 | 0.6 % | 87 | 0.5 % | 124 | 0.7 % | 113 | 0.6 % |
| All Three Mechanisms | 28 | 0.2 % | 39 | 0.2 % | 33 | 0.2 % | 50 | 0.3 % | 47 | 0.3 % |
| **TOTAL** | **16,820** | **100 %** | **17,437** | **100 %** | **18,163** | **100 %** | **17,262** | **100 %** | **18,156** | **100 %** |
| **TOTAL Δ from NCC** | • | • | **617** | **3.67%** | **1,343** | **7.98%** | **442** | **2.63%** | **1,336** | **7.94%** |

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*Table 6: Breakdown of Moderate Exposure by FM for the Various Climate States at the 100-Year RP Flood Hazard*

| **Flood Mechanism(s)** | **n Exposed (NCC)** | **% of Exposure (NCC)** | **n Exposed (RCP 4.5, 2050)** | **% of Exposure (RCP 4.5, 2050)** | **n Exposed (RCP 8.5, 2050)** | **% of Exposure (RCP 8.5, 2050)** | **n Exposed (RCP 4.5, 2080)** | **% of Exposure (RCP 4.5, 2080)** | **n Exposed (RCP 8.5, 2080)** | **% of Exposure (RCP 8.5, 2080)** |
|---|---|---|---|---|---|---|---|---|---|---|
| Fluvial | 73 | 0.7 % | 84 | 0.7 % | 104 | 0.9 % | 77 | 0.7 % | 97 | 0.8 % |
| Pluvial | 10,629 | 96.2 % | 10,960 | 95.7 % | 11,354 | 95.6 % | 10,815 | 95.3 % | 11,324 | 95 % |
| Storm Surge | 214 | 1.9 % | 248 | 2.2 % | 237 | 2 % | 283 | 2.5 % | 287 | 2.4 % |
| Fluvial and Pluvial | 41 | 0.4 % | 26 | 0.2 % | 44 | 0.4 % | 22 | 0.2 % | 36 | 0.3 % |
| Fluvial and Storm Surge | 68 | 0.6 % | 76 | 0.7 % | 91 | 0.8 % | 77 | 0.7 % | 96 | 0.8 % |
| Pluvial and Storm Surge | 21 | 0.2 % | 45 | 0.4 % | 43 | 0.4 % | 59 | 0.5 % | 57 | 0.5 % |
| All Three Mechanisms | 4 | 0 % | 13 | 0.1 % | 9 | 0.1 % | 20 | 0.2 % | 18 | 0.2 % |
| **TOTAL** | **11,050** | **100 %** | **11,452** | **100 %** | **11,882** | **100 %** | **11,353** | **100 %** | **11,915** | **100 %** |
| **TOTAL Δ from NCC** | • | • | **402** | **3.64%** | **832** | **7.53%** | **303** | **2.74%** | **865** | **7.83%** |

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*Table 7: Breakdown of Severe Exposure by FM for the Various Climate States at the 100-Year RP Flood Hazard*

| **Flood Mechanism(s)** | **n Exposed (NCC)** | **% of Exposure (NCC)** | **n Exposed (RCP 4.5, 2050)** | **% of Exposure (RCP 4.5, 2050)** | **n Exposed (RCP 8.5, 2050)** | **% of Exposure (RCP 8.5, 2050)** | **n Exposed (RCP 4.5, 2080)** | **% of Exposure (RCP 4.5, 2080)** | **n Exposed (RCP 8.5, 2080)** | **% of Exposure (RCP 8.5, 2080)** |
|---|---|---|---|---|---|---|---|---|---|---|
| Fluvial | 34 | 0.5 % | 35 | 0.5 % | 49 | 0.7 % | 33 | 0.5 % | 45 | 0.6 % |
| Pluvial | 6,585 | 96.3 % | 6,837 | 95.4 % | 7,133 | 95.3 % | 6,723 | 94.8 % | 7,114 | 94.6 % |
| Storm Surge | 175 | 2.6 % | 237 | 3.3 % | 235 | 3.1 % | 269 | 3.8 % | 283 | 3.8 % |
| Fluvial and Pluvial | 10 | 0.1 % | 7 | 0.1 % | 16 | 0.2 % | 6 | 0.1 % | 14 | 0.2 % |
| Fluvial and Storm Surge | 22 | 0.3 % | 26 | 0.4 % | 28 | 0.4 % | 26 | 0.4 % | 31 | 0.4 % |
| Pluvial and Storm Surge | 13 | 0.2 % | 19 | 0.3 % | 19 | 0.3 % | 30 | 0.4 % | 29 | 0.4 % |
| All Three Mechanisms | 1 | 0 % | 3 | 0 % | 1 | 0 % | 5 | 0.1 % | 4 | 0.1 % |
| **TOTAL** | **6,840** | **100 %** | **7,164** | **100 %** | **7,481** | **100 %** | **7,092** | **100 %** | **7,520** | **100 %** |
| **TOTAL Δ from NCC** | • | • | **324** | **4.74%** | **641** | **9.37%** | **252** | **3.68%** | **680** | **9.94%** |

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Of the 16,820 MCBF considered exposed in the baseline climate scenario (Table 5), 11,050 (65.7%) were considered to have moderate exposure (Table 6) and 6,840 (40.7%) were considered to have severe exposure (Table 7). Though pluvial flooding is the dominant source of all three exposure levels, storm surge has an increasing proportion of severe exposure in all climate change scenarios (Table 7). Although the total exposure increases for all climate scenarios, the effect of climate change seems more pronounced for severe exposure. Specifically, severe exposure increased for RCP 8.5 2050 and RCP 8.5 2080 between 9.3% and 10%, while any exposure and moderate exposure showed increases between 7.5% and 8.0% (Tables 5-7).

For a more detailed breakdown of the change in exposure associated with climate change projections, asset exposure was disaggregated into three general categories: (1) continued exposure, (2) new exposure, and (3) former exposure. Continued exposure refers to assets that were considered exposed to flooding at a given return period both in a non-climate change state and given altered climate change state. New exposure refers to the assets that were not considered exposed to flooding at a given return period but are exposed under an altered climate state. Former exposure refers to the assets that were considered exposed to flooding at a given return period but were not exposed under an altered climate state.

Of the 16,820 buildings that were considered exposed to any 100-year flood type and depth (i.e., fluvial, pluvial, and storm surge) under the NCC state, 16,806 continued to be exposed in the RCP 8.5 2080 climate state at any depth, while 14 were no longer considered exposed. Additionally, there were 1,350 new assets exposed to flooding due to climate change. This is summarized in Table 8. The result is a total estimated exposure of 18,156 buildings for the RCP 8.5 2080 climate state at any depth. An overview of this comparison is provided in Figure 4.

***Table 8: Exposure breakdown between the baseline NCC state and the RCP 8.5 2080 climate state for the 100-year return period using all flood mechanisms***

| **Exposure Breakdown** | **n** |
|---|---|
| Continued Exposure | 16,806 |
| New Exposure | 1,350 |
| No Exposure | 85,765 |
| Former Exposure | 14 |

For the 16,806 buildings classified as having ‘continued’ exposure both at the NCC and RCP 8.5 2080 climate states, we observed differences in the proportion of exposure that is considered moderate and severe. Of the 16,806 buildings, 11,044 (65.7%) were considered moderate at NCC conditions whereas 11,536 (68.6%) were considered moderate at RCP 8.5 2080

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conditions, a 4.5% (n = 492) increase in the moderately exposed buildings. Severe exposure increased as well. Of the 16,806 buildings, 6,837 (40.7%) were considered severely exposed at the NCC conditions, while 7,320 (43.6%) were considered severely exposed at the RCP 8.5 2080 conditions. This reflects a 7% (n = 483) increase in the severely exposed buildings.

The exposed properties were distributed all over the study site, which is to be expected from the widespread pluvial flood hazard estimation. The overwhelming majority of these assets continued to be exposed under the RCP 8.5 2080 climate state and, due to the diffuse nature of pluvial flooding, the new exposure was scattered throughout the study site. As depicted in Figure 5, in some cases we noted greater amounts of water leading to greater exposure on the periphery of regions affected under the NCC state (inset map of Figure 5). Such instances would be explained by more water occurring from flooding in the same areas exposed in the baseline non-climate change state, leading to an expansion of the flood extent and greater depths of water at previously exposed buildings.

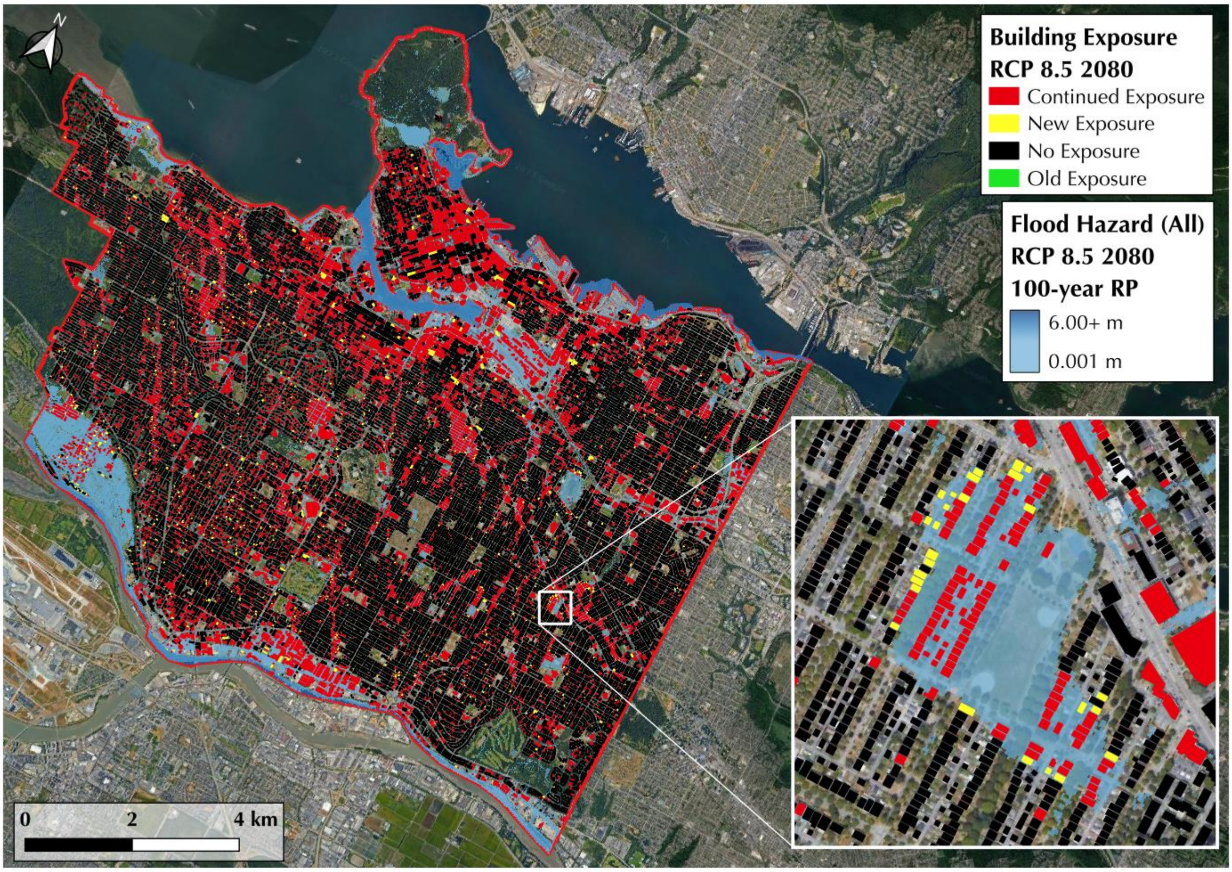


**Figure 5: Overview of Continued, New, and Former Exposure in Vancouver using the RCP 8.5 2080 Climate State at the 100-year return period. Other map data: Google Satellite Imagery ©2023, TerraMetrics ©2023 CNES / Airbus, Maxar Technologies ©2023**

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Generally, we expected that most properties exposed in a NCC state would also be exposed in a climate-altered state, largely due to assumptions about warmer air carrying more moisture and other flood modeling assumptions under an altered climate. A few buildings (n = 14) were determined to be exposed at the baseline non-climate change state that were classified as non-exposed at RCP 8.5 2080. For example, Figure 6 provides two of the three assets classified as ‘former’ exposure, which were considered exposed in the NCC state but not in the RCP 8.5 2080 climate state at the 100-year return period. Ultimately, these were investigated individually and determined to be all pluvial-sourced flooding at shallow flood depths and are likely artifacts of the flood hazard data representation and almost always occurred in small pockets of disjoint pools of water.


**Figure 6: Example of Two Assets Considered Exposed at the NCC State and not at RCP 8.5 2080 Climate State. Other map data: Google Satellite Imagery ©2023, CNES / Airbus, Maxar Technologies ©2023**

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## 5.0 Discussion

The Vancouver case study demonstrates the applicability and granularity of the flood hazard mapping tool for identifying local flood exposure under a changing climate. This simplified flood hazard mapping approach was able to capture changes to flood exposure based on different climate states, flood types, and return periods. Interestingly, most of the engineered flood hazard mapping in Canada pertains to fluvial flooding (MMM Group Limited, 2014), meaning pluvial and storm surge inclusions could reflect an uncaptured source of flood risk in Vancouver by stakeholders relying on publicly available engineered maps only.

More broadly, the higher resolution data (5-metre) constitutes an improvement from 30+ metre resolution models being produced nationally, although local engineered mapping is typically around 2-metre resolution. By modeling climate change, this type of exposure assessment enables mapping of changes to flood exposure for future climate states. Other benefits of this approach include its capacity to differentiate flood exposure based on the source of flooding, its scalability, and its ability to provide a generalized analysis for planners and policymakers. Although there is greater uncertainty in the pluvial flood estimation, it constitutes a largely unmapped source of risk that can become increasingly important in urban environments.

The use of higher resolution hazard data, climate change conditions and multiple flood mechanisms in this analysis improves upon mapping techniques that are often low resolution, lack climate change considerations, and are highly complex to develop (Cea & Costabile, 2022; Costabile et al., 2015; de Moel et al., 2009; Mudashiru et al., 2021; Teng et al., 2017). Moreover, this mapping approach demonstrates the relevance of physically-based modeling as a modern approach to flood hazard mapping that is less costly and onerous to produce than conventional approaches. This may be especially appealing to planners and engineers who can now more effectively argue that some communities should have policies encouraging property-level flood protections.

Although the model and case study demonstrate a general and easy-to-use approach to local flood hazard mapping, they have some limitations. First, the analysis does not distinguish between building types. When reviewing Figure 4 more closely, some structures were not identified as buildings based on the exposure dataset. Most of these structures are assumed to be sheds, but their exposure is still relevant. While this represents a limitation of the MCBF data, the use of this data in this model is a strength as well. This limitation is a product of the MCBF and its coding. In many parts of the world, modeling flood exposure is limited by poor or even non-existent exposure datasets, such that assumptions must be made by scientists regarding population density. Here, the produced flood hazard maps show that despite some limitations within the datasets used, the overall quality of the model remains high.

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Second, this model used a constant exposure dataset based on recent building data availability (2019). Conditions in 2050 and 2080 would also include more building and more exposure, which can constitute another considerable source of additional flood risk. It is anticipated that new buildings will contribute a considerable source of new exposure that will add to the risk in future climate conditions. With more buildings and exposure, it is likely that there will be more possible sources of flood exposure. For this analysis, exposure was held constant while flood hazard was modified to different climate change scenarios. Future research could consider the influence of new development on additional flood risk.

Third, this method for flood hazard mapping identified buildings using an estimated polygon from the source data, but it does not account for building information such as building type (residential, commercial, industrial, etc.). This approach makes it difficult to differentiate flood exposure by land use, classification, or for other relevant characteristics. Though there are inherent inaccuracies and a recency problem to the dataset – which was released in 2019 – the general flood exposure approach was the focus of this paper.

Finally, while the produced flood hazard maps using the model presented here are considered by industry to be a high resolution, local-scale flood models that are physical can improve this further (e.g., at a 1-metre or 2-metre resolution). This becomes computationally challenging, especially if the spatial extent of the area grows from a single city to a provincial or even national scale, to offer consistency. Further, comparisons and validation of the flood hazard data against local engineered mapping or past flood events could reveal the hazard accuracy to known events or to on-the-ground results in Vancouver. The strengths of this approach, however, are a reasonable trade-off since this efficient flood hazard mapping approach nevertheless produces visual outputs that would be valuable for future land use planning, emergency management, policymaking, and risk awareness. Additionally, the approach may be appealing to smaller municipalities that lack resources to pursue higher-resolution modeling.

Validation of the model results is needed to rectify some of these issues. For example, a manual inspection of structures throughout the study area and comparing the results of this model against others that have higher and lower resolutions would allow us to monitor the overall accuracy of the findings. In the absence of any validating experiments, these maps should be viewed through a cautionary lens. Moreover, this model identifies changes to exposure due to climate change but does not consider changing socioeconomic characteristics of the area or economic consequences of flooding. These are areas requiring further research.

## 6.0 Conclusion

The acceleration of flood risk caused by climate change and expanding development in flood-prone areas requires local flood hazard maps that will enable governments, non-governmental organizations, and others to plan and implement interventions that will protect assets and populations. However, flood hazard maps often fail to account for climate change, are developed through highly technical methodologies, depict exposure to only one source of flooding, and have a course resolution. Leading scholarship has suggested that simplified mapping approaches are needed to overcome these weaknesses while permitting practical use by non-experts.

This paper presented a simple modeling approach to produce local flood hazard maps using a moderate 5-metre resolution based on JBA Risk Management's 5-metre Baseline and Climate Change Flood Map Data for Canada. In using these data, we demonstrated an empirical approach to local flood hazard mapping that produces generalizable flood exposure information. The approach can model changes to flood exposure based on the flood type, climate change projections, and return periods. This is novel to flood hazard mapping because of its scalability and its ability to capture climate change and pluvial flood exposure. While certain limitations do exist – including the inability to differentiate exposure based on building type (e.g., residential versus commercial) – the approach enables local planners, policymakers, and other stakeholders to pursue flood risk management strategies.

Further research is needed to validate the findings of the current model and its replicability in other jurisdictions. Comparing the resulting local flood hazard map with maps produced using other methodologies – including physical and empirical models – and against historical flood events would allow us to validate the findings even further. Validating climate change hazard estimation remains a challenge due to the uncertainty surrounding climate change effects; however, this model constitutes a step forward in the use of forward-looking flood hazard and exposure estimation.

## Data Availability

As per the policy on data sharing, access to data used in this research can be made available upon reasonable request to JBA Risk Management. Access to the MCBF data can be found on GitHub (GitHub - microsoft/CanadianBuildingFootprints: Computer generated building footprints for Canada).

## Author Contributions

Connor Darlington developed the research methodology and carried out the data analysis. Jonathan Raikes prepared the manuscript with contributions from all co-authors.

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## Competing Interests

The authors declare that they have no conflict of interest.

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