Economic Exposure of Canadian Residential Properties to Flooding

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Abstract: Flood risk management (FRM) involves planning proactively for flooding in high-risk areas to reduce its impacts on people and property. A key challenge for governments pursuing FRM is to pinpoint assets that are highly economically exposed and vulnerable to flood hazards in order to prioritize them in policy and planning. This paper presents a novel flood risk assessment making use of a dataset that identifies the location, dwelling type, property characteristics, and potential economic losses of Canadian residential properties. The findings reveal that the average annual costs are $1.4B, but most of the risk is concentrated in high-risk areas. Data gaps are uncovered that justify replication through local validation studies. The results provide a novel evidence base for specific reforms in Canada's approach to FRM with a focus on insurance that improve both implementation and effectiveness.

Keywords: flood risk management; economic exposure; risk-based approaches; residential; climate change adaptation

1.0 Introduction

Flooding is one of the most prevalent natural hazards globally, with about 1.8 billion people directly exposed to 1-in-100-year floods (Rentschler, Salhab, and Jafino 2022). Flood risk is growing due to climate change, which is increasing the frequency and intensity of extreme weather and climate-related events, as well as expansion of development in flood-prone areas such as lands near rivers and along coastlines (Alfieri et al. 2016; Arnell and Gosling 2016; Hirabayashi et al. 2021; Kundzewicz et al. 2019; McDermott 2022). Faced with mounting flood damages and increasing risk, many countries are embracing flood risk management (FRM), a strategic framework designed to reduce the consequences of flooding by engaging a wide range of stakeholders and by implementing a diversity of strategies to reduce and manage flood-related impacts (Hegger et al. 2016; Klijn, Samuels, and Os 2008).

One of the key challenges for FRM is identifying areas and assets exposed to flood hazards and assessing the potential economic consequences of their inundation. This information is used to prioritize scarce resources towards stakeholders and actions that support mitigation, preparedness, response, and recovery. A failure to engage in such flood risk assessment often leads to *ad hoc* and reactionary policies, plans, and decisions that reflect a bias towards structural measures (Morrison, Westbrook, and Noble 2018). As such, there is demand for national level risk assessments that measure economic exposure to floods in a way that can inform FRM policy, planning, and decision-making. This is particularly the case for addressing reform in Canada's approach to recovery that involves the development of a national flood insurance program.

This paper examines flood risk to residential properties in Canada. It provides a national overview of the spatial distribution and concentration of economic exposure to flooding from pluvial, fluvial, and storm surge flooding, presenting a novel methodological approach and important insights for FRM. The paper begins with an overview of Canadian FRM, highlighting recent trends in current policy, planning, and implementation. It then presents the methodology adopted to assess the spatial distribution and concentration of flood risk in Canada, followed by the results. The paper concludes with a broader discussion on the significance of these findings relative to current academic and policy discourses on advancing FRM in Canada with a focus on flood insurance.

2.0 Canadian Flood Risk Management

Flooding is the most common and damaging natural hazard in Canada, which manifests in different forms (Buttle et al. 2016; Faulkner, Warren, and Burn 2016). Coastal regions, such as those in British Columbia and Atlantic Canada, are exposed to storm surge and sea-level rise. Inland areas near major rivers experience occasional fluvial (riverine) flooding when water levels rise due to heavy precipitation or spring snowmelt and overtop the banks. Pluvial (urban) flooding is an increasing problem for cities when heavy rainfall exceeds the capacity of stormwater drainage systems and excess water flows over land. Furthermore, climate change is projected to worsen all forms of flooding as Canada warms more rapidly than the global average (Grenier et al. 2024; Mohanty and Simonovic 2021).

Governments have implemented various measures to reduce flood risk, including floodplain mapping, infrastructure improvements, public information campaigns, and community development regulations (Doberstein, Fitzgibbons, and Mitchell 2019; Shrubsole et al. 2003). How these policies are designed, the locations where they are employed, and the extent they are resourced is dependent on a comprehensive and accurate assessment of flood risk, which comprises three components: the flood hazard, the exposure of assets to flood hazards, and the vulnerability of assets to flood-related impacts. For example, evidence that risk is concentrated in some locations justifies for funding for mitigation, restrictions on future development, and in the worst-case scenario, strategic relocation of residential property (Sayers et al. 2015; Hegger et al. 2016).

Developing such a risk assessment is a significant challenge in Canada because the availability and accessibility of data on these aspects of flood risk are limited (Natural Resources Canada 2023a). Most data are generated through provincial mapping studies that focus on regulatory flood mapping of riverine risk leading to a patchwork of coverage and little consideration for pluvial or coastal exposure. The federal government responded to this gap through a series of funding initiatives designed to generate more data along with guidelines to standardize across the country, but there remains no national-level high-resolution risk modeling (Natural Resources Canada 2023a; Public Safety Canada 2018; Natural Resources Canada 2023c; 2023b).

In recent years, several private vendor models have been developed at a national level that insurers and governments are using in studies to compare with existing datasets. These models represent an important starting point for building a national-level risk assessment when combined with existing data on exposure and vulnerability in Canada. This paper extends recent work using this data by developing a comprehensive, Canada-wide assessment of flood risk to residential buildings. The dataset combines information on the location, type, and property characteristics of residential dwellings with a third-party flood risk model. Analysis of the outputs offers an original perspective on flood risk for residential properties across Canada.

This study will benefit FRM in Canada by addressing the patchwork of existing models. In particular, the study will offer the first analysis critical to inform emerging reform in Canada's approach to flood recovery. Private flood insurance, which enables households to cope with the consequences of flooding, was historically unavailable in Canada, leaving property owners reliant on public disaster assistance (Sandlink et al. 2016). In 2015, however, a few insurers began offering an optional layer of protection for overland flooding to home insurance contracts (Thistlethwaite 2017). Since then, the availability of coverage has expanded: there are now more than 30 insurers active in the market and the industry reports that about 90 percent of households have access to flood insurance coverage (Insurance Bureau of Canada 2023). Approximately 40 percent of homeowners have purchased flood insurance coverage since the fall of 2022 (Johnston et al. 2023).

The availability, coverage, and cost of flood insurance varies substantially from one insurer to another for the same property, however. In high-risk areas, flood insurance is limited in availability, too expensive for most homeowners, and offers insufficient coverage (Darlington and Yiannakoulias 2022). In March 2023, the Government of Canada announced it would pursue a low-cost national flood insurance program that would extend adequate and affordable coverage to high-risk homeowners (Canada 2023). This study seeks to contribute to the design of this program and flood risk management more broadly through a comprehensive national-level flood risk assessment.

3.0 Data and Methods

This section describes the steps that were followed to build the residential flood risk dataset. The key steps were to: (1) determine the total number of dwellings, (2) geocode properties, (3) assign property characteristics, and (4) structure the exposure dataset. The flood risk model used to estimate prospective flood losses based on the exposure data is described in Section 3.5.

3.1 Dwellings

The first step involved determining the total number of dwellings. Statistics Canada sorts dwellings into ten different types (Statistics Canada 2022). These include: single-detached houses (Code 1), semi-detached houses (Code 2), row houses (Code 3), apartments or flats in a duplex (Code 4), apartments in a building that has five or more storeys (Code 5), apartments in a building that has fewer than five storeys (Code 6), other single-attached houses (Code 7), mobile homes (Code 8), other movable dwellings (Code 9), and collective dwellings (e.g., nursing homes, custodial facilities, religious establishments).

Table 1. Distribution of the number of non-collective dwellings in Canada per type and province

Province	Code 1	Code 2	Code 3	Code 4	Code 5	Code 6	Code 7	Codes 8-9	Total
NL	161,365 (72.5%)	8,600 (3.9%)	10,680 (4.8%)	27,490 (12.3%)	775 (0.3%)	12,250 (5.5%)	275 (0.1%)	1,165 (0.5%)	222,600
PE	43,785 (68.1%)	3,560 (5.5%)	2,685 (4.2%)	1,090 (1.7%)	120 (0.2%)	10,375 (16.1%)	35 (0.1%)	2,680 (4.2%)	64,330
NS	272,815 (63.8%)	21,375 (5%)	11,115 (2.6%)	13,030 (3%)	28,650 (6.7%)	64,580 (15.1%)	505 (0.1%)	15,250 (3.6%)	427,320
NB	228,840 (67.9%)	13,365 (4%)	9,705 (2.9%)	13,825 (4.1%)	4,225 (1.3%)	51,910 (15.4%)	980 (0.3%)	14,120 (4.2%)	336,970
QC	1,671,095 (44.7%)	198,365 (5.3%)	97,890 (2.6%)	270,310 (7.2%)	224,940 (6%)	1,242,160 (33.2%)	13,810 (0.4%)	22,845 (0.6%)	3,741,415
ON	2,942,450 (53.7%)	301,420 (5.5%)	504,335 (9.2%)	179,205 (3.3%)	983,255 (17.9%)	547,185 (10%)	8,300 (0.2%)	14,135 (0.3%)	5,480,285
MB	344,020 (66.5%)	18,145 (3.5%)	19,640 (3.8%)	7,300 (1.4%)	43,635 (8.4%)	74,795 (14.5%)	395 (0.1%)	9,490 (1.8%)	517,420
SK	321,205 (71.8%)	13,505 (3%)	19,785 (4.4%)	11,120 (2.5%)	10,955 (2.4%)	61,625 (13.8%)	555 (0.1%)	8,870 (2%)	447,620
AB	994,280 (61%)	98,225 (6%)	127,510 (7.8%)	43,295 (2.7%)	74,765 (4.6%)	246,670 (15.1%)	935 (0.1%)	45,140 (2.8%)	1,630,820
BC	865,435 (42.5%)	62,325 (3.1%)	168,415 (8.3%)	249,550 (12.2%)	221,550 (10.9%)	416,960 (20.5%)	3,115 (0.2%)	50,660 (2.5%)	2,038,010
YT	10,265 (60.2%)	1,265 (7.4%)	1,240 (7.3%)	690 (4%)	55 (0.3%)	1,990 (11.7%)	105 (0.6%)	1,430 (8.4%)	17,040
NT	8,520 (56.5%)	1,045 (6.9%)	1,630 (10.8%)	380 (2.5%)	290 (1.9%)	2,505 (16.6%)	100 (0.7%)	615 (4.1%)	15,085
NU	4,280 (43%)	970 (9.7%)	3,035 (30.5%)	195 (2%)	115 (1.2%)	1,345 (13.5%)	5 (0.1%)	5 (0.1%)	9,950
Canada	7,868,355 (52.6%)	742,165 (5%)	977,665 (6.5%)	817,480 (5.5%)	1,593,330 (10.7%)	2,734,350 (18.3%)	29,115 (0.2%)	186,405 (1.2%)	14,948,865

Table 1 shows the distribution of dwellings by type per province. There are nearly 15 million non-collective dwellings, and more than half (52.6%) are single-detached houses, but with large heterogeneity across provinces (e.g. 72-73% in Newfoundland and Labrador and Saskatchewan; 43% in British Columbia and Nunavut). The proportion of multi-dwelling units also varies widely across provinces: Ontario and British Columbia have the largest share of apartments in buildings with more than five storeys (18% and 11% respectively). Quebec has by far the largest proportion of apartments in buildings with five storeys or less (33% compared with 10% in Ontario, 21% in British Columbia and a Canadian average of 18%). These variations across provinces highlight different urbanization schemes, particularly in the largest cities.

Not all dwellings could be captured in the residential database. Due to a lack of data on the floor area, height of buildings, and number of storeys, we could not approximate the number of apartments located in basements or on the first floor. We therefore excluded apartments located in multi-dwelling units (Codes 5 and 6). This exclusion is reasonable since these dwellings are not typically targeted for flood insurance. Codes 5 and 6 represent 4.3 million dwellings in Canada, or approximately 30% of all dwellings, a percentage that reaches nearly 40% in Quebec. Lacking additional information on their characteristics, we also excluded other single-attached houses, mobile homes, and other movable dwellings (Codes 7-9) from the exposure dataset, but they represent only 1.4% of total dwellings. For the same reason, we excluded 24,140 collective (Code 10) dwellings from our analysis.

The flood risk analysis therefore focused predominantly on single-detached houses, semi-detached houses, row houses, and apartments or flats in a duplex (Codes 1-4). The latter input data from Statistics Canada thus included about 10.4 million homes, or 70% of the total number of dwellings.

Statistics Canada aggregates information on number of dwellings at the *dissemination block* and *dissemination area* levels. A dissemination block (DB) is an area bounded on all sides by roads and/or boundaries and is the smallest geographic area for which population and dwelling counts are disseminated. A dissemination area (DA) is a small, relatively stable geographic unit composed of one or more adjacent dissemination blocks with an average population of 400 to 700 persons. It is the smallest standard geographic area for which *all* census data are disseminated.

3.2 Geocoding Dwellings

Estimating flood hazard exposure requires the precise location of a dwelling, so we geocoded each of the 10.4 million dwellings by using the CanMap Address Points dataset from DMTI Spatial to translate their postal addresses to latitude and longitude. The dataset also enabled us to distinguish whether a property was detached, semi-detached, or part of a multi-dwelling unit (MDU). Figure 1 shows CanMap Address Points on a satellite image (Google Maps) of a sample neighborhood in Quebec. The green dots represent residential dwellings, red dots represent non-residential usage, and orange dots indicate mixed-use properties. The clustering of green dots at the bottom right is typical for semi-detached houses, duplexes, and MDUs.

We validated the accuracy of the coordinates by performing visual checks of hundreds of random locations. Coordinates in urban areas were highly reliable but accuracy was weaker in rural areas, where it was difficult to differentiate the main residence from separate garage or farm building.

Figure 1. CanMap Address Points over a satellite image in the province of Quebec (Satellite view from Google Maps)

Because the CanMap Address Points database was released before the 2021 Census data, it was impossible to perfectly reconcile the coordinates with the number of dwellings from Statistics Canada. Moreover, the census data showed some inconsistencies between contiguous DBs, so we used the number of dwellings per DA to assign locations for each dwelling. Consequently, for each dwelling and DA, we assigned locations from the DMTI dataset by first selecting residential properties, then mixed and unknown usages, and excluding MDUs. In cases where the number of dwellings reported by Statistics Canada was larger than the number of locations available in the CanMap Address Points data for a corresponding DA, we used coordinates from contiguous DAs, while making sure to avoid double counting. The overall process took 22 hours of computation, but we found a match for 95% of the total number of dwellings from Statistics Canada (about 9.8 million). As such, the exposure dataset reflects the current state of exposure data in Canada, along with its limitations, which are part of the typical uncertainties of flood risk modelling. We are confident that nearly all location points (above 99.5%) fall within 30m of their true location, which matches the resolution of the flood hazard model described below.

To determine the robustness of the process of combining Statistics Canada's number of dwellings with location information from CanMap Address Points, we also used location information for Quebec's built environment from the Ministère des Affaires municipales et de l'Habitation (MAMH). We then built a Quebec exposure dataset, ran the same flood model, and compared results (more details in Section 3.4.2).

3.3 Property Characteristics

The third step in the analysis involved assigning property characteristics to each dwelling using the Aggregate Exposure Information 2021 dataset from Opta Information Intelligence (now owned by Verisk). The dataset contains property information such as number of storeys, year of construction, whether or not there is a basement, and estimated reconstruction costs. The data are aggregated per DB or DA depending on the number of properties in an area and are further divided based on number of floors.

To assign a reconstruction cost to individual properties, we used the average per DB or DA. We then randomly assigned basements based on the proportion of buildings with a basement in each DB or DA while making sure such proportion is replicated as much as possible. Finally, for each dwelling we assigned a year of construction based on the average for its corresponding DB or DA. Because Opta's Aggregate Exposure Information is based upon an earlier geometry of DBs and DAs in Canada (2016), we had some mismatches in newer neighborhoods, which we corrected with the most recent and closest geometries of DAs from Statistics Canada.

The random assignment of characteristics to individual properties was necessary because the information was aggregated at the DB or DA level. This means neighborhood-level results are insufficiently precise for uses such as insurance underwriting or land-use planning. Across broader spatial scales (e.g., provincial), there is greater confidence that the data provide a realistic portrait of residential property exposure to flooding.

3.4 Canadian Exposure Datasets

The fourth and final step entailed organizing the exposure dataset in the requisite format to use it as an input in the flood hazard model. The requisite format required that each property be designated with (1) a unique identifier, (2) latitude/longitude coordinates, (3) building and contents value, (4) construction type, (5) number of storeys, (6) year built, (7) basement indicator, and (8) first-floor elevation.

3.4.1 Main exposure dataset

The coordinates were assigned as described in Section 3.2. Building values, number of storeys, year built, and basement indicator were calculated as described in Section 3.3. Based on consultation with actuaries, contents were calculated as 40% of the building value. Construction type was assumed to be wood framing, which is standard practice for residential units in Canada. Finally, the first-floor elevation was set at three feet above grade for buildings with a basement and one foot for buildings without a basement.

Table 2. Descriptive statistics on the Canadian exposure dataset

Province	Number of dwellings	Average Reconstruction costs ($)	Average Number of floors	Average Year built	% basement	Average First-floor elevation (feet)
NL	145,574	290,697	1.28	1979	88.9%	2.78
PE	51,029	344,903	1.28	1973	95.2%	2.90
NS	317,783	304,164	1.43	1970	86.4%	2.73
NB	263,508	307,420	1.34	1974	85.3%	2.71
QC	2,232,916	347,696	1.37	1975	94.2%	2.88
ON	3,780,380	491,485	1.61	1974	94.8%	2.90
MB	343,839	393,674	1.27	1970	88.7%	2.77
SK	322,306	328,540	1.21	1973	93.3%	2.87
AB	1,213,347	408,424	1.53	1987	91.8%	2.84
BC	1,146,297	505,582	1.35	1979	78.0%	2.56
YT	11,968	437,766	1.48	1984	53.5%	2.07
NT	6,712	444,815	1.39	1987	20.4%	1.41
NU	3,516	356,566	1.55	1982	9.8%	1.20
Canada	9,839,175	426,641	1.47	1976	91.3%	2.83

The overall Canadian exposure dataset contained information on 9,839,175 dwellings across Canada's 10 provinces and 3 territories (Table 2). The first column shows the Canada Post alpha code for each province and territory and the second column shows the number of dwellings in each. The third column displays the average reconstruction cost ($CAD 2021) per dwelling. The remaining columns show the average number of floors per dwelling (excluding homes with 3 or 4 floors), the average year built, the percentage of homes with a basement, and the average first-floor elevation (in feet).

3.4.2 Quebec exposure dataset (for validation purposes)

Some of the methods described above might have introduced some noise in the data because of the aggregated information. As such, we built a validation dataset using a geolocated assessment roll of Quebec's built environment. The assessment roll provided the latitude and longitude for each assessment unit in Quebec, along with details such as the number of floors, year of construction, and building usage. We filtered the roll to keep only residential units with one to four dwellings. The roll contained only rough property value information based on estimated reconstruction costs, so we compared the average building value for each DB (or DA) and computed an approximate individual reconstruction cost. This alternative exposure database comprised 1,945,843 properties (2,373,348 dwellings) with an average reconstruction cost of $349,679. Since the assessment roll lacked information about basements and first floor elevations, these data were added to the validation dataset using the same methods described above. Table 3 summarizes the key features of each exposure dataset.

Table 3. Comparison of exposure datasets

Feature	Canadian exposure dataset	Quebec exposure dataset
Geographical coverage	All of the 10 provinces (and 3 territories if desired)	Quebec only
Number of dwellings	Statistics Canada 2021 Census (2,232,916 dwellings for Quebec only)	MAMH Assessment Roll (2,373,348 dwellings)
Latitude/longitude coordinates	DMTI Spatial CanMap Address Points	MAMH Assessment Roll
Building and contents value	Average reconstruction costs per DB or DA, from Opta Aggregate Exposure	Individually assigned using average reconstruction costs from Opta but adjusted based upon MAMH Assessment Role
Construction type	Same (Woods)	
Number of storeys	Opta	Individual data from MAMH Assessment Roll
Year built	Average year built per DB or DA, from Opta Aggregate Exposure	Individual data from MAMH Assessment Roll
Basement indicator	Random assignment using Opta Aggregate Exposure	
First-floor elevation	Same approach, 3 ft if basement was assigned, 1 ft otherwise	

3.5 Flood Model

Once the residential property exposure database was completed, we sought to combine it with a flood hazard model by seeking one used widely by governments and industry. We acquired an academic license to KatRisk's flood model for Canada, which includes pluvial, fluvial and coastal (storm surge from tropical cyclones) flooding estimates below the 60th parallel at 30 m resolution, hence covering the 10 Canadian provinces with the exception of the northernmost part of Quebec. The firm describes the model as follows:

> Using numerical methods and physical equations that describe pluvial and fluvial flooding respectively, KatRisk uses precipitation data and the previously parameterized hydrologic and hydraulic models to compute return period-level flood maps. Return period flood maps show, for any location on a map, the severity of a flood associated with an annual occurrence. […] For fluvial flooding, maps are computed using information from hydrologic models including those that describe groundwater, snowmelt/snow-retention, soil/plant uptake, evaporation, how streamflow is routed downstream, and specifically how extreme streamflow is translated into an inundation footprint. For pluvial flooding, maps are computed with hydraulic equations evaluated using finite volume numerical methods. […] A modified version of the SLOSH model from NOAA is used to model storm surge footprints. A tidal wave model is then added to enhance storm surges that occur during high tides. (KatRisk, 2022, pages 5-6).

The hazard model has been validated with regulatory flood maps (Public Safety Canada, 2022) and it includes basic flood defenses data. Vulnerability of individual properties (damage modeling) is based on data from the U.S. Army Corps of Engineers and the U.S. Federal Insurance Administration. The loss modelling therefore accounts for the frequency of flooding, flood depth, and associated damage.

Outputs from KatRisk's flood model are available in two different formats. We received a table containing the Average Annual Loss (AAL) per property for both the main (Canada-wide) and validation (Quebec only) exposure datasets. The AAL is the amount of losses that are expected to occur on average on an annual basis or the expected loss before the application of any deductible or coverage limit.

In addition to this table, we obtained and analyzed an event set of 50,000 years of simulated events consistent with the hazard, vulnerability, and primary exposure dataset. Each entry of the event set provided the simulated year (one of 50,000), month and day, an event identifier along with the losses suffered for each property, aggregated at the DB level[1]. At the time when the study started, KatRisk was the only vendor in Canada that provided such event sets, which are important for risk analyses on aggregate losses that stem from floods in different locations in any given year. Incorporation of aspects of spatial dependence within and between watersheds is important for various insurance applications on portfolios, such as determining the cost of reinsurance, reserving and capitalization, pricing risk-sharing schemes, and so on. The data enabled us to analyze systemic risk from flooding in Canada, as described in the next section.

4.0 Residential Flood Risk in Canada

This section analyzes residential flood risk in Canada based on the flood model outputs provided by KatRisk and the property exposure dataset built in Section 3. Table 4 shows key descriptive statistics on the distribution of aggregate losses per province (in millions of 2021 dollars) and for the country including the average, standard deviation and several percentiles on total simulated losses broken down by province.

Table 4. Descriptive statistics on the distribution of aggregate losses per province in Canada (in millions of 2021 dollars)

Province	Average	Std dev.	Median	90%	95%	97.5%	99%	99.9%	Max.
NL	10	63	0	13	34	77	170	1,103	2,589
PE	2	16	0	2	8	21	53	229	889
NS	19	92	0	33	82	163	345	1,316	4,400
NB	34	120	1	76	161	299	571	1,434	3,526
QC	389	1,400	32	852	1,855	3,336	6,168	17,993	43,711
ON	408	1,620	23	857	1,819	3,484	6,843	21,818	60,345
MB	94	538	0	89	294	895	2,203	7,561	15,791
SK	43	162	3	92	213	352	660	2,162	5,042
AB	152	689	9	263	594	1,247	2,937	9,623	21,898
BC	268	783	38	643	1,260	2,185	3,536	9,675	25,015
Canada	1,419	2,883	522	3,460	5,708	8,658	13,227	33,826	79,872

[1] Losses were aggregated at the DB level for technical reasons due to the size of the portfolio. Such aggregation has no impact on results presented at the provincial or territorial level.

4.1 Average Annual Loss

About $1.4B in flood-related losses should be expected on average every year in Canada (Table 4). Ontario, Quebec, and British Columbia lead the country with the largest averages, which are proportional to their populations. It is difficult, however, to compare this $1.4B figure with other sources of data. The most comparable analysis to date was conducted by Public Safety Canada (PSC), which found an AAL of $2.9B (Public Safety Canada 2022). The discrepancy can be explained by the use of different data including vendor models[2] and a set of damage curves from the UK firm Fathom. The PSC analysis also included damage to contents for apartments in multi-dwelling units adding about 5 million additional dwellings to the study, which we excluded. At least one of the two additional vendors covers the three territories and models coastal flooding for Atlantic Canada.

We used the KatRisk flood model to analyze the Quebec exposure dataset for validation purposes. Since the hazard and vulnerability components were fixed, this exercise highlighted how different exposure assumptions affect loss estimates. AAL in Quebec using the Canada-wide dataset totaled $389M, as compared to the $320M with the Quebec exposure dataset. As such, we concluded that the Canadian exposure dataset seems to overestimate flood risk on average by about 20%. Although significant, the percentage is very small when compared to the uncertainty inherent in the overall analysis, which encompasses exposure, hazard, and vulnerability.

4.2 Extreme Losses and Systemic Risk

Flooding is a low-frequency, high-severity hazard: it occurs infrequently but its impacts are costly. This dynamic is clearly evident in the percentiles of the loss distribution in Table 4. For example, the median total loss is $522M, meaning there is a 50% chance that losses will be higher or lower in any given year. Similarly, the 90th percentile total loss is $3.5B (2.5 times the average), meaning there is a 90% chance that losses will be lower in any given year. The 99-th percentile is $13B (9 times the average) and the 99.9-th percentile is $34B (24 times the average). In statistical terms, this aggregate loss distribution is positively skewed with heavy tails.

The percentiles can also be converted to return periods (recurrence interval), meaning an estimated average time between events of the same magnitude. For example, the 99th percentile implies there is a 1% annual chance that losses will exceed $13B, equivalent to a flood of a 100-year magnitude. Return periods are misleading for communication purposes, however, because many factors affecting flood risk, such as urbanization and climate change, are dynamic over time.

In addition, Table 4 illustrates the outcome of pooling risks between provinces and across the country at a national level. We computed the ratio percentile over the average for each province and for Canada as a whole—a unitless metric to show a normalized measure of extreme losses. Across provinces, the 99th normalized percentile was between 13 and 23, whereas the Canada-wide normalized 99th percentile was 9. For the 99.9th percentile, the normalized percentile for provinces was between 35 and 110 (average 65), whereas the Canada-wide metric was 23.

[2] JBA Risk Management, Aon/ImpactForecasting and KatRisk

4.3 Concentration of Risk

Table 5 shows the descriptive statistics of Table 4 but normalized by the number of dwellings included in the study (provided in Table 2). Flood risk is concentrated in certain provinces, namely Quebec, British Columbia, and to a lesser extent, Manitoba. Given the different number of dwellings between the exposure datasets, the Quebec validation data yields an AAL per dwelling of $135 compared to $174 in Table 5, a difference of almost 30%. In this case, being able to assign an approximate reconstruction cost to each building rather than assigning the average to each building of a DB or DA in effect reduces the AAL for the province of Quebec. We believe this is because the most hazardous properties within each DB and DA tend to have lower values than the averages. The validation exercise with Quebec data highlights the value of having more precise exposure data for large-scale flood risk analyses.

Table 5. Descriptive statistics normalized by the number of dwellings

Province	Average	Median	90%	95%	97.50%	99%	99.90%	Maximum
NL	68	434	2	91	230	526	1,171	7,576
PE	46	318	0	39	157	414	1,041	4,480
NS	59	291	1	103	258	512	1,086	4,142
NB	128	455	5	289	610	1,134	2,166	5,442
QC	174	627	14	381	831	1,494	2,762	8,058
ON	108	428	6	227	481	922	1,810	5,771
MB	273	1,563	1	260	854	2,602	6,406	21,989
SK	133	504	9	287	660	1,094	2,048	6,708
AB	125	568	7	217	490	1,028	2,420	7,931
BC	234	683	33	561	1,099	1,906	3,085	8,440
Canada	144	293	53	352	580	880	1,344	3,438

Table 6 provides further evidence of the concentration of flood risk in Canada. The leftmost column shows the distribution of AAL across properties from the lowest to highest, whereas the right-hand side provides the distribution of AAL across properties from the highest to the lowest. Notably, the 50% least risky homeowners (4.9M homeowners) account for $74M of AAL, which amounts to 5% of the Canada-wide AAL. On the other hand, the 50% most risky homeowners (another 4.9M homeowners) accounts for 95% of the Canada-wide AAL.

Table 6. Cumulative distribution of AAL across properties, ranked from least to most risk and vice-versa

	Least risk		Most risk	
% of h/o	AAL ($K)	% of $	AAL ($K)	% of $
0.25%	78	0.01%	193,819	13.71%
0.50%	153	0.01%	337,801	23.90%
0.75%	231	0.02%	455,686	32.24%
1.00%	313	0.02%	554,504	39.23%
2.00%	644	0.05%	806,782	57.08%
5.00%	1,801	0.13%	1,024,759	72.50%
10.00%	4,083	0.29%	1,107,722	78.37%
20.00%	9,019	0.64%	1,196,316	84.64%
30.00%	25,026	1.77%	1,251,738	88.56%
40.00%	40,775	2.88%	1,305,320	92.35%
50.00%	73,973	5.23%	1,339,423	94.77%
60.00%	108,076	7.65%	1,372,620	97.12%
70.00%	161,657	11.44%	1,388,369	98.23%
80.00%	217,079	15.36%	1,404,376	99.36%
90.00%	305,673	21.63%	1,409,312	99.71%
95.00%	388,636	27.50%	1,411,594	99.87%
98.00%	606,613	42.92%	1,412,751	99.95%
99.00%	858,891	60.77%	1,413,083	99.98%
99.25%	957,709	67.76%	1,413,164	99.98%
99.50%	1,075,594	76.10%	1,413,243	99.99%
99.75%	1,219,577	86.29%	1,413,318	99.99%
100.00%	1,413,395	100.00%	1,413,395	100.00%

Similarly, the 10% riskiest homeowners account for as much as 78% of flood losses ($1.1B), which is equivalent to $1,130 on average per homeowner. This is much worse in the top 1%, where about 98,000 dwellings account for 39% of the Canada-wide flood losses ($555M), with an average AAL per homeowner of $5,700.

4.4 High risk vs. High Hazard

Flood risk is highly concentrated around the top percentiles of homeowners, so it is instructive to analyze how much of this concentration is determined by high economic exposure stemming from the value of the home and its contents. Table 7 illustrates how much of the overall risk is due to hazard versus exposure. The second column ranks the individual AAL for the top 20% of homeowners. For example, for 10% of homeowners, the individual AAL is above $124 and above $3,509 for 1% of homeowners, thus confirming the finding that risk-based flood insurance would be very expensive for a significant proportion of Canadians. In the third column, we express the AAL per $100,000 of total insurable value (TIV) (building and contents), which is a metric much closer to the hazard and vulnerability. We find that for 10% of homeowners, the AAL is above $22 per $100,000 of TIV, and for 1% of homeowners, this is above $675 per $100,000 of TIV.

Table 7. AAL and distribution of the TIV in the upper 20% of homeowners

			Average TIV	
Percentile	Average annual losses	AAL/TIV (x100K)	Ranked by AAL	Ranked by AAL/TIV
80%	71	12	651,786	565,731
85%	89	16	679,781	534,597
90%	124	22	697,784	544,953
91%	136	24	707,613	540,565
92%	153	28	722,518	509,394
93%	177	30	728,790	539,226
94%	215	38	724,435	543,674
95%	288	51	679,449	550,939
96%	446	82	598,729	567,925
97%	808	151	576,791	557,401
98%	1,617	304	563,521	553,510
99%	3,509	675	545,329	545,021
99.1%	3,779	733	553,086	539,695
99.2%	4,086	794	567,200	527,200
99.3%	4,436	864	561,500	533,665
99.4%	4,829	937	568,024	517,491
99.5%	5,285	1,027	575,717	514,919
99.6%	5,837	1,126	581,823	512,761
99.7%	6,514	1,253	599,963	497,904
99.8%	7,432	1,434	647,614	485,974
99.9%	8,968	1,673	828,311	472,676

The last two columns of Table 7 provide the average TIV for certain groups of homeowners. For example, for homeowners whose AAL is between $89 and $124 (between the 85-th and 90-th percentiles), the average TIV is nearly $680,000. But for homeowners in the upper 0.1%—when the AAL is above $8,968—the average TIV is $828,000. Given that the Canadian average TIV is $597,297[3] a substantial portion of homeowners in the top 20% riskiest dwellings have a TIV well above the Canadian average.

The last column orders properties according to the ratio of the AAL over the TIV, thereby ranking properties based upon their relative risk. This is an approach closer to the flood hazard and vulnerability, much less biased by the value of the building and content. In this case, the analysis is much clearer: the homes that are the most vulnerable to flooding have a TIV below the Canadian average. As the relative risk increases, the average TIV goes down.

Figure 2 illustrates the behavior of the average TIV when properties are ranked according to their AAL or their relative AAL (AAL over TIV). The horizontal red line represents the Canadian average. It is clear that when homes are ranked based on their relative risk, the TIV is well below the Canadian average, meaning that Canadian homes located in the floodplains typically have lower value. There are also important phenomena within the 99th percentile: the

[3] Mean reconstruction costs of $426,641 from Table 2 times 1.4 because the cost of contents was assumed 40% of the building's reconstruction costs

wealthiest homes are spuriously driving the largest individual AALs whereas the most vulnerable homes to flooding have much lower TIVs. Consequently, there should be very careful consideration to define what is a "high-risk" property for policy purposes. The previous findings showed that the riskiest properties typically have a TIV above the average, whereas the most vulnerable properties (using relative AAL) have lower than average TIV, and even lower within the 99-th percentile.

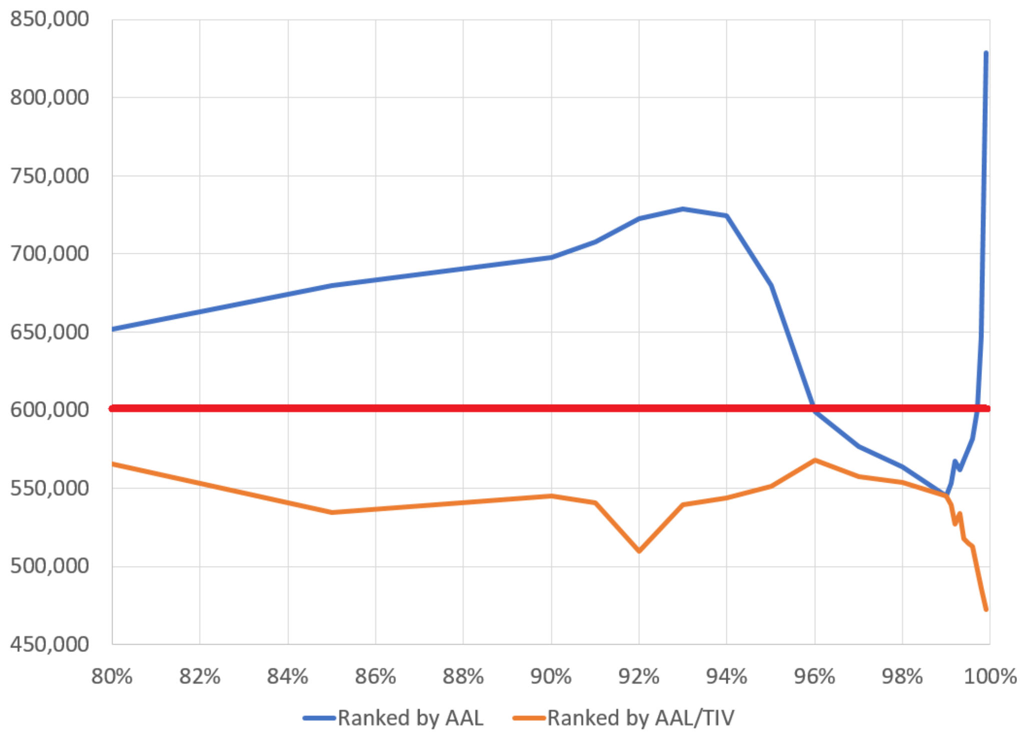

Figure 2. Average TIV according to various rankings of properties

This novel approach to assessing flood risk to residential property provides a replicable method that can be implemented in further national or more local studies using flood hazard, exposure and vulnerability data. Importantly, data on AAL, extreme losses and systemic risk, concentration of risk, and high risk relative to high hazard exposure reveal significant implications for Canada's approach to flood risk management. The following section will discuss these outcomes with a focus on replicating risk assessment and the financial management of flood through a recently proposed national insurance program.

5.0 Discussion

Canada's commitment to a risk-based approach to disaster management requires both the need for risk assessment across the country to prioritize areas that require resources, and policy design that appropriately delegates this risk between stakeholders and instruments they are responsible for implementing to enhance resilience (Thistlethwaite and Henstra 2019). In terms of flood risk assessment, this study identifies some significant gaps in existing data justifying the creation of novel data sets and validation studies.

5.1 Flood data gaps

As noted in Section 4.1, there is uncertainty over the total annual average losses with this study concluding a $1.4B total but Public Safety Canada's analysis finding a total of $2.9B. These differences in inputs highlight how values can differ justifying a model comparison between the vendors currently in use in Canada. For example, one possible validation method would be to compare estimates with historical observed losses from provincial and federal disaster financial assistance programs including residential dwellings, but also losses to infrastructure and public buildings. Aggregating this data represents a challenge at the national level but several provinces are developing data for risk models and maps that could be used for individual validation studies (e.g. IBI Group 2015; Darlington et al. 2024).

Validation of private vendor data with existing government outputs represents an important first step to improve risk assessment in the short term. Ultimately, a public national data set is necessary to meet future demand given the costs associated with identifying and aggregating data that is fragmented between private vendors, and governments. Validation of private vendor models using existing disaster assistance would also require cooperation from private insurers who cover losses associated with pluvial flood damage that is excluded from government recovery funding.

This study, like the PSC effort, required the acquisition of proprietary data only accessible to those with resources able to acquire expensive licenses such as insurers and governments. The federal government is working on addressing some gaps including the creation of depth-damage curves that incorporate local data on damage instead of relying on US or UK sources and a portal to publicly disseminate risk data. These efforts are long overdue given research suggesting that Canadians lack basic levels of spatial awareness of flood risk. This awareness gap limits the accountability needed to pressure governments into spending resources for risk reduction in the areas that need it most, or insurers into incorporating local investments in flood defences into premium reductions (Thistlethwaite and Henstra 2024).

5.2 Flood risk management

In addition to these findings on data gaps and validation, the study also revealed several important insights into Canada's approach to flood management. First, analysis on AAL, extreme losses, systemic risk, concentration of risk, and the contribution of exposure or hazard to risk represent the most comprehensive evidence to date supporting the adoption of flood risk management in Canada.

Analyses using AAL found that properties located into the highest 10% of risk account for 78% of flood losses, and the top 1% account for 39% of all losses. As a result, at a national level a relatively small exposure (e.g. 98,000 dwellings) account for disproportionate amount of risk. This concentration of risk justifies several ongoing reforms to Canadian flood risk management and offers some specific insight into policy design.

First, Canadian governments can use the findings of this study to justify a risk-based approach to funding disaster mitigation. The current approach exemplified by programs such as the Disaster Mitigation and Adaptation Fund (DMAF) award funding based on applications from lower tier governments that can favour cities or provinces with more resources able to meet the criteria rather than areas in high-risk zones. Increasing the federal contribution in the program for applications from high-risk communities from the current level of 40% to those adopted by the US federal government (i.e. 75%) is one way to address this discrepancy. Second, the concentration of risk clearly justifies restricting any future development in areas with high exposure to flooding. Provinces are responsible for land-use legislation in Canada, and several including Ontario, BC and Quebec can use the method in this study to prioritize where development restrictions should be enforced. The federal government could lead by example and use this data to ensure future spending on disaster assistance or infrastructure does not lead to re-building or new construction in high-risk areas.

5.3 Flood Insurance

Even with a broader embrace of risk assessment in flood mitigation and recovery, residual losses are inevitable given the severity of the exposure especially in high-risk locations. Volatility associated with the “fat tail” in these losses (see the percentiles provided in Table 4) could create instability in government budgets and the primary insurance market. Similar to governments in France, the United States and United Kingdom, the Canadian federal government is poised to intervene to address this volatility through the creation of a national Flood Insurance Program (FIP). The program’s objectives include reducing the burden of extreme losses on taxpayer funded disaster assistance[4], improving the availability of insurance coverage, and incentivizing community-level mitigation through market pricing (Public Safety Canada 2022).

The study also found clear evidence that pooling extreme losses is more efficient when done across the country because extremes have a much lower relative impact country-wide than in any given province. Although more efficiently diversified nationally, there remains a significant systemic risk that highlights the requirement for a FIP to count on a government backstop to limit the effect of extremes. Otherwise, the 99.9th percentile of aggregate losses, found to be $34B in Table 1, would be beyond the industry’s capacity to remain solvent (Kelly, 2021).

In terms of flood insurance design, the study offers novel insights on how to balance the objectives of expanding coverage that is affordable, while limiting government investment needed to subsidize premiums and provide a backstop in event of an extreme loss. AAL is a proxy for the pure premium under full coverage (no deductible, nor limit) without insurer administrative costs. The study confirms subsidization is necessary for market penetration in high-risk areas. AAL among the top 10% in terms of risk reveals an average of $1,130, with the top 1% at $5,700 annually. Studies consistently find that premiums at this level are a lot higher than what Canadian property owners are willing to pay for flood insurance (Thistlethwaite et al. 2018).

Subsidizing flood insurance in high-risk areas is not sustainable given the moral hazard it creates, and the potential for political opposition among taxpayers concerned the costs could increase in response to higher demand for insurance. Given the spatial concentration of exposure, risk-based pricing should be maximized as much as possible to ensure those benefiting from expanded coverage are paying for it. In addition, analysis on how risk is concentrated in Canada suggests that subsidies are not necessary for everyone in high-risk areas and should be subject to a form of affordability threshold via means (i.e. income) testing.

[4] Flood insurance is not currently available in high-risk flood areas through the private market meaning damage qualifies for government assistance. This damage will no longer qualify for government assistance once the FIP is introduced.

Among the 99th percentile, homes valued well above the Canadian average disproportionately contribute to AAL (see Figure 2). Some of these properties should not qualify for a subsidy as they can afford to self-insure or pay the full premium.

Finally, to limit the use of a government backstop in the event of a large loss year and reduce costs generally, the FIP should strongly consider excluding coverage for the top 1% of high-risk properties. Homeowners in this category of risk generate 39% of overall losses (see Table 6) increasing the likelihood for FIP funding to be wasted on rebuilding in areas exposed to repetitive loss. Limiting eligibility for these homes could generate savings used to fund a strategic relocation program similar to the Province of Quebec where property owners can choose to rebuild with a one-time offer of government assistance and self-insure or take a property buyout.

6.0 Conclusions

The acceleration of flood risk because of climate change and unsustainable development in high-risk areas requires an extensive examination into the economic exposure of residential properties to floods. This paper presented a methodology for determining the spatial distribution and concentration of residential risk to flooding in Canada. Several data sets were combined and analyzed to determine the total number of dwellings, their location and characteristics, and model the flood exposure of residential properties in Canada.

The findings reveal annual losses of approximately $1.4B on average, with most of the exposure generated by Ontario, Quebec and BC due to their large populations. These losses are disproportionally concentrated in the highest risk areas with those in the top 10% contributing to 78% of losses and those in the top 1% contributing to 39%. Consistent with most large impact and low-probability events, the 90th percentile loss is 2.5 times ($3.5B) the average and the 99.9th percentile loss is 24 times the average ($34B). Finally, analysis of the TIV revealed that large AAL is often driven by high property values with evidence that the most vulnerable homes have TIV below the Canadian average.

The paper contributes to existing literature in several ways. First, the paper's novel methodology for conducting an exposure analysis represents one of the first attempts at a national scale analysis of flood risk that combines its three central inputs including the hazard, exposure and vulnerability. Second, the analysis confirms the need for future studies including other private vendor models and government data. Specifically, validation studies comparing exposure at a national level with higher resolution local maps and models, and data generation on local damage curves represent logical next steps.

For the first time, Canada's shift towards a risk-based approach to flood management has compelling evidence. Implementing this shift requires incorporating findings from this risk assessment. In high-risk areas, the federal government should raise its contribution to mitigation funding to offset the burden on local authorities, identify and encourage limits on new development, fund strategic relocation, and restrict disaster assistance that leads to re-building. To ensure flood insurance is affordable and encourages mitigation, premiums should be risk-based so those who benefit pay, and subsidies should be limited to those who can demonstrate they cannot afford to pay through means testing. Finally, the insurance program should consider excluding coverage for the top 1% given the potential for volatility that could lead to a backlash among taxpayers supporting the subsidization.

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The authors declare they have no conflict of interest.

Data availability statement

Data from Statistics Canada and Quebec's MAMH are freely and openly available. Data from DMTI Spatial are used under a research licence available to a network of Canadian universities. Data from Opta Information Intelligence and KatRisk were acquired under an academic licence for scientific research purposes. The data can be acquired from the respective vendors.

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