Fathom climate-adjusted flood risk modelling for the Canadian Climate Institute: Methodology

Date: 24 May 2024

Document Version: 1.0

Data Version: 1.0

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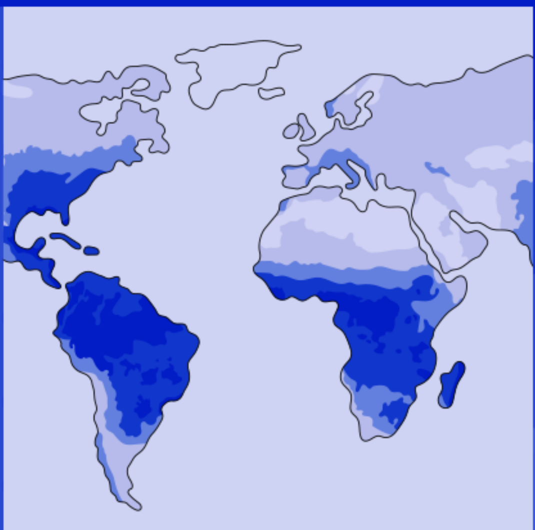

Document History

Version	Published	Summary of changes
1.0	24 May 2024	Initial version

Data History

Version	Released	Summary of changes
1.0	24 May 2024	Initial version

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Contents

1.0 Introduction

This document describes the methods by which Fathom's Global Flood Map (version 3.1) was used alongside Public Safety Canada's residential building dataset and Fathom's flood vulnerability functions to compute Canada's residential Average Annual Loss (AAL) incurred by fluvial, pluvial, and coastal flooding in 2020, 2030, and 2050.

The methods underpinning the Global Flood Map are described in a separate, confidential document. The reader can refer to Wing et. al 2024 for more details on the Global Flood Map Methodology.[1] The following sections outline the key methods and assumptions related to the vulnerability functions (section 2) and loss modelling (section 3), with key results presented in section 4.

[1] Wing, O., et. al (2024), A 30m Global Flood Inundation Model for Any Climate Scenario. Water Resources Research. https://doi.org/10.1029/2023WR036460

2.0 Vulnerability functions

Vulnerability functions are the mode by which flood hazard intensities are translated to their economic impact. Generally, this involves relating simulated flood depths to damage, expressed as a proportion of replacement value, for a variety of building classifications. Some sets of vulnerability functions, for instance in the UK[2] and Canada,[3] relate depth to absolute values of damage (i.e., in currency units, rather than a proportion). The choice between relative or absolute vulnerability functions is a subjective one, as no evidence has suggested one approach is more accurate than another. While some aspects of flood vulnerability are fixed (e.g., for certain building materials and labour), generally property-level flood damages are proportional to total value to some extent.[4] It is common practice to represent flood vulnerability as a simple deterministic relationship between depth and damage (i.e., a given depth always returns a certain damage), yet a wealth of literature notes the substantial and underappreciated uncertainty is these functions.[5] Commonly applied vulnerability functions are often derived from a small number of data points collected during relatively few events in confined geographic areas, rendering their generalised applicability at larger spatial and temporal scales questionable.

Here, we utilise the only known source of "big data"-derived vulnerability functions published in Wing et al.[3] With the use of over 2,000,000 flood insurance claims filed under the US Federal Emergency Management Agency (FEMA) National Flood Insurance Program (NFIP), the empirical relationship between depth and damage for a wide variety of residential buildings across different spatial and temporal settings can be captured. This enables the uncertain damage response to a given depth to be modelled explicitly, with the resulting risk output being generated with a full appraisal of its potential error.

20 vulnerability functions were developed: proportional damage to both structure and contents for 10 types of residential building.

1. 1-storey single-family residence with no basement
2. 1-storey single-family residence with a basement

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[2] Penning-Rowsell, E., et al. (2013), Flood and Coastal Erosion Risk Management: A Manual for Economic Appraisal. Routledge: UK.

[3] Natural Resources Canada (2020), Federal Flood Damage Estimation Guidelines for Buildings and Infrastructure. https://doi.org/10.4095/327001

[4] Wing, O., et al. (2020), New insights into US flood vulnerability revealed from flood insurance big data. Nature communications. https://doi.org/10.1038/s41467-020-15264-2

[5] Freni, G., et al. (2010), Uncertain in urban flood damage assessment due to urban drainage modelling and depth-damage curve estimation. Water Science & Technology. https://doi.org/10.2166/wst.2010.177

3. 2-storey single-family residence with no basement
4. 2-storey single-family residence with a basement
5. ≥3-storey single-family residence with no basement
6. ≥3-storey single-family residence with a basement
7. Split-level single-family residence with no basement
8. Split-level single-family residence with a basement
9. <3-storey multi-family condominium
10. ≥3-storey multi-family condominium

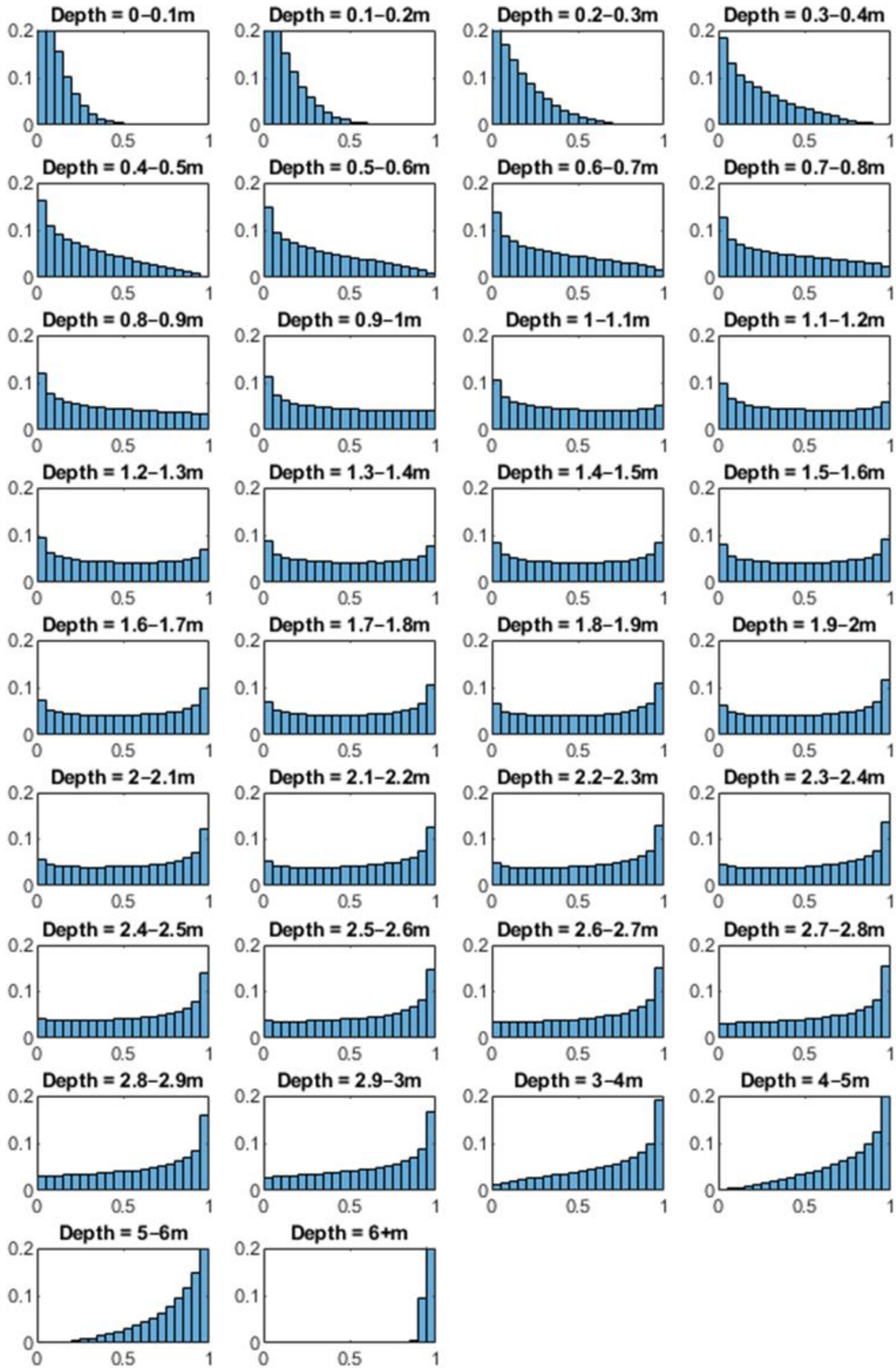
The methodology to construct functions for these building types broadly follows that set out in Wing et al., who noted the distinct bimodal beta distribution in damage-per-depth. Most damages are concentrated towards 0% and 100% damage, indicating flooded buildings tend to experience either minor or catastrophic damage. As flood depth increases, the beta distribution shifts towards a greater proportion of buildings experiencing 100% damage.
To model flood vulnerability using these beta distributions, flood depths must be discretised into bins within which the probabilistic damage response is assumed homogeneous. 34 depth bins were used; the lack of within-bin differentiation is generally reflective of the wider uncertainties of the risk modelling cascade. Note that these depths refer to the height of the water above the elevation of the first occupied floor. The bin edges are as follows (metres): [0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9, 2.0, 2.1, 2.2, 2.3, 2.4, 2.5, 2.6, 2.7, 2.8, 2.9, 3.0, 4.0, 5.0, 6.0, ∞]

To store the resultant distributions of damage in a manageable way, proportional damages are also discretised into 20 bins of even 5% spacings between 0% and 100%. Every depth bin expresses vulnerability via the probability its resultant damage falls within each damage bin (the total of which sum to 1). As such, the 20 functions contain 20 damage probabilities for 34 depths (20 * 20 * 34 = 13,600).

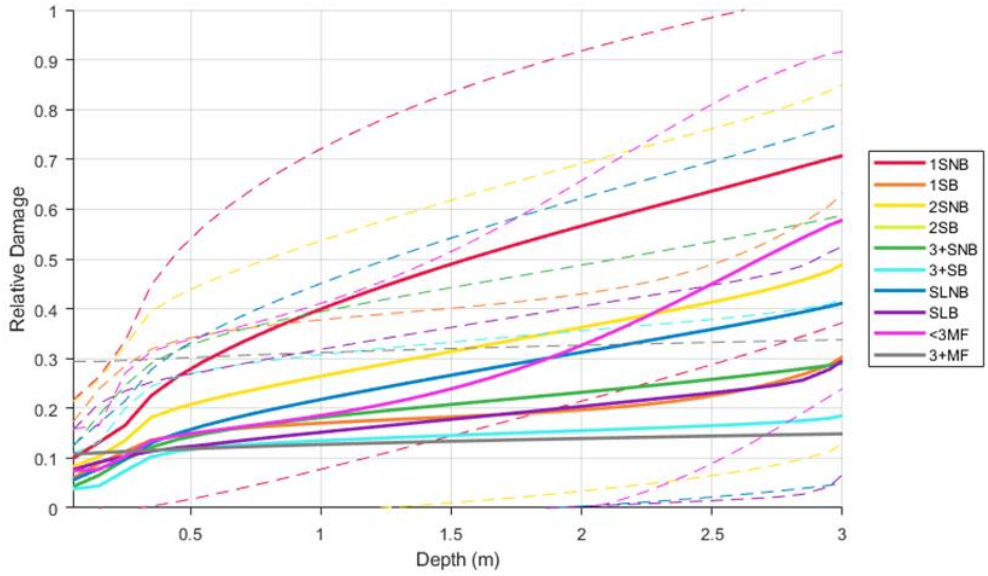
The functions are generated by fitting beta distributions to the proportional damage response at each depth increment in the NFIP claims database, for every building type. Where the number of data points for a given building-depth combination is less than 1000 (e.g., there are only 258 data points where a ≥3-storey multi-family condominium was inundated by 0.3 m of floodwater), these are supplemented with relative damages from analogous depth-damage functions from the US Army Corps of Engineers.[6] As per Wing et al., these functions fail to capture the variability of flood losses, but did have some skill in replicating observed central tendencies from the NFIP data – and so are useful in guiding the probabilistic functions developed here when empirical data are scarce.

[6] https://github.com/nhrap-hazus/FAST

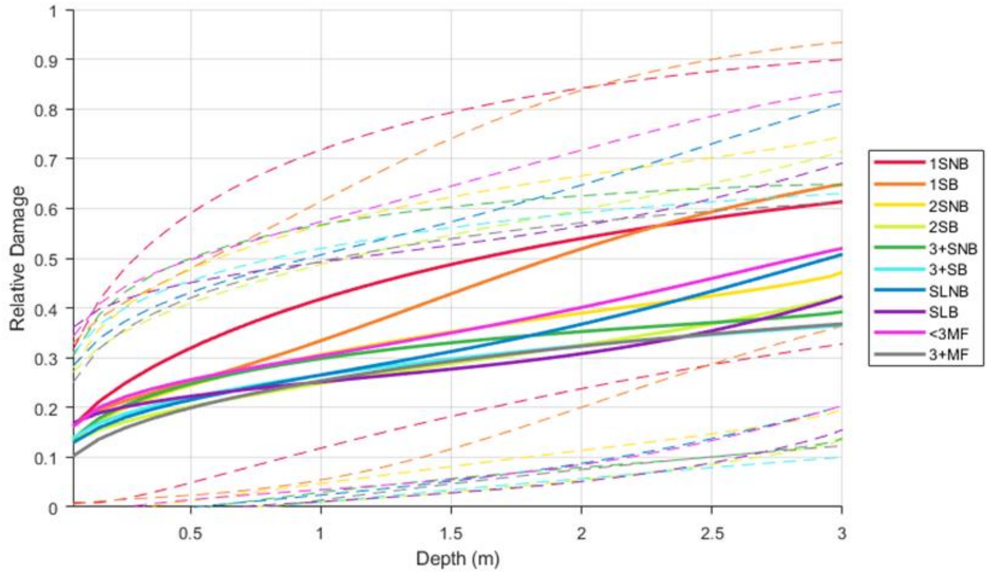
The following figures illustrate the developed probabilistic vulnerability functions. Firstly, the distributions of each depth bin are shown for an example building type. Then, the central tendency and variability of each function is shown for structure and contents damage.



Relative structure damage distributions for a 1-storey single-family residence with no basement, for all 34 depth bins. x axis: relative damage; y axis: probability.



Relative structural damage per depth for all building types. Solid lines: mean damage; dashed lines: 1 σ either side of the mean.



Relative contents damage per depth for all building types. Solid lines: mean damage; dashed lines: 1 σ either side of the mean.

3.0 Loss modelling

3.1 Computing the loss for a given probability

For each building location and return period, a hazard map depth is sampled. If the depth is non-zero, a universal ground floor height assumption of 0.2 m is subtracted from this depth. This is an uncertain parameter in loss estimates but is generally consistent with average ground floor heights for residential buildings reported in the US National Structure Inventory.[7] This 'depth above ground floor' is then placed into one of the 34 depth bins and the average relative damage within that bin is computed. This relative value is multiplied by the replacement cost of either the building structure or its contents to calculate a total damage in CAD.

The maximum sub-peril damage per return period is used per location in order to combine losses from fluvial, pluvial, and coastal flooding. Other possible approaches are:

- To sum the average annual loss for each peril. This would overstate the risk at each grid cell as perils are not independent: some events will include fluvial, pluvial and coastal perils and damage to a property already incurred from one peril should not be incurred again (within the same event) by another peril.
- To take the maximum peril-specific average annual loss. This would understate the risk at each grid cell as for different frequency regimes different perils could dominate and this effect would be missed.

The selected approach means that the combined AAL sits between these two alternative approaches above.

Flood defences

By default, this process was executed for the *defended* variant of the Global Flood Map and these are the results presented in section 4. *Undefended* AALs were also provided.

There are no complete datasets containing the exact locations and standards of flood defenses globally. We estimate defenses using the level of urbanization, based on the Global Human Settlement Layer built-up volume dataset (Pesaresi & Politis, 2023). This is combined with a global dataset of defense standards (FLOPROS; Scussolini et al., 2016) enhanced by local information through a collaboration with our partners, Risklayer (https://www.risklayer.com/), who provided additional national defense databases with a particular focus on dams. FLOPROS is available for all areas of Canada. Locations were divided into four urbanization categories (Urban-high, Urban-low, Suburban, Rural), and local defense standards were assigned by scaling the global defense standards, depending on the urbanization category. Flood defense standards are assumed to be highest in urbanized areas and decrease with the level of urbanization.

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[7] https://www.hec.usace.army.mil/confluence/nsi

Climate scenarios

AALs were computed for three climate scenarios:

- 2020. More specifically: the climate period 2010–2030 (i.e. observed climate from 2010–2020 and the projected climate under SSP2-4.5 from 2021–2030)
- 2030, SSP2-4.5. More specifically: the climate period 2020–2040.
- 2050, SSP2-4.5. More specifically: the climate period 2040–2060.

The median hazard layers were taken for each scenario.

Permanent water

Note that AALs were not computed for any building located within permanent water (either due to inaccurate building geolocation information or errors in the satellite observations of permanent inundation).

3.2 Integrating the probability–loss curve

AALs are computed using the ‘trapezium rule,’ whereby the area under the probability–loss curve is calculated using a series of trapeziums between losses at eight fixed return periods: 1 in [5, 10, 20, 50, 100, 200, 500, 1000]. The key assumptions made during this calculation:

- AALs were calculated within the [5,1000] return period range
- If non-zero damage is incurred at the 5-year return period, it forms a ‘leading trapezium’ (i.e. no interpolation to 0 damage at a higher frequency than 5 years)
- If zero damage is incurred at any simulated return period, it forms a ‘leading triangle’ (i.e. interpolation between the nearest non-zero damage return period and the zero damage return period)

This is mathematically described below, where D_x represents the damage with a 1 in *x* year probability:

$$\left[(\frac{1}{5}-\frac{1}{10})*\frac{(D_5+D_{10})}{2}\right]+\left[(\frac{1}{10}-\frac{1}{20})*\frac{(D_{10}+D_{20})}{2}\right]+\left[(\frac{1}{20}-\frac{1}{50})*\frac{(D_{20}+D_{50})}{2}\right]+\left[(\frac{1}{50}-\frac{1}{100})*\frac{(D_{50}+D_{100})}{2}\right]+$$
$$\left[(\frac{1}{100}-\frac{1}{200})*\frac{(D_{100}+D_{200})}{2}\right]+\left[(\frac{1}{200}-\frac{1}{500})*\frac{(D_{200}+D_{500})}{2}\right]+\left[(\frac{1}{500}-\frac{1}{1000})*\frac{(D_{500}+D_{1000})}{2}\right]$$

These assumptions are consistent with those published in Wing et al.[8]

3.3 Matching exposure data to vulnerability functions

The information contained within Public Safety Canada’s residential building database was used to find a corresponding vulnerability function from the library of 10 possibilities outlined in section 2. The table below describes this matching process for single-family residences:

[8] Wing, O., et al. (2022), Inequitable patterns of US flood risk in the Anthropocene. Nature climate change. https://doi.org/10.1038/s41558-021-01265-6

Vulnerability type	Public Safety Residential Exposure Variable
1-storey single-family residence with no basement	Apartment_2023 is not 1 Basement is 0 NUMBEROFSTOREYS is 1
1-storey single-family residence with a basement	Apartment_2023 is not 1 Basement is 1 NUMBEROFSTOREYS is 1
2-storey single-family residence with no basement	Apartment_2023 is not 1 Basement is 0 NUMBEROFSTOREYS is 2
2-storey single-family residence with a basement	Apartment_2023 is not 1 Basement is 1 NUMBEROFSTOREYS is 2
≥3-storey single-family residence with no basement	Apartment_2023 is not 1 Basement is 0 NUMBEROFSTOREYS is 3 or 4
≥3-storey single-family residence with a basement	Apartment_2023 is not 1 Basement is 1 NUMBEROFSTOREYS is 3 or 4

Note that split-level residences were not found within Public Safety Canada's database. Contents replacement cost was calculated as 40% of buildings replacement cost (represented by the `Replacement Cost` variable).

For multi-family residences, a more convoluted approach was required:

1. All multi-family units (`Apartment_2023` is 1) which lie on an identical latitude/longitude point were assumed to be part of the same building
2. The number of units within each building was computed
3. The contents replacement cost of each building was calculated as 50,000 CAD per unit
4. The number of units informed assignment the multi-family vulnerability types:
   a. ≤12 units is assigned '<3-storey multi-family condominium'
   b. >12 units is assigned '≥3-storey multi-family condominium'

Building damage was not computed for multi-family residences; only contents damage was considered.

4.0 AAL due to flooding in Canada

Defended Results

Geography	AAL (million CAD)		
	2020	2030	2050
Canada	1423	1503	1681
Alberta	146	152	162
British Columbia	314	332	391
Manitoba	48	48	49
Newfoundland and Labrador	35	38	46
New Brunswick	67	74	89
Northwest Territories	0.4	0.4	0.5
Nova Scotia	44	49	58
Nunavut	0.9	1.0	1.2
Ontario	293	308	338
Prince Edward Island	5	6	8
Quebec	453	477	520
Saskatchewan	11	12	12
Yukon	6	7	8

Undefended Results

Geography	AAL (million CAD)		
	2020	2030	2050
Canada	4808	4882	5050
Alberta	275	277	283
British Columbia	2294	2312	2375
Manitoba	332	333	334
Newfoundland and Labrador	38	41	49
New Brunswick	109	115	129
Northwest Territories	0.5	0.5	0.6
Nova Scotia	54	58	68
Nunavut	0.9	1.0	1.2
Ontario	659	670	692
Prince Edward Island	5	6	8
Quebec	1014	1040	1083
Saskatchewan	20	20	21
Yukon	6	7	8