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Bernard Deschamps, Philippe Gachon, Michel Leclerc, and Mathieu Boudreault

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Conflict of Interest Declaration

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Flooding: Toward a Municipal Contribution to Economic Risk Sharing

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Abstract

In Québec, flood damage costs have risen sharply over the past 40 years, partly due to population and property growth in flood-prone areas. This phenomenon is exacerbated by extreme weather events, such as torrential rains, some of which are on the rise in southern Québec in spring. Today, these costs are primarily covered by provincial and federal financial assistance programs and, to a lesser extent, by private insurance. These cost-sharing mechanisms give rise to moral hazard because they do not encourage municipalities or disaster victims to reduce risk. Municipalities need to be included in cost sharing because of their crucial role in land use planning and risk management. Similarly, disaster victims need to be included because they also have a role to play in reducing risk.

This paper proposes and analyzes an economic contribution mechanism for municipalities that distributes the cost of damage to residential buildings more equitably. (Equity refers to a fair and just distribution of the financial burden based on the relative level of exposure to risk and the ability to reduce the risk for all parties involved.) The contribution is calculated for three medium-sized municipalities in Québec based on the sum of the average annual damage to each of the residential buildings located in their jurisdictions, and on property values.

Three observations are drawn from this analysis: 1) a municipality's level of exposure is not correlated with its property value; 2) the low damage rate of a majority of buildings located in flood-prone areas justifies maintaining these buildings in these zones, provided that mitigation measures are implemented; and 3) relocating a minimum number of buildings would considerably reduce the municipality's economic contribution to damage costs. Implementing an economic contribution mechanism for municipalities and exposed citizens is intended to reduce the moral hazard and inequity generated by the current approach and encourage municipalities to implement mitigation and risk reduction measures. All stakeholders could equitably finance these measures.

Keywords: flood damage, flood risk sharing, moral hazard, economic equity, municipal contribution

JEL Codes: H76, H84, Q51, Q54

Flooding: Toward a Municipal Contribution to Economic Risk Sharing

1. Introduction

Over the past 40 years, we have observed a significant increase in the economic, social, and psychological consequences of flooding[1] (Berardelli 2021; Lazzarin et al. 2023). The increase is primarily due to population growth in at-risk areas (Bachand et al. 2022; Cao et al. 2022; Généreux et al. 2019; Golnaraghi et al. 2020; Maltais et al. 2023). This phenomenon is exacerbated by a lack of risk awareness (Bodoque et al. 2019; Valois et al. 2020) and the absence of regulations that promote mitigation and reduction, such as prohibiting the replacement of permeable surfaces with non-permeable material like asphalt or the use of basements as living areas (Public Safety Canada 2022). Without incentives that lead to concrete measures, demographic growth and the pressure to build 860,000 housing units in Québec by 2030 (CMHC 2023) will only accelerate this phenomenon and increase the vulnerability and exposure of populations in flood-prone areas.

The publication by the Québec government of new flood zone maps for river flooding, expected by the end of 2024, will also add to the concerns of municipalities and residents near watercourses. Many existing buildings will be in the new risk zones (Rémillard 2024). The presence of such buildings could lead to a drop in the market value of residential buildings and create difficulty in obtaining insurance and mortgages. Before these maps were even published, Québec's largest financial institution withdrew from mortgage financing for homes in high-risk areas (Lecavalier 2024).

This vulnerability is amplified by increasingly frequent and severe extreme weather events, including intense precipitation at all times of the year (Carvalho 2018; ECCC 2019; IPCC 2022) and those of short duration in urban areas (Yan et al. 2024). These extreme phenomena are responsible for exceptional floods that cause rivers to overflow their banks and produce runoff or pluvial flooding. These floods on land far from watercourses are increasingly frequent and damaging, and constitute a vastly underestimated risk (Faytre 2023; Prokešová et al. 2022; Yan et al. 2024).

One such consequence of this vulnerability is the skyrocketing cost of flood damage to residential buildings. Québec's 2017 and 2019 floods affected 293 and 240 municipalities, respectively.[2] As recently as spring 2023, at least 102 municipalities were affected by flooding.[3] Taxpayers primarily finance the cost of such damage through

1. The definition of flooding used in this article is that of the Institute for Catastrophic Loss Reduction (2020, p.13), i.e., the overflowing of the normal limits of a watercourse, or the accumulation of water over areas not normally submerged. Floods can be caused by exceptionally heavy rainfall, river flooding, backups of sewers, ice jams, or the failure of protective infrastructures such as dikes and dams (IPCC, 2012, p. 559).

2. See https://www.quebec.ca/gouvernement/politiques-orientations/plan-de-protection-du-territoire-face-aux-inondations/bilan-annuel-du-plan-de-protection-du-territoire-face-aux-inondations

3. See https://www.donneesquebec.ca/recherche/dataset/cartographie-des-inondations-du-printemps-2023

provincial and federal financial assistance programs. Private insurers offer only partial protection to individuals in low-risk areas. Finally, disaster victims must bear direct and indirect damage costs without adequate economic protection. Consideration for a fairer distribution of responsibility for the cost of damage to residential buildings is necessary.

Municipalities do not share these economic consequences. Several experts have asserted that current sharing mechanisms amplify the economic protection gap for the most vulnerable populations, meaning the difference between total losses and the indemnification mechanisms' payments (Feinman 2021). According to Ebbwater Consulting (2021), Canada's flood risk-sharing mechanisms are based on outdated economic concepts. Faced with sharp cost increases and the resulting loss of interest by governments and private insurers, flood risk sharing is set to change in Canada (Bourdeau-Brien et al. 2022) because it does not encourage municipalities or flood victims to reduce risk.

Leaving municipalities out of the cost-sharing arrangement raises the question of moral hazard. Moral hazard refers to a situation where there is no incentive for stakeholders to engage in less risky activities, knowing they will be compensated for any negative consequences (*The Economic Times* 2021). The scale of damage also leads to the need for greater consistency between those who should be responsible for risk reduction and those who should pay for damage to homes in flood-prone areas (Golnaraghi et al. 2020; Kousky and Kunreuther 2014). The amount paid in indemnities raises questions of equity and efficiency in using public funds and the integrity of their management. In this context, equity refers to a fair and just distribution of the financial burden based on the relative level of exposure to risk and the ability to reduce the risk for all stakeholders involved. The Québec government's introduction of a lifetime limit on successive flooding damage partly addresses the concern of moral hazard (Boudreault and Bourdeau-Brien 2020).

Furthermore, climate change is causing more frequent and intense extreme weather events, including floods. This puts a strain on existing flood risk-sharing schemes. These schemes face challenges due to two main factors: 1) reduced government involvement, and 2) increased financial burdens on individuals. Research by Ide et al. (2020) suggests that these pressures can lead to major changes at the institutional and political levels, which can potentially increase social tensions. To remain effective as the climate changes, these flood risk-sharing schemes need to be adapted.

Municipalities play an essential role in flood risk management through the power delegated to them by provincial governments (Carvalho 2018; Crick et al. 2018; Elliott 2017). For example, such power includes land use planning, local building codes and standards, emergency preparedness and response, and education and awareness. Flood risk must be managed through risk mapping, which considers the assessment of hazard, exposure, and vulnerability, from which decisions to implement mitigation, reduction, and prevention measures are derived (Aribisala et al. 2022). Despite flaws in flood risk management governance and land use planning practices, municipalities remain critical players in reducing the consequences associated with flooding (Province of Québec 2022).

The recent reduction in municipal powers in Québec over flood zone mapping and land use planning in 2022[4] in no way diminishes the importance of their role in flood risk management. Bill 50,[5] an Act to reform the *Civil Protection Act,* confirms municipalities' central role by stipulating that they are the primary authorities responsible for protecting people and property within their territory.

Municipalities are in the best position to understand their communities' specific needs. Finding and implementing practical solutions requires their active contribution. One of their main advantages is the ability to mobilize stakeholders and direct disparate interests toward a common cause (Henstra and Thistlethwaite 2017). Therefore, appropriate incentives must be put in place.

This study proposes a conceptual mechanism for sharing responsibility for the cost of flood damage to residential buildings that includes municipalities.

- Section two proposes three economic risk-sharing mechanisms.
- Section three presents the methodology for estimating damages to determine municipalities' economic participation in economic risk-sharing mechanisms.
- Section four presents a case study of three Québec municipalities exposed to flood risk to illustrate how municipalities could participate in sharing mechanisms. This section also discusses the effects of risk reduction on damages and the limitations of the methodology.
- The conclusion outlines conditions under which municipal involvement in covering restoration costs can help reduce moral hazard and inequities. In the long term, the sharing mechanism aims to control the growth of flood-related costs while adequately protecting at-risk property owners.

2. Economic Risk-Sharing Mechanisms

Risk sharing encompasses three elements: 1) the implementation of risk reduction measures; 2) the costs of implementing these measures; and 3) the economic costs associated with recovery, including compensation paid to disaster victims (Henstra and Thistlethwaite 2017). Economic risk sharing involves distributing the potential monetary losses associated with a risk among several stakeholders, such as disaster victims, taxpayers through various orders of government, those insured through private insurers, and consumers through private businesses. This sharing aims to reduce the impact of a loss concentrated on a single entity and promote a more equitable distribution of the burden

4. The transitional regime for managing flood zones, shorelines, and littoral zones came into effect in 2022, with the eventual adoption of a permanent framework in 2025.

5. Bill 50 is an Act to enact the *Civil Protection Act*, introduced to promote disaster resilience and amend various provisions relating to emergency communications centres and forest fire protection. See Chapter II, local and regional civil protection; Section I, general principles; Article 6: "Local municipalities are the primary authorities responsible for protecting people and property on their territory regarding civil protection." See https://coalitionavenirquebec.org/fr/blog/2024/01/31/projet-de-loi-pour-ameliorer-la-resilience-du-quebec-aux-sinistres/

among stakeholders. To analyze the feasibility of a municipal contribution, the economic risk is limited to recovery costs, that is, the compensation paid to owners or tenants of a principal residence when flood damage occurs.

In the context of climate change impacts, risk arises from the dynamic interactions among hazards, exposure, and vulnerability of affected systems (IPCC 2021). As established in the latest Intergovernmental Panel on Climate Change (IPCC) report, damaging consequences include those on lives; livelihoods; health and well-being; economic, social, and cultural assets and investments; infrastructure; services; ecosystems; and species (cf. Reisinger et al. 2020). These elements may involve uncertainties as to their magnitude and probability, and they may evolve due to socioeconomic changes and human decisions.

Risk can be assessed along two axes: mathematical (an exact science) and behavioural (a psychosociological science). The mathematical basis concerns probability theory, which enables uncertainty to be developed and quantified, and presented as a risk. The psychosociological basis is manifested in the theory of expected utility. Decision-makers evaluate the probability of occurrence and the consequences of their decisions (Amansou 2019). This author also points out that risk management requires a cross-functional approach known as integrated risk management (IRM, which considers all flood-related risks, including the direct damage to buildings, but also potential disruptions to infrastructure, public health risks, and economic impacts).

This concept of risk sharing is often associated with legal entities (such as insurers) or other institutional bodies (such as governments). On closer examination, however, individuals such as taxpayers, those insured, or claimants ultimately bear the cost of risk. For example, when governments use public funds to compensate claimants, taxpayers share the cost. All policyholders share in the compensation paid by insurers to disaster victims through the payment of insurance premiums. Finally, claimants assume the protection gap (lack of economic protection), because even if they qualify with insurers or government assistance programs, they are only partially compensated for the losses suffered (Campbell and Omran 2021).

The contribution of these three groups of individuals (taxpayers, those insured, and claimants) raises the question of equity in the context of whether a fair and just distribution of the financial burden is achieved. According to Lee and Parfitt (2022), those who have contributed most to the problem generally differ from those who pay the price, or at least they can purchase the means to put themselves out of harm's way. Table 1 illustrates who bears the economic risk, depending on whether the damage is covered by insurers (insurable damage), government assistance programs (eligible damage), or borne entirely by the victims (uninsured and ineligible damage). The protection gap falls entirely on the claimant without an adequate sharing mechanism.

This section analyzes and compares three existing economic risk-sharing mechanisms in which Québec municipalities could participate: 1) private flood insurance; 2) the Québec government's post-disaster financial assistance program; and 3) the reciprocal union. The principle of reciprocal union transfers the economic risk to a group of

Table 1. Contribution to flood-related property damage to homes			
Level of damage sustained	**Insurable damage**	**Eligible damage**	**Uninsured and ineligible**
Under the deductible or the initial portion of the loss	Disaster victims	Disaster victims	Disaster victims
Claims paid by insurer or government	Insured through premiums	Taxpayers	Disaster victims
Cost of damages in excess of coverage	Disaster victims	Disaster victims	Disaster victims

members. This mechanism is not currently used in the context of flood risk in Québec but is provided for in the Act respecting insurers.[6]

Table 2 compares these flood risk-sharing mechanisms according to three criteria: 1) the level of protection afforded to claimants, or the mechanism's ability to compensate claimants in the event of a flood; 2) equity in cost sharing for all stakeholders; and 3) incentives for flood prevention. The table reveals that reciprocal union could lead to better protection fairness in sharing the cost of damage as well as create an incentive for municipalities to implement mitigation measures. The rationale follows Table 2.

Table 2. Comparison of compensation mechanisms			
Mechanism	**Protection level**	**Fairness in sharing cost of damage**	**Prevention incentives**
Private insurance	Medium	Medium	Low
Financial assistance programs	Medium	Low	Low
Reciprocal union	High	High	High

2.1 Private flood insurance

Insurance is a mechanism for sharing economic risk among policyholders. The policyholders collectively assume the entire indemnity paid out by insurers in proportion to the risks the insurer assumes.

Level of Protection for Disaster Victims

Private flood insurance currently offers a partial level of protection, where offered. Not available in high-risk areas, this protection is offered as an optional addition (a rider) to

6. See *Insurers Act*, Chapter A-32.1, Section II, authorized reciprocal unions. https://www.legisquebec.gouv.qc.ca/fr/document/lc/A-32.1?langCont=fr - ga:l_ii-gb:l_xiii-h1

home insurance (Kagan 2021). Only 34 percent of flood damage in Canada between 2011 and 2021 was insured (18 percent worldwide) (Minano et al. 2024). Coverage varies from one insurer to another, as reflected in the different phrasing used by each. In Québec, flood insurance amounts are generally limited to $10,000, $25,000, and sometimes $50,000 in low- and moderate-risk areas. Policyholders can set their deductible to reduce the cost of insurance.

Private insurance provides a fast and efficient compensation process to help affected individuals and communities recover quickly from economic losses. Insurance premiums vary according to the level of flood risk in the area where the property is located and insurance limits (Davlasheridze and Miao 2021). The cost can be exceptionally high for policyholders when it is not subsidized by governments. This prompted the federal government to propose a national flood insurance program to reduce the cost of insurance for individuals living in flood-prone areas (Government of Canada 2023). According to Cannon et al. (2020), the main obstacles to purchasing flood insurance are a poor understanding of flood risk due to incomplete or fragmentary knowledge and the cost associated with insurance premiums.

Fairness in Sharing the Cost of Damage

The flood insurance system is equitable as it offers coverage against flood losses to all those exposed, regardless of risk. However, there are disparities in accessibility and affordability, particularly for those living in high-risk areas (Atlas Magazine 2024; Public Safety Canada 2022). A recent study by Lyle et al. (2024) suggests that better emergency preparedness and increased insurance take-up to manage residual risks promote social equity. (Social equity refers to the fair, just, and impartial treatment of all members of a society. It goes beyond simply treating everyone the same and focuses on ensuring everyone has the resources and opportunities they need to succeed, regardless of their background or circumstances [Svara and Brunet 2005].)

A distinctive feature of private insurance is the claims ratio. On average, insurers pay less than 66 percent of the premiums they collect in claims (Kagan 2021). In 2022, this rate was 52.4 percent. The remainder covers insurers' operating costs and profits.

Flood Prevention Incentives

Insurance policies that include incentives for flood prevention are more efficient for reducing the risk and therefore the cost of insurance. Such incentives can mean lower insurance premiums for those who implement prevention measures. However, these reductions may be negligible compared with the costs of adopting risk mitigation measures, particularly in areas at low risk of flooding (Hudson et al. 2019; Lucas et al. 2021). In addition, the short duration of private insurance contracts (generally 12 months) does not help encourage insurers or policyholders to invest in risk mitigation measures. Insurers also require repairs to be carried out according to the "identical replacement principle," which is based on restoring the damaged property to its original pre-loss condition without necessarily making any improvements or alterations. It is the opposite of the "build back better" approach, which aims to rebuild or repair by incorporating improvements or measures to strengthen resilience in the face of similar future events. This approach is advocated by the United Nations (UNDRR 2015).

2.2 Québec government financial assistance program

In Québec, disaster victims (homeowners, tenants, municipalities, and community organizations) can qualify for the General Financial Assistance Program Regarding Disasters (GFAPRD).[7] This mechanism involves risk sharing among taxpayers in different sectors or geographical areas using fiscal resources and institutions (Giovannini et al. 2022). Protection is quasi-universal in that it applies to disaster victims who have suffered a loss. The conditions of application to this program are set out in decree 673–2023 (March 29, 2023). For an event to be considered a flood, water from an overflowing watercourse must reach the property. The Province manages the compensation payment to disaster victims based on eligible damages through the Ministry of Public Security (MSP). The federal government reimburses the Province for a portion of the compensation it paid to disaster victims. Federal participation through Disaster Financial Assistance Arrangements (DFAA)[8] varies according to the extent of the damage but can reach up to 90 percent of eligible damages.

In response to the rising cost of DFAA over the past 40 years, the Government of Canada (2024) reiterated its intention of creating a national insurance program for residential properties in high-risk areas.[9] While this program, backed by the insurance industry, aims to reduce flood insurance costs for taxpayers by placing a greater burden directly on residents in flood-prone areas, it fails to address fairness concerns. This is because the federal government's role in subsidizing and capping premiums undermines the program's ability to promote a more equitable sharing of flood risk premiums (Government of Canada 2023; Public Safety Canada 2022). This program could also exacerbate moral hazard and disempower provinces, municipalities, and residents of flood-prone areas (Davlasheridze and Miao 2021; Kousky 2018).

Level of Protection for Disaster Victims

Depending on eligibility conditions and financial assistance limits, government financial assistance programs offer variable protection. Québec's GFAPRD is designed to provide last-resort assistance to homeowners and tenants affected by a disaster. Certain expenses are eligible for financial aid and others for compensation, such as temporary preventive measures put in place, eligible moveable property affected, and emergency work. However, the Québec government has recently limited the indemnities provided for in

7. Financial assistance for homeowners and tenants in flooding or other disasters. https://www.quebec.ca/securite-situations-urgence/urgences-sinistres-risques-naturels/obtenir-aide-sinistre/aide-financiere-proprietaires-locataires

8. In a large-scale natural disaster, the Government of Canada can provide financial assistance to provincial and territorial governments under Disaster Financial Assistance Arrangements (DFAA) managed by Public Safety Canada. https://www.publicsafety.gc.ca/cnt/mrgnc-mngmnt/rcvr-dsstrs/dsstr-fnncl-ssstnc-rrngmnts/index-en.aspx

9. See https://budget.canada.ca/2024/home-accueil-fr.html#pdf; https://budget.canada.ca/2024/home-accueil-en.html [English]

10. Financial assistance in the event of a flood or other disaster. https://www.quebec.ca/en/public-safety-emergencies/emergency-situations-disasters-and-natural-hazards/financial-assistance-and-compensation-flooding-or-disaster/financial-assistance-compensation-property-owners-tenants

the GFAPRD.[10] The new version imposes a lifetime limit on flood victims and is intended to discourage them from rebuilding in flood-prone areas (Boudreault and Bourdeau-Brien 2020). In addition, settlement delays and the complexity of government claims make the customer experience unpleasant and traumatic (Maltais et al. 2023). The absence of insurance in high-risk areas, combined with the introduction of a lifetime limit by the MSP, means that high-risk homeowners have no protection in the event of flooding after the lifetime limit is attained. The lack of economic protection seriously affects their ability to take out a mortgage (Lecavalier 2024).

Fairness in Sharing the Cost of Damage

The GFAPRD is based on the principle of solidarity, which encompasses mutual support, shared responsibility, and collective action. As a result, residents of areas not exposed to flooding pay for the damage suffered by occupants of buildings in flood-prone areas (Thourot 2023). This principle is now being challenged in several jurisdictions, notably the “CATNAT” scheme in France and the National Flood Insurance Program in the United States.

Flood Prevention Incentives

Compensation paid under disaster relief programs can be seen as insurance. This aid can encourage development in at-risk areas and discourage investment in mitigation measures (Ahmadiani et al. 2019; Landry et al. 2021). These programs are often counterproductive; they create moral hazard due to the economic security they provide and the lack of incentives to reduce risk (Davlasheridze and Miao 2021; Kousky 2019).

2.3 Reciprocal union

As noted in the introduction, reciprocal union is an alternative financing method to purchasing insurance or government assistance programs. It enables the cost of a claim to be shared among group members potentially exposed to the same risk (Norgaard 1964; Venezian 2005). It is a principle of cost-sharing solidarity among policyholders, where each contributes by paying their premium without any prior guarantee as to whether they will be compensated, or if another group member will be. This principle is based on cooperation and assistance among the affected parties, underlining the importance of collective responsibility. A reciprocal union could be an inter-municipal risk pool, where municipalities collect individual contributions and join forces to finance compensation and related expenses. This model enables risk to be diversified geographically and homogeneous risks to be selected. The contributions are then used to compensate those who suffer losses due to flooding. This mechanism can benefit small communities (Bernhardt et al. 2020).

Level of Protection for Disaster Victims

The level of protection offered by reciprocal union can be modulated according to need. This aims to promote access to coverage and reduce the opportunity to opt-out since participation is compulsory, which enables better reconstruction, speeds up benefits payment, and reduces the protection gap (Hudson et al. 2019). The claims coverage ratio is optimized, as a more significant proportion of premiums that are collected is used to pay claims, due to lower operating costs and the absence of capital remuneration to shareholders.

Fairness in Sharing the Cost of Damage

Reciprocal union allows economic risk to be distributed more equitably within the community. Pricing can be designed to ensure that the most vulnerable or economically disadvantaged people can benefit from coverage, in alignment with the principles of social equity. Pricing design makes economic flood protection more affordable and accessible to a more significant proportion of the population (Bernhardt et al. 2020).

Flood Prevention Incentives

Reciprocal union also promotes citizen awareness and involvement in implementing risk mitigation measures (Bouchard St-Amant et al. 2023; da Silva et al. 2020; Glaus et al. 2020). By creating incentives for risk reduction at both community and individual levels, the economic resilience of the community and its citizens is thereby strengthened. The regulatory (building codes) and economic (subsidies, tax breaks, or loans) incentives play an important role in reducing risk at the household level (Hanger et al. 2018; Hudson 2020). Incentives mitigate the impact of flooding and ensure that the benefits of risk reduction and economic protection are shared more equitably among all community members.

2.4 Choice of a sharing mechanism

Municipalities could contribute to the economic sharing of risk through one or another of these mechanisms, each with specific advantages and implications. The annual economic contribution of each municipality could be established by calculating the average annual estimated damage to a municipality's residential buildings. For example, annual contributions could be paid to a single insurer or a group of private insurers responsible for compensating disaster victims. This approach is inspired by the flood insurance program announced by the federal government in its 2024 budget, which should come into effect in 2025.

Similarly, these contributions could be paid to the Québec government to finance a portion of the GFAPRD and be used to subsidize local risk reduction and mitigation initiatives.

Lastly, these contributions could be paid into a common fund to pool resources. In a disaster, the funds collected would be used to compensate the victims. This mechanism would also make it possible to use an existing infrastructure held by municipalities, namely the Municipal Insurance Fund of Québec, created in 2003.[11]

Whichever sharing mechanism is chosen, it must be designed to: 1) provide a basic level of protection for all residents; 2) promote equity among the various stakeholders; and 3) encourage municipalities and individuals whose homes are located in a risk zone to implement risk mitigation measures.

3. Methodology to Estimate Damages from Floods

3.1 Damage curves

Depth-damage curves are the primary tool for estimating flood damage. These damage curves express the vulnerability of assets by establishing a relationship between inundation

11. See https://www.fondsfqm.ca/

depth and property damage (Bachand et al. 2022; Bouchard St-Amant et al. 2023). The inundation depth represents the effective water height in a building, measured from a reference floor. On average, the damage to buildings and property increases with water height (Doyon and Jean 2021; Merz et al. 2010). The curves are constructed either from empirical data from compensation histories or synthetic data based on vulnerability coefficients determined by experts (Aribisala et al. 2022; Deschamps et al. 2023; Romali et al. 2015; Xing et al. 2023).

Damage curves are also specific to a geographical region, notably due to the variability of geographical and climatic conditions within watersheds, construction methods and characteristics, and socioeconomic factors (Amirebrahimi et al. 2016; Bonnifait 2005; Chhabra et al. 2023; Wing et al. 2022).

The damage curves chosen for this project are those of the model by Doyon and Jean (2021), developed from data on homes compensated during the 2011 floods in the Lake Champlain and Richelieu River watersheds. They improve on the curves created by Bonnifait (2005) and those developed by Ouarda (Leclerc et al. 2003), based on empirical data from Québec.

Data Used for Calculation

The following data used for the calculation were provided by the *Communauté métropolitaine de Montréal* (CMM) for each of the 4,000 exposed residential buildings in three municipalities: coordinates x and y; use code; number of storeys; building value on the 2021 assessment roll; ground elevation and flood height in metres for each of six (6) return periods (recurrence intervals) from two-year to 350-year. Flood heights for each building are based on flows and water levels measured in the study region.

Damage Calculation

The method used to calculate damage to residential buildings (D$) is based on the MÉRIGE method for flood risk assessment and management, with the necessary adaptations to take account of available data (Marceau et al. 2023). Damage rates (TE) from six of the 12 curves (serviced areas only) in Doyon and Jean (2021) were interpolated to determine the damage rate for each flood height. Therefore, the damage (D$) to the building is given by

$$D\$ = TE * Assessment\ Value \quad (1)$$

where *D* is the damage ($), *TE* is the damage rate (between 0 and 1, depending on the water level in relation to the first floor), and *Assessment Value* is the value of the building as listed on the property assessment roll ($).

The main steps in calculating damage to residential buildings for each of the three municipalities are:

1. The choice of buildings to be included in the average annualized damage assessment (AAD$) (i.e., use code = 1000 for one or two-storey buildings located in exposed areas).
2. Addition of the number of floors when the number of floors was missing. By default, the number of 1 was assigned for missing data.

3. Random assignment of basement type. The following values randomly generated the presence or absence of a basement: 18 percent of residential buildings are without a basement (type = 0), 25 percent with an unfinished basement (type = 1) and 57 percent with a finished basement (type = 2) based on the distribution of data from Doyon and Jean (2021).
4. Calculation of first-floor height (GFH) in metres, since this data is not provided (i.e., ground elevation + 80 cm for buildings with basements and ground elevation + 15 cm for buildings without basements) (Tanguy et al. 2022).
5. Extracting the event damage rate (ETE%) of a building for each recurrence period (i.e., 2, 20, 50, 100, 200, and 350 years) from the curves of Doyon and Jean (2021). This rate is a function of the flood height relative to the first floor. It varies according to building type: one storey without a basement, one storey with a basement, one storey with a finished basement, two storeys without a basement, two storeys with a basement, and two storeys with a finished basement.
6. The calculation of a building's average annualized damage rate (TEAM%) is the result of summing the event rates multiplied by their annual probabilities of occurrence (Table 3) (i.e., 0.5; 0.45; 0.03; 0.01; 0.005; 0.002142857 for p2; p20; p50; p100; p200; and p350, respectively [recurrence periods used]). The probability intervals selected are the upper bounds for estimating damage rates. Lower exceedance probabilities would have resulted in lower average annualized damage rates.

Table 3. Probability intervals for each occurrence (upper bounds)

Occurrence	Probability	Distribution function	Probability mass	Period (years)
0	1	0	–	–
2	0.5	0.5	0.5	0–2
20	0.05	0.95	0.45	2–20
50	0.02	0.98	0.03	20–50
100	0.01	0.99	0.01	50–100
200	0.005	0.995	0.005	100–200
350	0.002857143	0.997142857	0.002142857	200–350
Infinite	0	1	0.002857143	350–infinite
		Sum	**1**	

7. The calculation of a building's average annualized damage (IDMA$) is the result of multiplying the average annualized damage rate (TEAM%) by its value on the assessment roll (building value). This value could be adjusted for greater precision according to different parameters, considering the cost of new construction, replacement, or repair.

8. The average annualized damage of a municipality (DMA$) is, therefore, the sum of the average annualized damage of the buildings in a municipality.

4. How Municipalities Can Participate in a Sharing Mechanism: A Case Study

This section illustrates how municipalities can participate in the scheme to share compensation paid to owners or tenants of a principal residence. Participation takes into account both individual and collective levels of risk. Assessing the potential damage costs is necessary before determining how municipalities should participate in this sharing scheme. Damage assessment involves quantifying the damage at the building level and calculating the total cost to the municipalities concerned. The total cost is then considered relative to the municipality's property value.

The model calls for mandatory contributions from municipalities and owners of residential buildings within their jurisdiction. All residential buildings would contribute to the sharing of compensation costs according to their level of risk and property value. All municipalities' total level of participation in the sharing mechanism could be capped to consider their tax capacity, and this would depend on future negotiations with the Québec government.

One way of establishing and collecting individual contributions would be through property taxation, which is already well-established in all municipalities. A municipality can adopt a bylaw to impose a fee structure to finance all or part of its activities or require a contribution paid for a service offered by another municipal body.

By combining risk distribution and risk reduction measures, this sharing scheme aims to achieve two main objectives: 1) to promote equity among the various stakeholders, and 2) to encourage municipalities and individuals whose homes are located in at-risk areas to implement risk mitigation measures.

4.1 Participating municipalities

Three municipalities in the *Communauté métropolitaine de Montréal* (CMM) were selected to illustrate the proposed sharing method. The choice of municipalities for the case study was based on the following criteria: 1) their flood history; 2) the availability of the data required for the calculations; and 3) their differences in population and exposure to flood risk. Due to the confidential nature of the data, particularly regarding exposure to flood risk, the names of the municipalities are not disclosed.

Table 4 presents a brief profile of the three selected municipalities, showing that residential land use varies from 39 to 54 percent of the total land uses. The average standardized assessment of Municipality 1, which has fewer inhabitants than the other two municipalities, is substantially lower than the other two. A lower assessment roll may indicate that this municipality would be less able to contribute to risk sharing.

4.2 Exposure rates and contributions

The municipality's annual damage exposure rate (TEAD%) is a relative measure of a municipality's level of risk and its economic capacity to deal with it. This rate is calculated

Table 4. Profile of study region				
Municipality	**Residential land use** (%)	**Residential standardized value** ($M) (VFUM$)	**Number of residential buildings***	**Average standardized residential value** (in $000)
Municipality 1	39	740	2,540	290
Municipality 2	48	3,000	7,513	400
Municipality 3	54	2,600	7,120	370
			17,173	

*__Note:__ The number of residential buildings is deducted from the residential property value and the average standardized assessment.
Sources: Minister of Municipal Affairs and Housing (retrieved November 15, 2023). https://www.mamh.gouv.qc.ca/repertoire-des-municipalites/fiche/municipalite/ and CMM https://observatoire.cmm.qc.ca/produits/portraits-territoriaux/

by dividing the sum of the average annual damage to buildings (DMA$) by the residential standardized property value (VFUM$).

Table 5 shows the annual damage (DMA$) for each of the three municipalities in the study area. The DMA$ is the sum of the estimated damages of each residential building within the municipality. These damages amount to $7.2 million for Municipality 1, $5.2 million for Municipality 2, and $618,000 for Municipality 3. Therefore, annual damage exposure rates are 0.97 percent, 0.17 percent, and 0.02 percent, respectively. A municipality such as Municipality 1 can have its territory proportionally more exposed to flood risk (0.97 percent) than a neighbouring municipality where 91 percent of the residential buildings are exposed.

Table 5. Exposure rate (TEAD%) by municipality						
Municipality	**Residential buildings at risk**			**DMA$**	**Average DMA$**	**TEAD%**
	#	**%**	**Total value** ($)			
Municipality 1	2323	91	336,744,300	7,178,507	3,090	0.97
Municipality 2	1407	19	244,811,000	5,227,268	3,715	0.17
Municipality 3	270	4	55,608,500	618,070	2,289	0.02
	4000	**23**	**637,163,800**	**13,023,844**	**3,256**	**0.20**

4.3 Damage rate distribution

Table 6 shows the distribution of damage rates for the entire study area. It groups damage rates by severity level. The calculation of damage rates per building (TEIB%) shows that 68 percent (709 + 2,036 cases out of 4,000) of residences in flood-prone areas would suffer minimal damage. Damaged buildings in the one to six percent range (18 percent or 718 cases) would suffer an average annual damage of less than $5,214. Damage rates above six percent account for a significant share of yearly damage (65 percent or $8,495,765, although they represent only 13.4 percent of the total cases [383 + 154 cases out of 4,000]). In a few instances, the concentration of damages suggests that mitigation measures, such as raising the ground floor or relocating the residential buildings, could be cost-effective.

Table 6. Distribution of damage rates (study area)

TEAM% range	DMA$	Buildings			Average DMA$	TEIB%
		Value ($)	#	%		
0	0	130,445,000	709	17.7	0	0.00
0+ to 1	784,169	328,558,400	2036	50.9	385	0.24
1 to 2	245,484	13,938,600	62	1.6	3,959	1.76
2 to 3	170,458	7,385,400	38	1.0	4,486	2.31
3 to 4	1,609,444	45,837,200	338	8.5	4,762	3.51
4 to 6	1,718,524	35,669,500	280	7.0	6,138	4.82
Sub-total 1–6%	3,743,910	102,830,700	718	18.0	5,214	3.64
6% to 10%	4,395,609	53,681,200	383	9.6	11,477	8.19
More than 10%	4,100,156	21,648,500	154	3.9	26,624	18.94
	13,023,844	**637,163,800**	**4,000**	**100.0**	**3,256**	**2.04**

Table 7 shows four examples of individual taxpayer contributions (CONT$) based on four levels of damage rate (TEAM%): 1) zero percent; 2) above zero but less than one percent; 3) between one and six percent; and 4) above six percent. The contribution presented omits the program's administrative costs, typically ranging from ten percent to 40 percent of the contribution. This table illustrates that the closer one gets to the five percent damage rate (TEIB%), the more essential mitigation measures become to reduce costs. It may be challenging to justify staying in flood-prone areas above a certain threshold (e.g., ten percent).

Table 7. Cases specific to each municipality

Municipality	TEAM% range	Cases	Building value at risk ($)	TEIB%	DMA$	CONT$
Municipality 1	0	1.1	295,500	0.00	–	–
	0+ to 1	1.2	310,000	0.01	21	21
	1 to 6	1.3	154,400	5.03	7,760	7,760
	> 6	1.4	215,000	44.26	95,168	95,168
Municipality 2	0	2.1	399,500	0.00	–	–
	0+ to 1	2.2	268,500	0.01	19	19
	1 to 6	2.3	191,500	5.03	9,624	9,624
	> 6	2.4	268,000	31.11	83,366	83,366
Municipality 3	0	3.1	393,500	0.00	–	–
	0+ to 1	3.2	197,000	0.01	14	14
	1 to 6	3.3	123,500	4.94	6,106	6,106
	> 6	3.4	114,000	37.71	42,994	42,994

4.4 Effects of risk reduction

This analysis also demonstrates that investment in mitigation and risk reduction measures should be prioritized to reduce the economic burden on taxpayers, as highlighted by Kotz et al. (2024). A study in the United States established that for every dollar spent on mitigation, taxpayers save an average of seven dollars in disaster response and recovery costs (National Institute of Building Sciences, 2019).

Moreover, simple risk reduction measures such as installing a back water valve, basement sump pump, proper lot grading, clearing gutters, and extending downspouts are inexpensive and practical (Evans and Feltmate 2019). Other research has shown that adopting Canada’s *National Guidelines for Building Flood Resistance* can have a benefit-cost ratio 11:1 for homes.

The Federal Emergency Management Agency (FEMA) in the United States offers flood insurance premium reductions to residential building owners who elevate their buildings. FEMA requires an elevation certificate, which allows for premium reductions of up to 41.7 percent (FEMA 2023). To illustrate the potential effect of risk reduction measures, two risk reduction scenarios (ground-floor elevation and relocation) are presented, despite the limitations inherent in the sample of available data.

Scenario 1 – Ground-Floor Elevation

Scenario 1 simulates a 60 cm ground-floor rise for the 718 (18 percent of the 4,000) buildings with annualized damage rates between one percent and six percent. Table 8 shows that total annualized damage (DMA$) is reduced by $1.8 million, from $13.0 million to $11.2 million. Similarly, the average annual damage (average DMA$) for this sub-group falls from $5,214 to $2,724, a reduction of 48 percent.

Table 8. Scenario 1 – Distribution of damage rates with first-floor elevation

TEAM% range	DMA$	Buildings			Average DMA$	TEIB%
		Value ($)	#	%		
0	0	130,445,000	709	17.7	0	0.00
0+ to 1	784,169	328,558,400	2036	50.9	385	0.24
1 to 2	1,106,682	75,492,500	516	12.9	2,145	1.47
2 to 3	295,312	13,388,000	110	2.8	2,685	2.21
3 to 4	337,359	9,673,700	69	1.7	4,889	3.49
4 to 6	216,130	4,276,500	23	0.6	9,397	5.05
Sub-total 1 to 6	1,955,483	102,830,700	718	18.0	2,724	1.90
6 to 10	4,395,609	53,681,200	383	9.6	11,477	8.19
> 10	4,100,156	21,648,500	154	3.9	26,624	18.94
	11,235,417	**637,163,800**	**4,000**	**100.0**	**2,809**	**1.76**

Table 9 shows the breakdown by municipality of the damage reduction resulting from raising the first floor of 718 buildings. The cost of raising the ground floor (cost of mitigation measures) is estimated at $47 million (an average of $65,000 per building).[12] The last column (DVAN0) indicates the estimated average number of years required to recover the cost of mitigation measures.

$$DVANO = Damage\ reduction\ /\ Cost\ of\ mitigation\ measures \quad (2)$$

12. The cost of raising the ground floor may vary considerably. An average of $65,000 was established for illustration purposes. Source: https://soumissionrenovation.ca/fr/blogue/combien-coute-soulever-maison and https://www.constructionrenovation.com/prix-agrandissement/ - agrandissement-pieux

Table 9. Scenario 1 – Effect of raising the first floor by 60 cm for 718 buildings					
Municipality	**Building**		**Damage reduction**	**Cost of mitigation measures**	**DVANO** (years)
	Value ($)	**#**			
Municipality 1	56,943,200	453	1,080,992	29,445,000	27.24
Municipality 2	39,339,500	228	620,307	14,820,000	23.89
Municipality 3	6,548,000	37	87,129	2,405,000	27.60
	102,830,700	**718**	**1,788,427**	**46,670,000**	**26.10**

In addition to raising the first floor, municipal regulation could also include a series of bylaws. For example, such bylaws could impose restrictions on finishing basements or ban building basements since the vast majority of damage in areas exposed to flooding is caused in basements.

Scenario 2 – Relocation

Given the rising cost of compensation, the relative effectiveness of protective infrastructure (Löschner et al. 2021; Nofal and van de Lindt 2020; Rasmussen et al. 2021), and as climate change intensifies, removing buildings from high-risk areas becomes a priority (Mach et al. 2019). Several authors (Boudreault et al. 2023; Cottar et al. 2021) confirm that relocation effectively reduces the cost of flood damage.

Scenario 2 simulates relocating 537 (13.4 percent) of the most at-risk buildings (TEAM% of six percent or more). Table 10 shows the effects of relocating the 537 buildings (4,000 minus 3,463). Relocation would reduce average annualized damage from $13 million) to $4.5 million, a reduction of $8.5 million annually.

Table 10. Scenario 2 – Effect of relocation on damage reduction						
TEAM% range	**New DMA$**	**Building**			**Average DMA$**	**TEIB%**
		Value ($)	**#**	**%**		
0	0	130,445,000	709	17.7	0	0.00
0+ to 1	784,169	328,558,400	2,036	50.9	385	0.24
1 to 2	245,484	13,938,600	62	1.6	3,959	1.76
2 to 3	170,458	7,385,400	38	1.0	4,486	2.31
3 to 4	1,609,444	45,837,200	338	8.5	4,762	3.51
4 to 6	1,718,524	35,669,500	280	7.0	6,138	4.82
	4,528,079	**561,834,100**	**3,463**	**86.6**	**1,308**	**0.81**

Table 11 shows the cost of purchasing the 537 buildings to be relocated represents $75 million (at property value). The last column (DVAN0) indicates the estimated average number of years required to recover the cost of mitigation measures.

Table 11. Scenario 2 – Effect of relocation on damage reduction per municipality

Municipality	Building		Damage reduction	DVAN0 (years)
	Value ($)	#		
Municipality 1	41,554,200	345	4,589,170	9.05
Municipality 2	30,855,500	173	3,575,185	8.63
Municipality 3	2,920,000	19	331,409	8.81
	75,329,700	**537**	**8,495,765**	**8.87**

These two risk reduction measures demonstrate that the sustainability of a new form of sharing must be based on developing resilience capacity upstream of a flood. These measures would reduce socioeconomic damage and protect taxpayers' investments (Long 2017).

Municipality 1's exposure rate in this case study is high (0.97 percent of standardized property value). While the average tax burden of residential buildings is around $2,000,[13] the average annualized damage cost of each residential building in this municipality is $3,090 (i.e., $7.2 million divided by 2,323 buildings) (see Table 5). That is, to cover the cost of the contribution to the sharing system, the municipality would have to more than double (2.5 times) the residents' tax burden.

Because of this overexposure, a compensation and transition mechanism could be implemented to help the municipality cope with this new economic burden. This mechanism could take the form of annual economic assistance from the Québec government to 1) cap the municipality's contribution and 2) subsidize reduction and mitigation measures. This economic assistance could also come partly from other municipalities (members of the same regional municipality, for example) through a cost-sharing mechanism that would consider each municipality's relative property value. A zero-damage rate would still entail a minimum mandatory contribution. Such a contribution by all residents is desirable to ensure more significant equity and risk sharing among stakeholders.

4.5 Limitations

This illustration of the contribution of municipalities and residential building owners has a certain inherent degree of uncertainty. First, the flood zone maps assume that the

13. Sources: Minister of Municipal Affairs and Housing (retrieved November 15, 2023). https://www.mamh.gouv.qc.ca/repertoire-des-municipalites/fiche/municipalite/ and CMM https://observatoire.cmm.qc.ca/produits/portraits-territoriaux/

hydrometeorological factors that cause flooding are constant throughout the year (e.g., the effect of ice jams and exceptional situations caused by torrential rains are excluded). Nor do these preliminary calculations consider the potential presence of protective structures, such as dikes, dams, or river flow management. Moreover, the maps do not consider the increasingly frequent pluvial flooding caused by extreme meteorological phenomena in areas not generally exposed to the risk of direct river flooding (Bellerose 2023; Ducas 2023; Normandin 2012). These extreme events amplify the uncertainty associated with potentially flood-prone areas.

Second, the damage estimation method generates a high variability, particularly at the building scale. The damage curves establish a relationship between flood height and property damage in the context of fluvial flooding (Bachand et al. 2022; Bonnifait 2005; Doyon and Bouchard St-Amant 2020; Doyon and Jean 2021). The height of the first floor of each building had to be estimated as this data was not available at the building level. In addition, the damage to the buildings presented is calculated based on the assessment roll value. This value is not necessarily representative of the cost of repair or replacement. In a recent study, experts determined that the assessment roll value should be increased by 50 percent to better reflect its replacement cost (Deschamps et al. 2023). These calculations also exclude damage to moveable property and exterior fixtures and fittings. The same study established the value of real estate and exterior fixtures and fittings at 35 percent and 15 percent of the building's replacement cost, respectively.

As a result, calculations of a municipality's average annual damage and buildings (DMA$) are presented solely to illustrate the sharing model only. Estimates of yearly average damage for each municipality must consider more elaborate criteria, including specific building characteristics, and be based on more comprehensive flooding data. Furthermore, the new flood maps to be published at the end of 2024 could substantially modify the average annual damage.

5. Conclusion

Despite the recent reduction in their powers concerning flood zone mapping and land use planning, municipalities play an essential role in the economic management of flood risk. The risk-sharing method proposed in this study juxtaposes risk pooling with individual and collective risk levels. It also implies compulsory participation for all residential buildings. The ultimate choice of sharing mechanism will have to consider 1) the level of protection for all residents; 2) equity among the various stakeholders; and 3) the extent to which municipalities and individuals are encouraged to implement risk mitigation measures. To achieve these objectives, reciprocal union seems an appropriate mechanism.

The level of participation required of each municipality in the sharing arrangement could be adjusted according to various criteria that consider, for example: 1) the type of land use (residential vs. commercial); 2) the quality of protective infrastructure (drainage capacity, dikes); 3) risk reduction and mitigation measures, notably through regulation; 4) the degree of preparedness for intervention; and 5) risk awareness and education efforts.

The damage estimation methodology should be improved to reduce the variability and uncertainty of average annual damage. Other factors contributing to damage should also be considered, while incorporating techniques for adjusting damage curves.

Improvement of the methodology would make it possible to produce more reliable cost-benefit analyses and better guide decisions, since they would be based on evidence of damage reduction.

The damage estimates show that most buildings suffer relatively low levels of damage, and as a result, a wall-to-wall approach to reducing exposure or vulnerability is not necessary. Establishing a building's compliance must also consider other non-economic factors, such as emergency response and life safety. Establishing a certificate of resilience or compliance, along with those issued by FEMA (2022), would help reduce the economic and social consequences of mass relocation or a drop in the value of buildings in high-risk areas. This type of certificate could be based on the resilience principles and practices promulgated, for example, by Architecture Without Borders or the Intact Climate Adaptation Centre.[14]

Contributions could be levied through property taxes and determined according to the risk level of each residential building. The use of property tax requires careful attention to ensure its acceptability. Targeted communication emphasizing the fairness and transparency of the tax process will be necessary. In addition, the acceptability of the proposed approach could represent a challenge for municipalities, which are already feeling the burden of additional responsibilities without the benefit of additional resources. These resources should, therefore, be reassessed to ensure the feasibility of the proposed cost-sharing model.

Implementing such a model will also require a transfer mechanism from the Québec government to enable more exposed municipalities to adjust their budgets. This transition could take several years and require exemplary cooperation between the various orders of government (federal, provincial, and municipal).

Involving municipalities and at-risk individuals in compensation payments could reduce the sense of inequity and foster accountability for municipalities and their residents. However, this sharing model can only be perpetuated with investment in incentive programs to adopt mitigation measures. In any case, building resilience before, during, and after floods is essential to reduce the damage, not only economically, but also socially and psychosocially, in the long term. This damage is and will continue to increase in the context of future climatic and socio-environmental upheavals. Acting now to anticipate risks will help reduce the consequences, whatever their nature. A rigorous assessment of future risks and the resulting adaptation measures requires joint consideration of climate change, changes in exposure, and vulnerability (O'Neill et al. 2022; Tebaldi et al. 2023).

14. See https://www.asf-quebec.org/nos-programmes/resilience-climatique/ and https://www.centreintactadaptationclimat.ca/infographies/#Inondations; https://www.intactcentreclimateadaptation.ca/climate-ready-infographics/#Flooding [English]

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