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GESTION DU RISQUE D'INONDATIONS AU QUÉBEC : VERS UNE CONTRIBUTION ACCRUE DES MUNICIPALITÉS

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AVANT-PROPOS

L'origine de cette thèse puise ses racines dans une conviction profonde. Celle-ci a été forgée au fil de plus de trente ans d'expérience dans le secteur de l'assurance municipale, où j'ai œuvré à titre de courtier d'assurance spécialisé et de cadre supérieur. Cette conviction est que les municipalités possèdent une capacité remarquable à innover et à se prendre en charge face à des défis majeurs, particulièrement lorsqu'elles sont directement impliquées dans les solutions. Cette conviction s'est notamment cristallisée lors de la crise d'assurance qui a secoué le monde municipal québécois au début des années 2000. Face à un marché qui les laissait démunies, les municipalités ont alors démontré une volonté collective de développer une vision à long terme et un nouveau modèle d'affaires, soit la création de la Mutuelle des municipalités du Québec (MMQ), aujourd'hui le Fonds d'assurance des municipalités du Québec (FAMQ), une initiative que j'ai eu le privilège de piloter et de diriger par la suite.

Le succès du FAMQ a été une leçon marquante. Il a démontré de manière éloquente que lorsque la prévention est priorisée et que les municipalités sont financièrement impliquées et responsabilisées dans la protection de leurs propres actifs, le risque peut être mieux géré et ses coûts, maîtrisés. Bien que le FAMQ visait les actifs municipaux, cette expérience a fait naître l'interrogation fondamentale au cœur de cette thèse : un principe similaire d'implication financière pourrait-il inciter les municipalités à s'engager plus activement dans la réduction du risque d'inondations affectant cette fois les actifs des citoyens sur leur territoire? Cette intuition, nourrie par la réussite d'un modèle où l'engagement financier a été synonyme de meilleure gestion du risque, a motivé cette recherche doctorale. Elle est étayée par une connaissance approfondie des mécanismes assurantiels et des enjeux de gouvernance municipale. L'ambition est donc d'explorer si ce principe éprouvé peut être transposé pour renforcer la résilience des communautés québécoises face au fardeau croissant des inondations.

Au-delà du travail de recherche formel, cette démarche doctorale a été enrichie par de nombreuses occasions de partager les réflexions émergentes et d'engager le dialogue sur les enjeux de la gestion du risque d'inondations et du rôle des municipalités au Québec. Cet engagement s'est manifesté par des présentations lors de divers colloques et congrès scientifiques, tels que le congrès de l'ACFAS, le colloque Villes inondables d'ARIAction, les séminaires du RIISQ et de Centr'Eau et des rencontres avec de jeunes chercheurs ou des centres universitaires spécialisés. Parallèlement, la volonté de rejoindre un public plus large s'est concrétisée par la publication de plusieurs articles de vulgarisation dans des médias comme *La*

Conversation et *Sciences 101*, ainsi que par des participations à des émissions de radio et des entrevues avec la presse. Ces multiples interactions ont non seulement permis de diffuser les questionnements au cœur de cette thèse, mais aussi d'affiner la compréhension des préoccupations des différents acteurs concernés et de confirmer la pertinence sociétale du sujet. À cela s'ajoute un travail de collaboration continue avec Michel Leclerc (INRS) pour améliorer la méthodologie d'estimation des dommages causés par les inondations aux bâtiments résidentiels, un projet qui se poursuit en parallèle de cette thèse. Mon implication se prolonge également auprès de l'équipe du bureau de projet de la Communauté métropolitaine de Montréal, avec laquelle je collabore sur différentes initiatives visant la sensibilisation des municipalités au risque d'inondations.

« *A child born in 2025 will have a much higher likelihood of experiencing a "1-in-100 year" flood* »

UNDRR GAR 2025 lifelines (2025)

TABLE DES MATIÈRES

LISTE DES FIGURES

LISTE DES TABLEAUX

LISTE DES ABRÉVIATIONS, DES SIGLES ET DES ACRONYMES

Abréviation	Signification
AAFCC	Accords d'aide financière en cas de catastrophe (du gouvernement fédéral)
AMF	Autorité des marchés financiers
ASC	Administrateur de sociétés certifié (Collège des Administrateurs de Sociétés de l'Université Laval)
BAC	Bureau d'assurance du Canada
CAG	Cadre analytique de gouvernance (Hufty)
CatIQ	Catastrophe Indices and Quantification Inc.
CBCI	Community-Based Catastrophe Insurance
CMM	Communauté métropolitaine de Montréal
CPA	Comptable professionnel agréé
CPTAQ	Commission de protection du territoire agricole du Québec
CRD	Capital Regional District (pour la Colombie-Britannique, par analogie avec MRC)
CRS	Community Rating System (NFIP américain)
DFAA	Disaster Financial Assistance Arrangements (équivalent anglais des AAFCC)
DMA	Dommage annuel moyen d'un bâtiment (Average Annualized Damage)
ECCC	Environnement et Changement climatique Canada
ESCER	Centre pour l'étude et la simulation du climat à l'échelle régionale
FAAC	Fonds d'atténuation et d'adaptation en matière de catastrophes (Infrastructure Canada)
FAMQ	Fonds d'assurance des municipalités du Québec (anciennement MMQ)
Farciq	Fonds d'assurance responsabilité professionnelle du courtage immobilier du Québec
FEMA	Federal Emergency Management Agency (États-Unis)
FQM	Fédération québécoise des municipalités
GFAPRD	General Financial Assistance Program Regarding Disasters (PGAF en anglais)
GNDR	Global Network of Civil Society Organisations for Disaster Reduction
I.A.R.D. (IARD)	Incendie, Accidents et Risques Divers (assurance de dommages)
IBC	Insurance Bureau of Canada (équivalent anglais du BAC)
ICC	Institut climatique du Canada
IFoA	Institute and Faculty of Actuaries
IGIF	Inspecteur général des institutions financières (ancien nom de l'AMF)
IMFG	Institute on Municipal Finance and Governance (Université de Toronto)

IPCC	Intergovernmental Panel on Climate Change (Groupe d'experts intergouvernemental sur l'évolution du climat)
IRM	Integrated Risk Management (Gestion intégrée des risques)
ISE	Institut des sciences de l'environnement (possiblement, selon contexte des présentations)
LAU	Loi sur l’aménagement et l’urbanisme
LQE	Loi sur la qualité de l’environnement
LSCRS	Loi sur la sécurité civile visant à favoriser la résilience aux sinistres
MAMH	Ministère des Affaires municipales et de l'Habitation
MAMSL	Ministère des Affaires municipales, du Sport et du Loisir (ancien nom)
MAP	Maîtrise en administration publique (ÉNAP)
MELCC	Ministère de l’Environnement et de la Lutte contre les changements climatiques (ancien acronyme)
MELCCFP	Ministère de l’Environnement, de la Lutte contre les changements climatiques, de la Faune et des Parcs
MIABC	Municipal Insurance Association of B.C.
MMC	Montreal Metropolitan Community
MMQ	La Mutuelle des municipalités du Québec (maintenant FAMQ)
MRC	Municipalité régionale de comté
MSP	Ministère de la Sécurité publique (du Québec)
NBCC	National Building Code of Canada (Code national du bâtiment du Canada)
NFIP	National Flood Insurance Program (États-Unis)
OBV	Organisme de bassin versant
OECD	Organisation de coopération et de développement économique
OGAT	Orientations gouvernementales en aménagement du territoire
OPI	Ouvrage de protection contre les inondations
PGAF	Programme général d’indemnisation et d’aide financière lors de sinistres réels ou imminents (du Québec)
PGRI	Plan de gestion du risque d'inondations (par les MRC)
PIB	Produit intérieur rut
PNAC	Programme national d'atténuation des catastrophes
PNSC	Politique nationale de sécurité civile
PPP	Partenariat public-privé
PPRLPI	Politique de protection des rives, du littoral et des plaines inondables (abrogée)
RAMHHS	Règlement sur les activités dans des milieux humides, hydriques et sensibles

REAFIE	Règlement sur l'encadrement d'activités en fonction de leur impact sur l'environnement
REARMMH	Règlement sur l'encadrement d'activités sous la responsabilité des municipalités réalisées dans des milieux hydriques
RCI	Règlement de contrôle intérimaire (par les MRC)
RIISQ	Réseau Inondations InterSectoriel du Québec
ROPI	Règlement sur les ouvrages de protection contre les inondations
SADD	Schéma d'aménagement et de développement durable (par les MRC)
SFHA	Special Flood Hazard Area (NFIP américain)
SPC	Sécurité Publique Canada
STE	Savoirs traditionnels écologiques
TCM	Test du capital minimal (pour les assureurs)
TEAD	Taux d'exposition annuel aux dommages (pour une municipalité)
TEAM	Taux d'endommagement annuel moyen (pour un bâtiment)
TEIB	Taux d'endommagement par bâtiment
UMQ	Union des municipalités du Québec
UMRCQ	Union des municipalités régionales de comté et des municipalités locales du Québec (ancien nom)
UNDRR	United Nations Office for Disaster Risk Reduction (Bureau des Nations Unies pour la prévention des catastrophes)
UNEP	United Nations Environment Programme (Programme des Nations Unies pour l'environnement)
USACE	US Army Corps of Engineers
VFUM	Valeur Foncière Uniformisée Moyenne (possiblement, selon contexte du Chapitre 4)
WMO	World Meteorological Organization (Organisation Météorologique Mondiale)

RÉSUMÉ

Face au fardeau croissant des inondations fluviales au Québec et aux limites des mécanismes d'indemnisation actuels, cette thèse explore si une participation financière des municipalités à ces mécanismes pourrait les inciter à renforcer leur rôle dans la réduction du risque. L'hypothèse centrale est que l'absence actuelle de cette participation freine les initiatives locales de réduction du risque. La littérature néglige souvent le rôle des municipalités dans ce partage des coûts. Cette recherche comble donc une lacune en examinant l'impact potentiel d'une participation financière sur l'internalisation des coûts du risque et sur le renforcement des incitatifs municipaux en gestion du risque d'inondations.

Structurée autour d'un chapitre établissant le cadre conceptuel et de quatre articles de recherche, la thèse analyse d'abord la gouvernance et les failles incitatives des systèmes d'aide post-catastrophes actuels, notamment par une comparaison des modèles du Québec et de la Colombie-Britannique. Elle identifie ensuite les facteurs contributifs aux dommages résidentiels relevant de l'influence municipale, grâce à des entrevues semi-structurées auprès de 45 experts en estimation des dommages. Un modèle innovant de contribution municipale proportionnelle au risque, s'appuyant sur des estimés de dommages basés sur les courbes de submersion-dommages, est ensuite proposé. En dernier lieu, la faisabilité et l'acceptabilité de cette contribution sont évaluées auprès de 35 acteurs et experts du monde municipal québécois.

Cette démarche en quatre temps permet une meilleure compréhension des défis liés à la gestion du risque d'inondations par les municipalités québécoises. L'analyse des mécanismes de gouvernance et des systèmes d'aide post-catastrophes discutés au chapitre 2 met en lumière des failles incitatives structurelles qui limitent l'engagement municipal proactif, confirmant la complexité d'une action concertée entre les différents paliers de gouvernement. En identifiant les facteurs contributifs aux dommages résidentiels sous l'influence municipale, le chapitre 3 identifie les leviers d'action potentiels, tout en soulignant les contraintes liées aux aménagements hérités et aux limites perçues du pouvoir municipal.

Quant à l'instauration d'une contribution financière directe, le chapitre 5 révèle un scepticisme marqué des municipalités, infirmant en partie l'hypothèse d'un effet incitatif simple. Les préoccupations soulevées, telles que la complexité de mise en œuvre du modèle proposé au chapitre 4, les contraintes d'aménagement héritées et les limites perçues du pouvoir d'action municipal, convergent vers la nécessité d'explorer des alternatives. Celles-ci pourraient inclure un soutien conditionnel ou des incitatifs non-financiers pour responsabiliser les municipalités sans les pénaliser. Cette thèse contribue ainsi à une

compréhension nuancée des leviers d'action pour une gestion municipale plus proactive et durable du risque d'inondations, tout en enrichissant la littérature sur l'efficacité des mécanismes de partage des risques en contexte de changements climatiques.

Mots-clés : Inondations, municipalités, gouvernance, facteurs contributifs, incitatifs, partage des coûts.

ABSTRACT

Given the growing burden of river flooding in Quebec and the limitations of current compensation mechanisms, this thesis explores whether financial participation by municipalities in these mechanisms could encourage them to strengthen their role in risk reduction. The central hypothesis is that the current lack of such participation hinders local risk reduction initiatives. The literature often overlooks the role of municipalities in this cost-sharing. This research fills a gap by examining the potential impact of financial participation on the internalization of risk costs and on strengthening municipal incentives for flood risk management.

Structured around a chapter establishing the conceptual framework and four research articles, the thesis first analyzes the governance and incentive flaws of current post-disaster assistance systems, notably through a comparison of the Quebec and British Columbia models. It then identifies the factors contributing to residential damage within the municipal sphere of influence, based on semi-structured interviews with 45 damage assessment experts. An innovative model of municipal contribution proportional to risk, based on damage estimates using flood-damage curves, is then proposed and empirically evaluated for feasibility and acceptability among 35 municipal stakeholders and experts in Quebec.

The results of this thesis provide a deeper understanding of the challenges faced by Quebec municipalities in flood risk management. The analysis of governance mechanisms and post-disaster assistance systems (Chapter 2) highlights structural incentive flaws that limit proactive municipal engagement, confirming the complexity of coordinated action between different levels of government. By identifying factors contributing to residential damage under municipal influence (Chapter 3), the research pinpoints potential levers for action while highlighting constraints related to legacy developments and perceived limits to municipal power.

As for the introduction of a direct financial contribution, Chapter 5 reveals marked skepticism on the part of municipalities, partly refuting the hypothesis of a simple incentive effect. The concerns raised, such as the complexity of implementing the proposed model (Chapter 4), legacy development constraints, and perceived limits to municipal power, point to the need to explore alternatives. These could include conditional support or non-financial incentives to empower municipalities without penalizing them. This thesis thus contributes to a nuanced understanding of the levers for more proactive and sustainable municipal flood risk management while enriching the literature on the effectiveness of risk-sharing mechanisms in the context of climate change.

Keywords: Floods, municipalities, governance, contributing factors, incentives, cost sharing.

INTRODUCTION

Le risque lié aux événements hydrométéorologiques extrêmes, notamment les inondations, s'intensifie avec l'accélération des changements climatiques et est classé parmi les préoccupations majeures à court et long termes à l'échelle mondiale (Intergovernmental Panel on Climate Change, 2023 ; World Meteorological Organization, 2025). En effet, le Global Risks Report 2025 place les événements hydrométéorologiques au 2^{e} rang des risques les plus graves à court terme, et au 1er rang dans une perspective de dix ans. L'augmentation du nombre et de l'intensité des inondations fluviales et pluviales à travers le monde est une tendance préoccupante qui devrait s'accentuer au cours des prochaines décennies (World Economic Forum, 2025). L'Institute and Faculty of Actuaries (IFoA) met même en garde contre un risque « d'insolvabilité planétaire » si des mesures urgentes ne sont pas prises pour contrer le réchauffement climatique, avec des pertes potentielles de 50 % du Produit Intérieur Brut (PIB) mondial entre 2070 et 2090 (Trust *et al.*, 2025).

L'intensification de ces événements météorologiques extrêmes (vagues de chaleur, tempêtes, inondations), conjuguée au vieillissement des infrastructures, à l'augmentation de l'exposition (Grant *et al.*, 2025) et de la vulnérabilité socio-environnementales complexifient considérablement l'évaluation de l'efficacité des mécanismes de protection financière et des mesures de réduction du risque (O'Connor *et al.*, 2023 ; United Nations Environment Programme, 2023 ; United Nations Office for Disaster Risk Reduction, 2022). Les incertitudes scientifiques, l'interdépendance des risques et les facteurs socio-économiques ajoutent à cette complexité, rendant difficile la prévision des coûts futurs (United Nations Development Programme, 2020) et constitue le principal problème qui conduit différentes régions du monde vers des points de basculement de la non-assurabilité (United Nations Environment Programme, 2023).

À l'instar des autres pays nordiques, le réchauffement climatique observé (au cours des sept dernières décennies) au Canada est en moyenne le double du réchauffement mondial (Bush et Lemmen, 2019). Le Québec est particulièrement concerné par les changements climatiques, notamment en raison de l'étendue de son territoire et de l'importance de son vaste réseau hydrographique. Le Québec est ainsi exposé, voire sensible ou vulnérable face à l'augmentation anticipée des précipitations annuelles (Ogden et Gachon, 2019 ; Zhang *et al.*, 2019), et à l'intensification des extrêmes horaires et quotidiens de précipitation (Cannon et Innocenti, 2019).

Cette sensibilité accrue aux aléas climatiques entre directement en conflit avec les schémas historiques d'occupation du territoire (Cao *et al.*, 2022). En effet, l'expansion historique des villes et villages s'est souvent faite à proximité des cours d'eau, attirant résidences, commerces et infrastructures le long des rives (Andrews, 1993). Cette proximité, combinée à l'augmentation attendue des débits de pointe ou des pluies intenses, accroît la vulnérabilité de nombreuses communautés québécoises face aux inondations. Cette vulnérabilité touche les infrastructures municipales essentielles (routes, réseaux d'aqueduc et d'égout), les activités économiques et particulièrement les bâtiments résidentiels concentrés dans ces zones historiquement développées (Hudson et Berghäuser, 2023 ; Sécurité Publique Canada, 2022 ; Thomas et Fakiroff, 2024).

L'augmentation des dommages : une problématique multifactorielle

L'augmentation importante du coût des dommages causés par les inondations constitue un défi majeur (Chakraborty *et al.*, 2020 ; Mayer-Jouanjean et Bleau, 2018). Cette croissance des dommages est le résultat d'une interaction complexe de facteurs. D'une part, les facteurs climatiques et hydrométéorologiques se manifestent par des événements météorologiques extrêmes de plus en plus fréquents et sévères, incluant des précipitations intenses tout au long de l'année et des pluies diluviennes de courte durée en milieu urbain (Carvalho, 2018 ; Intergovernmental Panel on Climate Change, 2022 ; Reinhart *et al.*, 2025 ; Yan *et al.*, 2024). Ces phénomènes engendrent des débordements de rivières, des ruissellements et des crues pluviales soudaines, touchant aussi des territoires éloignés des cours d'eau, un risque souvent sous-estimé (Faytre, 2023 ; Prokešová *et al.*, 2022 ; Yan *et al.*, 2024). La superposition de ces aléas avec d'autres (ex: tempêtes hivernales) ou la rupture d'infrastructures vieillissantes exacerbe également les conséquences de ces événements (Bush et Lemmen, 2019 ; Lulham *et al.*, 2023).

D'autre part, les facteurs anthropiques jouent un rôle prépondérant. Le développement résidentiel continu dans les plaines inondables, souvent non désignées, pour répondre à la croissance démographique et économique, est l'un des principaux contributeurs à l'accroissement des dommages (Cottar *et al.*, 2021 ; Golnaraghi *et al.*, 2020 ; Lorinc, 2022 ; Sécurité Publique Canada, 2024 ; Ward *et al.*, 2020a). Cette occupation des plaines inondables, historiquement favorisée par l'expansion urbaine autour des cours d'eau (Andrews, 1993 ; Cao *et al.*, 2022 ; Sécurité Publique Canada, 2022), est directement liée aux rôles des municipalités. La croissance démographique québécoise (+9,3% entre 2017 et 2024), l'inflation des coûts de construction (+86,7% sur la même période au Canada) et la hausse des prix du marché immobilier augmentent significativement la valeur des bâtiments à risque et, par conséquent le coût du rétablissement post-inondation (Statistique Canada, 2025a, 2025b, 2025c, 2025d). S'y ajoutent la dégradation des milieux naturels, le vieillissement de la population (+27,7% des 65 ans et plus au Canada entre 2017 et 2024), et un important déficit d'infrastructures (Rowe et Chapple, 2025), qui augmentent la vulnérabilité générale aux catastrophes.

Les conséquences économiques : un fardeau croissant et un déficit de protection

Ces facteurs se traduisent par une augmentation fulgurante des coûts économiques liés au rétablissement post-inondations (toutes les valeurs monétaires sont exprimées en dollars courants). Le coût annuel des Accords d'aide financière en cas de catastrophes (AAFCC) du gouvernement fédéral a bondi de 54 millions de dollars (1970-1994) à 2,1 milliards de dollars annuellement en 2021-2022. Environ 75% des indemnisations des AAFCC sont attribuables aux inondations (Bureau du Directeur Parlementaire du Budget, 2016, 2022 ; Honegger et Oehy, 2016). Des études récentes estiment les dommages annuels moyens aux propriétés résidentielles canadiennes à environ 1,4 milliard de dollars (Morin *et al.*, 2025), voire 2,97 milliards de dollars, dont 861,3 millions pour le Québec selon Sécurité Publique Canada (2022). Ces projections sont d'autant plus réalistes que les pertes assurées au Québec ont totalisé 2,7 milliards de dollars en 2024 pour l'ensemble des aléas (Bureau d'assurance du Canada, 2025 ; Floyd, 2025), dépassant le record de la tempête de verglas de 1998. Pourtant, ces montants assurés ne représentent qu'une fraction (entre 25% et 60%) des dommages totaux (Honegger et Oehy, 2016 ; Lee et Parfitt, 2022 ; Moudrak *et al.*, 2018).

Au Québec, les sinistrés doivent supporter une part de plus en plus lourde des coûts de réparation (Sécurité Publique Canada, 2022). L'introduction d'une limite à vie sur les inondations successives dans le programme d'assistance financière du gouvernement provincial depuis avril 2019 contribue à ce phénomène (Boudreault et Bourdeau-Brien, 2020 ; Gouvernement du Québec, 2025a). De plus, les assureurs privés sont quasi absents de l'assurance contre les inondations fluviales et offrent des protections limitées pour d'autres types de dommages par l'eau (Boudreault, 2021b). Certains assureurs ont même cessé d'offrir toute forme de protection contre les inondations dans des territoires spécifiques (Laurie, 2024 ; Spector, 2024). Les garanties limitées offertes par les assureurs et la remise en question des programmes d'aide gouvernementaux mènent à un déficit de protection financière croissant (Bernhardt *et al.*, 2020 ; Global Federation Insurance Association, 2023 ; Talo, 2024), correspondant à l'écart entre les dommages réels et les ressources financières disponibles pour les couvrir (Feinman, 2021).

Les mécanismes actuels de protection financière publics et privés qui permettent d'indemniser les sinistrés soulèvent la question du manque d'incitation à réduire le risque, ce qui est qualifié de risque moral (Sécurité Publique Canada, 2022) ou encore d'aléa moral (Davlasheridze et Miao, 2021 ; Hudson et Berghäuser, 2023 ; Kousky, 2018). L'aléa moral, à ne pas confondre avec l'aléa climatique, survient lorsqu'un acteur (par exemple, une municipalité) prend des décisions risquées, comme permettre la construction en zone inondable, en sachant que les conséquences négatives (par exemple, le coût des réparations) seront supportées par d'autres (Laffont et Martimort, 2002b). L'enjeu majeur est que la société approche ou dépasse le point où le risque socio-économique devient un risque social, où ni le privé ni l'État ne peuvent plus offrir une protection financière adéquate face aux catastrophes (Chaire Pari, 2024).

Dans ce contexte, la population du Québec fait face aux limites manifestes des mécanismes actuels de protection financière. Considérant les responsabilités importantes (mais parfois sous-financées) dévolues aux municipalités en matière de réduction du risque d'inondations, la problématique centrale de cette thèse s'intéresse au rôle effectif et potentiel des municipalités québécoises dans la gestion du risque d'inondations. Partant de l'hypothèse clé que l'absence de contribution financière directe de ces dernières aux coûts d'indemnisation freine leurs initiatives de prévention, cette recherche explore comment une meilleure répartition des responsabilités financières pourrait lever cet obstacle et améliorer la gouvernance du risque. Ce faisant, cette recherche vise à combler une lacune dans la compréhension des leviers d'action municipaux et à éclairer les politiques publiques pour une gestion plus responsable, équitable et efficace du risque d'inondations fluviales au Québec. Plus spécifiquement, cette recherche vise à mieux comprendre les mécanismes de gouvernance en jeu et à identifier les facteurs contribuant aux dommages, ainsi que les leviers d'action municipaux pour les réduire. Elle analyse également des modèles de partage de risque incluant une contribution municipale, puis évalue la faisabilité et l'acceptabilité de cette approche. Pour ce faire, cette thèse par articles s'articule autour de cinq chapitres et d'une conclusion générale.

Structure de la thèse

Le premier chapitre clarifie d'abord les concepts essentiels relatifs au phénomène des inondations, à la nature du risque et aux facteurs contributifs. Ensuite, la gouvernance incluant le cadre légal et institutionnel définissant les rôles des acteurs est examiné, ainsi que les dimensions humaines et comportementales qui modulent la gestion de ce risque. Une analyse critique des principaux mécanismes de partage du risque financier existants, au Canada comme à l'international, est également présentée. Cette démarche fondamentale permet de mettre en lumière des lacunes significatives dans les approches actuelles de protection et de gestion du risque par les municipalités, et conduit logiquement aux objectifs, questions de recherche et contributions attendues de cette étude.

Les chapitres 2 à 5 explorent un aspect spécifique de la gestion du risque d'inondations par les municipalités du Québec. Le chapitre 2 inclut un article publié par l'Institute on Municipal Finance and Governance (IMFG) de l'Université de Toronto. Cet article analyse les mécanismes de gouvernance et d'aide financière en cas de catastrophe, et vise à identifier les obstacles à la réduction du risque d'inondations au niveau municipal. Il s'appuie sur une analyse comparative des pratiques et des politiques en Colombie-Britannique et au Québec, et vise à identifier les leviers d'action des municipalités.

Le chapitre 3 inclut un article publié dans la revue International Journal of Disaster Risk Reduction. Cet article analyse les facteurs contributifs aux dommages causés par les inondations aux bâtiments résidentiels, et permet d'identifier les leviers d'action dont disposent les municipalités pour réduire les dommages économiques. Il s'appuie sur une série d'entrevues semi-structurées auprès de 45 experts en estimation des dommages, et d'un sondage auprès de ces mêmes experts de manière à prioriser les facteurs identifiés lors des entrevues.

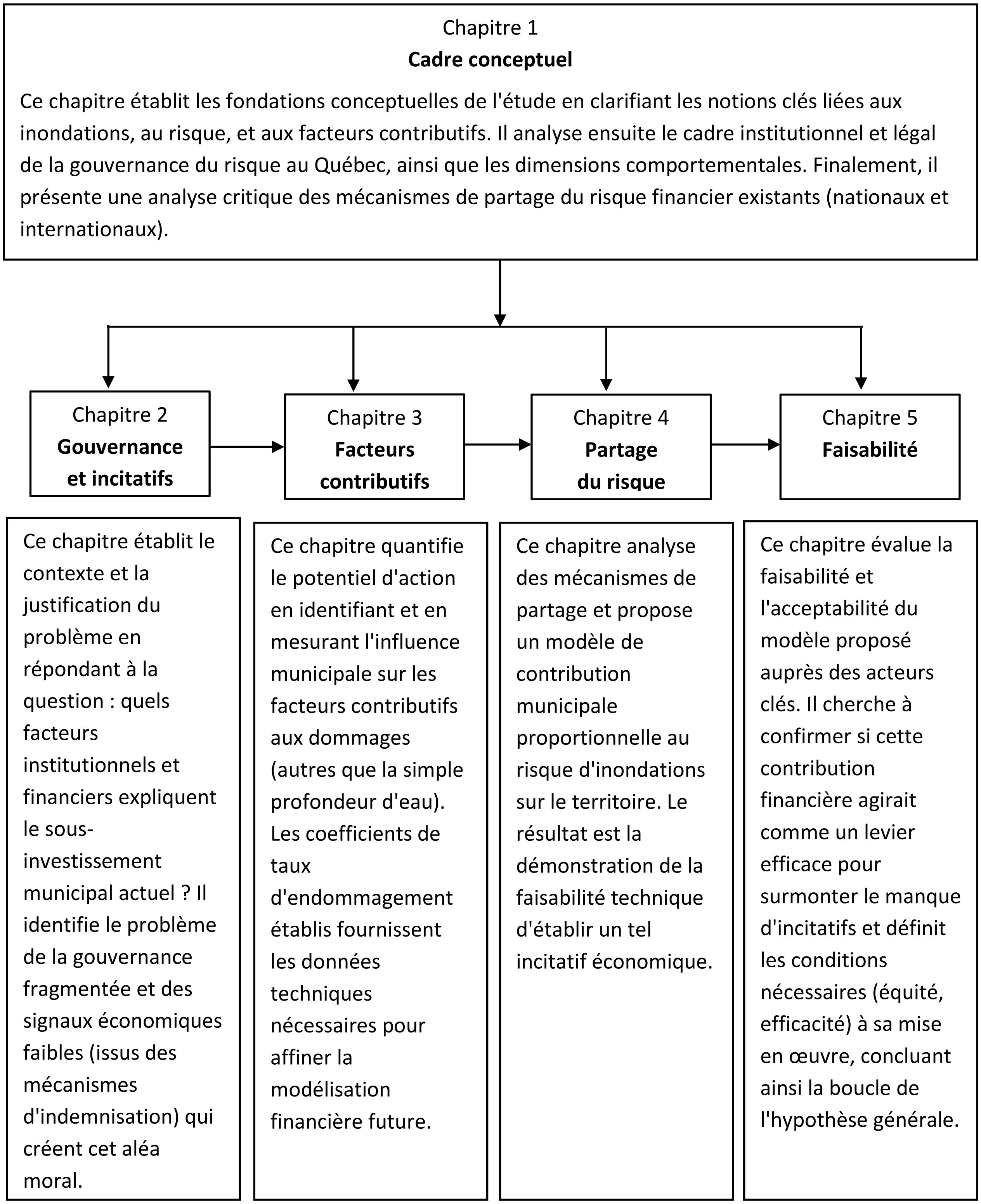
Le chapitre 4 inclut un article publié par l'Institute on Municipal Finance and Governance (IMFG) de l'Université de Toronto. Cet article explore divers mécanismes de partage du risque financier, et vise à déterminer comment les municipalités pourraient contribuer financièrement à ces mécanismes. Il s'appuie à la fois sur une revue de littérature concernant les mécanismes de partage de risque, et sur une méthodologie d'estimation des dommages basée sur des courbes de submersion-dommage.

Enfin, le chapitre 5 présente un article soumis le 14 mai 2025 chez Canadian Water Resources Journal. Il explore la faisabilité d'une contribution municipale au partage du coût des dommages, et permet de déterminer le caractère incitatif de cette contribution sur la gestion du risque par les municipalités. Il s'appuie sur une série d'entrevues semi-structurées auprès de 35 représentants du monde municipal et spécialistes en politiques publiques.

La conclusion générale synthétise et intègre les principaux résultats issus des quatre chapitres (2 à 5), apportant une réponse nuancée à la question de recherche centrale. Elle met en évidence les contributions originales de la thèse – sur les plans théorique, méthodologique et pratique – notamment en termes de nouvelles connaissances et de démarches proposées pour la gestion du risque. Pour terminer, après avoir discuté des implications des résultats et des limites de l'étude, elle formule des recommandations concrètes pour les politiques publiques et suggère des pistes pour les recherches futures.

En résumé, cette étude contribue à une meilleure compréhension des défis et des opportunités liés à la gestion du risque d'inondations par les municipalités. Elle propose également des pistes de solution pour améliorer la résilience des communautés face aux inondations fluviales, en combinant des approches théoriques, empiriques et pratiques. La figure 1.1 présente les liens entre les différents chapitres.

Figure 1- Interdépendance des chapitres



CHAPITRE 1
CADRE D'ANALYSE DU RISQUE D'INONDATIONS ET DE SON PARTAGE FINANCIER : ENJEUX ET OBJECTIFS POUR LES MUNICIPALITÉS QUÉBÉCOISES

Ce chapitre introductif pose les fondements de l'étude sur la gestion du risque d'inondation face aux changements climatiques au Canada et au Québec. Il débute par une définition de l'aléa inondation, le concept de risque et les facteurs qui exacerbent les dommages. La gouvernance et le cadre légal de la gestion du risque sont examinés, détaillant les principes, la répartition des rôles intergouvernementaux et les évolutions réglementaires récentes. Les dimensions humaines et comportementales sont également abordées, pour comprendre l'influence de la perception du risque, de l'attachement au territoire et de l'absence d'incitatif sur les décisions. Une analyse des mécanismes de partage du risque financier (assurance privée et publique) est ensuite présentée, s'appuyant sur des études de cas internationales et canadiennes pour en tirer des leçons pertinentes pour une participation financière municipale structurée. Le chapitre se termine par la présentation des objectifs de recherche, formulés en réponse directe aux lacunes et besoins identifiés.

1.1 Comprendre le phénomène des inondations

Le Québec, avec son vaste réseau hydrographique et ses variations climatiques saisonnières majeures marquées par une longue phase solide de l'eau qui permet de stocker d'important volume d'eau disponible lors de la phase de dégel au printemps, est particulièrement exposé au risque d'inondations. Cette section définit comment les inondations fluviales se distinguent des autres types d'inondations par leur lien direct avec le débordement des cours d'eau. Les concepts clés liés au risque d'inondations (aléa, exposition et vulnérabilité) sont également expliqués afin d'en clarifier le sens donné à chacun d'entre eux lors de leur utilisation dans les prochains chapitres.

1.1.1 Types d'inondations

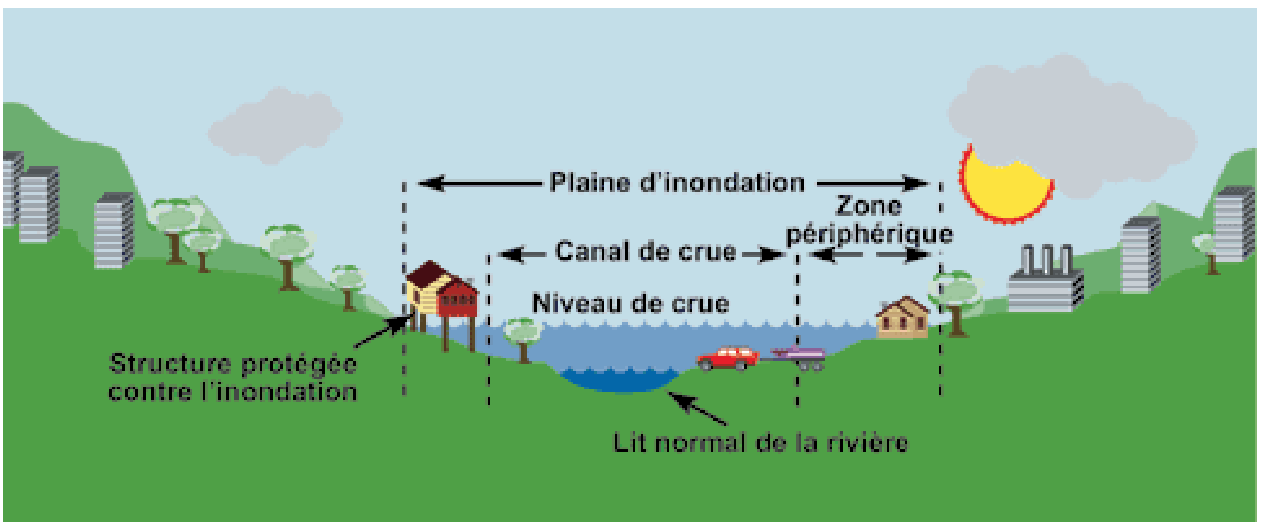
Les inondations, définies de manière générale comme une accumulation d'eau dans des zones qui ne sont pas normalement submergées (Intergovernmental Panel on Climate Change, 2012b, 2022), peuvent être classées en diverses catégories. Les inondations fluviales résultent du débordement d'un cours d'eau lors de crues. Les inondations pluviales, découlent de précipitations abondantes et souvent intenses qui excèdent la capacité d'infiltration des sols et d'évacuation des réseaux d'assainissement, provoquant un ruissellement de surface rapide (Al-Rawas *et al.*, 2024). Leur fréquence et leur gravité sont d'ailleurs susceptibles d'être accrues par l'augmentation de l'intensité des précipitations extrêmes liée aux changements climatiques (Intergovernmental Panel on Climate Change, 2021a). Les inondations par embâcle de glace surviennent lorsque des amoncellements de glace qui peuvent obstruer l'écoulement normal de l'eau au sein d'un cours d'eau, causant des montées des eaux en amont et potentiellement des vagues subites lors de la débâcle, endommageant berges et infrastructures (Belore *et al.*, 1990 ; Beltaos, 2007 ; Turcotte *et al.*, 2017). Un autre type d'inondation est celle provoquée par une rupture d'ouvrage, comme un barrage ou une digue, qui se caractérise par la libération soudaine et souvent dévastatrice d'importants volumes d'eau (Alvi et Alvi, 2023 ; ASCE/EWRI, 2011 ; Federal Emergency Management Agency (FEMA), 2013). Les inondations côtières, aussi appelées submersions marines, correspondent à une élévation anormale du niveau de la mer. Elles sont générées par la combinaison de phénomènes météorologiques, tels que le vent qui pousse l'eau vers la côte (pente hydraulique) et génère des vagues, ainsi que l'effet de baromètre inversé (une basse pression atmosphérique provoquant une hausse locale du niveau de l'eau). À ces facteurs s'ajoute l'augmentation continue du niveau marin due au réchauffement des océans, principalement causée par la dilatation thermique de l'eau, et la fonte des glaciers continentaux (Didier, 2020 ; Institute for Catastrophic Loss Reduction, 2020 ; Intergovernmental Panel on Climate Change, 2012b ; Word Meteorological Organization, 2011a). Enfin, les inondations par remontée de nappe se produisent lorsque le niveau de la nappe phréatique, souvent saturée par des précipitations prolongées ou une fonte des neiges importante, monte jusqu'à affleurer à la surface du sol, provoquant des inondations lentes mais pouvant durer plusieurs semaines (Morrissey *et al.*, 2021 ; Robins et Finch, 2012 ; Upton et Jackson, 2011).

Afin d'adapter les mesures de gestion des risques aux réalités locales, il est important de distinguer les types d'inondations, puisque leurs mécanismes de formation spécifiques commandent des interventions municipales différentes. Par exemple, les inondations fluviales nécessitent des digues ou des systèmes d'alerte hydrologique, tandis que les inondations pluviales exigent l'amélioration du drainage urbain. Les inondations côtières, elles, appellent la protection du littoral et des alertes aux ondes de tempête. Cette recherche se concentre sur les inondations fluviales en raison du cadre légal et réglementaire québécois bien établi pour cet aléa, ainsi que la disponibilité d'outils d'estimation des dommages aux bâtiments résidentiels.

1.1.2 Inondations fluviales

Une inondation fluviale survient lorsque le débit d'un cours d'eau (ruisseau, rivière, fleuve) excède la capacité de son lit mineur, conduisant à un débordement où l'eau s'élève au point d'inonder les terres adjacentes (Bourgault *et al.*, 2022 ; Word Meteorological Organization, 2011c). Ces terres inondées constituent la plaine inondable, définie comme une zone généralement de faible altitude par rapport aux cours d'eau et adjacente à un cours d'eau, naturellement sujette aux inondations périodiques et faisant partie intégrante de l'écosystème fluvial. Ces plaines connaissent des cycles de hauts et de bas niveaux d'eau, tant sur de longues périodes que de manière saisonnière (Environnement Canada, 2009). Les submersions les plus importantes se produisent souvent dans la section principale d'écoulement où l'eau circule le plus rapidement. La figure 1.1 illustre une plaine inondable et ses caractéristiques.

Figure 1-1 Plaine inondable



Source : https://www.canada.ca/fr/environnement-changement-climatique/services/eau-apercu/volume/inondations/renseignements-generaux.html (Environnement Canada, 2009)

Les inondations fluviales se manifestent principalement de deux manières. D'une part, les crues lentes et progressives, qui résultent typiquement de précipitations modérées mais persistantes ou de la fonte graduelle du manteau neigeux sur de vastes bassins versants. Ces crues lentes permettant une certaine anticipation malgré une durée d'inondation potentiellement longue. D'autre part, les crues rapides sont souvent provoquées par des précipitations intenses et concentrées sur une période plus courte, ou par la rupture soudaine d'un obstacle naturel (comme un embâcle de glace ou de débris) ou artificiel (tel qu'un barrage). Elles affectent surtout les petits et moyens bassins versants, notamment en régions montagneuses ou à forte pente, et se caractérisent par une montée des eaux brutale laissant peu de temps pour l'alerte (Ward et Robinson, 2000).

L'occurrence, l'ampleur et la durée des inondations fluviales dépendent d'une interaction complexe de plusieurs facteurs. Les caractéristiques du bassin versant, telles que sa taille, sa forme, sa pente, son type de couverture végétale et sa capacité de stockage de l'eau, jouent un rôle déterminant sur la vitesse et le volume du ruissellement. De même, la morphologie du lit du cours d'eau et de sa plaine d'inondation (largeur, profondeur, sinuosité, présence de méandres, rugosité et occupation du sol) influence directement la vitesse d'écoulement et l'étendue de la zone submergée. Un lit endigué ou artificialisé peut d'ailleurs exacerber les inondations en amont ou en aval. Les conditions hydrométéorologiques, notamment l'intensité, la durée et la répartition spatiale des précipitations ainsi que les conditions de température favorisant la fonte des neiges, sont également des éléments déclencheurs. Enfin, les activités humaines, comme l'urbanisation et l'imperméabilisation des sols, certaines pratiques agricoles, la déforestation, la rectification des cours d'eau, la construction en plaine inondable, ou encore une mauvaise gestion des ouvrages hydrauliques peuvent modifier significativement le régime des crues et aggraver considérablement les risques d'inondation (Word Meteorological Organization, 2011b).

1.1.3 Définition et composantes du risque d'inondations

Selon le Groupe d'experts intergouvernemental sur l'évolution du climat (Intergovernmental Panel on Climate Change, 2021b), le risque est la possibilité que des conséquences négatives surviennent pour les systèmes humains ou les écosystèmes. Dans le contexte du changement climatique, ces risques peuvent provenir des impacts potentiels de ces changements, mais aussi des réponses humaines face à ces derniers. Ces conséquences négatives peuvent affecter divers aspects, tels que la vie humaine, les moyens de subsistance, la santé et le bien-être ; les biens matériels et les investissements économiques, sociaux et culturels ; les infrastructures et les services ; ainsi que les écosystèmes eux-mêmes et les espèces qui les composent.

Le risque d'inondations est la résultante de l'interaction entre l'aléa, l'exposition et la vulnérabilité (Chakraborty *et al.*, 2022 ; Cutter *et al.*, 2013 ; Oppenheimer *et al.*, 2014). Un aléa est un événement ou une activité, naturelle ou humaine, qui entraîne des conséquences néfastes sur les personnes, les biens et l'environnement. Ces conséquences incluent les pertes humaines, les impacts sur la santé, les dommages matériels et les perturbations socio-économiques. Les aléas couvrent un large spectre de phénomènes, des risques naturels aux risques technologiques et sociétaux (United Nations Office for Disaster Risk Reduction, 2022). L'aléa inondation est caractérisé par des paramètres tels que la hauteur d'eau, la vitesse du courant, l'étendue de la zone inondée, la durée de l'inondation et la fréquence de l'événement. L'aléa inondation est aussi influencé par des facteurs naturels (précipitations, fonte des neiges, tempêtes) et anthropiques, tels que les changements climatiques, l'urbanisation, la déforestation, et la modification des cours d'eau (Al-Rawas *et al.*, 2024 ; Bush et Lemmen, 2019 ; Carvalho, 2018).

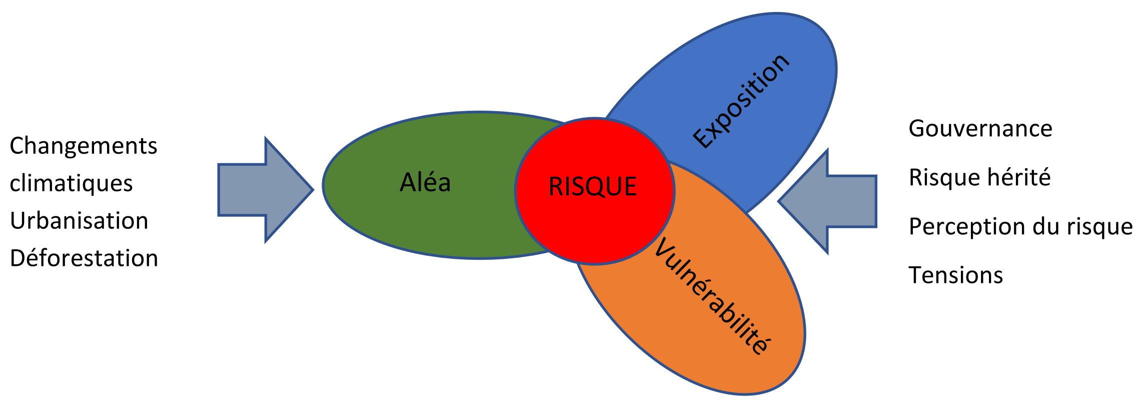
L'exposition représente la présence d'éléments (personnes, biens, infrastructures, activités économiques, écosystèmes) susceptibles d'être affectés par l'inondation. Elle est quantifiée par la valeur monétaire des actifs exposés, mais peut aussi inclure des aspects non monétaires tels que le nombre de personnes touchées, la valeur patrimoniale des biens culturels, ou la valeur écologique des écosystèmes (Balica *et al.*, 2012 ; United Nations Office for Disaster Risk Reduction, 2022).

La vulnérabilité se définit comme étant la propension des éléments exposés à subir des dommages en cas d'inondations. Elle dépend des caractéristiques intrinsèques de ces éléments (par exemple, la conception des bâtiments, la nature des activités économiques, la capacité d'évacuation des populations) et de leur capacité d'adaptation et de résilience. La vulnérabilité est influencée par des facteurs socio-économiques, institutionnels, culturels et environnementaux (Messner et Meyer, 2006 ; United Nations Office for Disaster Risk Reduction, 2022). La résilience est la capacité d'une communauté exposée aux inondations de s'adapter, en résistant ou en se transformant, pour établir et maintenir un niveau de fonctionnement acceptable (Gouvernement du Québec, 2025c).

L'aléa, l'exposition et la vulnérabilité sont en grande partie le résultat de choix socio-économiques et sociopolitiques (Oppenheimer *et al.*, 2014). Ainsi, les municipalités peuvent agir directement sur ces trois composantes, par exemple, en optimisant l'utilisation de la nature pour réduire le ruissellement (aléa), en réduisant la construction en zone inondable (exposition) et en appliquant des normes de construction strictes (vulnérabilité). De même, ces composantes sont directement liées au chapitre 3 qui traite des facteurs contributifs aux dommages et au chapitre 4 qui intègre ces trois composantes dans l'estimation des dommages potentiels aux bâtiments résidentiels. Ainsi, la définition du risque d'inondations dans le cadre de cette thèse intègre les trois composantes. La figure 2 illustre la relation entre les trois composantes du risque d’inondations.

Le Bureau des Nations Unies pour la réduction des risques de catastrophes (UNDRR) souligne qu’il est tout aussi important de prendre en compte le contexte socio-économique et le fait que la perception des risques et des facteurs sous-jacents (par exemple, l’attachement au territoire) n'est pas forcément la même pour tout le monde. Un risque peut être jugé acceptable ou admissible en fonction de la situation sociale, économique, politique, culturelle, technique et environnementale d'une société. Le risque se construit donc socialement et chaque société définit des niveaux acceptables ou inacceptables de risque. Le risque devient encore plus subjectif lorsque des pertes de vies humaines font partie de l’équation (United Nations Office for Disaster Risk Reduction, 2016).

Figure 1-2 Composantes du risque



Adaptation de « Illustration of the core concepts of Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) ». Figure SPM.1 (Intergovernmental Panel on Climate Change, 2012b).

1.1.4 Facteurs contributifs aux dommages et leur évaluation

La littérature scientifique souligne que l'évaluation économique des pertes potentielles dues aux inondations, conjuguée à une compréhension approfondie des facteurs qui contribuent aux dommages, constitue un levier important pour inciter les municipalités à prioriser la réduction des coûts associés à ces sinistres (Hlinkova et Espinosa, 2023 ; Kreibich et Thieken, 2008 ; Paulik *et al.*, 2023 ; Rehan, 2018). Dans cette optique, Tanguy *et al.* (2022) insistent sur la nécessité d'intégrer une diversité de facteurs contributifs qui affectent l'aléa (comme la durée de l'événement), l'exposition des biens (telle que leur valeur en zone inondable) et la vulnérabilité physique (par exemple, le type de construction). À l'instar de nombreux autres auteurs (ex : Amirebrahimi *et al.*, 2016 et De Risi *et al.*, 2013), Shrestha *et al.* (2021) relèvent que sans une telle intégration, les estimations des dommages matériels directs, quel que soit l'outil utilisé, peuvent être contestées, limitant ainsi leur pertinence lorsqu'il s'agit de justifier des mesures de réduction du risque au niveau de la propriété.

Corroborant cette perspective, Aribisala *et al.* (2022), après avoir passé en revue les méthodologies d'estimation des dommages à micro-échelle, concluent que les modèles d'estimation (y compris ceux basés sur des courbes de submersion-dommages) qui ne considèrent qu'un nombre limité de paramètres explicatifs sont inadéquats pour rendre compte de la complexité des dommages aux bâtiments. Ces modèles doivent impérativement capturer d'autres facteurs pertinents. Ces auteurs préconisent également une approche méthodologique combinant données empiriques et synthétiques pour le développement d'outils d'estimation plus fiables. Cette exigence de rigueur se reflète dans les cadres internationaux, tel que le Cadre de Sendai pour la réduction des risques de catastrophe, qui recommande des évaluations du risque d'inondations robustes, impliquant une analyse multidimensionnelle des facteurs contributifs, pour développer et mettre en œuvre des stratégies efficaces de réduction du risque (Amadio *et al.*, 2019).

La littérature continue de mettre en évidence l'importance de facteurs additionnels, tels que ceux liés à l'aléa (Galasso *et al.*, 2021 ; Merz *et al.*, 2013), aux caractéristiques des bâtiments (Kaoje *et al.*, 2021 ; Paulik *et al.*, 2023) ou aux comportements humains (Duhamel *et al.*, 2022 ; Köhler *et al.*, 2023) pour expliquer la variabilité des dommages réels et affiner les évaluations. Néanmoins, l'incertitude associée à ces facteurs demeure élevée (Shrestha *et al.*, 2021 ; Thieken *et al.*, 2005) et limite leur application pour justifier des mesures d'atténuation ciblées (Wagenaar *et al.*, 2016). Par conséquent, développer une compréhension approfondie des facteurs contributifs aux dommages, particulièrement ceux relevant de l'action municipale, apparaît comme une nécessité. Le chapitre 3 vise justement cette identification et priorisation.

1.1.4.1 Analyse des facteurs contributifs

Merz *et al.,* (2013) ont confirmé la hauteur de submersion comme étant le facteur le plus décisif dans l'explication du taux d'endommagement dans le cadre d'une étude qui s'appuie sur 2158 entrevues post-inondation. Les auteurs ont utilisé des arbres de décision pour établir des corrélations entre vingt-huit (28) différents facteurs et le taux d'endommagement. Les auteurs reconnaissent l'importance de facteurs contributifs tels que : 1) la valeur du bâtiment et l'empreinte au sol ; 2) la distance du bâtiment d'un cours d'eau; 3) la turbidité des eaux ; 4) la durée de l'événement; et 5) le débit et la vitesse de la montée des eaux. Les auteurs soulignent également l'importance des équipements de protection tels que les drains français, systèmes de captation des eaux, sacs de sable, imperméabilisation des solages, clapets antiretour et pompes de submersion. Cependant, ils émettent une réserve quant à leur efficacité en raison des comportements humains liés à leur utilisation (entretien, expérience et disponibilité). Duhamel *et al.* (2022) vont dans le même sens en soulignant que l'âge et le statut du résident sont des variables déterminantes dans l'adoption des équipements de protection. Selon ces auteurs, les personnes plus âgées et les locataires sont moins susceptibles d'utiliser les équipements. Cependant, pour Köhler *et al.*, (2023), les résidents ayant eu l'expérience d'une ou plusieurs inondations sont plus susceptibles d'utiliser ce type d'équipement.

Duhamel *et al*. (2022) identifient comme facteur contributif l'accès au site par le réseau routier et la présence de mesures d'atténuation telles que des systèmes d'évacuation de l'eau, des dispositifs anti-refoulement et l'imperméabilisation des fondations. La turbidité de l'eau (contamination) est également un facteur aggravant, mentionné par Amirebrahami *et al.* (2016) et Shrestha *et al.* (2021). Certains modèles d'estimation des dommages, dont celui de la Federal Emergency Management Agency (Hazus) et celui du US Army Corps of Engineers (USACE) intègrent ce type de facteurs (vitesse d'écoulement, durée de l'événement, présence de débris et le taux de contamination de l'eau) dans le calcul des dommages (Galasso *et al.*, 2021). Enfin, la probabilité d'occurrence de l'inondation, bien que n'étant pas un facteur direct de dommages, influence les choix des mesures d'atténuation et d'adaptation, comme le soulignent Balica *et al.* (2009), Messner et Meyer (2006), Towfiqul Islam *et al.* (2021) et Ward *et al.* (2011).

D'autres auteurs (Kaoje *et al.*, 2021 ; McGrath *et al.*, 2015 ; Neubert *et al.*, 2016 ; Paulik *et al.*, 2023 ; Shrestha *et al.*, 2021) évoquent l'importance des caractéristiques de construction qui influencent le niveau des dommages par l'eau à un bâtiment. Les plus courants sont : 1) l'élévation du rez-de-chaussée ; 2) la structure du bâtiment ; 3) le type d'usage du rez-de-chaussée; 4) le niveau d'entretien du bâtiment; et 5) l'année de construction. Dans une analyse de 247 bâtiments endommagés par les inondations en Nouvelle-Zélande, Paulik *et al*. (2023) démontrent une amélioration de la performance prédictive des modèles d'estimation lorsque l'on considère ces facteurs. Cependant, les auteurs insistent sur l'importance de l'hétérogénéité des bâtiments dans le calcul du taux d'endommagement pour réduire l'incertitude. Enfin, dans une étude de la capacité prédictive de trois modèles australiens d'estimation des dommages, Hasanzadeh Nafari et Ngo (2018) ont démontré que la prise en compte d'un plus grand nombre de facteurs contributifs peut améliorer la capacité prédictive des modèles. Le tableau 1.1 présente quelques facteurs contributifs répertoriés dans la revue de littérature. Les composantes du risque sont identifiées pour chacun de ces facteurs entre (parenthèse).

Tableau 1.1 Exemple de facteurs contributifs aux dommages par l'eau à des bâtiments résidentiels

Facteur contributif	**Description**	**Certains auteurs**
Aménagement paysager (Vulnérabilité)	L'impact de la pente et du relief du terrain sur l'écoulement et l'accumulation de l'eau.	Huang *et al*. (2022); Towfiqul Islam *et al.* (2021).
Année de construction (Vulnérabilité)	L'année de construction est corrélée avec les codes du bâtiment et peut expliquer la variation de dommages entre deux bâtiments	Wing *et al*. (2020); (Paulik *et al.*, 2023); Neubert *et al*. (2016); Duhamel *et al.* (2022); Kaoje *et al.* (2021); McGrath *et al.* (2015); Shrestha *et al.* (2021).
Conception et état d'entretien des réseaux en eau (Aléa)	Le rôle des systèmes de drainage municipaux dans l'atténuation des inondations.	Arya et Kumar (2023); Sandink (2015).
Débit, courant et vitesse de la montée des eaux (Aléa)	Le rôle de la vitesse d'écoulement dans les dommages structurels, en particulier à de faibles profondeurs d'inondation.	Aribisala *et al.* (2022); Kelman et Spence (2004); Merz *et al.* (2013); Kreibich *et al.* (2009).
Distance du bâtiment par rapport à un cours d'eau et élévation du sol (Exposition)	Concept de gestion des zones inondables et le lien entre la proximité de l'eau et le risque d'inondations et la probabilité de survenance des dommages.	Balica *et al.* (2009); Towfiqul Islam *et al.* (2021); Merz *et al.* (2013); Messner and Meyer (2006); Galasso *et al.* (2021).
Durée de l'événement (Aléa)	Le rôle de la durée de l'événement et de la présence de l'eau dans les dommages. Effets de la capillarité des matériaux.	Mohor *et al.* (2020); Aribisala *et al.* (2022); Merz *et al.* (2013); Shrestha *et al.* (2021).
Élévation du rez-de-chaussée (Vulnérabilité)	L'élévation du rez-de-chaussée est le plancher de référence pour le calcul des dommages.	Doyon et Jean (non publié); Kaoje *et al.* (2021); Neubert *et al.* (2016); Paulik *et al.* (2023).

Facteur contributif	Description	Certains auteurs
Équipement de protection à l'échelle du bâtiment (Vulnérabilité)	L'importance des équipements de protection tels que les drains français, rez-de-chaussée surélevé, systèmes de captation des eaux, installation sécurisée des réservoirs d'huile, sacs de sable, imperméabilisation des solages, clapets antiretour et pompes de submersion contribue à réduire les dommages	Duhamel *et al.* (2022); Mertz *et al.* (2013); Köhler *et al.* (2023).
Hydrométéorologiques et pédologiques ou géomorphologiques (Aléa)	Rôle de ces facteurs qui sont loin d'être négligeables, notamment parce qu'ils peuvent affecter la durée, la vitesse de montée des eaux ou le type d'inondations	Buffin-Bélanger *et al.* (2022)
Obligation de se conformer aux nouveaux codes de construction (Vulnérabilité)	Le rôle du code de la construction dans la résilience aux inondations. La critique de la reconstruction "à l'identique" s'aligne sur le concept "Reconstruire en mieux".	Czajkowski (2019); UNDRR (2023); Kougkoulos *et al.* (2021).
Préparation et compétence de la municipalité (Vulnérabilité)	L'accent mis sur l'éducation du public et la collaboration soulignant le rôle de l'engagement communautaire dans la gestion des risques d'inondation.	Jean *et al.* (2023)
Probabilité de survenance (période de retour) (Aléa)	La période de retour, souvent exprimée en années, (par exemple 10 ans, 100 ans), est une mesure statistique de la fréquence d'un événement dépassant une magnitude spécifique	Balica *et al*. (2009); Messner and Meyer (2006); Towfiqul Islam *et al.* (2021); Merz *et al.* (2013); Ward et al. (2011);
Profondeur ou hauteur de submersion (Aléa)	Facteur déterminant pour expliquer le taux d'endommagement	Merz *et al.* (2013); Aribisala *et al.* (2022); Chhabra *et al.* (2023); Doyon et Jean (non publié); Bonnifait (2005).
Sous-sol transformé en espace de vie (Vulnérabilité)	Prise en compte de la présence et du type de sous-sol dans l'évaluation des dommages. La préoccupation concernant les matériaux organiques et les appareils sanitaires explique les différentiels de dommages.	Doyon et Jean (non publié)
Temps de réponse pour la réduction des dommages	Le rôle important de l'intervention rapide dans l'atténuation des dommages.	Kreibich *et al.* (2005); Landaverde *et al.* (2022).
Turbidité des eaux (Aléa)	Niveau de contamination au moment de l'intervention et charge de sédiments	Merz et al. (2013); Galasso *et al.* (2021); Amirebrahami *et al.* (2016); Shrestha *et al*. (2021).

Facteur contributif	Description	Certains auteurs
Type de sol (Vulnérabilité)	Le type de sol influence directement sa capacité à drainer l'eau	Miller (2024); Towfiqul Islam *et al.* (2021); Lachance (2022); Zamor et Dussault (2023).
Type de programme d'indemnisation et modalités de règlement (Vulnérabilité)	Démontre comment les retards et les limites des programmes d'indemnisation peuvent aggraver les dommages.	Bourova *et al.* (2022); Maltais *et al.* (2023).

Note : Ces facteurs sont tirés d'une revue de littérature scientifique sur les facteurs contributifs aux dommages par l'eau en préparation du deuxième article.

1.1.4.2 Courbes de submersion-dommages comme outil d'évaluation

L'utilisation de courbes de submersion-dommages est la méthode la plus courante pour estimer les dommages matériels directs causés par les inondations fluviales aux bâtiments résidentiels (Hammond *et al.*, 2015 ; Jongman *et al.*, 2012 ; McGrath *et al.*, 2019 ; Oubennaceur *et al.*, 2019). Construites à partir de données empiriques (historique d'indemnisations) ou synthétiques (coefficients d'experts) (Amadio *et al.*, 2016 ; Aribisala *et al.*, 2022 ; Xing *et al.*, 2023), les courbes de submersion-dommages établissent qu'une hauteur de submersion plus élevée entraîne généralement des dommages plus importants (Bachand *et al.*, 2022 ; Doyon et Bouchard St-Amant, 2020). La hauteur de submersion est la hauteur d'eau effective dans un bâtiment depuis un plancher de référence (Bachand *et al.*, 2022 ; Bonnifait, 2005 ; Doyon et Jean, non publié).

La relation entre profondeur de submersion et taux d'endommagement est marquée par une grande incertitude (Molinari *et al.*, 2020 ; Wagenaar *et al.*, 2016). Si ces courbes offrent une estimation utile à l'échelle d'un quartier, leur précision pour les bâtiments individuels est limitée car elles omettent des facteurs structurels spécifiques (Leclerc *et al.*, 2003). Face à ces enjeux, des études récentes visent à améliorer la modélisation des dommages, afin de mieux représenter la complexité de la relation entre profondeur de submersion et taux de dommages. Wing *et al.* (2020) confirment l'influence significative de variables autres que la profondeur d'eau (valeur, âge du bâtiment, localisation, type d'eau). Zarekarizi *et al.* (2020) démontrent comment la prise en compte de multiples incertitudes (risque, actualisation, vulnérabilité) peut modifier les décisions d'adaptation. Alors que Mohor *et al.* (2021) soulignent l'importance des mécanismes de dommages propres aux différents types d'inondations (souvent combinés) pour expliquer l'incertitude des modèles. Néanmoins, la validation de ces modélisations avancées de l'incertitude demeure un défi important (Shrestha *et al.*, 2021 ; Thieken *et al.*, 2005).

Au Québec, l'estimation des dommages s'appuie sur des courbes de submersion-dommages basées sur des données empiriques (Bachand *et al.*, 2022). Plusieurs modèles ont ainsi été développés pour le contexte québécois, comme ceux de Ouarda (Leclerc *et al.*, 2003), Bonnifait (2005), et plus récemment en 2021 Doyon et Jean (non publié). Ces derniers ont notamment élaboré un ensemble de 12 courbes qui tentent d'intégrer certaines variations dans les caractéristiques des bâtiments résidentiels (nombre d'étages, type de sous-sol, connexion aux services municipaux), reflétant une volonté d'affiner les estimations en tenant compte de facteurs au-delà de la simple profondeur d'eau. Ce sont les courbes de submersion-dommages de Doyon et Jean qui ont été utilisé dans l'estimation des dommages annualisés moyens présentés au chapitre 4.

1.2 Gouvernance du risque et cadre légal du risque d'inondations au Canada et au Québec

Afin de mieux cerner les défis complexes auxquels les municipalités québécoises sont confrontées dans la gestion proactive du risque d'inondation, cette section (1.2) propose une revue de la littérature consacrée à la gouvernance de ce risque. Le concept de la gouvernance se définit comme l'ensemble des processus collectifs qui façonnent la prise de décision et l'action publique (Hufty, 2007) et son rôle dans l'établissement du cadre organisationnel et la répartition des responsabilités (Filippi, 2022 ; Golnaraghi *et al.*, 2020 ; Hutter, 2016). L'analyse porte ensuite sur les obstacles à une gestion efficace du risque, sur les capacités réglementaires, adaptatives et intégratives qu'une gouvernance performante requiert (Van der Molen, 2018), ainsi que sur le rôle déterminant du choix et de l'application des instruments d'action publique (Glaus *et al.*, 2021 ; Lascoumes et Le Galès, 2005). Cette exploration des fondements théoriques et des enjeux pratiques de la gouvernance du risque d'inondations est importante. Elle pose les bases de son application et de ses défis spécifiques au niveau municipal discutés au chapitre 2. De plus, elle permet de comprendre le contexte institutionnel et décisionnel dans lequel toute proposition visant à améliorer le partage du risque financier (discutée au chapitre 5) doit s'inscrire et trouver sa pertinence.

1.2.1 Importance de la gouvernance au Canada

Des études comme celles de Hegger *et al.* (2016a) et Rasmussen *et al.* (2021) soulignent l'importance d'un modèle de gouvernance clair, de stratégies diversifiées, de cohésion, d'implication des parties prenantes, de ressources adéquates, et d'un leadership politique fort pour une gestion efficace du risque. Bien qu'il n'existe pas de modèle unique (Driessen *et al.*, 2016), l'efficacité et la légitimité de la gouvernance sont des éléments clés (Silva et Acheampong, 2015).

La gestion du risque d'inondations repose sur une gouvernance multiniveaux où les municipalités jouent un rôle pivot (United Nations Office for Disaster Risk Reduction, 2015a). Cependant, des études canadiennes (Feltmate *et al.*, 2020a ; Feltmate et Moudrak, 2021 ; Gauthier *et al.*, 2022) révèlent des lacunes, notamment en matière d'aménagement du territoire, d'application déficiente des politiques provinciales et d'un manque de pouvoir des provinces pour imposer leurs normes aux municipalités. Ces lacunes contribuent à l'augmentation du coût des dommages, mettent en lumière le rôle central des municipalités, et justifie la nécessité d'approfondir, comme le propose le chapitre 2, la compréhension des mécanismes spécifiques à la gouvernance municipale. Mieux comprendre ces mécanismes permettrait d'identifier des leviers efficaces pour réduire le risque d'inondations (Cooper, 2010 ; De Vries, 2000 ; Filippi, 2022 ; Morrison *et al.*, 2018).

1.2.2 Défis de gouvernance : instruments d'action publique et leur limite

Les instruments (législation, infrastructures, urbanisme, partage du risque) traduisent les priorités politiques en actions (Henstra, 2015) et permettent aux municipalités d'assurer une gouvernance du risque (Hegger *et al.*, 2014). Cependant, leur choix et mise en œuvre sont complexes et dépendent du contexte sociopolitique (Glaus *et al.*, 2021 ; Green, 2011 ; Henstra *et al.*, 2018 ; Hill et Varone, 2021 ; Sterner et Robinson, 2018).

Au-delà des facteurs contextuels et des capacités propres à chaque municipalité (tels que l'expérience, les priorités multiples, la perception du risque et l'accès aux ressources) identifiés par Lalancette et Charles (2022), la littérature met également en évidence des défis systémiques de gouvernance qui conditionnent le choix et l'efficacité des instruments d'action publique. En effet, la capacité des municipalités québécoises à gérer efficacement le risque d'inondations est souvent entravée par un réseau complexe de facteurs interconnectés, dont 1) une gouvernance multiniveaux parfois incohérente (Feltmate *et al.*, 2020b ; Henstra et Thistlethwaite, 2017b); 2) des conflits d'intérêts (Dordi *et al.*, 2022 ; Feiock *et al.*, 2008); et 3) une perception du risque qui peut être limitée (Feltmate *et al.*, 2020a ; Jacob *et al.*, 2023).

1.2.2.1 Incohérence institutionnelle et la décentralisation

Le manque de cohérence et de coordination entre les niveaux de gouvernement (municipal, provincial, fédéral) est un obstacle majeur (Feltmate *et al.*, 2020a ; Hegger *et al.*, 2016a ; Henstra et Thistlethwaite, 2017b ; Hutter, 2016). Un discours politique sur l'autonomie locale qui ne s'accompagne pas d'un transfert de pouvoir réel crée des incohérences (Bisaro *et al.*, 2020 ; Bubeck *et al.*, 2018). Cette inadéquation entre responsabilités déléguées et soutien centralisé mène à des déficiences systémiques (Crosweller et Tschakert, 2021) et à un cloisonnement qui entrave la mise en œuvre des instruments (Raikes *et al.*, 2023 ; Rasmussen *et al.*, 2021 ; Reghezza-Zitt et Jon, 2019 ; Van der Molen, 2018). La décentralisation peut aussi surcharger les petites municipalités aux compétences limitées (Beucher, 2008 ; De Vries, 2000 ; Larrue *et al.*, 2016), soulignant le besoin d'une collaboration étroite entre tous les acteurs (Ansell *et al.*, 2020 ; Hufty, 2007).

1.2.2.2 Conflits d'intérêt

Les intérêts économiques priment souvent sur les enjeux sociaux et environnementaux (Beucher, 2008 ; Dordi *et al.*, 2022), avec des groupes de pression influençant le choix et l'application des instruments (Mai *et al.*, 2020). Les municipalités peuvent privilégier le développement économique et les revenus fiscaux au détriment de la réduction des risques (Feiock *et al.*, 2008 ; Fruehauf, 2024 ; Pilette, 2019), notamment sous l'influence des promoteurs immobiliers (Wiering *et al.*, 2018) et face à des résidents réticents aux contraintes (Alalouf-Hall et Fontan, 2020 ; Fruehauf, 2024 ; Van der Molen, 2018). Les décisions politiques sont prises dans un contexte d'intérêts conflictuels et de pressions diverses (Feiock *et al.*, 2008). L'interaction complexe de ces conflits avec d'autres contraintes demeure insuffisamment comprise (Biesbroek *et al.*, 2013 ; Burch, 2010).

1.2.2.3 Méconnaissance du risque

Une connaissance insuffisante du risque et un manque de données adéquates entravent une gouvernance efficace (Feltmate *et al.*, 2020a ; Raikes *et al.*, 2023). L'absence de méthodes standardisées complique l'évaluation de l'efficacité des stratégies (Rözer *et al.*, 2022) et mène à une sous-estimation du risque (Jacob *et al.*, 2023 ; von Wirth *et al.*, 2016). Les évaluations traditionnelles intègrent mal les incertitudes (climatiques, hydrologiques, vulnérabilité des bâtiments) et favorisent une gestion réactive et une allocation inégale des ressources (Driessen *et al.*, 2016 ; Rözer *et al.*, 2022). Cette incertitude peut aussi paralyser la prise de décision politique (Green, 2011 ; Ridha *et al.*, 2022 ; Varone *et al.*, 2013) et influencer la sélection des instruments (Glaus *et al.*, 2021 ; Henstra *et al.*, 2018).

1.2.3 Les parties prenantes et leurs rôles

La gestion des inondations au Québec est une responsabilité partagée entre de multiples acteurs. Cette répartition des rôles, bien que nécessaire, complexifie la gouvernance, car aucune entité n'est seule responsable de l'ensemble de la gestion du risque d'inondations. Le Québec pourrait s'inspirer de plusieurs pays comme le Royaume-Uni, où la gestion du risque d'inondations est organisée de manière centralisée à travers des politiques nationales intégrées qui facilite la gouvernance (Chan *et al.*, 2022). La décentralisation des compétences en gestion de l'aménagement du territoire, complexifiée par le grand nombre de municipalités au Québec (le Québec représente plus de la moitié des élus municipaux au Canada), crée un défi majeur (Dillabough et Lucas, 2025). Ce défi réside dans la fragmentation des capacités techniques et des efforts d'adaptation, ce qui mène à une coordination complexe des politiques et à des disparités de résilience sur le territoire. L'objectif n'est pas d'atteindre une unité impossible, mais de réaligner les incitatifs et les normes à l'échelle provinciale afin de garantir que l'action locale (la décentralisation) soit homogène et efficace face à un risque qui, lui, ne connaît pas les frontières municipales (l'inondation fluviale). Le tableau 1.2 synthétise les rôles clés de ces parties prenantes, illustrant la nature fragmentée des compétences et la nécessité d'une approche intégrée.

Tableau 1.2 Rôles et responsabilités des parties prenantes dans la gestion du risque d'inondations

Acteur	**Responsabilité**	**Rôles Clés**
Gouvernement fédéral	Soutien et coordination nationale	Financement, normes et réalisation de cartographie, recherche météorologique, soutien d'urgence, aide financière (AAFCC).
Gouvernement du Québec (MSP)	Coordination Sécurité Civile	Coordination sécurité civile, plan national, aide financière aux sinistrés et municipalités, soutien aux municipalités.
Gouvernement du Québec (MELCCFP)	Réglementation et gestion hydrique	Gestion des barrages/niveaux d'eau, cartographie, réglementation des rives/littoral/plaines inondables, autorisations de travaux.
Gouvernement du Québec (MAMH)	Aménagement du territoire	Cadre normatif aménagement (dont inondations), soutien aux municipalités en aménagement, orientations gouvernementales (OGAT).
Hydro-Québec	Gestion des crues	Gestion des barrages sur des rivières importantes, telles que la rivière des Outaouais, Gatineau, Sainte-Marguerite, etc.
MRC	Coordination et planification régionale	Schéma d'aménagement et de développement durable (SADD), plan de sécurité civile/d'urgence, soutien aux municipalités locales, règlements de contrôle intérimaire (RCI).
Municipalité locale	Première ligne et gestion territoriale	Responsabilité première sécurité civile, règlements d'urbanisme, prévention/mitigation locale, préparation/intervention, sensibilisation, délivrance de permis.
Bureaux de projets (MAMH)	Expertise et accompagnement	Amélioration des connaissances (cartographie), intégration gestion du risque dans l'aménagement, accompagnement des municipalités.
Organisme de Bassin Versant (OBV)	Planification et concertation par bassin	Plan directeur de l'eau (PDE), concertation interacteurs, acquisition/diffusion d'information, sensibilisation/éducation, soutien/accompagnement.
Commission mixte internationale	Gestion des eaux	Gestion des eaux frontalières des Grands Lacs et du St-Laurent.
Acteurs privés (Promoteurs/Individus)	Conformité et vulnérabilité	Conformité aux réglementations, évaluation des risques, influence sur la demande, entretien de propriété, mesures de protection.
Acteurs privés (Entreprises/Institutions financières/Assureurs)	Conformité et financement du risque	Conformité normes environnementales/urbanisme, protection des actifs, évaluation/tarification risque (assureurs), prêts d'adaptation (banques).

1.2.4 Transition et modernisation du cadre légal et réglementaire

La compréhension du rôle et des limites de l'action municipale en matière de gestion du risque d'inondations nécessite un examen attentif du cadre légal et institutionnel québécois. Cette section présente les pouvoirs et responsabilités des municipalités, ainsi que le rôle des autres parties prenantes. L'objectif est de délimiter le contexte juridique et les marges de manœuvre influençant les décisions locales.

Au Canada, la tendance est à la reconnaissance des municipalités comme gouvernements responsables, bien que le potentiel pratique de cette reconnaissance reste à approfondir (Taylor et Dobson, 2020). À l'instar d'autres provinces, le rôle des municipalités québécoises dans la gestion des inondations fluviales s'inscrit dans un cadre légal et réglementaire en constante évolution, qui définit les instruments d'action publique disponibles et façonne leur action.

1.2.4.1 Refonte de l'encadrement de la gestion du risque d'inondations

Les inondations majeures de 2017 et 2019 au Québec ont accéléré une refonte de l'encadrement de la gestion des zones inondables. Un décret temporaire en 2019 a d'abord imposé une gestion plus rigoureuse et un moratoire sur certaines constructions. Ce régime a été remplacé en 2022 par un régime transitoire abrogeant l'ancienne *Politique de protection des rives, du littoral et des plaines inondables* et instaurant une réglementation uniforme déléguée aux municipalités, accroissant ainsi leurs responsabilités.

En 2024, de nouveaux projets de règlements issus du *Plan de protection du territoire face aux inondations* ont été publiés et adoptés en juin 2025 (visant une entrée en vigueur le 1er mars 2026). Ces projets visent à renforcer davantage l'encadrement avec de nouvelles classifications de zones inondables (très élevée, élevée, modérée, faible), des mesures de protection plus strictes, et un nouveau cadre pour les ouvrages de protection (OPI). Le *Règlement sur l'encadrement d'activités sous la responsabilité des municipalités réalisées dans des milieux hydriques* (REARMMH) en est la pièce maîtresse, déléguant largement son application (permis, inspections, sanctions) aux municipalités locales. Ce nouveau régime prévoit notamment une cartographie actualisée (considérant aléa, changements climatiques, ouvrage de protection contre les inondations) qui pourrait agrandir significativement les zones protégées, et la possibilité pour les MRC d'élaborer des Plans de gestion du risque d'inondations (PGRI) sous conditions strictes et approbation ministérielle. La gestion des ouvrages de protection contre les inondations (OPI) et des zones de mobilité des cours d'eau est également précisée, imposant de nouvelles obligations d'étude et de planification aux municipalités. L'impact réel de ce nouvel encadrement sur l'incitation municipale à réduire le risque d'inondations reste à évaluer.

1.2.4.2 Principales lois applicables et droit acquis

En attendant le nouveau cadre, le régime transitoire s'appuie sur la *Loi sur l'aménagement et l'urbanisme* (LAU), la *Loi sur la qualité de l'environnement* (LQE) et la *Loi sur la sécurité civile visant à favoriser la résilience aux sinistres* (LSCRS). La LAU structure la planification territoriale et les outils d'urbanisme (schémas des MRC, plans locaux) permettant de réglementer les usages et de limiter le risque. La LQE, depuis 2017, encadre les interventions en milieux humides et hydriques, impliquant les municipalités dans les autorisations ministérielles et leur confiant des responsabilités de gestion et de conformité. La LSCRS (2024) renforce leur rôle en planification de la résilience et en gestion des sinistres.

Enfin, le principe du droit acquis est maintenu, permettant aux propriétaires de bâtiments existants légalement en zone inondable de conserver certains droits (reconstruction, agrandissement sous conditions d'immunisation), même si la réglementation actuelle est plus restrictive. Cette situation peut limiter la capacité des municipalités à imposer des restrictions optimales dans les secteurs déjà développés, illustrant une des contraintes inhérentes à la gouvernance du risque en territoire occupé.

1.3 Dimensions humaines et comportementales face au risque d'inondations

Au-delà de la gouvernance et du cadre légal de la gestion du risque d'inondations (abordés en section 1.2), la réponse des communautés et l'efficacité des politiques publiques sont profondément façonnées par un ensemble de dimensions humaines et comportementales. Ces facteurs influencent non seulement la manière dont les risques sont perçus et évalués par les citoyens et les élus, mais aussi leur propension à adopter des mesures de prévention, leur réaction face aux sinistres, et leur adhésion aux mécanismes de partage des coûts. La présente section explore trois de ces dimensions fondamentales : la perception du risque, qui module l'attention portée à l'aléa inondation; l'attachement au territoire, qui peut influencer les décisions en matière d'aménagement et d'adaptation; et le phénomène de l'aléa moral, qui questionne les incitatifs à la prudence lorsque les conséquences financières sont mutualisées ou transférées.

L'analyse de ces aspects humains et comportementaux permet d'une part d'éclairer les dynamiques, les freins et les leviers potentiels au sein de la gouvernance municipale du risque d'inondations (chapitre 2). D'autre part, la prise en compte de ces réalités est indispensable pour concevoir et évaluer l'acceptabilité d'un nouveau modèle de partage du risque financier (chapitre 4 et 5) pour les municipalités québécoises.

1.3.1 Perception du risque

La perception du risque influence les comportements face au danger. Par ailleurs, cette perception, ainsi que les réactions aux risques et aux événements réels, sont également modelées par des processus motivationnels (Oppenheimer *et al.*, 2014). De même, la perception du risque est influencée par une multitude de facteurs qui interagissent de manière complexe. Morin (2008) reprend une série de 10 facteurs interdépendants qui modulent cette perception et, par extension, peuvent influencer l'approche municipale :

1. Le sentiment de contrôle ou de maîtrise : Lorsqu'une municipalité estime avoir un grand contrôle sur un risque (ex: via des infrastructures de protection), elle peut sous-estimer le risque résiduel et ainsi négliger d'autres mesures préventives complémentaires (aménagement, sensibilisation).
2. La familiarité (expérience de l'aléa) : Une municipalité ayant récemment vécu une inondation majeure sera généralement plus encline à percevoir le risque comme élevé et à investir dans des mesures de prévention et des politiques d'aménagement restrictives.
3. Le temps (depuis le dernier événement) : L'éloignement temporel d'une inondation peut conduire une municipalité à relâcher sa vigilance et ses investissements en prévention, illustrant le « cycle de l'oubli », même si le risque objectif demeure.
4. L'incertitude scientifique : Face à une grande incertitude (ex: projections climatiques), une municipalité peut hésiter à engager des dépenses importantes pour des mesures préventives dimensionnées pour des scénarios futurs flous, préférant parfois des options moins coûteuses ou plus flexibles.
5. Le degré de confiance dans les institutions : La confiance qu'une municipalité accorde aux évaluations et recommandations des instances supérieures (gouvernements, experts) conditionne sa propension à adopter les mesures de prévention suggérées.

6. Le caractère involontaire (risque imposé) : Une municipalité percevra un risque comme plus grave et inacceptable si elle le juge imposé par des facteurs externes (ex: gestion des eaux en amont), ce qui peut intensifier ses demandes d'actions correctives.
7. L'injustice ou l'iniquité dans l'exposition : Si une inondation affecte de manière disproportionnée des secteurs ou groupes vulnérables de la municipalité, cela peut accroître la perception d'injustice et la pression pour des mesures de protection ciblées.
8. L'origine (naturelle vs humaine) : Un risque d'inondations perçu comme étant d'origine humaine (ex: défaillance d'un ouvrage) sera jugé moins acceptable par une municipalité et mènera à une plus forte recherche de responsabilités qu'un aléa purement naturel.
9. L'attention médiatique : Une forte couverture médiatique des inondations, même ailleurs, peut sensibiliser les élus et citoyens d'une municipalité et l'inciter à renforcer ses propres mesures de prévention par anticipation.
10. L'effroi suscité par le risque (intensité, conséquences) : Des événements catastrophiques (pertes de vies, destructions) peuvent marquer durablement une municipalité, la rendant plus disposée à investir dans la protection et à maintenir un haut niveau de sensibilisation au risque.

1.3.2 Attachement au territoire

La théorie de l'attachement au territoire offre un éclairage sur la décision, parfois perçue comme irrationnelle, des individus de demeurer en zone à risque. Ce lien affectif, symbolique et fonctionnel envers un lieu (Reese *et al.*, 2019 ; Scannell et Gifford, 2010 ; von Wirth *et al.*, 2016) peut se manifester par un sentiment d'appartenance et d'identité si fort que le lieu est jugé irremplaçable malgré les risques (Scannell et Gifford, 2017).

Au Québec, le développement historique le long des cours d'eau, motivé par des facteurs géographiques et socio-économiques (Andrews, 1993 ; Cosens et Gunderson, 2021), a créé une proximité qui est aujourd'hui source de vulnérabilité. Cette situation a parfois été aggravée par un faux sentiment de sécurité lié aux ouvrages de protection (Hanger *et al.*, 2018) et par des modifications environnementales qui augmentent la vulnérabilité des communautés (Doberstein *et al.*, 2018). Cette vulnérabilité est exacerbée par les changements climatiques.

Pour les décideurs municipaux, cet attachement au territoire, tant celui des citoyens que potentiellement le leur, engendre des défis considérables. La pression citoyenne et la crainte de mesures impopulaires peuvent freiner la mise en œuvre de mesures de réduction du risque, de relocalisation, ou de plans d'urbanisme qui tiennent compte du risque (Cadoret, 2017). Les municipalités se retrouvent ainsi à arbitrer entre la sécurité publique et la préservation de l'identité communautaire et du tissu social. Ce dernier, bien que précieux pour la résilience post-catastrophe, peut aussi rendre plus ardues les mesures de réduction du risque impliquant des changements majeurs (Reese *et al.*, 2019). De plus, l'attachement au territoire peut renforcer le biais du statu quo (Samuelson et Zeckhauser, 1988), incitant les municipalités à différer l'adoption de mesures préventives, même en étant conscientes des risques, car l'effort perçu pour introduire des changements semble surpasser les bénéfices anticipés.

1.3.3 Phénomène de l’aléa moral

L'aléa moral, tel que conceptualisé par (Laffont et Martimort, 2002a) et défini précédemment, trouve une illustration particulièrement éclairante dans le contexte de la gestion du risque d'inondations par les municipalités québécoises. En effet, l'existence de programmes d'aide financière post-catastrophe provinciaux et fédéraux et de l’assurance privé, qui couvrent une part substantielle des coûts des dommages, peut être perçue comme une forme d'entente implicite. Dans ce cadre, une municipalité pourrait être moins rigoureuse dans ses décisions d'aménagement du territoire ou dans ses investissements en matière de prévention.

Sachant que les conséquences financières négatives majeures d'une inondation (coûts de réparation, indemnisation) seront en grande partie assumées par les paliers de gouvernements supérieurs plutôt que par son propre budget, elle pourrait, par exemple, être tentée d'autoriser le développement en zones inondables pour augmenter ses revenus fonciers, ou encore de différer des travaux coûteux de mise aux normes ou d'entretien de ses infrastructures de protection. Ce découplage entre le pouvoir décisionnel local et la responsabilité financière directe des conséquences des sinistres est susceptible de conduire à une prise de risque accrue à l'échelle locale, augmentant ainsi la vulnérabilité globale et les coûts pour l'ensemble de la collectivité.

Cependant, la présence d'un aléa moral dépend du contexte (Hudson et Berghäuser, 2023). Selon les auteurs, plus la probabilité de dommages est faible, moins il est probable que l’aléa moral soit observé. À l'opposé, plus la probabilité de dommages augmente, plus il y a de chances d'observer l'aléa moral. L'aléa moral peut donc prendre différentes formes et se combiner à la perception du risque et l'attachement au territoire pour expliquer le manque de proactivité de certaines municipalités face au risque d'inondations. L'aléa moral peut donc se manifester de diverses façons, notamment une municipalité peut être :

- Incitée à investir dans des infrastructures de protection coûteuses, comme des digues ou des systèmes de drainage, même si ces mesures ne sont pas économiquement justifiées. La pression politique des résidents des zones inondables et la crainte de critiques en cas d'inondation peuvent pousser les municipalités à privilégier des solutions visibles et rassurantes, sans tenir compte de leur efficacité réelle.
- Tentée d'autoriser la construction dans des zones inondables, malgré les risques connus. Les recettes fiscales générées par de nouveaux développements peuvent inciter les municipalités à prendre des décisions qui augmentent l'exposition aux inondations à long terme.
- Réticente à mettre en œuvre des programmes de relocalisation volontaire, malgré les risques évidents, car elles craignent de perdre des habitants et des recettes fiscales. L'aléa moral peut se manifester par une minimisation des risques pour justifier le maintien des populations en zone inondable, en comptant sur l'aide gouvernementale en cas de catastrophe.
- Réticente à légiférer sur l'utilisation des sous-sols et sous-estimer les risques spécifiques liés aux occupations des sous-sols en zone inondable, par exemple en autorisant des aménagements complets (chambres, salles de jeux) malgré le risque élevé d'inondation. Cette attitude peut s'expliquer par la volonté de maintenir l'attractivité du marché immobilier et de ne pas décourager les constructions, en reportant la responsabilité de la protection des biens sur les propriétaires.
- Laxiste dans l'application des normes en zone inondable, par exemple en accordant des dérogations ou en fermant les yeux sur des non-conformités. Les municipalités peuvent être tentées de privilégier le développement économique à court terme, en comptant sur les assurances et l'aide gouvernementale pour couvrir les coûts des dommages en cas d'inondation.
- Négligente dans l'entretien des infrastructures de drainage ou de protection contre les inondations, en comptant sur des interventions d'urgence en cas de problème.
- Incitée à minimiser l'adaptation au changement climatique et l'augmentation du risque d'inondations et se concentrer sur des solutions à court terme, en reportant les décisions difficiles sur les générations futures.

- Incitée à minimiser ou omettre de communiquer clairement le risque d'inondations aux résidents (asymétrie d'information). La crainte de faire baisser la valeur des propriétés ou de décourager l'investissement peut conduire les municipalités à diffuser une information incomplète ou biaisée, ce qui réduit la capacité des résidents à prendre des décisions éclairées.

L'aléa moral se manifeste aussi auprès des individus. Sachant qu'ils seront secourus financièrement en cas de sinistre, les individus adoptent un comportement plus risqué, créant ainsi un aléa moral. Ils sont ainsi moins enclins à investir dans des mesures d'atténuation et de réduction du risque (par exemple, relocalisation, surélévation du rez-de-chaussée, imperméabilisation), s'ils anticipent une intervention de l'assurance ou des programmes d'aide gouvernementaux (Kousky, 2018).

1.4 Mécanisme de partage du risque financier : analyse comparative et pertinence pour les municipalités

Les programmes d'assistance financière post-catastrophe privés et publics, bien que nécessaires, sont largement critiqués pour leur absence d'incitatifs à investir dans la prévention (Davies, 2016 ; Davlasheridze et Miao, 2021 ; Henstra *et al.*, 2018 ; Hudson et Berghäuser, 2023 ; Raschky et Schwindt, 2008) et à créer un aléa moral (Landry *et al.*, 2021 ; Michel-Kerjan, 2019 ; Rocle *et al.*, 2021 ; Shughart II, 2011), tout en soulevant des enjeux d'équité (Alalouf-Hall et Fontan, 2020 ; Fruehauf, 2024 ; Rendon *et al.*, 2021). De plus, ces mécanismes ne tiennent pas compte des conséquences évolutives du risque (Henstra *et al.*, 2018) et peuvent nuire à une reconstruction améliorée et plus résiliente (Barraqué et Moatty, 2020), Dans ce contexte, l'exclusion des municipalités des systèmes de partage direct des coûts financiers est identifiée comme un frein à leur priorisation effective des mesures de réduction du risque (Dordi *et al.*, 2022 ; Lalancette et Charles, 2022 ; Rasmussen *et al.*, 2021). Cette exclusion alimente le débat sur la répartition des responsabilités quant au paiement des dommages et à la mise en œuvre de la réduction des risques (Kousky et Kunreuther, 2014).

Malgré la reconnaissance de la faiblesse des mécanismes d'indemnisation, une lacune majeure persiste, soit la compréhension fine de la manière dont l'absence de responsabilité financière directe des municipalités pour les dommages influence concrètement leurs incitatifs à investir dans la prévention (Kousky et Kunreuther, 2014). Si les limites des systèmes actuels sont critiquées, peu de recherches explorent en profondeur des mécanismes alternatifs de partage du risque impliquant une contribution municipale directe (piste suggérée par Henstra *et al.* 2018) ou évaluent leur potentiel à réaligner les incitatifs, surtout lorsque les instruments de partage existants sont jugés sous-utilisés (Thistlethwaite et Henstra, 2017) et leur efficacité globale mal évaluée (Driessen *et al.*, 2016 ; Heikkila et Huang, 2014).

C'est précisément pour explorer ces enjeux que la présente section procède à une analyse comparative de différents mécanismes de partage du risque financier (assurance privée, programmes d'aide post-catastrophe, et unions réciproques). L'objectif est d'identifier les forces, les faiblesses et les enseignements pertinents, avec une attention particulière portée à leur applicabilité potentielle aux municipalités québécoises. Cette démarche est importante pour développer la proposition développée au chapitre 4 et présentée au monde municipal au chapitre 5.

1.4.1 Assurance privée comme mécanisme de partage du risque

L'assurance est un mécanisme clé de partage du risque permettant de transférer un risque individuel à une collectivité d'assurés en échange d'une prime (Kousky *et al.*, 2021). Les sciences actuarielles ont contribué à quantifier le risque en termes de probabilité et de gravité, permettant ainsi de déterminer les primes d'assurance et d'ouvrir la voie à un transfert mutuellement avantageux à une compagnie d'assurance. L'assurance privée constitue donc un pilier du partage du risque (Hanger *et al.*, 2018 ; Hudson *et al.*, 2019). Le Cadre de Sendai pour la réduction des risques de catastrophe mentionne explicitement l'assurance et la nécessité de promouvoir des mécanismes de transfert des risques de catastrophe afin de réduire l'impact financier des catastrophes sur les gouvernements et les sociétés (United Nations Office for Disaster Risk Reduction, 2015b).

1.4.1.1 Régimes d'assurance contre les inondations : comparaison et défis

Hudson *et al.* (2019) ont comparé les différents régimes d'assurance contre les inondations en Europe afin d'identifier les capacités à faire face à l'augmentation du risque. L'étude évalue différents aspects tels que le taux de pénétration de l'assurance, l'incitation à la réduction des risques, le coût pour les ménages à faible risque et l'inabordabilité de l'assurance pour les ménages à haut risque. L'étude souligne la performance souvent supérieure des modèles de partenariat public-privé (PPP) selon une évaluation multicritères. La comparaison démontre que la pérennité de l'assurance privée face au changement climatique dépend fortement du lien établi entre les primes et les efforts concrets de réduction des risques. L'analyse comparative met également en évidence les arbitrages nécessaires, notamment entre l'abordabilité pour les ménages à haut risque et le coût pour ceux à faible risque. Ainsi, les auteurs offrent une perspective holistique et des enseignements généralisables pour orienter les décideurs dans la conception de mécanismes de partage de risque d'inondations plus robustes et équitables.

Kousky et Kunreuther (2018) soulignent pour leur part que les assureurs privés ont des difficultés à offrir une protection complète et que le secteur de l'assurance se heurte à des défis. Les catastrophes sont des événements de faible probabilité mais de conséquences élevées ce qui peut entraîner des problèmes d'asymétrie d'information (antisélection) et d'aléa moral (Botzen, 2019). De plus, la capacité de diversification des assureurs est limitée face à des événements systémiques affectant de vastes zones. Plusieurs auteurs, dont Botzen (2019) et Kousky (2018), reconnaissent aussi que le partage du risque par l'assurance privée est plus efficace lorsqu'il est étroitement lié à des programmes de réduction des risques.

1.4.1.2 L'influence de l'assurance sur la réduction du risque d'inondations

Hanger *et al.* (2018) ont réalisé une étude afin de déterminer de quelle manière, les mécanismes d'assurance contre les inondations et l'aide publique post-catastrophe influencent les décisions des ménages en matière de réduction du risque d'inondations. L'étude examine l'efficacité des incitations spécifiques offertes par les assureurs (comme les réductions de primes) et par les pouvoirs publics (soutien financier, en nature ou informatif). Elle vise également à évaluer si une compensation publique après sinistre pourrait avoir un effet négatif, en décourageant les individus à investir dans la réduction du risque. Les auteurs ont mené une enquête téléphonique auprès de 1849 décideurs au sein de ménages situés dans des zones inondables en Autriche, Angleterre et Roumanie. Ces pays ont été sélectionnés en raison de leurs systèmes d'assurance et de compensation fondamentalement différents.

Les auteurs concluent que l'assurance inondation est, dans l'ensemble, positivement associée à l'adoption de mesures de réduction des risques par les ménages. Les assureurs disposent de mécanismes incitatifs à la réduction des risques (limites de couverture, franchises, garanties, conseils en ingénierie du risque, sensibilisation). Cependant, leur mise en œuvre pratique est souvent limitée. Parallèlement, les incitations publiques qui favorisent la réduction des risques sont également associées à une meilleure préparation des ménages. Une autre limitation est soulignée par les auteurs, les grandes infrastructures publiques de protection peuvent engendrer un sentiment de sécurité qui, paradoxalement, est lié à un niveau plus faible de préparation individuelle. Bien que d'autres études (Davies, 2016 ; Davlasheridze et Miao, 2021 ; Kousky *et al.*, 2018), suggèrent un potentiel d'aléa moral ou d'effet dissuasif de la part des indemnités en provenance de l’assurance ou l’aide publique, les auteurs ont constaté aucun soutien à l'existence d'un aléa moral chez les ménages assurés. Au contraire, les ménages détenant une assurance inondation étaient même un peu plus susceptibles d'avoir mis en place des mesures de réduction des risques.

1.4.1.3 Contexte canadien et québécois

Sandink *et al.* (2015) ont analysé le contexte canadien de l’assurance contre les inondations en le comparant aux approches internationales (Royaume-Uni, États-Unis, France, Allemagne). Les auteurs ont également analysé l'état actuel de la couverture d'assurance contre les dommages par l'eau pour les propriétaires canadiens et examiné les programmes publics d'aide aux sinistrés. L'étude repose sur une revue de la littérature et des rapports gouvernementaux et de l'industrie de l'assurance. Les auteurs soulignent que des opportunités existent pour le marché de l’assurance à condition d'adopter une tarification basée sur le risque et surtout de partager la responsabilité de la réduction des risques. Cependant, ils concluent que le système canadien actuel montre ses limites face à l’augmentation des dommages causés par les inondations. De même, une assurance inondation privée plus complète se heurte à des défis considérables, dont : 1) des problèmes d'assurabilité inhérents au risque d'inondations notamment en raison du risque hérité, du caractère non aléatoire du risque et de la concentration de propriétés dans une même zone géographique ; 2) un manque de données adéquates sur les risques; 3) la complexité en matière de tarification; 4) une faible incitation à la réduction des risques individuels; et 5) l'abordabilité pour les zones à haut risque. L’abordabilité pour les zones à haut risque demeure un défi non pas d'un point de vue de l'économie pure (où la tarification élevée est souhaitable pour décourager l'exposition), mais d'un point de vue de la viabilité du marché et de la justice sociale. Si les primes nécessaires pour couvrir le risque sont si élevées qu'elles deviennent inabordables pour les résidents, ces derniers ne souscriront pas à l'assurance. Cela signifie que le marché privé échouera à atteindre une pénétration adéquate dans les zones où le risque est le plus grand, ce qui perpétue la dépendance aux programmes d'aide gouvernementaux (PGAF). Cette dépendance favorise ainsi l'aléa moral que l'assurance est censée résoudre.

Thistlethwaite (2017) a réalisé une étude qui analyse l'émergence de l'assurance inondation au Canada et comment le secteur tente de concilier les pressions réputationnelles et réglementaires avec les aspects économiques de l'assurance. L’étude s’appuie principalement sur des entretiens semi-structurés avec des responsables de l'industrie de l'assurance au Canada. L’auteur conclut que l'émergence de l'assurance contre les inondations au Canada, a été déclenché par les pressions des gouvernements suites aux inondations 2013 en Alberta. Face aux risques réputationnels et réglementaires, les assureurs canadiens ont développé une offre d'assurance facultative et basée sur le risque. L'auteur souligne l'importance des facteurs institutionnels dans la gouvernance des risques, rejoignant des observations faites au Royaume-Uni ou en Allemagne. Cependant, l'étude souligne une lacune majeure, soit : cette initiative de l'industrie s'est faite sans la coordination et l'appui nécessaires des politiques gouvernementales pour assurer une pénétration suffisante du marché. L'industrie exigeait que l'État investisse adéquatement dans la cartographie des plaines inondables, car les cartes disponibles sont souvent obsolètes, empêchant la tarification précise du risque. De plus, le gouvernement a été critiqué pour ne pas avoir augmenté les investissements dans les infrastructures de défense afin de réduire l'exposition générale et de rendre l'assurance plus abordable. Enfin, toujours selon l'auteur, le problème majeur réside dans le programme fédéral d'aide financière en cas de catastrophes (AAFCC), qui, en agissant comme « assureur de dernier recours pour les provinces », crée un puissant aléa moral et une incitation limitée à souscrire une assurance ou à réduire les risques. Par conséquent, la viabilité à long terme de ce modèle canadien est incertaine.

Pour remédier à la situation, le gouvernement du Canada a formé le Groupe de travail sur l'assurance contre les inondations et d'aide à la relocalisation pour élaborer un programme national d'assurance inondation à faible coût au Canada. Ce programme vise à protéger les ménages à risque élevé qui n'ont pas accès à une assurance adéquate. Le Budget fédéral de 2024 a annoncé la création d'une filiale de la Société canadienne d'hypothèques et de logement (SCHL) pour offrir la réassurance contre les inondations, tandis que le Budget de 2023 avait déjà proposé 31,7 millions de dollars sur trois ans (à compter de 2023-2024) pour l'établissement du programme. Des consultations sont en cours avec les provinces et territoires sur sa viabilité financière et le partage des coûts. Le programme, qui vise à couvrir tous les types et niveaux de risque d'inondations à l'échelle nationale, nécessitera une cartographie précise et des investissements en réduction du risque.

1.4.2 Mécanismes de partage du risque

Afin d'explorer comment l'assurance publique et les mécanismes apparentés peuvent structurer le partage du risque financier lié aux inondations, cette section analyse trois exemples internationaux distincts, soit le National Flood Insurance Program américain (NFIP), le régime CatNat français, et le fonds de réassurance Flood Re britannique. Bien qu'il existe de nombreux autres dispositifs à travers le monde, ces trois régimes ont été sélectionnés non pour leur exhaustivité, mais pour la diversité des approches qu'ils illustrent, allant d'un programme majoritairement public, à des partenariats public-privé complexes et à un fonds de réassurance soutenus par l'État. Leur examen est particulièrement pertinent pour la réflexion sur une implication accrue des municipalités québécoises. En effet, ils offrent des perspectives variées et des leçons précieuses sur l'intégration des collectivités locales dans les schémas d'indemnisation et les incitatifs (ou leur absence) à la réduction des risques à l'échelle municipale, ainsi que le financement de la prévention. Ces régimes éclairent également les défis liés à l'abordabilité et à la transition vers une tarification plus actuarielle, autant d'enjeux cruciaux pour le contexte québécois.

1.4.2.1 National Flood Insurance Program américain

Le National Flood Insurance Program (NFIP) américain, exemple de régime public créé en 1968 suite au retrait du privé, est la principale source d'assurance inondation résidentielle (Kousky et Kunreuther, 2018). Kousky (2018) a analysé qualitativement (revue de littérature, rapports gouvernementaux, données NFIP) cinq aspects du programme : modélisation/communication des risques, rôles public/privé, adoption, incitations à la réduction des risques, et tarification/financement, visant sa modernisation et la réduction de son déficit.

L'étude de Kousky (2018) a mis en évidence des lacunes importantes du programme, notamment des cartes de zones inondables souvent obsolètes n'intégrant pas les risques climatiques futurs et une communication du risque insuffisante pouvant créer un faux sentiment de sécurité. En raison du rôle limité du secteur privé, le NFIP domine le marché de l’assurance contre les inondations. Cependant, les taux de souscription au NFIP sont en déclin, particulièrement hors des zones à haut risque (SFHA). Des incitations à la réduction des risques, comme le Community Rating System (CRS), existent mais leur participation est limitée (Kousky, 2018). La tarification, mélangeant taux basés sur le risque et taux subventionnés, génère d'importantes subventions croisées, des problèmes d'abordabilité et un endettement considérable du programme. L’auteure conclut à la nécessité de réformes substantielles (mise à jour des cartes, meilleure communication, révision des subventions, plan de financement clair, prise en compte de l'abordabilité) et suggère d'évaluer l'intégration de la couverture inondation aux polices d'assurance habitation standard.

Le NFIP américain, malgré ses faiblesses, démontre tout de même un lien direct entre les actions municipales de réduction du risque et des incitatifs financiers pour les résidents (par exemple, via les primes d'assurance). Au Québec, les municipalités ne sont pas intégrées de manière comparable dans de tels mécanismes. Cette situation justifie d'analyser comment une participation municipale plus structurée pourrait contribuer à une meilleure gestion des risques d'inondation dans la province.

1.4.2.2 Régime CatNat en France

Un deuxième exemple est le mécanisme d'assurance public-privé de la France, le régime d'indemnisation des catastrophes naturelles, dit « régime CatNat ». Il repose sur le principe que lorsque l'état de catastrophe naturelle est déclaré par arrêté, les assureurs sont tenus d'indemniser les victimes au titre de la « garantie CatNat ». Cette garantie est obligatoire dans tout contrat garantissant les dommages aux biens. En parallèle, les assureurs peuvent souscrire une police de réassurance auprès de la Caisse centrale de réassurance (CCR). La CCR est une entreprise publique de réassurance qui agit au nom et pour le compte de l'État français. Son rôle est de réassurer les assureurs privés qui couvrent les risques de catastrophes naturelles (inondations, tremblements de terre, tempêtes, etc.) en France. Le régime est financé par une cotisation additionnelle basée sur la prime des contrats d'assurance, la « surprime *CatNat* ». (Barraqué et Moatty, 2020). Le taux de cette surprime obligatoire est passé de 12 % à 20 % au 1er janvier 2025 (Lavarde, 2024).

Lavarde (2024), rapporteure spéciale de la commission des finances du Sénat, a analysé le *CatNat*, via des auditions auprès de multiples parties prenantes (assureurs, associations professionnelles, administrations, experts, élus), afin de formuler des recommandations pour garantir son équilibre financier et son équité face aux changements climatiques. Son étude soulève des défis majeurs tels que l'équilibre financier menacé par l'augmentation des sinistres ; des problèmes d'équité (perception de bénéfice inégal, difficultés d'indemnisation, acceptabilité de la mutualisation) ; un manque de lisibilité sur les risques couverts ; une prévention jugée insuffisante et déconnectée de son financement ; et des faiblesses dans les garanties aux assurés.

Pour assurer la pérennité du régime, Lavarde (2024) propose des réformes incluant l'indexation automatique de la surprime, une réflexion sur le périmètre du risque, le renforcement des garanties des assurés (refus d'assurance, paiement unique de franchise), l'encadrement des expertises et l'assouplissement des règles d'indemnisation. Un accent renouvelé sur la prévention est jugé nécessaire, via des mécanismes incitatifs (modulation de franchise, élargissement du fonds Barnier) et une meilleure corrélation entre recettes de la surprime et dépenses de prévention. L'auteure conclut que des réformes sont essentielles pour la soutenabilité, l'équité, la clarté du régime et une meilleure prise en charge des sinistrés. L'étude d'un tel système national structuré, qui tente d'articuler indemnisation, prévention et responsabilités partagées, contraste avec la situation au Québec où le rôle et les leviers financiers des municipalités dans un cadre de gestion du risque d'inondations méritent d'être approfondis.

1.4.2.3 Fonds de réassurance Flood Re au Royaume-Uni

Le Flood Re, fonds de réassurance britannique créé en 2015, a remplacé le « Gentlemen's Agreement ». Cet accord garantissait que l'assurance contre les inondations resterait largement disponible et abordable pour la plupart des propriétaires, même ceux situés dans des zones à risque élevé. En échange de cette garantie de couverture, le gouvernement s'engageait à investir dans des mesures de protection contre les inondations. *Flood Re* demeure une mesure transitoire jusqu'en 2039 visant une transition de l'assurance privée vers une tarification basée entièrement sur le risque. Sa gouvernance, issue du secteur privé, s'appuie sur l'engagement du gouvernement britannique en matière de protection, prévention, préparation et législation sur l'aménagement du territoire (Surminski et Eldridge, 2014).

Surminski (2018) a analysé Flood Re selon les critères suivants : son influence sur la modélisation et la communication des risques, sa capacité à inciter à la réduction des risques, son impact sur les taux de souscription et la distribution des coûts, et sa viabilité à long terme face aux risques climatiques. L'étude, basée sur une approche méthodologique mixte (analyse de données de 2017, entretiens avec des acteurs clés, et revue de littérature), visait aussi à fournir des enseignements pour d'autres gouvernements.

L'auteur indique que Flood Re fonctionne comme un arrangement de réassurance transitoire qui soutient efficacement le marché privé. Cet arrangement garantit l'abordabilité de l'assurance inondation par des subventions croisées, sans responsabilité financière directe du gouvernement (sauf l'insolvabilité du fonds). Le coût réel du risque est peu visible pour les consommateurs et le taux de souscription est très élevé (95-98%) grâce à l'inclusion standard de la couverture et aux exigences hypothécaires, Flood Re visant surtout l'abordabilité pour les propriétés à haut risque.

Cependant, Surminski (2018) constate une faiblesse majeure : l'absence quasi totale d'incitations directes à la réduction des risques pour les propriétaires, assureurs ou le gouvernement. Le système formalise une subvention croisée des propriétés à haut risque par celles à faible risque. De plus, la tarification basée sur les tranches d'imposition locale introduit une autre subvention liée à la richesse. Ce manque d'incitation pose un défi fondamental à la viabilité à long terme de Flood Re face à l'aggravation des risques (développement en zones exposées), rendant la transition vers une tarification basée sur le risque réel très incertaine. Si Flood Re atteint ses objectifs immédiats d'accessibilité et de disponibilité, son incapacité structurelle à encourager la réduction des risques soulève des interrogations sur sa soutenabilité. L'exemple de Flood Re illustre ainsi une déconnexion souvent observée : la protection financière est organisée via une subvention croisée sans pour autant créer d'incitatifs forts pour que les acteurs (y compris les municipalités via leurs décisions d'aménagement) qui peuvent agir sur le risque local agissent pour le réduire. Cette observation est particulièrement pertinente pour le Québec, où les municipalités jouent un rôle clé dans l'aménagement du territoire mais où les mécanismes pour les inciter financièrement à une gestion proactive du risque d'inondations et à la réduction de la vulnérabilité sont peu développés.

1.4.2.4 Contexte canadien et québécois

Contrairement aux exemples américain, français et britannique, qui s'appuient sur des programmes d'assurance ou de réassurance spécifiques contre les inondations, le Canada ne dispose pas, au niveau fédéral, d'un régime national d'assurance généralisé contre les inondations. Toutefois, une initiative est en cours pour y remédier. La stratégie fédérale pour la gestion financière des conséquences des catastrophes a plutôt reposé historiquement sur un mécanisme d'aide post-événement, soit les Accords d’aide financière en cas de catastrophe (AAFCC). Établis en 1970 et administrés par Sécurité publique Canada, l’objectif des AAFCC est d'aider les provinces et territoires à couvrir les coûts d'intervention et de rétablissement. Le déclenchement de l'aide fédérale survient lorsque les dépenses admissibles d'une province ou d'un territoire dépassent un seuil minimal basé sur sa population. La participation financière du gouvernement fédéral est alors déterminée par une formule par habitant et est structurée en tranches, avec des taux de contribution fédérale croissants pour chaque palier de dépenses.

La gestion de l'aide financière et l'indemnisation des victimes relèvent de la responsabilité des provinces et territoires, qui sont ensuite partiellement remboursés par le fédéral. Par conséquent, les AAFCC ne traitent pas directement les réclamations des particuliers. Chaque province a la latitude d'adapter les règles fédérales, ce qui peut entraîner des variations dans la couverture et les montants d'aide entre les provinces. Les AAFCC ne couvrent pas les dépenses pour lesquelles une assurance est disponible à un coût raisonnable (ce qui inclut les refoulements d'égout pour les particuliers). Sont également exclus les dommages subis par les grandes entreprises, les pertes de revenus, les dommages aux récoltes et ceux causés aux résidences secondaires. Pour les particuliers, la couverture se limite généralement aux dommages provoqués par le débordement de cours d'eau.

Depuis le 1er avril 2025, les AAFCC ont été modernisés afin d'accélérer l'aide financière, d'accroître les investissements en atténuation stratégique des catastrophes et d'encourager la réduction des risques, en phase avec la Stratégie nationale d'adaptation du Canada. Cette refonte majeure introduit un partage des coûts élargi pour couvrir l'intervention d'urgence, les pertes non assurables des maisons et petites entreprises, la réparation résiliente des infrastructures, le soutien direct aux personnes fortement touchées et les mesures d'atténuation stratégique. De plus, le programme modernisé offre des incitatifs financiers aux provinces et territoires qui investissent de façon proactive dans la réduction des risques, une souplesse accrue pour adapter l'aide aux besoins communautaires spécifiques et des investissements fédéraux accrus pour la reconstruction et l'atténuation (concept de construire mieux), tout en renforçant le soutien aux populations vulnérables (Sécurité Publique Canada, 2021 ; Sécurité publique Canada, 2025).

En complément aux AAFCC, le gouvernement fédéral soutient l'atténuation des catastrophes par divers programmes, dont deux principaux se distinguent. Le Fonds d'atténuation et d'adaptation en matière de catastrophes (FAAC) d'Infrastructure Canada vise à renforcer la résilience des communautés via des investissements dans des projets d'infrastructure à grande échelle. De manière plus ciblée, le Programme national d'atténuation des catastrophes (PNAC), créé en 2015 en réponse aux risques croissants, est le seul programme fédéral entièrement dédié à l'atténuation pré-catastrophe des inondations. Il offre un soutien financier aux provinces pour des projets d'évaluation et d'atténuation du risque, en partie pour répondre à la demande des assureurs.

Au Québec, les sinistrés d'une catastrophe naturelle peuvent se qualifier pour le Programme général d'indemnisation et d'aide financière lors de sinistres réels ou imminents (PGAF). Ce mécanisme implique le partage des risques entre les contribuables de différents secteurs ou zones géographiques, en utilisant les ressources et les institutions fiscales (Giovannini *et al.*, 2022). La protection est quasi universelle en ce sens qu'elle s'applique aux propriétaires et aux locataires sinistrés (résidences principales). Les conditions d'application de ce programme sont prévues dans divers décrets. Pour que l'événement soit considéré comme une inondation, l'eau d'un cours d'eau qui déborde doit atteindre le terrain de la résidence. C'est la province à travers son ministère de la Sécurité publique qui gère le versement des indemnités aux sinistrés, basées sur des dommages admissibles.

Le PGAF vise à offrir une aide de dernier recours aux propriétaires et aux locataires touchés par un sinistre. Certaines dépenses sont admissibles à une aide financière et d'autres à une indemnisation, par exemple, les mesures préventives temporaires mises en place, les biens meubles admissibles touchés et les travaux d'urgence. Cependant, le gouvernement du Québec a récemment limité les indemnités prévues à son programme (Gouvernement du Québec, 2025b). Cette nouvelle version impose une limite à vie aux victimes d'inondations et vise à les décourager à reconstruire dans les zones inondables (Boudreault et Bourdeau-Brien, 2020). De plus, les délais de règlements et la complexité des demandes d'indemnisation auprès du gouvernement rendent l'expérience client défavorable et même traumatique (Maltais *et al.*, 2023).

Un point fondamental à souligner dans ces mécanismes dominants au Canada et au Québec est l'absence des municipalités comme contributrices financières directes. Cette déconnexion entre leur rôle en gestion du risque et leur responsabilité financière est au cœur de l'hypothèse d'aléa moral (ou du manque d'incitatif) étudiée dans cette thèse.

1.4.3 Union réciproque comme mécanisme de partage du risque

L'union réciproque est un moyen de financement alternatif à l'achat d'assurance ou aux programmes d'aide gouvernementaux. L'union permet de répartir le coût de la réalisation d'un sinistre entre les membres d'un groupe soumis potentiellement au même risque (Norgaard, 1964 ; Venezian, 2005). Il s'agit d'un principe de solidarité entre les assurés, où chacun contribue en versant sa cotisation sans garantie préalable quant à savoir s'il sera lui-même indemnisé ou si cela concernera un autre membre du groupe. Ce principe repose sur une coopération et une assistance entre les différentes parties affectées, soulignant l'importance de la responsabilité collective. Ce partage peut être volontaire ou obligatoire au sein des membres d'une communauté. Le mécanisme d'union réciproque se distingue de l'assurance privée traditionnelle par sa gouvernance et ses incitatifs économiques. Alors que l'assurance privée est détenue par des actionnaires et vise le profit, l'union réciproque est détenue par ses membres/assurés et vise la réduction du risque collectif. Cette structure permet d'utiliser les fonds excédentaires pour financer des investissements communautaires en réduction du risque créant un lien direct entre l'action collective et la réduction des coûts pour les membres, ce qui est difficilement réalisable avec des polices individuelles standard. En internalisant une partie du risque au niveau local, l'union devient un puissant outil de gouvernance pour les communautés, les incitant à agir concrètement pour la résilience.

1.4.3.1 Les unions réciproques : un modèle d'assurance catastrophe innovant

Bernhardt *et al.* (2020) analysent ce concept d'union réciproque qu'ils nomment Community-Based Catastrophe Insurance (CBCI). La CBCI est définie comme un programme d'assurance organisé au niveau local (par un gouvernement local ou un groupe communautaire) qui assure les propriétés individuelles au sein de cette communauté. L'objectif principal de leurs travaux est d'explorer un nouveau modèle d'assurance catastrophe, présenté comme une approche innovante pour combler le déficit de protection persistant face aux catastrophes naturelles. L'étude vise spécifiquement à définir la CBCI et ses caractéristiques et à identifier ses bénéfices potentiels, notamment l'incitation à réduire le risque. Les auteurs examinent également comment la CBCI pourrait s'intégrer dans l'écosystème existant des assurances publiques et privées, dans le but ultime d'encourager son exploration comme partie intégrante des stratégies de gestion des risques.

L'étude repose essentiellement sur une approche qualitative, supportée par des entretiens menés auprès d'un large éventail de parties prenantes, incluant membres de communautés, régulateurs, réassureurs et gestionnaires de risques. Ces échanges ont contribué au développement conceptuel des modèles de prestation et de la feuille de route d'implémentation. L'étude s'appuie également sur l'analyse de travaux antérieurs concernant l'assurance communautaire, notamment pour les inondations. Bien que l'étude se concentre sur les États-Unis, les modèles sont conçus pour être potentiellement applicables dans d'autres contextes.

Les auteurs reconnaissent d'abord l'existence d'un déficit de protection majeur et persistant aux États-Unis, où de nombreux ménages et entreprises manquent des ressources financières pour se reconstruire après une catastrophe, en raison de contraintes d'abordabilité, d'une sensibilisation limitée ou de biais comportementaux. Les auteurs soulignent le potentiel significatif de la CBCI pour améliorer la résilience financière collective et individuelle, fournir une assurance jugée plus abordable et fiable, et surtout, créer des incitations efficaces à la réduction des risques tant au niveau de la communauté que des individus.

L'étude insiste sur la grande flexibilité de la CBCI qui peut jouer divers rôles, complétant ou remplaçant potentiellement les mécanismes d'assurance traditionnels, et facilitant la collaboration entre communautés et assureurs privés. Une feuille de route itérative est proposée pour guider sa mise en œuvre, impliquant une définition claire des besoins, l'engagement des parties prenantes et la conception d'une solution de transfert de risques adaptée. Selon les auteurs, la CBCI pourrait réduire les primes grâce au pouvoir d'achat groupé, à une meilleure qualité de données et à une potentielle intégration avec des aides ciblées. Un avantage clé du modèle réside dans sa capacité à créer des incitations financières directes pour des investissements communautaires dans la réduction des risques, ce qui est difficile à réaliser avec des polices individuelles.

Le succès de ce mécanisme dépendrait de l'engagement collaboratif de toutes les parties prenantes (résidents, assureurs, réassureurs, partenaires gouvernementaux) et de la capacité à définir une solution de transfert de risque mutuellement bénéfique. La CBCI est donc un outil prometteur pour renforcer la résilience des communautés face aux catastrophes. Ce modèle suggère également une piste où la communauté locale, potentiellement organisée ou soutenue par la municipalité, pourrait internaliser une partie du risque et ainsi développer des incitatifs spécifiques à la réduction du risque, contrastant avec les systèmes actuels.

1.4.3.2 Contexte canadien et québécois

Ce troisième mécanisme ne constitue pas une forme d'organisation prédominante ou particulièrement développée au Canada pour fournir de l'assurance contre les catastrophes naturelles. Cependant, ce mécanisme est prévu dans la Loi sur les assureurs du Québec (Gouvernement du Québec, 2024). Dans ce contexte, une union réciproque, pourrait prendre la forme d'un pool de risques intermunicipaux financé par les contributions des individus collectées par les municipalités. Un tel pool peut être particulièrement pertinent pour les petites communautés tel que le souligne Bernhardt *et al*. (2020) et ainsi diminuer l'écart de protection global (Hudson *et al.*, 2019). Ainsi, une union réciproque ou un pool de risques intermunicipaux pourrait représenter une innovation de gouvernance où les municipalités québécoises joueraient un rôle financier actif dans la gestion du risque d’inondations.

1.5 Objectifs de recherche

Dans un contexte d'aggravation des conséquences économiques des inondations et du manque de connaissances pour les réduire, l'objectif général de cette recherche est de mieux comprendre les capacités d'action des municipalités québécoises en matière de réduction du risque d'inondations fluviales. L'étude vise ultimement à orienter les politiques publiques vers une gestion plus responsable, équitable et efficace de ce risque au Québec, en identifiant et en évaluant spécifiquement comment l'instauration d'une participation financière des municipalités aux coûts d'indemnisation des sinistrés pourrait transformer leur rôle dans cette gestion.

L'hypothèse sous-jacente est qu'en excluant les municipalités de la responsabilité financière directe du coût des indemnisations, les incitatifs à réduire le risque associé aux inondations au niveau municipal ou local sont faibles, voire inexistants. Cet objectif général est décliné en quatre objectifs spécifiques, chacun étant exploré dans un chapitre dédié :

1. Identifier les mécanismes de gouvernance et les instruments d'action publique utilisables par les municipalités pour la gestion du risque d'inondation (Chapitre 2).
2. Identifier et prioriser les facteurs contribuant aux dommages aux bâtiments résidentiels et déterminer l'influence municipale sur ces facteurs (Chapitre 3).
3. Analyser divers mécanismes de partage du risque financier et proposer un nouveau modèle de contribution économique municipale proportionnelle au risque (Chapitre 4).
4. Évaluer la faisabilité technique et l'acceptabilité politique d'un modèle concret de partage du risque financier intégrant une contribution municipale proportionnelle au niveau de risque sur leur territoire (Chapitre 5).

Le Tableau 1.3 présente en détail ces objectifs, les hypothèses associées, les résultats attendus, et les questions de recherche auxquelles chacun des chapitres cherche à répondre. Le Tableau 1.4 précise le cadre méthodologique de la recherche.

Tableau 1.3 Cadre logique de la recherche

Niveau	Objectif(s)	Hypothèse(s)	Résultats attendus	Question(s) de recherche
Général	Général : Combler une lacune dans la compréhension des leviers d'action municipaux et à éclairer les politiques publiques pour une gestion plus responsable, équitable et efficace du risque d'inondations au Québec.	L'absence de participation financière directe des municipalités québécoises aux mécanismes d'indemnisation des inondations engendre un aléa moral et des incitatifs insuffisants à l'adoption de mesures proactives de réduction du risque. L'instauration d'une contribution financière municipale, en créant un lien économique direct avec les coûts des dommages, favoriserait une gestion plus efficace et une internalisation accrue des coûts du risque par les administrations locales.	Identification des mécanismes de gouvernance qui contribuent à l'aléa moral, des instruments d'action publique et des facteurs contributifs aux dommages. Analyse des mécanismes de partage du risque; proposition d'une démarche d'estimation et d'un modèle de contribution municipale.	Comment les municipalités québécoises peuvent-elles contribuer efficacement à la réduction du risque d'inondations fluviales ?
Chapitre 2 (Gouvernance et incitatifs)	Spécifique 1 : • Identifier les mécanismes de gouvernance et les instruments d'action publique utilisables. • Identifier les principaux mécanismes d'indemnisation utilisés présentement. • Analyser comment les municipalités peuvent contribuer à la réduction du risque.	Malgré l'existence d'instruments d'action publique variés relevant de leur compétence, les municipalités québécoises sous-utilisent leur potentiel en matière de prévention des inondations en raison d'une combinaison de facteurs : une gouvernance fragmentée du risque, des signaux économiques (incitatifs) faibles ou contradictoires provenant des mécanismes d'indemnisation, et des obstacles liés à la capacité administrative et aux pressions socio-politiques locales.	Meilleure compréhension des rôles/responsabilités municipaux. Identification des obstacles à la mise en œuvre et des stratégies pour les surmonter. Description des mécanismes d'indemnisation et leur fonctionnement. Recommandations sur les instruments à privilégier	Quels facteurs institutionnels et financiers expliquent le sous-investissement municipal actuel dans la prévention? Quelles sont les principaux instruments d'action publique mis en œuvre et quelles leçons en tirer? Quels sont les principaux mécanismes d'indemnisation qui viennent faciliter le rétablissement ? Quels sont les instruments à privilégier ?
Chapitre 3 (Facteurs contributifs)	Spécifique 2 : • Identifier et prioriser les facteurs contribuant aux dommages (bâtiments résidentiels) ;	L'action municipale en réduction des dommages résidentiels est limitée par une méconnaissance de l'impact réel et de leur degré de contrôle sur des facteurs clés autres que la profondeur	Identification et priorisation des facteurs clés (incluant ceux sous influence municipale). Établissement de coefficients pour affiner l'estimation des dommages et améliorer les analyses	Quels sont les principaux facteurs contributifs aux dommages par l'eau au secteur résidentiel ? Quel est le degré d'influence des municipalités sur ces facteurs ? Quels leviers d'action les

Niveau	Objectif(s)	Hypothèse(s)	Résultats attendus	Question(s) de recherche
	• Déterminer l'influence municipale sur ces facteurs ; • Établir des coefficients de taux d'endommagement.	de submersion (ex : normes et aménagement). La priorisation et la quantification de ces facteurs via des coefficients sont donc essentielles pour démontrer ce potentiel d'action et améliorer la précision des estimations.	coûts-bénéfices des mesures de réduction.	municipalités peuvent-elles utiliser pour les réduire ? Comment intégrer efficacement des coefficients du taux d'endommagement dans les modèles ?
Chapitre 4 (Modèle de Partage)	Spécifique 3 : • Analyser/comparer des mécanismes de partage des risques; • Proposer un nouveau modèle de contribution économique municipale proportionnelle au risque; • Calculer cette contribution économique pour des cas types.	L'instauration d'une contribution financière municipale directement liée à l'ampleur du risque d'inondation sur leur territoire, et calculée à l'aide des outils existants, créerait un incitatif économique fort pour les municipalités à adopter des mesures proactives de réduction du risque. Ce modèle de partage des coûts favoriserait également une plus grande équité et encouragerait les particuliers à prendre des mesures d'atténuation en réponse au signal de risque.	Démonstration de la faisabilité technique d'établir une contribution proportionnelle au risque pour chaque municipalité. Mise en évidence que cibler les bâtiments/municipalités à haut risque peut réduire substantiellement le coût des indemnités.	Quels mécanismes innovants de partage du risque financier pourraient responsabiliser financièrement les municipalités sans aggraver les inégalités ? Comment établir la contribution proportionnelle au risque de chaque municipalité ? Comment le modèle d'estimation des dommages permet-il d'orienter l'établissement de stratégies de réduction du risque spécifiques à chaque municipalité ?
Chapitre 5 (Faisabilité et acceptabilité)	Spécifique 4 : • Explorer l'acceptabilité et la faisabilité d'un nouveau mode de partage (contribution municipale); • Déterminer si cela peut inciter à la réduction du risque; • Identifier les facteurs influençant cette priorisation.	L'instauration de contributions municipales proportionnelles au risque pourrait inciter les municipalités à prioriser les mesures de réduction du risque et favoriser l'équité entre les parties prenantes, sous réserve de son acceptabilité et de sa faisabilité.	Perception des experts/acteurs municipaux sur une contribution proportionnelle. Détermination des enjeux, conditions de mise en œuvre et défis (équité, efficacité). Recommandations pour une meilleure gestion du risque. Confirmation/infirmation de l'hypothèse d'incitation à la réduction du risque.	Dans quelle mesure une contribution financière municipale aux coûts d'indemnisation peut-elle agir comme un levier efficace pour surmonter le manque d'incitatifs actuel et inciter les municipalités québécoises à prioriser la réduction du risque d'inondations fluviales ? Quelles sont les conditions nécessaires à la mise en œuvre d'un mode de partage du risque financier efficace et équitable ? Quelles sont les conditions nécessaires à la réduction du risque d'inondations ?

Tableau 1.4 Cadre méthodologique

Chapitre	Méthode(s) / approche(s)	Données / livrables méthodologiques	Fonction principale de l'analyse
Chapitre 2 Gouvernance et incitatifs	Revue de littérature et analyse institutionnelle. Comparaison entre deux provinces.	Cadre légal (lois provinciales, programmes d'aide, instruments d'action publique). Mécanismes de partage de risque (assurance, aide gouvernementale)	Établir le contexte d'aléa moral en démontrant le désalignement des incitatifs et des responsabilités municipales.
Chapitre 3 Facteurs contributifs	Consultations d'experts (n=45 experts) Méthode inspirée de Delphi. Sondage quantitatif (n=35 experts) avec Lime Survey.	Facteurs prioritaires : 40 facteurs (7 des 10 principaux sous juridiction municipale). Coefficients : valeurs médianes (type de sol, âge du bâtiment) pour ajuster les courbes.	Identifier les leviers d'action municipaux et fournir des coefficients d'ajustement pour réduire l'incertitude dans les estimations de dommages.
Chapitre 4 Modèle de partage	Modélisation technique (calculs de dommages) et étude de cas (3 municipalités de la Communauté métropolitaine de Montréal).	Modèle de courbes de dommage de Doyon et Jean (2021). Données : 4 000 bâtiments (hauteurs de crue, rôle d'évaluation, type de sous-sol, etc.). Indicateur : dommages annualisés moyens.	Illustrer la faisabilité technique d'établir une contribution municipale proportionnelle au risque et fournir d'exemples de mesures de réduction (relocalisation, élévation).
Chapitre 5 : Faisabilité et acceptabilité	Entretiens qualitatifs semi-dirigés (n=35 acteurs) et analyse thématique.	Échantillon : élus et fonctionnaires municipaux, experts externes. Thèmes : efficacité/incitation, équité, faisabilité financière, et pouvoir de contrôle municipal.	Évaluer l'acceptabilité du modèle et valider l'hypothèse d'un effet incitatif direct. Identifier les obstacles (gouvernance, risque hérité) et les alternatives.

CHAPITRE 2

HOW CAN MUNICIPALITIES IN BRITISH COLUMBIA AND QUÉBEC CONTRIBUTE TO FLOOD RISK REDUCTION?

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Résumé

Les pertes liées aux inondations sont en hausse au Canada et les assurances privées restent coûteuses, voire inexistantes dans les zones à haut risque. Malgré l'introduction d'une assurance contre les inondations terrestres en 2015, à la suite de l'invitation lancée par le gouvernement fédéral au secteur des assurances à participer au partage des risques liés aux inondations, les programmes fédéraux et provinciaux d'aide financière en cas de catastrophe couvrent toujours une grande partie de ces coûts. À mesure que les risques augmentent, les gouvernements s'interrogent sur la viabilité du financement de ces pertes par les contribuables, ce qui laisse aux municipalités un risque résiduel important. Le nombre croissant de personnes et de biens occupant des zones inondables, y compris les infrastructures publiques, a contribué à la forte augmentation des coûts des dommages causés par les inondations. Sur la base d'une analyse documentaire et de discussions avec des experts, ce chapitre décrit le rôle des municipalités dans la gestion du risque d'inondations et montre comment l'aide financière accordée par les provinces et le gouvernement fédéral aux municipalités pour les dommages causés par les inondations en Colombie-Britannique et au Québec peut être contre-productive pour favoriser la gestion du risque d'inondations au niveau municipal. Nous concluons que les municipalités peuvent jouer un rôle plus proactif en intégrant la réduction des risques comme objectif clé de l'aide financière en cas de catastrophe et proposons trois instruments politiques spécifiques pour aider à réduire le nombre croissant de personnes vivant dans des zones inondables : la cartographie des zones inondables, l'aménagement du territoire et la relocalisation des propriétés à haut risque.

Mots clés : gouvernance des risques, instruments d'action publique, aide financière en cas de catastrophe, aménagement du territoire, cartographie du risque d'inondations.

Codes JEL : H77, Q54, R11

Abstract

Flood-related losses are on the rise in Canada and private insurance remains costly or unavailable in high-risk areas. Despite the introduction of overland flood insurance in 2015, following the federal government's invitation to the insurance industry to participate in flood risk-sharing, federal and provincial disaster financial assistance programs still cover a large portion of these costs. As the risks increase, governments are questioning the sustainability of using taxpayers' money to finance such losses, leaving municipalities with significant residual risk. The growing number of people and assets occupying floodprone areas, including public infrastructure, has contributed to the sharp increase in flood damage costs. Based on a literature review and discussions with experts, this paper describes the municipal role in flood-risk management and shows how provincial and federal financial assistance to municipalities for flood damage in British Columbia and Québec may be counterproductive in fostering flood-risk management at the municipal level. We conclude that municipalities can play a more proactive role in incorporating risk reduction as the key objective of disaster financial assistance and propose three specific policy instruments to help reduce the growing number of people living in flood zones: flood mapping, land-use planning, and the relocation of high-risk properties.

Keywords: risk governance, policy instruments, disaster financial assistance, land-use planning, flood-risk mapping

JEL Codes: H77, Q54, R11

2.1 Introduction

Canadian municipalities[1] have powers and responsibilities to reduce the consequences of flooding, making them crucial actors in managing flood risk. Municipalities own 60 percent of public infrastructure in Canada (Fédération canadienne des municipalités, 2024) and are expected to provide a safe living environment for their communities. Floods expose municipalities and communities to significant economic and social costs. By far, flooding remains the costliest source of property damage in Canada[2] (Ressources Naturelles Canada, 2023). These costs are increasing rapidly with the combined effects of climate change (Carvalho, 2018) and continued residential development in floodplains to accommodate population growth and economic development (Cottar *et al.*, 2021 ; Golnaraghi *et al.*, 2020 ; Lorinc, 2022 ; Ward *et al.*, 2020b).

According to Public Safety Canada, “Eighty percent of Canadian cities are built on flood plains and with climate change, recovery costs for flood disasters will continue to increase” (Public Safety Canada, 2020). As a result, more than 20 percent of residential properties are exposed to a high risk of flooding (Chakraborty *et al.*, 2022). The Insurance Bureau of Canada (IBC) also provides evidence that 19 percent of the Canadian population lives in flood-prone areas (Insurance Bureau of Canada, 2022b). Yet these numbers underestimate the risk, as they omit the risks of rainfall, ice jams, runoff from sewer backups, infrastructure failures, and extreme short-term precipitation.

Canada has long allowed people, assets, and infrastructure to occupy flood-prone areas. In 1975, the government of Canada launched the Flood Damage Reduction Program to discourage future development in areas at high risk of flooding. Federal and provincial governments agreed to avoid building any future “flood-vulnerable developments” in flood-prone areas. This agreement was not enforced in any meaningful way, however, and development continued to take place in flood plains (Bruce, 2013).

[1] In this text, we use the term “municipalities” to include all forms of local and regional governments, including cities, towns, villages, rural or metropolitan municipalities, regional authorities, and special. purpose boards or commissions.

[2] Following a similar trend, insured losses have also increased substantially in the last 20 years. In 2021 alone, these losses amounted to $2.1 billion ($2.3 billion in 2020) (Insurance Bureau of Canada 2022b).

This paper highlights the mismatch between the financing of recovery from flood damage and the municipal role in flood risk management. It is organized in three sections. First, we provide a picture of municipal flood-risk management responsibilities in British Columbia and Québec. That picture derives from our analysis of academic and grey literature as well as interviews with experts in flood-risk management. Our research focuses on British Columbia and Québec because of our network of contacts in these provinces and because both provinces have faced major floods in the last few years, allowing us to observe the response of municipalities to such events. Second, we explain how flood-risk management is financed and review the role and limitations of the current cost-sharing schemes.

Finally, we discuss the role of three specific policy instruments available to municipalities to reduce the number of people, assets, and infrastructure elements exposed to floods: flood mapping, land-use planning, and relocation of high-risk properties.

The November 2021 Pacific Northwest floods that affected British Columbia led to at least $675 million in insured damage, making it the province's costliest natural disaster in history (Castonguay, 2022). However, that amount does not include damage to infrastructure and uninsured properties. In this regard, Aon, a reinsurance broker, estimates that the economic damage amounts to more than US$2 billion (Dalton, 2021). Aaron Sutherland, Vice-President for the Western and Pacific Regions at the Insurance Bureau of Canada, confirms this figure. "We already know that the damage that will be covered by government programs will exceed several billion dollars. The majority of the damage will be borne by the state" (Castonguay, 2022).

Québec municipalities have also been severely affected by two recent floods: 293 municipalities were affected in 2017 and 240 in 2019. The Province paid a total of $1 billion in financial assistance for these two floods (Ministère des Affaires Municipale et de l'Habitation du Québec, 2020) and a significant proportion of that cost was borne by the federal government through Disaster Financial Assistance Arrangements (DFAA). In addition to government assistance, the spring floods of 2017 and 2019 cost insurers nearly $325 million and involved 20,200 insurance claims (Insurance Bureau of Canada, 2022a). More than half of the flooded lots were located outside designated flood zones (Ministère des Affaires Municipale et de l'Habitation du Québec, 2021a).

Historically, dams, dikes and other structural works have been used as risk-reduction methods (Nofal et van de Lindt, 2021 ; Thistlethwaite et Henstra, 2017). However, these structures have also created a false sense of security about the effectiveness of structural measures to reduce flood risks. Many of these structures redistribute risks rather than reduce them overall (Hawley *et al.*, 2012). Moffat and Bakos (2022) agree that these structures are important but argue that they should not be the centerpiece of risk-management strategies. Reducing the number of properties in high-risk areas can be a more effective strategy in the long term. The limitations of the dike systems were well illustrated when the dikes failed in British Columbia in 2021 and in Québec in 2019 following major floods.

Providing flood protection to communities in British Columbia and Québec is for the most part a municipal responsibility. Flood-risk mapping, land-use planning, and relocation programs are instruments available to municipalities to reduce the consequences of the growing exposure of assets in flood zones. However, the choice and implementation of these instruments are complex and subject to the availability of funding as well as to dynamics such as:

- the decentralization of flood-management responsibilities from the provinces to the local governments without the appropriate resources.
- pressure from interest groups with divergent and competing priorities (particularly true in relation to flood mapping and land-use planning).
- short-term budgetary constraints and political imperatives that take precedence over complex long-lasting investments.
- the moral hazard associated with existing post-disaster assistance, which discourages municipalities from investing in flood-risk management.

As a result, most municipalities have difficulties treating flood risk as a priority, particularly since they are excluded from current cost-sharing schemes (Dordi *et al.*, 2022 ; Henstra *et al.*, 2020 ; Lalancette et Charles, 2022 ; Rasmussen *et al.*, 2021). Not surprisingly, the magnitude of flood damage leads to debates about who is responsible for paying for the damage, and therefore who is accountable for implementing risk reduction measures (Kousky et Kunreuther, 2014).

Currently, damage is for the most part compensated for by federal and provincial post-disaster assistance programs and, to a lesser extent, by private insurers. As much as 70 percent of the flood-related federal disaster assistance payments are spent on fixing and rebuilding public infrastructure (municipal infrastructure for the most part), in comparison to approximately 15 percent on residential losses (Insurance Bureau of Canada, 2019).

This situation has been described as the "welfare state approach" to the management of flood hazards (Bergsma, 2019). This type of governing, whereby the federal and provincial governments fund municipal post-disaster recovery while municipalities remain responsible for the implementation of flood-risk management strategies, needs to be reviewed.

2.2 Flood-Risk Management: A Delegated Authority

Authority for flood-risk management activities is spread across different levels of government – federal, provincial, regional, and municipal – as well as the private sector, and across many divisions within each of these administrations (environment, public safety, infrastructure). In this paper, flood risk is defined as the cumulative effects and the interaction of flood hazards, which are affected by the changing climate and the growing exposure and vulnerability of human, socioeconomic, and biological systems to flooding[3] (Dordi *et al.*, 2022 ; Intergovernmental Panel on Climate Change, 2022).

The specific role of municipalities in flood-risk management is set out by provincial governments in a series of acts such as the British Columbia Emergency Program Act and the Québec Civil Protection Act[4]. Such legislation defines the municipal regulatory framework, sets municipal flood-risk management responsibilities for providing flood protection measures, and sets eligibility conditions and the limits of financial assistance for municipalities, property owners, and organizations to facilitate recovery after a flood. In British Columbia, the provincial government must consult municipalities before making decisions that affect them, whereas in Québec, the government is not legally obliged to consult with municipalities before enacting such changes (Taylor et Dobson, 2020).

British Columbia's municipal system consists of 161 local municipalities ranging in population from 100 to more than 630,000 people, 27 Regional Districts, two Metropolitan Communities[5] , and nine watershed

[3]Definitions of key terms used in this paper are presented in Appendix A.

[4] Appendix B contains a list of the main acts governing municipal risk management in British Columbia and Québec

[5] Vancouver and Victoria.

basins. The province has a total population of 5 million inhabitants (British Columbia Civic Info, 2022 ; British Columbia Tomorrow Society, 2021 ; Meloche et Vaillancourt, 2021).

In comparison, Québec has a population of 8.4 million. Its 1,107 local municipalities range in population from 10 to more than 1.8 million people. There are 87 Regional County Municipalities, two Metropolitan Communities[6] and 40 watershed basins (Ministère des Affaires Municipale et de l'Habitation du Québec, 2021b ; Regroupement des Organismes de Bassins Versants du Québec, 2021).

Table 2.1 shows the distribution of local municipalities by population in both provinces. Although consensus is lacking in the literature on how decentralization and centralization influence the performance of public governance (Kuo et Wang, 2014), the decentralization of flood-risk management authorities to such a large number of local governments raises questions of standardization in the interpretation of provincial policies and also complicates monitoring of policy implementation.

Tableau 2.1- Distribution of Local Municipalities by Province

Municipal Population	Size	British Columbia		Québec	
1 – 9,999	Small	104	64.2%	1,005	90.7%
10,000 – 99,999	Medium	48	29.6%	93	8.4%
100,000 – 499,999	Large	8	4.9%	8	0.7%
500,000+	Very large	2	1.2%	2	0.2%
Total		**162**		**1,108**	

Sources: Ministère des affaires municipales et de l'Habitation (https://www.quebec.ca/gouvernement/gestion-municipale/organisation-municipale/decret-population)and CivicInfo BC. (https://www.civicinfo.bc.ca/municipalities.php?type=ss&population=&region=&rd=)

The role of the Regional District in British Columbia differs from that of Québec Regional County Municipalities. Similar to local municipalities, Regional Districts regulate land-use planning in electoral

[6]Montréal and Québec.

areas[7] (British Columbia Ministry of Municipal Affairs, 2021). In Québec, Regional County Municipalities have a planning and supervisory role in land-use planning by their local municipalities (Meloche *et al.*, 2016 ; Ministère des Affaires Municipale et de l'Habitation du Québec, 2021b).

According to Red Dragon Consulting (2021a), larger municipalities are better prepared for floods than smaller municipalities, because of (1) their capacity to generate funds, (2) the availability of specialized resources in emergency management, and (3) support from various sectors, such as public works and engineering. Larger municipalities can better manage floods before seeking aid from the Province, whereas smaller municipalities often prove inadequate in their responses to floods.

Smaller municipalities rely on provincial support to access subject-matter experts and obtain resources to operate emergency centers, acquire field equipment, and hire trained staff. Smaller municipalities face the same resource challenges with the implementation of pre-disaster risk-reduction and mitigation measures. The simple act of filing an application for a government grant requires small municipalities to hire consultants because of the lack of internal resources. These costs are a deterrent to risk reduction efforts (Alalouf-Hall et Fontan, 2020).

Feltmate and Moudrak (2021) conducted a survey evaluating the flood preparedness of large Canadian cities. The authors concluded that there has been no material improvement in municipal flood-risk preparedness since 2015, the last year a similar survey was conducted. Although the study reveals that land-use planning is self-assessed positively by the largest participating cities, the authors argue that the lack of legislative power to enforce provincially established standards within municipal areas helps explain why flood damage continues to be widespread. In land-use planning particularly, additional research would be useful to provide a more in-depth overview of the situation among small and medium-sized municipalities in both provinces.

The risk management legal framework applicable to municipalities is constantly evolving. Following an exceptional wildfire in 2017 and floods in 2018, Emergency Management BC undertook a review of the *Emergency Program Act*. The review included integrating the United Nations Sendai Framework for

[7] Electoral areas in British Columbia are communities outside municipal boundaries, often referred to as rural or unincorporated areas.

Disaster Risk Reduction[8] and putting the emphasis on disaster risk reduction (Red Dragon Consulting, 2021b). Then, following the 2021 floods in British Columbia, the provincial government acknowledged its failure to protect communities from floods (Hunter, 2022a). In connection with the flood-risk management legal framework, the Public Safety Minister of British Columbia, Mike Farnworth, said the Province is revisiting the 2003 delegation of flood-risk management to municipalities as part of new legislation expected in 2022, given that “many communities don’t have that capacity” (McElroy, 2021, p. 5). As of early 2023, the draft legislation is still in the works.

In Québec, following floods in 2017 and 2019, the provincial government issued a temporary order establishing a special planning zone to promote more rigorous management of flood zones[9]. The transitional regulation is associated with two high-risk flooding zones: the 20-year recurrence flood (high current zone) and the 100-year recurrence flood (low current zone). Québec defines a flood zone as a space that is likely to be occupied by water from a lake or watercourse. Its boundaries are established according to the most recent available flood maps, to which have been added the areas affected by the 2017 and 2019 floods (Ministère de l’Environnement et de la Lutte contre les Changements Climatiques Québec, 2022).

That order affected 776 municipalities for which it replaced local and regional planning and development regulations. It also established a moratorium on the construction of new buildings and on the reconstruction of buildings damaged by flooding in designated high-risk flood plains and flooded areas. This temporary regime has been replaced by a transitional set of regulations, which lift the construction ban imposed in the special planning zone and identify the activities (works, construction, or other interventions) carried out on shorelines, coastlines, and flood zones that require authorization from the municipality (Ministère de l’Environnement et de la Lutte contre les Changements Climatiques Québec, 2022).

[8] See Appendix A for definition.

[9] Approximately 32,000 lots are located in flood zones in Québec. Most are occupied by dwellings (56 percent). The remaining lots contain industries, businesses, or utilities, or are vacant (Ministère de l’Environnement et de la Lutte contre les changements climatiques 2022: 10).

These provisions also provide the terms and conditions applicable to municipal authorities, along with accountability requirements and penalties for violations. The government acknowledges that limiting the construction of new buildings to certain lots in already developed areas will result in a reduction in the future property tax revenues for the municipalities and may limit municipalities' expansion (Ministère de l'Environnement et de la Lutte contre les Changements Climatiques Québec, 2022). It has yet to offer compensation to municipalities.

2.3 Financing Flood Risk Management

Various pre-disaster financial assistance programs have been established by the federal government and the provinces to support municipalities in implementing flood risk reduction measures. In addition, post-disaster assistance offered by the federal and provincial governments as well as by commercial insurers is available to municipalities to fund disaster recovery. However, there is a fundamental misalignment of incentives, because municipalities do not adequately bear the costs of flood damage and yet are expected to mitigate the risks.

As a result, government assistance programs in Canada are under scrutiny because of growing costs and their failure to promote risk reduction (Golnaraghi *et al.*, 2020). In a survey conducted by Red Dragon Consulting of 65 governmental and insurance experts, respondents reported that municipalities' ability to allow development and increase tax revenue while any damage to these properties are funded by non-municipal post-disaster assistance has led to increasing exposure in flood zones (Red Dragon Consulting, 2021b).

The current programs require municipalities to implement risk-reduction strategies, but there is no municipal financial contribution to recovery when the strategies fail. According to Ebbwater Consulting (2021), post-disaster assistance in Canada is related to "past economic concepts." Facing skyrocketing flood-damage costs, key stakeholders are likely to challenge the current post-disaster assistance approach.

Davlasheridze and Miao (2021) examined multiple post-disaster assistance programs implemented by the U.S. government to support state and municipalities as well as households and private businesses. They concluded that efficiency gains could be realized by revisiting how funding is distributed across programs and government agencies. For example, when assistance is provided through long-term risk reduction, such as property buybacks in high-risk areas, rather than through direct financial recovery assistance, the funds generate greater social benefit in the long run. Mol *et al.* (2020) confirm that implementing risk-reduction measures before a catastrophic event is a more profitable approach and suggest researching the incentives that motivate people to reduce risk.

According to the Insurance Bureau of Canada, studies have shown that investments in risk reduction and mitigation have a return on investment of $6 in future averted losses for every $1 spent. Those investments are critical to helping municipalities adapt to the changing climate and reduce risks from extreme weather (Insurance Bureau of Canada et Federation of Canadian Municipalities, 2020).

2.3.1 Pre-disaster mitigation funding

Many grants and fiscal programs are available to municipalities. However, these sources of funding are ad hoc, only partially cover the needs, and are often conditional, making it difficult for municipalities to implement long-term strategies (Federation of Canadian Municipalities, 2020).

For example, municipalities in British Columbia have access to the Emergency Management Assistance Program and the Disaster Mitigation and Adaptation Fund. In Québec, municipalities can benefit from the Programme de résilience et d'adaptation face aux inondations. Municipalities of both provinces can also access the Green Municipal Fund, managed by the Federation of Canadian Municipalities, and the Canada Community-Building Fund, a shared federal-provincial program. Nevertheless, as Cheung and Gamage (2022, p. 7) report, "Leaders and policymakers have called the grant system too patchwork and unpredictable."

As Carvalho (2018) points out, municipalities should be able to finance a large portion of their flood-risk management projects, but the reality is different and probably impractical for smaller municipalities. Municipalities are coping with growing responsibilities without appropriate additional funding and are already struggling to meet day-to-day operational costs.

2.3.2 Post-disaster assistance

In this paper, post-disaster assistance refers to (1) financial transfers from the British Columbia government to municipalities to help finance recovery expenses that are not insured, (2) financial transfers from the Québec government to municipalities to help finance recovery expenses, (3) financial transfers from the federal government to the provinces, when recovery costs exceed an individual province's threshold, defined as a dollar amount per capita, and (4) private or public insurance purchased by municipalities when available (Henstra et Thistlethwaite, 2017a). Unfortunately, these programs contribute to the misalignment of incentives. By virtue of the support they provide, municipalities see little need to invest in risk mitigation.

British Columbia Disaster Financial Assistance

Municipalities in British Columbia are entitled to file for reimbursement for damage to assets and infrastructure through the Emergency Program Act – Compensation and Disaster Financial Assistance Regulation. B.C. municipalities can claim 80 percent of eligible expenses subject to a deductible of $1,000 per claim. Eligible expenses are costs required to repair or restore infrastructure to its pre-flood functionality, such as equipment and materials, public buildings, and public works, including roads, bridges, dams, dikes, flood control and irrigation systems, and publicly owned sewer and water utilities.

The following are excluded from eligible expenses: (1) recoverable expenses from other assistance programs, and the amount of money a plaintiff is entitled to in lawsuits and (2) expenses for which insurance was reasonably and readily available. Nevertheless, a municipality that has elected for self-insurance is entitled to assistance, even though private insurance could have been purchased. Assistance is conditional on having provided notice to the Provincial Emergency Program of any civil litigation initiated by the municipality to recover some or all of the losses, costs or damage suffered as a result of the disaster (British Columbia Emergency Management, 2021).

Québec Disaster Financial Assistance

In Québec, municipalities can apply for financial assistance through the Programme général d'indemnisation et d'aide financière lors de sinistres réels ou imminents (General Indemnity and Financial Assistance Program Regarding Actual or Imminent Disasters). Assistance is granted for expenses additional to the current expenses of the municipality for damage to essential property, such as buildings or land, infrastructure, roads, dams, vehicles, and equipment.

To be eligible, municipalities must have put in place flood-risk reduction measures and have adopted a civil protection plan established according to the "Regulation respecting warning and mobilization procedures and minimum rescue services required for the protection of persons and property in the event of a disaster" under the Civil Protection Act. However, this condition does not apply to residents. Whether or not a municipality has flood-risk reduction measures in place will not disqualify a resident of the municipality who wants to claim for damage. This situation contributes to the lack of incentives to reduce flood risk.

Financial assistance usually excludes damage to property corresponding to an insurable risk to the extent that insurance is offered in the area. Since April 2019, exclusions also apply to previously damaged buildings for which financial assistance has already been provided. The financial assistance granted corresponds to 100 percent of the reasonable costs incurred, minus the municipality's financial contribution per capita as shown in Table 2.2 (Ministère de la Sécurité Publique Québec, 2022).

Tableau 2.2 - Example of $100,000 Eligible Damage for a Municipality of 5,000 Inhabitants

Eligible Flood Damage by Tranche		**Municipality**		**Provincial Government**	
First 3 dollars per capita	$15,000	100%	$15,000	0%	$0
4th and 5th dollars per capita	$10,000	75%	$7,500	25%	$2,500
6th and 7th dollars per capita	$10,000	50%	$5,000	50%	$5,000
Additional dollars per capita	$65,000	25%*	$16,250	75%	$48,750
Total eligible damage	$100,000	43.75%	$43,750	56.25%	$56,250

*25 percent for the following dollars of eligible per capita expenditures for Quebec municipalities with a population of 1,000 or more and 15 percent for municipalities with a population of less than 1,000.
Sources: Programme général d'indemnisation et d'aide financière lors de sinistres réels ou imminents – Municipalités et organismes communautaires. Section 1.9: Calcul de l'aide financière. Ministère de la Sécurité publique du Québec (2022).

Federal Disaster Financial Assistance Arrangements (DFAA)

Catastrophic flood losses remain largely financed by the Government of Canada through the DFAA, administered by Public Safety Canada. When the response and recovery costs of a flood exceed an individual province's or territory's threshold, defined as a dollar amount per capita, the DFAA provides financial assistance to provincial and territorial governments. Consequently, the DFAA assistance is paid to the province or territory – not directly to affected municipalities, nor to individuals or businesses. DFAA also excludes expenses for assets that could have been insured at a reasonable cost.

The financial assistance paid by the provinces to beneficiaries is partly reimbursed by the Government of Canada through the DFAA when the eligible expenses for disaster response and recovery exceed an initial threshold of $3.38 per capita[10] . As Table 2.3 shows, a $250-million flood would trigger from the DFAA a financial contribution of 68 percent in Québec and 81 percent in British Columbia (Public Safety Canada, 2021). Therefore, the recovery from damage caused by recent catastrophic flooding in British Columbia and Québec was largely financed by the federal government.

Tableau 2.3 - Example of DFAA Provincial Distributions

Damage Scenarios	**British Columbia (Canada) Contribution**	**Québec (Canada) Contribution**
$100,000,000	48% (52%)	80% (20%)
$250,000,000	19% (81%)	32% (68%)
$500,000,000	10% (90%)	16% (84%)
$1,000,000,000	5% (95%)	8% (92%)

Source: Public Safety Canada (2021)

The DFAA is currently under review. Public Safety Canada has been mandated to find solutions to reduce the federal financial contribution to and improve the efficiencies of the program. One option would be to involve the private insurance industry in a risk bearing capacity for damage caused to individual properties. Unfortunately, municipalities do not qualify for this insurance scheme, since it is restricted to individual property owners.

The Insurance Bureau of Canada (IBC) is co-chairing with Public Safety Canada the Working Group on the Financial Management of Flood Risk, now renamed the Task Force on Flood Insurance and Relocation. In March 2022, Canada's public safety minister Bill Blair stated that Canada is "one step closer to a National Flood Insurance Program" (DiSabatino, 2022). In a report published in June 2019, among various post disaster assistance programs set up by other countries, IBC recommended the creation of a high-risk pool, inspired by the United Kingdom Flood Re program, to improve the efficiency of the existing DFAA (Insurance Bureau of Canada, 2019).

[10] Threshold subject to change; as of November 2022, the threshold is $3.38.

Flood Re was introduced in 2015 to allow the insurance industry to make the transition to an entirely risk-based pricing system. This measure aims to address the lack of flood insurance for high-risk personal properties and is funded by a tax paid by U.K. insurers on all home insurance policies (Department for Environment, Food and Rural Affairs U.K., 2021). However, the very existence of Flood Re builds on national and local governments' commitment to invest in protection, prevention, and preparedness and to establish appropriate land-use planning measures (Surminski et Eldridge, 2014). Whereas the United Kingdom's private insurance sector has long experience with flood risk coverage, in Canada, flood insurance has been introduced gradually and recently (in 2015 and 2016) through federal intervention. Therefore, the culture of collaboration between the private sector and the government is dissimilar in both countries.

Municipal flood insurance

Municipalities can purchase commercial insurance to transfer the risk associated with flooding to private or public insurers in exchange for a risk-based insurance premium. Some larger municipalities may choose to self-insure for non-catastrophic events and buy reinsurance directly for high-cost events. Flood risks expose the municipalities on two fronts: (1) floods can damage municipal assets and infrastructure, and (2) floods can trigger legal liabilities when municipal infrastructure fails to protect the community (Henstra et Thistlethwaite, 2017a)[11].

Flood insurance remains available in a restricted number of flood-prone zones. Coverage is offered with capped limits of insurance and large deductibles, a situation that calls for high premiums. Even with policy limits and deductibles, expected losses remain high, along with annual premiums. Unclear limitations and the inconsistent application of policies by claims adjusters are also a problem (Red Dragon Consulting, 2021b). As a result, overland flood insurance in Canada remains a challenge for municipalities, business owners, and agricultural producers. For example, private insurers in British Columbia often refuse to provide flood coverage if a municipality is located within 15 kilometers of the location of a past flood (T. Barnes, personal communication, January 11, 2022). The private insurance industry argues that missing

[11] The flood insurance market for individual property owners is discussed in Appendix C.

and outdated flood maps[12], improper infrastructure, and deficient land-use planning are the main reasons for the lack of coverage (Insurance Bureau of Canada, 2019).

From the insurance industry perspective, flood insurance must meet three basic conditions to be viable and profitable: (1) damage and its magnitude under different scenarios must be measurable, (2) there must be sufficient demand for coverage to generate a critical mass of premiums, and (3) hazards must be diversified either geographically or by type of risk, such as fire, earthquake, or tropical storms (Kousky, 2019).

As David Richards, co-founder and CEO of EQUA Specialty Risk Partners Corporation, puts it, "Environmental factors are wreaking havoc... Two years ago, about 10 companies were writing in the municipal lines space. Now, there are three or four. It wouldn't be a surprise to see that number drop" (Malik, 2021, p. 2).

Nevertheless, some British Columbian municipalities can rely on the Municipal Insurance Association of B.C. (MIABC) for overland flood insurance. MIABC was formed in 1987 by 144 municipalities upon the recommendation of the Union of B.C. Municipalities. MIABC is a reciprocal insurance pool owned by its members that offers damage insurance to members. In total, almost 90 percent of municipalities make up the membership of the MIABC, representing 50 percent of the province's population (Municipal Insurance Association of British Columbia, 2022). Roughly 50 percent of the MIABC members purchase full flood coverage as part of their property insurance policies[13].

In Québec, municipal insurance is provided by two municipal associations: La Fédération québécoise des municipalités (FQM) and l'Union des municipalités du Québec (UMQ). Twenty years ago, facing high premiums and restricted access to commercial damage insurance, the smaller municipalities in Québec (those with fewer than 25,001 inhabitants), with the sponsorship of the FQM, formed their own mutual insurance company, the Mutuelle des municipalités du Québec (MMQ). The MMQ (now Fonds d'assurance

[12] Canada is among a minority of members of the Organisation for Economic Co-operation and Development (OECD) that lack a national flood plain mapping program. Many communities continue to rely on the Flood Damage Reduction Program–era maps of 1975. MMM Group, a consultancy hired a few years ago to assess the situation, found that half the maps still in use are between 18 and 40 years old (McClearn, 2019).

[13] Data provided by MIABC on January 11, 2022.

des municipalités du Québec)[14] provides commercial insurance to 1,137 municipal entities (local, regional, boards, etc.), including overland flood insurance to 344 municipalities (Mutuelle des municipalités du Québec 2022)[15].

UMQ followed suit by introducing custom insurance programs for about 200 additional municipalities. By grouping 12 to 20 municipalities with deductible pooling, UMQ was able to retain a group of private insurers (Union des municipalités du Québec, 2022). Both programs are available to all Québec municipalities and require a five-year commitment at the time of registration.

2.4 Key Municipal Instruments to Reduce Flood Risks

Municipalities have the responsibility to adopt and use policy instruments to manage the risk of flooding. These policy instruments constitute a system of collective actions to steer target groups' behaviour to solve societal problems (Glaus *et al.*, 2021). Table 2.4 lists 11 examples of policy instruments that municipalities can use to reduce the consequences of flooding.

In this paper, we have organized policy instruments into four risk management strategies: (1) identification, (2) reduction, (3) funding, and (4) recovery. Four criteria can be applied when assessing the impacts and the effects of selected policy instruments: (1) economic efficiency and effectiveness, (2) distribution of benefits or costs across income groups, regions, and over time, (3) political feasibility of the process by which decisions are taken and actors involved, and (4) ability to address uncertainties, since the impacts and effects of a given measure carry a level of uncertainty (Glaus *et al.*, 2021).

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[14] Private Bill 202. An Act respecting the insurer activities of the Fédération québécoise des municipalités locales et régionales (FQM) and its amalgamation with, by absorption of, La Mutuelle des municipalités du Québec. Date of assent: December 8, 2021.

[15] Data provided by Fonds d'assurance des municipalités du Québec on January 14, 2022.

Tableau 2.4 - Examples of Risk Management Strategies and Instruments

Risk Management Strategies		Types of Policy Instruments
	Identification	*Purpose: Develop risk awareness and social acceptance* Flood-zone mapping Communication Co-construction and participation
Proactive	Reduction Prevention Mitigation Defence	*Purpose: Reduce the costs of the risk* Land-use planning Relocation and property buyout Building codes and standards Infrastructure
	Funding	*Purpose: Support implementation of risk reduction* Taxes and credits Subsidies and loans
Reactive	Recovery	*Purpose: Support and facilitate recovery* Governmental financial assistance Public and private insurance

Adopting instruments requires the participation of diverse public and private stakeholders, each with different objectives that can lead to frictions and conflicts of interest (Driessen *et al.*, 2016 ; Ebbwater Consulting Inc, 2021). For instance, land developers promote the construction of housing or commercial projects, homeowners and businesses are concerned about infrastructure such as flood dikes, and insurers prefer market-based solutions to compensate losses. These competing interests limit collaboration and impair efforts to reduce risk (Mai *et al.*, 2020).

Risk reduction remains a challenge, since municipalities are asked to restrict development in high-risk flood areas but rely on property taxes as their main source of revenue (Golnaraghi et al. 2020), creating a mismatch in responsibility and accountability (Kocornik-Mina *et al.*, 2015 ; Pilette, 2019).

Managing risk across jurisdictions is even more complex, since municipal jurisdictions rarely correspond to watersheds. In both provinces, watershed organizations rely on consultation with stakeholders (including various departments of the municipalities and provincial government) to establish a framework for watershed planning. Unfortunately, agreement on how to manage floods is often impaired by differing interests, values, and standards. The need for more deliberation and participatory mechanisms between municipalities and watershed organizations is clear (Columbia Basin Watershed Network (CBWNS), 2022 ; Horning *et al.*, 2016 ; Jacob et Dupras, 2021).

The challenges associated with watershed management have been recognized by the Organization for Co-operation and Economic Development (OECD) which identified five main obstacles: (1) territorial fragmentation, (2) poor multi-level governance, (3) limited local expertise, (4) unclear roles and responsibilities, and (5) insufficient resource allocation (Horning *et al.*, 2016).

Nevertheless, municipalities can use a combination of instruments to reduce growing exposure in flood zones and to integrate the impacts of climate change into risk-management strategies (Mai *et al.*, 2020). Among the available policy instruments to reduce the accumulation of people and assets in flood-prone areas, municipalities can prioritize flood mapping to identify and communicate the risks, land-use planning to halt the accumulation of assets in flood zones, and relocation to remove properties most at risk of flooding. These three instruments are key measures to reduce exposure (Glaus *et al.*, 2021 ; Ministère de la Sécurité Publique du Québec, 2018).

2.4.1 Flood mapping

Identifying and understanding flood risk allows municipalities to implement measures to keep people, assets, and infrastructure out of flood-prone areas. Flood-risk experts emphasize the need to enhance flood-risk knowledge. Municipal policy instruments can be ineffective if communities do not understand flood risk or support flood-risk measures (Boyer-Villemaire *et al.*, 2014). Unfortunately, flood-risk knowledge is one of the most significant gaps in municipal flood-risk management and surveys continue to show that flood-risk perception and awareness are low among municipalities and property owners (Golnaraghi *et al.*, 2020 ; Natural Resources Canada, 2018).

In a recent survey of Canadians living in designated flood risk areas, only 6 percent of respondents correctly reported that they lived in a high-risk flood zone; half expressed no concern at all about flooding; and fewer than one quarter believed that the risk of flooding would increase in the future (Ziolecki *et al.*, 2020). Flood risk is out of sight and mind. If the problem is not well understood, it is difficult to convince stakeholders to act (Ebbwater Consulting Inc, 2021).

In addition, property buyers make purchases without being aware of the flood risk to which their new property is exposed, leading to anger and frustration if a flood occurs (Red Dragon Consulting 2021b). Given the scarcity of publicly available flood-risk information, many municipalities and property owners remain unaware of their flood risk (Ziolecki *et al.*, 2020). Moffat and Bakos (2022) recommend disclosure that a property is located in a flood zone at the time of a real-estate transaction. More communication is also needed to increase awareness among banks, mortgage lenders, and other financial institutions about their responsibilities in flood-risk reduction (Golnaraghi *et al.*, 2020).

Flood mapping allows the establishment of (1) the boundaries of a potential flood based on the type and likelihood of an event, (2) specific impacts of flooding on critical infrastructure and assets, and the location and distribution of the vulnerable populations, and (3) public action and allocation of the corresponding financial resources (Association of Professional Engineers and Geoscientists of BC (APEGBC), 2017 ; Natural Resources Canada, 2018 ; Rocle, 2019). Therefore, adequate and up-to-date flood-zone maps are a key component in reducing the costs of flood damage.

However, the decentralized approach to flood mapping in both provinces creates confusion and represents an obstacle to proactive flood-risk reduction (Biron, 2019 ; Feltmate *et al.*, 2020a ; Golnaraghi *et al.*, 2020). The lack of commonly accepted flood-risk assessment standards, financial and technical constraints, other municipal priorities, and the reluctance to restrict land development have contributed to deficiencies in flood-zone mapping. In addition, most maps in British Columbia and Québec are not standardized and are outdated, with a median age of 18 years (Golnaraghi *et al.*, 2020 ; Moffat et Bakos, 2022). Feltmate, Moudrak, and Bakos (2020a) confirmed flood-risk mapping deficiencies in a survey conducted among British Columbia and Québec experts, who stated that flood maps had been at best partially updated in the last five years.

British Columbia introduced a provincial flood-zone mapping program in 1974. The program ended in early 2000, after the completion of about 70 flood-zone maps. In 2004, municipalities inherited the responsibility for flood-risk mapping. According to Woo *et al.* (2021), the lack of centralized direction from the British Columbia government has impeded local efforts to carry out flood-risk mapping. Most communities in British Columbia have not completed flood mapping. Those that have use a variety of mapping approaches, rendering flood-risk assessment on a watershed basis very complex.

Québec municipalities face the same challenges. The Province recognizes that the current regulatory flood maps are inadequate (Ministère de l'Environnement et de la Lutte contre les Changements Climatiques Québec, 2022). To address the challenges, Québec recently enacted a new transitional regime that governs works permitted on riverbanks and shorelines and in flood-prone areas, and that grants extensive powers to the Province related to flood mapping, although the Province may choose to delegate flood mapping to some municipalities. Nevertheless, the revision of flood mapping is still the responsibility of several ministries, which support a range of different programs, making it difficult to know who is accountable for delivery (Biron, 2019).

To support flood-mapping efforts, the Province also launched INFO-Crue to target 50 watersheds in southern Québec. INFO-Crue plans to deliver by 2023: (1) flood-mapping tools incorporating provisions for climate change, (2) a real-time flood forecasting system, and (3) flood mapping information to enhance flood-related decision-making (Bisaillon, 2022).

Concurrently, the federal government updated the Federal Flood Mapping Guidelines in 2021 to help advance and strengthen flood mapping across the country (Public Safety Canada, 2020). However, provinces and municipalities are concerned that the deployment of national flood maps may create redundancy and confusion. Improved coordination between stakeholders is required to improve access to flood maps and reduce deficiencies in flood-risk mapping (Golnaraghi *et al.*, 2020).

Municipalities certainly have a role to play in flood mapping, but neither decentralization nor the watershed approach have produced optimal results in British Columbia and Québec. Furthermore, the absence of a central authority to prioritize flood-risk management in general remains a weakness in both provinces. Governments could take inspiration from the Environment Agency in the United Kingdom and the Ministry of Ecological and Inclusive Transition in France. Both bodies have, as a priority, responsibility for managing flood and coastal erosion risks (Biron, 2019).

2.4.2 Land-use planning

The main instrument available to municipalities to reduce the current level of exposure and prevent it from growing is land-use planning. Land-use planning seeks to achieve (1) the coordination of land use and other policies, (2) the functional organization of land uses and their regulation, (3) socio-economic development while protecting the environment, and (4) the fair distribution of economic gains (Silva et Acheampong, 2015). Therefore, part of land-use planning involves legal restrictions on the location, type, scale, and density of development in flood-risk areas. The enforcement of these restrictions requires the cooperation of all levels of government, developers, builders, realtors, and the public. These measures are subject to negotiation, since they can affect the economic activities of local communities (Feiock *et al.*, 2008 ; Krieger, 2013 ; Löschner *et al.*, 2021).

When floods occur, the presence of buildings and infrastructure in flood-prone areas reveals the failure to take flood risks into account in land-use planning (Alalouf-Hall et Fontan, 2020). Development within flood plains is (and has historically been) a shared responsibility between municipalities and provincial governments. Nevertheless, municipalities are responsible for understanding the risks of flooding in their jurisdictions and making appropriate land-use decisions, so that developments are built in a manner that limits flood damage and ensures public safety (Feltmate *et al.*, 2020a).

According to Tamsin Lyle, Principal at Ebbwater Consulting, urban development in British Columbia has taken place in flood plains sheltered by 1,100 kilometres of intermittently maintained dikes owned by a variety of governments, farmers, and other authorities or stakeholders. Breaches in the dikes caused flooding in 1948 in the Lower Mainland and again in 2021. In the past, British Columbia's flood-risk management relied on engineering infrastructure to protect people. For example, flooding in the Fraser Valley in 1948 affected approximately 30,000 people, whereas the 2021 flood in the same area affected 350,000 people. Today, the Province needs to consider other options, such as building more flood-resilient homes, changing land-use patterns, and moving critical infrastructure and vulnerable people out of high-risk zones (McSheffery et Chernecki, 2021).

Modern history in Québec shows that municipalities have easily obtained exemptions to build new residential properties, commercial real estate, or infrastructure in flood-prone areas. For example, Alalouf-Hall and Fontan (2020) state that each year, the Ministère de l'Environnement et de la Lutte contre les changements climatiques (MELCC) authorizes dozens of projects in flood plains and wetlands, even though these flood plains are intended to act as buffer zones during floods.

Land-use planning as currently practised is one of the major contributing factors to flood damage throughout Canada. Preventing construction or reconstruction in flood zones is the most practical and cost-effective way to reduce future damage from flooding (British Columbia government, 2018 ; Feltmate *et al.*, 2020a ; Glaus *et al.*, 2021 ; Ministère des Affaires Municipale et de l'Habitation du Québec, 2020). As mayor Craig Snodgrass of High River, British Columbia, has pointed out, "Local governments need to bear some responsibility for allowing developments in the first place" (Hunter, 2022b, p. 5).

2.4.3 Relocation

Another avenue available to municipalities to reduce exposure to flood damage is to finance the relocation of the most vulnerable properties, particularly buildings experiencing recurrent flooding or those located in a flood zone but outside the area protected by structural measures (Cottar *et al.*, 2021 ; Mazzoleni *et al.*, 2021 ; Red Dragon Consulting, 2021a ; Schwaller *et al.*, 2022). Under some conditions, relocation makes economic sense. The full cost of remaining in place is double the cost of relocation, not even considering the cost of health and emergency services (Saunders-Hasting *et al.*, 2020).

According to Siders (2019), the question is no longer whether to use this option, but when and how to implement it. Kousky and Kunreuther (2018) recommend increasing government funding for the purchase of properties in the most at-risk areas and those experiencing repeated flooding. Relocation of properties in high-risk areas of recurrent flooding is also part of the analysis of Public Safety Canada's Task Force on Flood Insurance and Relocation.

However, the buyout process remains long and bureaucratic, sometimes coupled with a lack of transparency. Relocation programs produce social, economic, and psychological dislocation and potential tax losses for communities (Peterson *et al.*, 2020 ; Schwaller *et al.*, 2022). The success of such programs depends on (1) the social environment and degree of attachment to place, (2) the price paid and the conditions of relocation, (3) the severity of the damage and the availability of insurance, (4) risk perception, and (5) the degree of trust in the authorities and the level of co-construction (Rocle *et al.*, 2021 ; Schwaller *et al.*, 2022).

Both provinces studied here have some experience with relocation initiatives. The Community Charter and the Local Government Act and Expropriation Act in British Columbia allow municipalities to buy back properties that are in the way of dikes and other flood works, provided that affected owners are given fair notice and that they get market value for their properties (Tritschler, 2021). For example, following historic floods in 2018, the community of Grand Forks in British Columbia initiated a Land Acquisition Program to buy out about 130 properties in the high-risk flood plain areas in North Ruckle, South Ruckle, and Johnson Flats, as well as some downtown properties, to construct dikes and create green infrastructure and natural flood plains to provide room for high-water flows during floods (Dinsdale, 2020).

Québec's 2019 flood triggered the demolition and purchase of nearly 400 residential and commercial buildings downtown in the small municipality of Ste-Marie de Beauce[16] . The city hall, fire station, primary school, and industrial park were relocated away from the flood zone. Pointe Gatineau is another example: the two record floods of 2017 and 2019 triggered home buyouts by the government of Québec. Following the 2017 flood, provincial legislation banned home reconstruction in areas where the annual probability of flooding exceeds 5 percent and facilitated relocation of flood victims through a special program. Unfortunately, restrictions to the buyout program were introduced after another major flood in 2019 (Saunders-Hasting *et al.*, 2020).

Relocation efforts do not have unanimous approval within the affected communities. Some residents refuse to be relocated. For example, the small municipality of Constance Bay in Ontario was rebuilt twice after massive flooding in 2017 and 2019; in May 2022, hundreds of residents were asked to evacuate when flooding occurred once more (Hunter, 2022b). Nevertheless, with adequate financial support from the federal government and the provinces, municipalities can be more proactive in relocating high-risk properties.

2.5 Conclusion

The growing number of people, assets, and infrastructure elements in flood-prone areas has led to a sharp rise in flood-damage costs in British Columbia and Québec, and the impacts of climate change are intensifying the risks. As flooded communities face economic losses, and social and environmental consequences, damage caused by repeated flooding has shown that the current flood-risk governance structures and post-disaster assistance programs are unsustainable.

Municipalities of both provinces can prioritize flood mapping, land-use planning, and relocation to reduce the costs of flood damage. However, the lack of incentives to implement these efforts has contributed to the sharp increase in the costs of flooding. Solving the problem of increasing exposure in flood-prone areas requires understanding how municipalities select and deploy policy instruments in the context of pressures from various interest groups. Even when there is a clear rationale for intervention, the choice of policy instruments by a municipality is difficult. Indeed, balancing the economic, social, and ecological

[16] Québec Bill 994, "An Act to empower local municipalities to exercise a pre-emptive right to acquire immovables," was adopted in June 2022.

dimensions of flooding is rarely feasible, even when the selected instruments are socially acceptable and efficient (Glaus *et al.*, 2021).

At present, most flood damage costs are financed through federal and provincial programs. As a result, municipalities have relied on post-disaster assistance to repair and rebuild municipal assets and infrastructure as well as to address damage to the properties of their residents. Unfortunately, these programs have not contributed to better flood risk awareness among municipal decision-makers, nor have they reduced the numbers of people, assets, and infrastructure elements in flood-prone areas. On the contrary, such programs provide a false sense of security and dissuade municipalities from prioritizing flood-risk management. Indeed, although municipalities are responsible for implementing risk-reduction measures, they do not share the cost of flood damage.

With the federal and provincial governments looking for ways to reduce the financial costs of post-disaster assistance and the limited availability of flood insurance, municipalities and communities are expecting increased flood-related expenditures. Furthermore, floods cause more and more damage in the context of climate change because of aging infrastructure.

It is time to revise the current governance model and propose a new risk-sharing scheme that motivates municipalities to prioritize flood-risk reduction. A new scheme should reward municipalities for their investments and efforts in risk mitigation, while penalizing those that fail to act by compelling municipalities to assume a greater part of post-flood compensation. Such a scheme would better align stakeholders' interests compared with the status quo.

Further research is needed on the design of municipalities' financial contribution to ensure that this new role does not simply become an additional financial burden, imposed without adequate accompanying governance and policy instrument reform. Conducting this research should be an urgent priority, considering (1) the current unsustainable costs sharing scheme, (2) the challenges posed by climate change with respect to flood risk management, and (3) the unique local knowledge available among municipalities.

CHAPITRE 3
FLOODING: CONTRIBUTING FACTORS TO RESIDENTIAL FLOOD DAMAGE IN CANADA

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Résumé

La gestion des risques d'inondation doit s'appuyer sur la meilleure estimation possible des dommages potentiels afin de prendre des décisions éclairées. Les courbes de profondeur d'inondation sont la méthode la plus couramment utilisée pour estimer les dommages directs aux biens. Bien que très répandue, cette méthode comporte un degré d'incertitude élevé, car elle ne tient généralement compte que d'un nombre limité de facteurs. Cet article vise à identifier et à hiérarchiser les facteurs supplémentaires contribuant aux dommages causés par les inondations qui devraient être pris en compte dans l'estimation des dommages afin de réduire l'incertitude.

Quarante-cinq experts canadiens, dont des experts en sinistres, des ingénieurs, des estimateurs et des entrepreneurs, ont identifié et classé par ordre de priorité 40 facteurs contribuant aux dommages causés par les inondations dans les bâtiments résidentiels, au-delà du facteur traditionnel de profondeur d'inondation. L'analyse révèle que les municipalités jouent un rôle important, car sept des dix facteurs les plus importants relèvent de leur responsabilité, en collaboration avec les autorités provinciales qui établissent les réglementations et les politiques générales. La responsabilité partagée englobe des facteurs clés tels que la distance entre un bâtiment et un cours d'eau dans le cadre de l'aménagement du territoire, le respect obligatoire des nouveaux codes de construction et la conception et l'entretien des infrastructures essentielles telles que les réseaux d'égouts. Compte tenu de ces responsabilités étendues, les municipalités canadiennes ont un rôle crucial à jouer dans la réduction proactive du risque d'inondations et l'atténuation de l’effet des inondations. L'avis des experts sur la hiérarchisation des facteurs renforce la nécessité d'intégrer un éventail plus large de facteurs de vulnérabilité physique et d'exposition dans les outils d'estimation du risque d'inondations et devrait encourager les municipalités à collecter et à optimiser l'utilisation de ces facteurs.

Mots clés : Facteurs contributifs, dégâts causés par l'eau, courbes de dommages, inondations, Canada

Abstract

Flood risk management must rely on the best estimate of potential damages to make oriented decisions. Flood depth damage curves are the most used method of estimating direct property damage. Although widespread, this method involves high uncertainty, as limited factors are typically considered. This paper aims to identify and prioritize additional contributing factors to flood damage that should be considered in damage estimation to reduce uncertainty.

Forty-five Canadian experts, including adjusters, engineers, estimators, and contractors, identified and prioritized 40 factors contributing to flood damage in residential buildings beyond the traditional inundation depth factor. Analysis reveals that municipalities play a significant role, as seven of the ten most important factors fall under their responsibility in collaboration with provincial authorities who establish overarching regulations and policies. Shared responsibility encompasses key factors such as the distance of a building from a water course as part of land use planning, obligatory compliance with new building codes, and the design and maintenance of critical infrastructure like sewer systems. Given these extensive responsibilities, Canadian municipalities have a crucial role in proactively reducing flood risk and mitigating the impact of flood events. Expert judgment on the prioritization of factors reinforces the need to integrate a broader range of physical vulnerability and exposure factors into flood risk estimation tools and should encourage municipalities to collect and optimize the use of these factors.

Keywords: Contributing factors, water damage, damage curves, floods, Canada

3.1 Introduction

Flooding is a significant concern in Canada, representing the most frequent and costly natural disaster with substantial social, economic, and environmental repercussions (Burn et Whitfield, 2016 ; Buttle *et al.*, 2016 ; Couillard, 2024). Over 1.5 million Canadian homes are in high-risk flood zones, and the projected cost of flood damage could increase three to five times by mid-century, reaching over $5.5 billion annually (Insurance Bureau of Canada, 2024b).

Canadian municipalities play a central role in flood risk management, particularly given the responsibilities delegated to them by the provinces for risk mapping, land use planning, issuance of building permits, infrastructure management and disaster response (Feltmate *et al.*, 2020a ; Taylor et Dobson, 2020). Floods can be caused by heavy rainfall, river flooding, sewer overflow and its receiving water body, ice jams or the failure of protective infrastructures such as dykes and dams (Intergovernmental Panel on Climate Change, 2012a).

Flood risk arises from the interplay of three key factors: the hazard (e.g., flood depth), the exposure of assets and people to the hazard, and their vulnerability to damage (Dordi *et al.*, 2022). Flood vulnerability arises from the combination of a building's exposure to flood events, the magnitude of those events, and the system's inherent capacity to withstand, respond to, and recover from their impacts (Balica *et al.*, 2009). The estimation of potential economic losses is one way of encouraging municipalities to give priority to reducing the risk of flooding and its consequences (Hlinkova et Espinosa, 2023 ; Rehan, 2018). The definition of flooding used in this article is that of the Institute for Catastrophic Loss Reduction (Institute for Catastrophic Loss Reduction, 2020), i.e., overflowing the normal limits of a watercourse or accumulating water over areas not usually submerged. Consequences include the costs of direct and indirect material damage and social, psychosocial and environmental harms (Bachand *et al.*, 2022 ; Maltais *et al.*, 2023).

The use of flood depth damage curves is the most commonly employed method of estimating direct property damage caused by flooding to buildings (Amirebrahimi *et al.*, 2016 ; Oubennaceur *et al.*, 2019). These curves are used both in the event framework, i.e., on the individual scale of a building to estimate damage per loss, and on the broader scale in risk analysis or in asset management, which considers all probabilities of potential hazard (i.e., flood occurrence) and their consequences. Risk analysis can be used to develop cost-benefit analyses of risk mitigation or measures to reduce flood consequences that would apply to a given territory, such as a municipality.

These damage curves express the physical vulnerability of assets by combining this vulnerability with hazard and exposure data (Sassi, 2010). They are constructed either from empirical data derived from compensation (indemnity) histories or synthetic data, i.e. based on vulnerability coefficients determined by field experts (Aribisala *et al.*, 2022 ; Xing *et al.*, 2023). These curves thus establish a relationship between inundation depth and property damage (Bachand *et al.*, 2022 ; Bonnifait, 2005 ; Doyon et Jean, non publié). The inundation depth represents the effective water height in a building, measured from a reference floor (Bachand *et al.*, 2022 ; Bonnifait, 2005 ; Doyon et Jean, non publié).

These curves show that, on average, the damage to buildings and property increases with inundation depth. Damage is expressed as a percentage of the total cost of reconstruction or the property value of the building. This percentage is formulated as a damage rate, a non-dimensional value that is more straightforward to compare (Merz *et al.*, 2010). Other depth-damage curves relate water height directly to monetary damage (Penning-Rowsell *et al.*, 2005).

Nevertheless, the contributing factors to water damage are numerous and interconnected. Inundation depth is consistently identified as the most decisive factor, as highlighted by Merz *et al*. (2013) from an analysis of 2158 post-flood interviews and confirmed by Aribisala *et al.* (2022). These latter authors also include water flow velocity**,** the flow rate and speed of the rising waters**,** as well as the duration of the event**,** a factor also noted by Shrestha *et al.* (Shrestha *et al.*, 2021). Beyond the characteristics of the flood itself, the structure and quality of the building significantly influence the level of damage. Amirebrahami *et al.* (2016), Kaoje *et al*. (2021), Neubert *et al*. (2016) and Paulik *et al.* (2023) identify the elevation and type of use of the ground floor, the number of floors, the presence of a basement, the height of openings, the materials used, the level of building maintenance, and the year of construction as contributing factors. Duhamel *et al.* (2022) further emphasize the importance of site access via the road network and the presence of mitigation measures such as water evacuation systems, backflow preventers, and foundation waterproofing. Water turbidity (contamination) is also an aggravating factor, mentioned by Amirebrahami *et al*. (2016) and Shrestha *et al.* (2021). Finally, the probability of occurrence of the flood, although not a direct damage factor, influences prevention and adaptation choices, as emphasized by Balica *et al.* (2009), Messner and Meyer (2006), and Towfiqul Islam *et al*. (2021).

The most widespread damage curves only reflect the average level of expected damage without considering the uncertainty (spreading) around this average (Merz *et al.*, 2004). According to Merz *et al.* (2004), the relationship between inundation depths and damage rates exhibits high uncertainty in empirical data due to numerous challenges to documenting factors. While these curves provide an unbiased estimate of risk at the scale of a local neighborhood (Leclerc *et al.*, 2003), they fail at the scale of individual buildings due to the absence of data on aggravating or beneficial factors.

Several recent studies have innovated by modelling this uncertainty in several ways. For example, Wing *et al.* (2020) propose stochastic damage curves. These curves express the relationship between inundation depth and damage rate by a random variable distributed according to a beta distribution, whose parameters are estimated using empirical data. Wing *et al.* (2020) analyzed 976,363 claims files from the U.S. National Flood Insurance Program. They conclude that there is a link between the level of damage and the inundation depth, but several other factors contribute to the damage. Such factors include building value, building age and the related jurisdiction, the geographic location and the type of floodwater (freshwater or saltwater).

Other authors, such as those identified in Zarekarizi *et al*. (2020), exploit deep uncertainty, where several damage curves are considered simultaneously to reduce this uncertainty. Deep uncertainty refers to situations where the future is highly uncertain, and traditional probability distribution functions cannot adequately represent or predict the range of possible outcomes. However, the results of uncertainty modelling are challenging to validate or confirm when compared to empirical field data (Shrestha *et al.*, 2021 ; Thieken *et al.*, 2005). Other authors have used Bayesian multilevel models to estimate the normalized damage for different flood types. This approach accounts for the lack of detailed or structured data and the variability in losses caused by different flood types (Mohor *et al.*, 2021).

While numerous studies have contributed to our understanding of flood damage estimation, the models currently employed in Canada still face limitations in accurately capturing the full range of factors that influence losses. Furthermore, this uncertainty increases with higher water levels (Ressources Naturelles Canada et Sécurité Publique Canada, 2021). These damage curves are criticized because they rely principally on the inundation depth as a single explanatory factor (Amirebrahimi *et al.*, 2016 ; Merz *et al.*, 2004 ; Zarekarizi *et al.*, 2020).

Several flood damage models have been developed for Canadian contexts, including Ouarda's model (Leclerc *et al.*, 2003) based on the 1996 Saguenay flood (Lin *et al.*, 2002), Bonnifait's model (Bonnifait, 2005) incorporating data from three events that occurred in the province of Quebec (municipalities of Saguenay, Sorel, and Chateauguay), and, more recently, the Doyon and Jean model (Doyon et Bouchard St-Amant, 2020 ; Doyon et Jean, non publié); utilizing empirical data from the 2011 Richelieu floods (see Ref. (Saad *et al.*, 2016). Doyon and Jean (non publié) developed a set of 12 damage curves that account for variations in residential building characteristics, such as the number of stories (one or two), the presence and type of basement, and whether the property is connected to municipal water and sewage systems. According to Doyon and Jean (non publié), the damage rate correlates better with the flood height, as it is dimensionless and varies between 0 and 1.

Estimates of direct material damage resulting from these curves can be challenged, mainly when used to justify implementing flood risk reduction or mitigation measures at the property level (Amirebrahimi *et al.*, 2016 ; Shrestha *et al.*, 2021). A reliable estimate of the damage must integrate various factors influencing the hazard (e.g., event duration), physical vulnerability (e.g., soil type) and exposure (e.g., the value of exposed property located in flood-prone areas) (Tanguy *et al.*, 2022). To account for the various factors influencing flood damage, some estimation models, such as those used by the Federal Emergency Management Agency (see Hazus risk modelling; (Federal Emergency Management Agency (FEMA), 2023a)) and the U.S. Army Corps of Engineers (USACE), incorporate additional hazard factors into their calculations. These factors include flow velocity, the duration of the flood event, the presence of debris, and the level of water contamination (Galasso *et al.*, 2021).

Given the high uncertainty and the lack of sufficient empirical data to quantify the effects of these numerous factors at the individual level, resorting to expert judgment is necessary. This method enables structuring the experience and practical knowledge of insurance and engineering professionals to identify and prioritize the vulnerability factors that truly modulate the damage sustained. Integrating this expertise is essential for developing more reliable estimation tools that go beyond water depth alone and thus better target the levers for action under municipal influence (such as land-use planning and building codes).

This study aims to identify and prioritize additional contributing factors to flood damage, moving beyond the traditional focus on inundation depth. We hypothesize that incorporating these extra factors into damage estimation will reduce the underlying uncertainty. Furthermore, we suggest that municipalities significantly influence some of these contributing factors, implying that municipal policies and actions can mitigate the overall consequences of flood events.

3.2 Methodology and data

The methodology used to identify and prioritize the main contributing factors to flood damage beyond inundation depth is based on a two-step approach inspired by the Delphi method. The Delphi method is a valuable structured communication technique for gathering and synthesizing expert opinions on a complex topic (Elmer *et al.*, 2010a).

3.2.1 Expert selection

Our research engaged 45 Canadian experts, including adjusters, engineers, and estimators. These professionals, drawn from the insurance, loss adjusting, engineering, disaster restoration, and construction sectors, provided diverse perspectives on the factors contributing to flood damage in residential buildings. Identifying and selecting these experts involved leveraging the principal author's extensive network of contacts within the insurance industry, developed over 30 years of experience. This network allowed for identifying key organizations, including significant property and casualty insurers, loss-adjusting firms, engineering firms specializing in damage assessment, disaster restoration firms, and building construction companies. The principals of these organizations were contacted and asked to delegate experts within their firms to participate in the study. This process ensured the inclusion of experts with direct experience in emergency response, damage estimation, and post-flood restoration work, particularly during the major floods of 2017, 2019, and 2022 observed over Eastern Canada.

3.2.2 Expert consultation

The 31 consultations among the 45 experts were held in groups of 1 or 2 (one group hosted six experts), lasted between 30 and 45 min and took place via videoconference from February to April 2023. Table 3.1 summarizes the experts' professional backgrounds, highlighting their relevant expertise, current roles, and the diversity of the sectors involved in flood damage to residential buildings. Claims adjusters dominate the list, with 33 % of the total, followed by damage appraisers (27 %), legal or judicial engineers, and legal experts (18 %).

The expert consultations served a dual purpose: 1) to generate a comprehensive list of contributing factors to flood damage to residential buildings and 2) to provide qualitative insights that would enrich the interpretation of the quantitative survey results. This approach allowed for a more holistic understanding of the factors influencing flood damage, going beyond mere rankings to explore the underlying reasons and nuances behind the experts' opinions.

A structured method was adopted to facilitate the interviews and ensure consistency in data collection. A one-page document outlining the research objectives and providing examples of three contributing factors (duration of event, replacement cost, presence of basement) were provided to the experts to guide the discussions. A note-taking form was also developed to categorize the identified factors into three main themes: hazard, exposure, and vulnerability. During the audio-recorded interviews (29 out of the 31 interviews), the author recorded the mentioned factors, and this information was then compiled into an Excel spreadsheet to track the frequency of each factor's occurrence across all interviews and establish a mention rate, i.e., the number of times a given factor was mentioned divided by the total number of experts. This systematic process allowed for efficient data collection and analysis, ensuring that all relevant factors were captured and categorized appropriately.

The experts consulted were asked to identify contributing factors to the damage, regardless of the type of flood (pluvial, fluvial, infrastructure failure, and sewer overflow), without the support of a list of potential factors (except for the three above-mentioned) and a moderator's help. Experts were also asked to consider a standardized reference building. As illustrated in Fig. 3.1, this reference building is defined as a recent, single-family home with 1 or 2 stories, built in 2022 or later (the year the new Quebec Construction Code came into force). The home features a semi-finished basement with a height of 240 cm (8 feet). The basement walls are insulated with a plasterboard finish, and the floor is concrete. This standardization ensures consistency and facilitates comparison across different responses.

Tableau 3.1 The profile of expert consulted

Profile of the 45 experts	Number	Percentage
Damage appraisers	12	27%
Claims adjusters	15	33%
Disaster restoration	4	9%
Legal or judicial engineers/experts	8	18%
Other (architect, contractor, consultants, actuaries)	6	13%
Total (27 companies and 31 consultations)	**45**	**100%**

Figure 3-1 Typical Canadian single dwelling

Image generated by Adobe Firefly 2024-11-09.

After the consultations, the 45 experts were invited to participate in an online survey. A quantitative survey instrument was developed based on the results of the qualitative analysis to prioritize the identified factors and establish coefficients. The questionnaire consisted of two parts in French and English: 1) prioritization of factors and 2) establishment of coefficients. Thirty-five (35) duly completed the questionnaire on the " UQAM *Lime* Survey Software " platform (ID 385246) during April and May 2023. Most of the experts who responded to the survey are appraisers (34 %), claims adjusters (29 %), legal or judicial engineers/experts (12 %) and disaster restoration (8 %). The remaining respondents were architects, consultants and one contractor (17 %). The questionnaire is available at Survey 385246.

3.2.2.1 Priorization of factors by experts

To simplify the prioritization of 40 contributing factors to flood damage, the first part of the survey organized these factors into five categories: 1) drainage capacity, 2) building resilience, 3) intervention, 4) reconstruction, and 5) flood characteristics. A list of contributing factors and their related categories is presented in Appendix D. Experts were then asked to rank the factors within each category. The weighted average method was used to mitigate potential bias from this grouping and emphasize the factors ranked highest by the experts.

Additionally, the weighted average method helps reduce potential bias by considering that experts may have different confidence levels in their rankings. The highest two ranks (1 and 2) were assigned a value of ’3’, indicating their critical importance. Rank 3 was assigned a value of ’2’, reflecting moderate importance. The lowest two ranks (4 and 5) received a value of ’1’, signifying relatively lower importance. Thus, for a given factor, the sum of the values assigned is always 10. For example, for a question with five answer choices, the sum of the values of the ranks is 3 + 3 +2 + 1 +1 = 10.

The value for each rank was then multiplied by the number of respondents ($NbRR_i$) who chose to rank the factor in one of the five possible ranks. The final ranking for each statement was then calculated by summing the relative weight of each rank assigned by respondents. The Relative Weight One resulting from this method is:

$$\textit{Relative Weight One} = \Sigma\{\textit{Rank value}_i(\textit{weight}) * \mathrm{NbRR}_i\} \tag{1}$$

The simple average method was also used as a validation check to ensure the robustness of the weighted average method. The simple average method calculates the factor ranks by dividing the number of respondents (NbRs) who chose that factor, regardless of rank, by the number of choices associated with the category (Cs). Thus, the Relative Weight Two is:

$$\textit{Relative Weight Two} = (\textit{NbRs} \div \textit{Cs}) \tag{2}$$

Both methods produced a similar ranking of the 40 factors, as Appendix D presents. However, some discrepancies were observed in the rankings of certain factors, which can be attributed to the distinct methodologies employed by each method. The weighted average method was ultimately chosen to analyze the results since it corresponds to how the survey was organized and allows for greater emphasis on the factors ranked highest by the experts.

3.2.2.2 Setting damage rate coefficients

The second part of the survey sought to gather quantitative judgments from experts on the potential influence of factors such as soil type, year of construction, building value, and the distribution of values within a residential building. These factors were selected for their prevalence in the study area, ease of data access, and feasibility in integrating them into the damage estimation process. The median values are used to present the coefficients, as they provide a more robust measure of the typical effect and are less susceptible to outliers and skewed distribution. The difference between the median and average values generated by the Lime Survey platform highlights the potential influence of extreme estimations by some experts.

3.2.3 Analysis and data processing

The resulting data underwent a systematic processing and analysis following the expert consultations. First, the qualitative data gathered during the interviews was meticulously reviewed and organized. The contributing factors identified by the experts were then categorized into three primary themes: hazard, exposure, and vulnerability. This categorization allowed for a structured analysis of the factors.

A mention rate was calculated to quantify the relative consciousness of each factor. The calculation divided the number of times the experts mentioned a specific factor over the number of experts. This process provided a preliminary assessment of the relative significance of each contributing factor.

The Lime Survey resulting data was exported to an Excel spreadsheet for analysis. Then, the weighted average method was applied to assign different weights to each rank the respondents gave to assess the factors' relative importance. This approach yielded a final prioritization scheme, capturing the expert opinions on the significance of each contributing factor to flood damage.

3.3 Results

3.3.1 Prioritization of the first ten factors

Table 3.2 lists the top ten factors contributing to flood damage, as ranked by the experts. The Mention Rate column indicates the frequency with which each factor was mentioned during the initial consultations, while the Ranking column shows the final ranking assigned by the experts in the survey. Seven of these ten factors (1, 3, 4, 5, 7, 8, and 9) fall under municipal jurisdiction, highlighting municipalities' critical role in flood risk management. The remaining three factors are typically the responsibility of other stakeholders, such as provincial governments or insurers (compensation programs), or are inherent characteristics of the flood hazard (flow velocity and duration of the event).

3.3.1.1 Distance of building and ground elevation (1st factor in Table 3.2)

The experts in the survey ranked this contributing factor as their top choice (see Table 3.2). During the consultations, the experts also mentioned that the mere presence of a building in a flood zone (lower ground level or near a river) is the main factor in the damage rate. This factor acts as a trigger for the probability of damage occurring.

This probability of occurrence is recognized as the most appropriate contributing factor for modelling the effects of flooding on the built environment. The links between the probability of occurrence and the level of damage make it possible to develop damage functions expressed as a percentage of damage (Balica *et al.*, 2009 ; Elmer *et al.*, 2010b ; Galasso *et al.*, 2021 ; Messner et Meyer, 2006 ; Towfiqul Islam *et al.*, 2021).

3.3.1.2 Flow, current and speed of rising water (2nd factor in Table 3.2)

Experts ranked the factor related to current flow and velocity near buildings as their second choice, even if this factor was only mentioned a few times during the interviews (Table 3.2). While it could be argued that flow velocity and the speed of rising water represent two distinct factors, they are treated here as a single, combined factor due to their interconnected impact on building vulnerability. The water can exert pressure on building structures, leading to intense erosion and submersion effects. The greater the velocity of floodwater, the greater the likelihood of structural damage to buildings. For example, "*a velocity of* 3 m/s *combined with a head of 1 m exerts sufficient pressure to cause structural damage to a residential brick building wall* " (Doyon et Jean, non publié, p. 30) [Translation by the author]. This pressure can be positive, pushing the element inwards, or negative, generating suction (Amirebrahimi *et al.*, 2016).

Similarly, a rapid rise in water levels during a flash flood can reduce the reaction time of authorities and residents, making it more challenging to implement mitigation or protection measures.

According to Kelman and Spence (2004), McBean *et al.* (1987), and Merz *et al.* (2013), flow velocity is correlated with the damage rate at low inundation depths. Kreibich *et al.* (2009) provide evidence that flow velocity would be higher in hilly landscapes than in flat terrain. However, according to these authors, flow velocity alone shows no significant relationship with the damage rate of residential buildings. Conversely, their study highlights that flow velocity is crucial in predicting structural damage to road infrastructure.

Tableau 3.2 Hierarchy of contributing factors to flood damages according to experts

Top ten contributing factors to flood damage	**Mention rate (45 experts)**	**Ranking (35 experts)**
Distance of building from a watercourse or ground elevation	31%	1
Flow, current and speed of rising water	7%	2
Response time for mitigation work	36%	3
Basement converted into living space	40%	4
Obligation to comply with new building codes	31%	5
Event duration	49%	6
Design of and state of maintenance of sewer and water systems	44%	7
Landscaping (topography, mineralization)	49%	8
Readiness and competence of the municipality	11%	9
Type of compensation program and settlement terms	13%	10

Sources: Lime Survey (ID 385246) of 35 experts during April and May 2023 and 31 videoconference consultations of 45 experts from February to April 2023.

3.3.1.3 Response time for damage reduction (3rd factor in Table 3.2)

The experts ranked response time as the third most important factor influencing flood damage (Table 3.2). Response time refers to the time required for a post-disaster restoration team to arrive on-site and begin damage reduction, which aims to minimize further damage to the property. A swift response can significantly reduce the extent of damage by promptly addressing issues such as water extraction, debris removal, and drying of the affected areas.

Several factors can affect damages, including the duration of the flood event, the degree of preparedness of the municipality, the accessibility of damaged buildings, the availability of qualified experts, and the level of contamination. For example, oil contamination can lead to a three-times increase in damage to buildings. Sewage contamination also increases damages to contents and buildings (Kreibich *et al.*, 2005). Floodwaters can become contaminated with sewage, chemicals, and debris, posing health risks and potentially delaying restoration until contamination is addressed. According to Landaverde *et al.* (2022), neglecting proper cleaning, disinfection, and renovation can have significant negative consequences for flood-affected households, even with minimal water intrusion.

3.3.1.4 Basement converted into living space (4th factor in Table 3.2)

Experts say a fully finished basement is the fourth most important contributing factor (Table 3.2). The layout and presence of goods located in the basement directly impact the damage rate by increasing damage costs according to the value of the materials and goods. According to experts, this transformation of basements into living environments is a recent phenomenon, sometimes taking place a few years after the building has been constructed and households have been enlarged or enriched. According to the experts, organic materials such as wood, carpets, upholstery, and drywall are particularly susceptible to mould problems.

In addition, the presence of sanitary appliances in basements increases the risk of sewer overflow. Most damage curves consider the presence or absence of basements and their finished nature. However, the lack of available data on the type of basement finish can lead to uncertainty in risk analyses. In a study carried out in Quebec in 2011 after the spring flood (see Ref. (Saad *et al.*, 2016) and published in 2021, covering 1639 damaged and compensated homes in the Richelieu river basin around 18 % of residential buildings had no basement, 25 % had an unfinished basement, and 57 % had a finished basement (Doyon et Jean, non publié).

3.3.1.5 Obligation to upgrade to new building codes (5th factor in Table 3.2)

The experts ranked the obligation to upgrade buildings to the National Building Code of Canada (NBCC) in the event of damage as the fifth most important factor (Table 3.2). While the NBCC does not explicitly address flood resilience, it provides information relevant to reducing water damage, such as guidelines for water accumulation and disposal, protection against surface and groundwater, waterproofing of basements, drainage and plumbing system integrity. Retrofitting is often correlated to the age of the building and may entail additional costs not covered by current compensation programs.

Experts criticize this situation since rebuilding "as previously" does not improve the building's resilience. Indeed, according to recent studies (Czajkowski, 2019 ; Kougkoulos *et al.*, 2021), adopting the "Building Back Better" concept would be necessary to mitigate flood damage. This concept is one of the five principles of the Sendai Framework adopted by the United Nations Office for Disaster Risk Reduction (UNDRR) in 2015 (United Nations Office for Disaster Risk Reduction, 2023). The Sendai Framework is a voluntary international agreement to reduce disaster risk and losses by 2030. It emphasizes understanding disaster risk, strengthening governance, enhancing preparedness for effective response and recovery and investing in resilience. The government of Canada ratified the Sendai Framework in 2017 (Sécurité publique Canada, 2022), reinforcing the need to adapt Canadian building practices concerning flood risk (see Ref. (Boyer Villemaire *et al.*, 2017)).

3.3.1.6 Event duration (6th factor in Table 3.2)

The duration of water inside a building after a flood has been ranked the sixth most important factor by the experts, as shown in Table 3.2. Experts pointed out that the duration of the event plays a significant role in determining the damage rate due to the capillarity of materials and moisture levels. Duration can also significantly affect response times. Event duration is an inherent hazard characteristic, describing the time the flood persists. In contrast, response time reflects the post-flood intervention, precisely the speed at which restoration teams can arrive and initiate damage mitigation.

Mohor *et al.* (2020) confirm the expert opinion that the duration of the event is a statistically significant predictor of the amount of damage caused by the flood. The duration of the event causes more damage because it gives the water more time to saturate the building materials. The work carried out by Aribisala *et al.* (2022), Merz *et al.* (2013), Shrestha *et al*. (2021), and McBean *et al.* (1987) also confirm that the importance of the duration of the event is underestimated. Indeed, prolonged humidity favours the growth of moulds, fungi, and rot. Moreover, water that stagnates over time may contain contaminants such as chemicals, bacteria, pathogens, or toxic substances. Contaminants can damage materials, mechanical, electrical, and electronic systems and furniture and cause health problems for occupants (as substantial respiratory health impacts for affected households) (Landaverde *et al.*, 2022). According to Doyon and Jean (non publié), a more than seven or 14-day duration does not lead to higher damage rates.

3.3.1.7 Design of sewer and water supply systems (7th factor in Table 3.2)

According to the experts, the seventh most important contributing factor is the design of aqueduct, sanitary or storm drainage systems (combined or separate), including their state of maintenance (Table 3.2). The experts agreed that the design of drainage systems, their upgrading and their degree of maintenance could significantly impact a residential area's ability to evacuate water efficiently. Insufficient drainage capacity or clogged pipes can lead to back-ups (overloading), overflowing pipes and overflowing stormwater or wastewater drainage systems. As a result, water can back up into buildings through sewers and drains, causing considerable damage.

These networks can also become obsolete through dysfunctions (e.g., non-return valves) or rapid real estate development exceeding the network's design capacities. Other authors (Arya et Kumar, 2023 ; Sörensen et Mobini, 2017) demonstrate that inadequate or failing municipal drainage systems can lead to increased damage during heavy rains.

3.3.1.8 Landscaping (8th factor in Table 3.2)

Experts confirm that the layout of the land on which the building is located, including topography, soil mineralization level, vegetation (natural or landscaped), building size and footprint, are important contributing factors. This factor was ranked eighth by the experts (Table 3.2). They pointed out that the land's slope and relief influence how water flows down or accumulates during a flood. For example, a poorly landscaped slope can direct water runoff toward the building, neighbouring building, or property.

On the other hand, a flat or trough-shaped ground can cause water to stagnate around the building, increasing the risk of infiltration. Thus, the elevation of the building in relation to the water level can significantly affect the damage rate, particularly during extreme weather events such as very intense, short-duration rainfall. According to Huang *et al.* (2022) and Towfiqul Islam *et al.* (2021), adequate landscape planning and design can positively impact flood mitigation.

3.3.1.9 Readiness and competence of the municipality (9th factor in Table 3.2)

According to the experts, a municipality's degree of preparedness and competence ranks ninth in importance (Table 3.2). A well- prepared municipality will have response protocols, mobilize resources quickly, and effectively coordinate evacuation and damage mitigation operations (Jean *et al.*, 2023). A history of repeated flooding can positively affect municipal preparedness levels (Merz *et al.*, 2010) and individuals (Maltais *et al.*, 2023), reducing direct and indirect damage.

Another component related to municipal jurisdiction is the level of public awareness and education efforts on flood risks, mitigation measures and behaviours to adopt in the event of a flood. Similarly, municipal jurisdiction refers to the municipality's ability to work collaboratively with other entities, such as government agencies, regulatory bodies, emergency services and community organizations. This collaboration enables an exchange of information, coordination of efforts and pooling of resources to better cope with flooding and reduce damage to residential buildings (Deschamps *et al.*, 2023).

3.3.1.10 Type of compensation program and settlement terms (10th factor in Table 3.2)

Delays and compensation conditions imposed by governments and private insurers rank tenth among the experts on the contributing factors (Table 3.2). While the existence of compensation programs is beneficial in aiding flood victims, the specific conditions and processes associated with these programs can sometimes exacerbate damage. Delays in settlement, disputes over eligible damage, and limitations on coverage can hinder the timely repair and restoration of damaged property. This extended exposure to the elements can lead to further deterioration and increased damage. The settlement terms are rarely discussed in the literature as contributing to direct damage.

However, studies show that the delays and complexity of the claims process affect claimants' health and financial resources. Not to mention that these delays also force claimants to take time off work. They also generate great stress and slow recovery (Maltais *et al.*, 2023). For example, following the 2017 and 2019 floods in Quebec, average settlement times for claims submitted to the Quebec Ministry of Public Safety were 221 days in 2019 and 521 days in 2017. These delays have deferred repair or relocation work, leaving disaster victims in prolonged, precarious and transitional situations (Maltais *et al.*, 2023 ; Zenker *et al.*, 2024).

3.3.2 Damage rate coefficient

The rationale for establishing damage rate coefficients is to refine the accuracy of damage estimations at the building level. The coefficients make it possible to consider certain factors' positive or negative effects to explain the dispersion of damage around the mean and improve the expected damage result. Two contributing factors were selected: soil type and year of construction. Two other critical components of the damage estimation using the damage curves were also elected: building value and the distribution of values within a residential building.

For instance, a building on clay soil might experience more damage (heaving, cracks, hydrostatic pressure) than a comparable building on sandy soil due to drainage and water retention differences. Similarly, the age of a building can influence its resilience to flood damage, with older buildings potentially being more susceptible to damage due to outdated construction materials or techniques (Miller, 2024). Furthermore, accurately determining building value and its distribution within a residential building is also crucial for refining damage estimations, as the damage rate is expressed as the ratio of damage to building value

3.3.2.1 Soil type

Experts were asked to assign a coefficient to two different soil types, with sandy soil as the baseline with a coefficient of 100 (see Table 3.3). Attributing a coefficient allowed for a relative comparison of the impact of different soil types on damage. For example, clay soil was judged to result in 20 % higher damage than sandy soil, with a median coefficient of 120. Table 3.3 shows the coefficients assigned by 20 experts (n = 20).

Two characteristics raised during the consultations are the instability of clay soil, which exerts pressure on the subsoil structure, and ferrous ochre, a geological deposit often found in clay soils. When exposed to water, ferrous ochre dissolves, forming a gelatinous substance that can clog drains and drainage systems in residential buildings.

Tableau 3.3 Effect of clay soil on building damage rate

Sandy soil = base 100 (n = 20)	**1st quartile**	**Median**	**Average**	**Maximum**
Coefficient	85	120	106	150

The Régie du bâtiment du Québec (Régie du bâtiment du Québec, 2023) states that taking the necessary measures to limit the risk of foundation subsidence when constructing a building on clay soil is vital. According to Towfiqul Islam *et al.* (2021), soil type directly influences its capacity to drain water. A sandy soil contains sand and gravel, making it a very porous and permeable substrate that does not retain water. Clay is a heavier, more compact soil that is difficult to drain, which favours surface runoff and even increases the risk of landslides when saturated with water (Ministère de l'Agriculture, Pêcherie et de l'Alimentation, 2023), as demonstrated by events in the Saguenay region in summer 2023 (Lachance, 2022 ; Zamor et Dussault, 2023). However, one expert points out, "If there is adequate drainage around the foundation of a building, the damage to buildings will be similar." This view suggests that soil type has a negligible influence on the damage rate during major floods if adequate drainage is put in place. However, this respondent's slight divergence does not significantly influence the overall group average.

3.3.2.2 Year of construction

Acknowledging the influence of building codes on construction practices, experts assigned coefficients to different construction periods, with the period 2022 and after (reflecting the most recent code) serving as the baseline with a coefficient of 100. Table 3.4 shows the median and average coefficients assigned by 25 experts (n = 25) according to four construction periods. The periods shown correspond to the main updates to the Quebec construction code. The experts do not attribute significant differences in the coefficients between 2015 and 2022, reflecting the experts' judgment that the construction code updates introduced in 2022 did not substantially alter building vulnerability compared to the 2015 code.

Tableau 3.4 Influence of construction period on the damage rate

After 2022 = base 100 (n = 25)	**Between 2015 and 2022**	**Between 1985 and 2014**	**Between 1965 and 1984**	**Before 1965**
Median	100	110	120	130
Average	100	111	127	138

For most experts, recent buildings are better constructed to resist flood damage. New buildings benefit from drainage, plumbing and electrical system improvements. Electrical systems are better protected against water infiltration, and plumbing systems are fitted with backflow prevention devices. Wing *et al.* (Wing *et al.*, 2020) confirm that the average age of the housing stock in a region can impact the extent of damage suffered during a major flood. Newer buildings are less likely to suffer catastrophic losses for a given inundation depth than older ones. This factor can explain the differences in damage observed between 2 buildings (Paulik *et al.*, 2023). According to Neubert *et al.* (2016), the most effective way of grouping buildings according to their characteristics is to define building age groups since there is always a direct link between the year of construction and building characteristics. Depending on different periods of real estate development, the structure and type of materials and construction codes can influence its resilience to a flood.

However, initial consultations with experts also revealed that certain recent construction standards, particularly regarding waterproofing, require specialized expertise and meticulous on-site execution, which can sometimes be difficult to guarantee. Furthermore, other experts contend that these new standards, aimed at creating watertight foundations, may paradoxically increase structural damage. This is because lateral hydrostatic pressure or vertical Archimedes' thrusts exerted on the structure can cause more significant damage. These experts argue that "welcoming water" (i.e., allowing controlled flooding of the basement or crawl space) can minimize stress on the structure. Yet, the coefficients attributed to buildings constructed between 2015 and 2022 in our study do not reflect the potential impacts of these new waterproofing standards on structural damage.

3.3.2.3 Building and content value

Table 3.5 shows that the 27 experts (n = 27) assigned a median coefficient of 150 % for the building and 35 % for the content. In this context, a base of 100 represents the building's assessed value as listed in the municipal assessment roll. This assessed value often underestimates the actual replacement cost. According to the experts, the property value published in the municipal registers could thus be increased by 50 % to approximate the replacement cost of the building. Therefore, a coefficient of 150 % suggests that the replacement cost of the building is estimated to be 1.5 times its assessed value in the municipal roll. Appendix E illustrates how building value may affect the damage rate calculation. For the contents, a median coefficient of 35 % indicates that their replacement cost is estimated to be 35 % of the building's assessed value, although the content value can vary significantly depending on factors such as the neighborhood, the type of housing, and socio-demographic factors.

Tableau 3.5 Coefficient related to the value of the building and its contents

Property value = base 100 (n = 27)	**Minimum**	**Median**	**Average**	**Maximum**
Replacement cost coefficient	110	150	150	180
Content value coefficient	20	35	42	90

The age of the building, the date of the last assessment roll, the level of maintenance and renovation work conducted, and sometimes not declared to the municipality can significantly affect the replacement cost coefficient. The relationship between property value and replacement cost can vary from one municipality to another, depending on the real estate market or the location factor (for example, a site offering an exceptional view of a body of water). Similarly, the content value varies widely from one building to another and depends on the sector. According to the experts, the type of content and the use of the building are linked to the occupant's social status.

Building value is a critical factor in flood damage assessments (Moel et Aerts, 2011). Merz and Thieken (2009) also state that building value is crucial when converting the relative damage into an absolute monetary value, but they do not delve into the specifics of this conversion process. Meanwhile, Jongman *et al.* (2012) stress that accurate estimation of building values is crucial for reliable flood damage assessments. They point out that discrepancies in asset valuation methods can lead to differences of up to a factor of two in estimated damages. According to the Federal Guidance Guide on Estimating Flood Damage to Buildings and Infrastructure, damage estimates should consider replacement cost, not the depreciated cost nor the municipal assessment roll value (Ressources Naturelles Canada et Sécurité Publique Canada, 2021).

In our survey, experts estimated the value of building contents to be approximately 35 % of the building value. Often used in insurance assessments, this ratio reflects the proportion of value attributed to personal belongings, furniture, and other contents within a residential building. However, it is important to note that the percentage attributed to contents can vary significantly depending on the homeowner's lifestyle, the age and type of building, and the presence of high-value items. While some sources suggest a range between 30 % and 80 % (see Ref. (Lavin, 2022 ; Wawanesa, 2022)), determining a precise ratio requires a detailed assessment of the specific contents and their replacement value.

3.3.2.4 Value distribution within a residential building

The value distribution within a residence and its contents is presented in Table 3.6 according to 20 experts (n = 20). Experts have broken down the values for the three floors (basement, first floor, 2nd floor) of a single-family residential building. The finished basement includes a living environment (bathroom, kitchen, living room, bedroom) for allocation purposes.

Tableau 3.6 - Breakdown of home replacement costs and contents

Distribution in % of total building value (median) (n = 20)	**Basement**	**GROUND FLOOR**	**2^{nd} floor**	**Total**
One floor with a basement	20	80	0	100
One floor with a finished basement	40	60	0	100
One floor without a basement	0	100	0	100
Two floors with a basement	20	50	30	100
Two floors with a finished basement	30	43	27	100
Two floors without a basement	n/a	63	37	100

Accurately estimating flood damage requires understanding how value is distributed within a building. Value distribution data allows for a more precise allocation of losses, recognizing that different areas may have different reconstruction costs. For instance, while some basements may be simple storage spaces with minimal finishing, others might contain high-end finishes, increasing their value and potential repair costs. One expert noted that "sometimes basements are more expensive to rebuild than the 2nd floor".

This understanding is crucial because flood damage often concentrates in specific areas, particularly basements and ground floors. Knowing the relative value of each floor helps determine the overall financial impact. Data from the Richelieu flood (Doyon et Jean, non publié) showed that nearly 85 % of the damages occurred below the first floor. Therefore, if a basement represents 40 % of a building's total value and is completely damaged, the estimated loss would be significantly higher than if it only represented 20 %. Considering variations in construction, occupancy, and contents, this nuanced approach leads to more accurate and reliable damage estimations.

3.4 Discussion

This study examined a broader range of factors that contribute to flood damage in residential buildings, going beyond the traditional focus on inundation depth. The analysis included a detailed examination of the top 10 contributing factors and a comprehensive list of 40 factors (see Appendix D), providing a deeper understanding of the multifaceted nature of flood damage. While the impact of these additional factors were not empirically tested on reducing uncertainty in damage estimation, we theorize that incorporating them, including elements such as soil type could improve the accuracy of these estimations and risk assessments. The potential application of this approach is illustrated in Appendix E, suggesting a pathway towards more effective flood risk mitigation strategies.

Future research should focus on empirically validating the hypothesis that incorporating these extra factors into damage estimation will reduce the underlying uncertainty, quantifying the impact of each factor on the overall uncertainty.

The consultations and survey also revealed the influence of municipal governments on these factors, confirming the second hypothesis and recognizing their potential role in reducing overall flood risk. Seven of the ten most important contributing factors fall under the shared responsibility of municipal and provincial governments. These factors include the distance of a building from a water course as part of land use planning, obligatory compliance with new building codes, and the design and maintenance of critical infrastructure like sewer systems. For example, municipalities can implement land-use planning policies to restrict development in flood-prone areas, enforce compliance with new building codes that enhance flood resilience, and invest in green infrastructure to improve drainage capacity and reduce the risk of sewer backups. Canadian municipalities are central in proactively mitigating the consequences of flood events, as extreme precipitations and flood severity are anticipated to rise or be more frequent under ongoing climate change, especially across eastern North America (see Ref. (Tabari, 2020)). Developing a deeper understanding of the role of these factors in a municipal context and analyzing how municipalities use these factors to reduce the consequences of flooding would merit further work.

The expert survey also provided coefficients for adjusting damage rates based on the aggravating (>1.0) or mitigating (<1.0) effects of specific factors. These factors are interdependent and do not act in isolation. Further research is needed to explore the combined impact of multiple contributing factors, where the interaction between these factors can either amplify or diminish the overall damage. For example, the combination of soil type and year of construction, warrants further investigation to better understand building vulnerability. Furthermore, incorporating insights from geologists and hydro-geomorphology experts regarding soil properties, drainage patterns, and erosion susceptibility will be crucial for developing more accurate and nuanced damage estimations, particularly given the significant influence of soil type on potential damage.

Our panel of experts, predominantly consisting of professionals from the Canadian insurance industry, assigned inundation depth a relatively low ranking of 11th in terms of importance. This ranking should be understood as a reflection of their professional judgment and experience in the field, rather than the result of an empirical, post-damage study. It may be attributed to the fact that, within this specific professional context, damage assessments are often predicated upon a more comprehensive set of factors extending beyond inundation depth. Nevertheless, the experts concur with the existing literature, acknowledging that inundation depth remains a critical factor and confirming that damage increases proportionally with rising water levels (Aribisala *et al.*, 2022 ; Doyon et Bouchard St-Amant, 2020 ; Merz *et al.*, 2013). However, there is high uncertainty in this relationship (Wing *et al.*, 2020) and discrepancies exist regarding the depth at which significant damage occurs (Chhabra *et al.*, 2023). This complexity is acknowledged, as various factors can influence damage at the same depth.

To further contextualize our findings, Table 3.7 compares the top 10 contributing factors identified by our expert panel with existing literature. This comparison highlights the alignment and discrepancies between our results and established knowledge, underscoring the study's contribution to understanding flood damage.

Tableau 3.7 Comparison of expert contributing factors with literature

Rank	**Contributing Factor**	**Comparison with Literature**	**Supporting Literature**
1	Distance of Building from a Watercourse and Ground Elevation	Aligns with the concept of floodplain management; emphasizes the link between proximity to water and flood risk. The emphasis on the "probability of damage occurring" resonates with literature that links the probability of occurrence with damage levels.	Balica *et al.* (2009); Towfiqul Islam *et al.* (2021); Messner and Meyer (2006); Galasso *et al.* (2021)
2	Flow, Current, and Speed of Rising Water	Consistent with studies emphasizing the role of flow velocity in structural damage, particularly at low inundation depths; echoes concerns about flash floods.	Kelman and Spence (2004); Merz *et al.* (2013); Kreibich *et al.* (2009)
3	Response Time for Damage Reduction	Highlights the critical role of rapid response in mitigating damage, a factor less prominent in existing literature.	Kreibich *et al.* (2005); Landaverde *et al.* (2022)
4	Basement Converted into Living Space	Aligns with studies that consider the presence and type of basement in flood damage	Doyon et Jean (non publié)

Rank	Contributing Factor	Comparison with Literature	Supporting Literature
		assessments. The concern about organic materials and sanitary appliances reflects the understanding of differential damage based on material types and basement functionality.	
5	Obligation to Upgrade to New Building Codes	The building code's role in flood resilience is indirectly acknowledged through its guidelines on water management and protection. The criticism of rebuilding "as previously" aligns with the "Building Back Better" concept.	Czajkowski (2019); UNDRR (2023); Kougkoulos *et al.* (2021)
6	Event Duration	Aligns with studies highlighting the role of water duration in damage due to material capillarity and moisture levels. Echoes the claim that the importance of event duration is underestimated in current flood damage assessments.	Mohor *et al*. (2020); Aribisala *et al*. (2022); Merz *et al.* (2013); Shrestha *et al.* (2021)
7	Design and State of Maintenance of Sewer and Water Supply Systems	Aligns with studies emphasizing the role of municipal drainage systems in flood mitigation. The recognition of obsolete or inadequate drainage systems reflects the understanding of infrastructure failure as a contributing factor to flood damage.	Arya and Kumar (2023); Sandink (2015)
8	Landscaping	The impact of land slope and relief on water flow and accumulation is consistent with studies on hydrology and floodplain management. The emphasis on adequate landscaping aligns with research promoting green infrastructure and nature-based solutions for flood mitigation.	Huang *et al.* (2022); Towfiqul Islam *et al.* (2021)
9	Readiness and Competence of the Municipality	Consistent with literature on disaster preparedness and community resilience. The emphasis on public education and collaboration aligns with studies highlighting the role of community engagement in flood risk management.	Jean *et al*. (2023)
10	Type of Compensation Program and Settlement Terms	While the literature acknowledges the impact of compensation delays on recovery, the direct contribution of compensation programs to physical damage is less explored. This study highlights how delays and limitations in compensation programs can exacerbate damage.	Bourova *et al*. (2022); Maltais *et al.* (2023)

3.5 Limitations

This study acknowledges several limitations associated with expert consultations and surveys. Expert opinions are inherently subjective and can be influenced by personal experiences, professional backgrounds, and individual biases. This subjectivity introduces uncertainty into the results, as different experts may prioritize factors differently or have varying interpretations of the same factor.

Secondly, it is important to acknowledge potential biases that may have influenced the experts' responses. For example, the fact that most respondents come from the insurance industry could introduce a bias toward factors typically considered in insurance claims assessments. Since most water damage insurance claims result from sewer backups rather than river overflows, this may have skewed their perspectives on the relative importance of different contributing factors. Additionally, the specific wording of survey questions or response scales format could have influenced the results.

Thirdly, there is uncertainty associated with the process of eliciting and synthesizing expert opinions. While designed to reduce bias and encourage consensus, the Delphi method still involves a degree of uncertainty. The selection of experts, formulating questions, and interpreting responses can all introduce variability in the results.

Finally, the study's focus on residential buildings limits the generalizability of the findings to other types of structures or infrastructure. Future research should consider expanding the scope of the study to include a broader range of building types and land uses.

3.6 Conclusion

This study provides a unique perspective on flood damage by incorporating expert judgment to identify and prioritize contributing factors. This approach goes beyond traditional reliance on inundation depth to uncover additional factors, such as response time for damage reduction, the obligation to upgrade to new building codes, and the design and maintenance of sewer systems. Furthermore, our findings confirm the significant role that municipalities can play in flood risk reduction. By influencing seven of the top ten contributing factors identified, municipalities can actively implement measures to mitigate flood damage and enhance community resilience. These findings offer valuable insights for refining damage estimations, improving risk assessments, and informing flood mitigation strategies.

This study also provides a foundation for understanding the complex interplay of factors contributing to flood damage. By exploring these interactions and integrating diverse expertise, future studies can refine these coefficients, enhance existing models, and investigate additional factors relevant to flood risk assessment. For example, as observed in recent flood events from heavy rainfall in different climatic regions (see Ref. [85]), debris and other materials shared with water harm buildings and infrastructures.

The data needed (e.g. type of basement, obligation to comply with new building code, landscaping and soil type) to integrate these contributing factors in the damage curves models is usually available but scattered across many databases. These datasets could be centralized and made available, as Elmer *et al.* (2010a) suggested. One way of putting this into practice would be to require such data to be collected on the property assessment roll data. This practice would be consistent with research showing that flood risk affects property values and the municipal assessment role (Bakos *et al.*, 2022).

Future research should prioritize a proof-of-concept study incorporating actual flood data from past disasters to strengthen the validity and applicability of the damage rate coefficients. A proof of concept involves collecting empirical data on building damage, inundation depth, soil type, year of construction, and other relevant factors. By comparing the expert-derived coefficients with this real-world data, researchers can further validate and calibrate their accuracy and reliability, ultimately leading to more robust flood risk estimation tools. Furthermore, expanding this research's scope by exploring these factors' applicability in diverse geographic and hydroclimatic contexts is essential. Such additional research will help determine the generalizability of the findings and identify any regional variations that need to be considered.

The accelerating economic costs and consequences of flooding on populations and infrastructures under ongoing climate change (see (World Meteorological Organization, 2021)) call for rapid implementation of measures. A better understanding of the contributing factors and how they can be used in damage estimates will help public authorities, insurers, and households make better investment decisions to reduce vulnerability to flood risk. There is an urgent need to develop credible cost-benefit analyses that can be used to justify flood risk mitigation and reduction measures financially. These measures are essential to reduce people's vulnerability and increase their ability to cope with flood risks.

CHAPITRE 4
FLOODING: TOWARD A MUNICIPAL CONTRIBUTION TO ECONOMIC RISK SHARING

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Résumé

Au Québec, les coûts liés aux inondations ont fortement augmenté au cours des 40 dernières années, en partie à cause de la croissance démographique et immobilière dans les zones inondables. Ce phénomène est exacerbé par des phénomènes météorologiques extrêmes, comme les pluies torrentielles, dont certaines sont de plus en plus fréquentes dans le sud du Québec au printemps. Aujourd'hui, ces coûts sont principalement couverts par des programmes d'aide financière provinciaux et fédéraux et, dans une moindre mesure, par des assurances privées. Ces mécanismes de partage des coûts donnent lieu à un aléa moral, car ils n'incitent pas les municipalités ni les victimes de catastrophes à réduire les risques. Les municipalités doivent être incluses dans le partage des coûts en raison de leur rôle dans l'aménagement du territoire et la gestion des risques. De même, les victimes de catastrophes doivent être incluses, car elles ont également un rôle à jouer dans la réduction des risques.

Cet article propose et analyse un mécanisme de contribution économique pour les municipalités qui répartit plus équitablement le coût des dommages causés aux bâtiments résidentiels. (L'équité désigne une répartition juste et équitable de la charge financière en fonction du niveau relatif d'exposition au risque et de la capacité à réduire le risque pour toutes les parties concernées.) La contribution est calculée pour trois municipalités de taille moyenne au Québec sur la base de la somme des dommages annuels moyens causés à chacun des bâtiments résidentiels situés sur leur territoire et de la valeur des propriétés.

Trois observations peuvent être tirées de cette analyse : 1) le niveau d'exposition d'une municipalité n'est pas corrélé à la valeur de ses propriétés ; 2) le faible taux de dommages de la majorité des bâtiments situés dans des zones inondables justifie le maintien de ces bâtiments dans ces zones, à condition que des mesures d'atténuation soient mises en œuvre ; et 3) la relocalisation d'un nombre minimal de bâtiments réduirait considérablement la contribution économique de la municipalité aux coûts des dommages. La mise en place d'un mécanisme de contribution économique des municipalités et des citoyens exposés vise à réduire l'aléa moral et l'iniquité générés par l'approche actuelle et à encourager les municipalités à mettre en œuvre des mesures d'atténuation et de réduction des risques. Toutes les parties prenantes pourraient financer ces mesures de manière équitable.

Mots clés : dommages causés par les inondations, partage des risques d'inondation, aléa moral, équité économique, contribution municipale. Codes JEL : H76, H84, Q51, Q54

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.

The 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

4.1 Introduction

Over the past 40 years, we have observed a significant increase in the economic, social, and psychological consequences of flooding[17] (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.*, 2020 ; 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 (Sécurité Publique Canada, 2022). Without incentives that lead to concrete measures, demographic growth and the pressure to build 860,000 housing units in Québec by 2030 (Société Canadienne d'Hypothèque et de Logements, 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 (Bush et Lemmen, 2019 ; Carvalho, 2018 ; Intergovernmental Panel on Climate Change, 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).

[17] 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).

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[18]. As recently as spring 2023, at least 102 municipalities were affected by flooding[19]. Taxpayers primarily finance the cost of such damage through 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) leading them to potentially expose themselves to greater risk than if they were not insured (Laffont et Martimort, 2002b). 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 et 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

[18] 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

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

a lifetime limit on successive flooding damage partly addresses the concern of moral hazard (Boudreault et 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 (Ministère de l'Environnement et de la Lutte contre les Changements Climatiques Québec, 2022).

The recent reduction in municipal powers in Québec over flood zone mapping and land use planning in 2022[20] in no way diminishes the importance of their role in flood risk management. Bill 50[21], an Act to

[20] 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.

[21] 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/.

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 et Thistlethwaite, 2017a). 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.

4.2 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 et Thistlethwaite, 2017a). Economic risk sharing involves distributing the potential monetary losses (downside risk) 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 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 (Intergovernmental Panel on Climate Change, 2021b). 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: one mathematical-economic and the other psycho-sociological (behavioral). The mathematical basis concerns probability theory, which enables uncertainty to be quantified. This is integrated into Expected Utility Theory, the primary *economic* model where decision-makers are assumed to rationally evaluate the probability of occurrence and the consequences of their decisions (Amansou, 2019). The psycho-sociological basis, in contrast, explains how and why *actual* decision-makers often deviate from this rational model (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. It is worth noting that in this presentation, each subsequent group is a subset of the preceding one. 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 et 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 - high-income and wealthy households - 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 4.1 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.

Tableau 4.1 - 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	Insureds through premiums	Taxpayers	Disaster victims
Cost of damages in excess of coverage	Disaster victims	Disaster victims	Disaster victims

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 members. This mechanism is not currently used in the context of flood risk in Québec but is provided for in the Act respecting insurers[22]. Table 4.2 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 4.2.

[22] 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

Tableau 4.2 - 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

4.2.1 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 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 et 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 (Gouvernement du 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, this system faces significant challenges regarding equity, a concept which necessitates explicit definition in this context. The initial principle of actuarial equity (where premiums reflect individual risk) often conflicts with the goal of social equity (which aims for fair and affordable access to protection for all). Disparities in accessibility and affordability are particularly acute for those living in high-risk areas (Atlas Magazine, 2024 ; Sécurité Publique 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. This concept is central to flood risk management because it directly addresses the unequal distribution of losses and the need for affordable protection, especially for vulnerable populations who are disproportionately affected by climate risks. 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 et 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 (United Nations Office for Disaster Risk Reduction, 2015a).

4.2.2 Québec and federal governments financial assistance programs

In Québec, disaster victims (homeowners, tenants, municipalities, and community organizations) can qualify for the General Financial Assistance Program Regarding Disasters (GFAPRD)[23]. The 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)[24] 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[25]. 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 (Gouvernement du Canada, 2023 ; Sécurité Publique Canada, 2022). This program could also exacerbate moral hazard and disempower provinces, municipalities, and residents of flood- prone areas (Davlasheridze et Miao, 2021 ; Kousky, 2018).

[23] 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-fi -locataires

[24] 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

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

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 namely 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 the GFAPRD[26]. The new version imposes a lifetime limit on flood victims and is intended to discourage them from rebuilding in flood-prone areas (Boudreault et Bourdeau-Brien, 2020) in an effort to reduce flood risk. 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 of solidarity 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

[26] 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

economic security they provide and the lack of incentives to reduce risk (Davlasheridze et Miao, 2021 ; Kousky, 2019).

4.2.3 Reciprocal union

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.

4.2.4 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[27]. 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.

[27] See https://www.fondsfqm.ca/

4.3 Methodology to Estimate Damages from Floods

4.3.1 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 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 et Jean, non publié ; 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 (non publié), 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 Montreal Metropolitan Community (MMC) 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 (non publié) were interpolated to determine the damage rate for each flood height. Therefore, the damage (D$) to the building is given by

$$D\$ = TE * \text{Assessment Value} \tag{1}$$

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 (non publié).
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 (non publié). 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 4.3) (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.

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.

Tableau 4.3 - Probability intervals for each occurrence (upper bounds)

Occurrence	Probability	Distribution function	Probability mass	Period
0	1	0		
2	0,5	0,5	0,5	Between 0 and 2 years
20	0,05	0,95	0,45	Between 2 years and 20 years
50	0,02	0,98	0,03	Between 20 years and 50 years
100	0,01	0,99	0,01	Between 50 years and 100 years
200	0,005	0,995	0,005	Between 100 years and 200 years
350	0,002857143	0,997142857	0,002142857	Between 200 years and 350 years
Infini	0	1	0,002857143	Between 350 years and infinite
		Sum	1	

4.4 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.

4.4.1 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 4.4 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.

Tableau 4.4 - Profile of study region (2022 assessment role)

Municipality	**Residential land use**	**Residential standardized value (VFUM$) (in $M)**	**Number of residential buildings***	**Average standardized residential value. (in $000)**
Municipality 1	39%	740	2540	290
Municipality 2	48%	3000	7513	400
Municipality 3	54%	2600	7120	370
			17173	

4.4.2 Exposure rates and contribution

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 by dividing the sum of the average annual damage to buildings (DMA$) by the residential standardized property value (VFUM$). Table 4.5 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.

Tableau 4.5 - Exposure rate (TEAD%) by municipality

Municipality	**Number of Residential Buildings at Risk**	**% of Residential Buildings at Risk**	**Total Values of Buildings at Risk $**	**DMA$**	**Average DMA$**	**TEAD%**
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%

4.4.3 Damage rates distribution

Table 4.6 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 13.5 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 4.7 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).

Tableau 4.6 - Distribution of damage rates (study area)

TEAM% range	DMA$	Building Values $	Nb of Buildings	% of Buildings	Average DMA$	TEIB%
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% to 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%
Total	13 023 844	637 163 800	4000	100,0%	3 256	2,04%

Tableau 4.7 - 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%	-	-
Municipality 1	0+ to 1%	1.2	310 000	0,01%	21	21
Municipality 1	1% to 6%	1.3	154 400	5,03%	7 760	7 760
Municipality 1	More than 6%	1.4	215 000	44,26%	95 168	95 168

Municipality	TEAM% Range	Cases	Building Value at Risk $	TEIB%	DMA$	CONT$
Municipality 2	0%	2.1	399 500	0,00%	-	-
Municipality 2	0+ to 1%	2.2	268 500	0,01%	19	19
Municipality 2	1% to 6%	2.3	191 500	5,03%	9 624	9 624
Municipality 2	More than 6%	2.4	268 000	31,11%	83 366	83 366
Municipality 3	0%	3.1	393 500	0,00%	-	-
Municipality 3	0+ to 1%	3.2	197 000	0,01%	14	14
Municipality 3	1% to 6%	3.3	123 500	4,94%	6 106	6 106
Municipality 3	More than 6%	3.4	114 000	37,71%	42 994	42 994

4.4.4 Effect 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 et 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 (Federal Emergency Management Agency (FEMA), 2023b). 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 4.8 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 4.9 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[28] (cost of mitigation measures) is estimated at $47 million (an average of $65,000 per building). 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 (2)

Tableau 4.8 - Scenario 1 - Distribution of damage rates with first-floor elevation

TEAM% Range	DMA$	Building Values $	Nb of Buildings	% of Buildings	Average DMA$	TEIB%
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%
More than 10%	4 100 156	21 648 500	154	3,9%	26 624	18,94%
Total	11 235 41	637 163 800	4000	100,0%	2 809	1,76%

[28] The cost of ground floor elevation may vary considerably. An average of $65 000 was established for illustration purposes.

Tableau 4.9 - Scenario 1 - Effect of raising the first floor by 60 cm for 718 buildings

Municipality	Building Values $	Nb of Building	Damage Reduction $	Cost in $ of mitigation measures	DVAN0 (years)
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
Total	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 et 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 4.10 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.

Tableau 4.10 - Scenario 2 - Effect of relocation on damage reduction

TEAM% range	New DMA$	Building Values $	Nb of Buildings	% of Buildings	Average DMA$	TEIB%
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%
	4 528 079	561 834 100	3463	86,6%	1 308	0,81%

Table 4.11 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.

Tableau 4.11 - Scenario - Effect of relocation on damage reduction per municipality

Municipality	Purchased Building Values $	Nb of Buildings	Damage Reduction $	DVAN0 (years)
Municipality 1	41 554 200	345	4 589 170	11,47
Municipalit2 2	30 855 500	173	3 575 185	10,8
Municipality 3	2 920 000	19	331 409	11,08
	75 329 700	537	8 495 765	11,17

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 [29], 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 4.5). 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. The 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.

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

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 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 et Bouchard St-Amant, 2020 ; Doyon et Jean, non publié). 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.*, 2025). 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.

Furthermore, the financial metrics presented, specifically the calculation of the "DVAN0" (Net Annual Value of Damage at a zero-discount rate), serve as simplified, illustrative payback period ratios intended to demonstrate the relative long-term cost-effectiveness of damage mitigation measures, like home elevation and relocation scenarios. This approach has two key limitations: first, the implicit use of a zero discount rate undervalues the true cost of capital for municipalities or individuals, artificially shortening the payback period and making the financial justification of the works seem easier than it would be with a positive discount rate; second, the relocation scenario (Table 4.11) omits the indirect but significant potential cost of lost recurring property tax revenue for the municipality, which would substantially increase the real cost of the operation. Consequently, while the Chapter successfully proves the substantial value of risk reduction in terms of avoided annualized damages (a key finding for collective resilience), it acknowledges that a more comprehensive financial model, integrating both positive discount rates and fiscal impacts, is necessary to transform these simplified DVAN0 calculations into a reliable, direct municipal budgetary decision-making tool.

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.

4.6 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.

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).

CHAPITRE 5
FLOODING: EVALUATING MUNICIPAL FINANCIAL CONTRIBUTION AS AN INCENTIVE FOR RISK REDUCTION IN QUEBEC

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Résumé

Face aux limites des mécanismes actuels d'indemnisation des inondations fluviales, qui incitent peu les municipalités québécoises à la prévention, cette recherche évalue si l'instauration d'une contribution financière municipale proportionnelle au risque pourrait accroitre leur engagement dans la réduction du risque. Basée sur des entrevues semi-dirigées auprès de 35 acteurs et experts du monde municipal au Québec et au Canada, l'étude explore la faisabilité, l'acceptabilité et l'effet incitatif potentiel de cette approche dans un contexte d'occupation existante du territoire et de bouleversements climatiques.

Les résultats révèlent un faible consensus et un fort scepticisme quant à l'efficacité et la pertinence de ce mécanisme de partage des risques financiers. L'hypothèse initiale d'un effet incitatif direct des contributions municipales sur la réduction des dommages causés aux infrastructures privées individuelles est donc infirmée par les perceptions recueillies. Les participants ont principalement exprimé des préoccupations concernant la complexité de mise en œuvre, la compatibilité avec les pouvoirs municipaux jugés limités par les contraintes institutionnelles et l'historique d'aménagement du territoire, et l'efficacité de l'incitatif financier face à de tels obstacles. La recherche souligne également que les municipalités engagent déjà des coûts importants liés aux mesures d'urgence et à la réparation des infrastructures après les inondations, lesquels ne sont pas toujours entièrement compensés.

Cette recherche conclut donc sur la nécessité d'explorer des voies alternatives pour encourager l'action municipale, telles qu'un soutien financier conditionnel ou des incitatifs non financiers destinés aux municipalités. Cette analyse approfondie et inédite de la perspective municipale québécoise sur ce mode spécifique de partage financier du risque, permet de mettre en évidence les défis concrets et les pistes privilégiées par les acteurs de terrain. L'objectif est de renforcer la résilience locale, tout en contribuant à éclairer les discussions sur la responsabilité, la reddition de comptes et les processus décisionnels pour la gestion du risque d'inondations.

Mots clés : municipalités, inondations, partage du risque, gouvernance et incitatif.

Abstract

Faced with the limitations of current river flood compensation mechanisms, which offer little incentive for risk reduction action by Québec municipalities, this research evaluates whether implementing a municipal financial contribution proportional to risk could increase their engagement in risk reduction. Based on semi-structured interviews with 35 municipal actors and experts, this study explores the feasibility, acceptability, and potential incentive effect of such an approach within the context of the built environment and climate risk.

The findings reveal a lack of consensus and significant skepticism among participants regarding the effectiveness and appropriateness of this financial risk-sharing mechanism. The collected perceptions do not support the initial hypothesis that direct financial contributions incentivize municipalities on reducing damages to individual private infrastructures. The main concerns raised by participants relate to implementation complexity, compatibility with municipal powers often perceived as limited by institutional constraints and historical planning, and the very effectiveness of the financial incentive in overcoming these obstacles. The research also highlights that municipalities already incur significant costs related to emergency measures and infrastructure repair post-flooding, which are not always fully compensated.

This research concludes that alternative pathways, such as conditional financial support or non-financial incentives, are needed to encourage proactive municipal action in flood risk reduction. Its unique contribution lies in its in-depth analysis of the Québec municipal perspective on this specific mode of financial risk-sharing. The study illuminates the concrete challenges and preferred strategies identified by local stakeholders for enhancing local resilience, thereby informing discussions on responsibility, accountability, and decision-making processes for managing climate-related risks in the built environment.

Keywords: municipality; flooding; risk sharing; governance; and incentive.

5.1 Introduction

Recurring flooding inflicts escalating socioeconomic damages (Burn et Whitfield, 2016 ; da Silva *et al.*, 2020 ; Grenier *et al.*, 2024), particularly for residential property owners and tenants. Recent major flood events in Québec (2017, 2019, 2023, and 2024) underscore these disasters' rising economic costs and vulnerability (Insurance Bureau of Canada, 2024a ; Ministère des Affaires Municipale et de l'Habitation du Québec, 2021a). For instance, insured losses from extreme weather in Québec (including fluvial flooding) reached $2.7 billion in 2024 alone, surpassing previous records (Floyd, 2025 ; Insurance Bureau of Canada, 2024c), and these insured losses represent only a fraction (25%-60%) of total damages (Honegger et Oehy, 2016 ; Lee et Parfitt, 2022 ; Moudrak *et al.*, 2018).

Currently, the economic burden of fluvial flood damage to residential buildings is primarily borne by Canadian and Québec taxpayers through federal Disaster Financial Assistance Arrangements (DFAA) and Québec's Programme général d'indemnisation (PGAF), with limited involvement from private insurers, especially in high-risk areas (Boudreault, 2021a ; Kousky et Kunreuther, 2018). These existing compensation mechanisms, while providing aid, present significant limitations: they offer minimal incentives for municipalities and cities (hereafter "municipalities") to prioritize risk reduction measures (Davies, 2016 ; Davlasheridze et Miao, 2021 ; Kousky et Kunreuther, 2018 ; Raschky et Schwindt, 2008). Lack of incentive can foster a "moral hazard," where a lack of direct financial accountability disincentivizes proactive risk mitigation (Laffont et Martimort, 2002b). Consequently, despite growing awareness of factors like climate change (Intergovernmental Panel on Climate Change, 2022) and historical development in floodplains (Andrews, 1993 ; Cosens et Gunderson, 2021 ; Sécurité Publique Canada, 2022) which exacerbate exposure, a significant financial protection gap persists (Feinman, 2021).

While the crucial role of municipalities in land-use planning and risk management is recognized, their potential position in the financial sharing of flood risk remains underexplored (Thistlethwaite et Henstra, 2017). This research addresses this gap by investigating a novel approach: a municipal financial contribution to compensation costs proportional to their flood risk exposure. This proportionality is conceptualized based on quantifiable risk indicators, such as those derived from average annualized damages calculated using depth-damage curves, a methodology detailed in previous work by other authors (Bonnifait, 2005 ; Deschamps *et al.*, 2024 ; Doyon et Jean, non publié ; Leclerc *et al.*, 2003 ; Oubennaceur *et al.*, 2019). The central research question is: To what extent can a municipal financial contribution to compensation costs act as an effective lever to overcome current disincentives and encourage Québec municipalities to prioritize river flood risk reduction?

This study focuses explicitly on river flood risk and how municipalities in Québec manage it within the existing provincial regulatory framework. The hypothesis is that such contributions could directly link local land-use decisions and the financial burden of risk.

5.2 Methodology

This study employed a qualitative approach to empirically evaluate the proposed municipal financial contribution's feasibility, appropriateness, and acceptability—a novel and potentially controversial concept. Semi-structured interviews in French and English were chosen as the primary data collection method, allowing for in-depth exploration of the nuanced perceptions, specific concerns (e.g., equity, administrative capacity, incentive effectiveness), and perceived constraints (political, and institutional) of the municipal actors who would be directly affected by such a mechanism (Adams, 2015 ; Merriam, 2009). This approach provided the flexibility to understand diverse actor logics within varied local contexts across Québec and British Columbia.

The research followed a structured process broadly aligned with established steps for conducting and analyzing semi-structured interview data (e.g., (Adeoye-Olatunde et Olenik, 2021). An interview guide covered key themes: general perception of the proposed contribution, potential influence on municipal risk reduction behaviours, implementation challenges and requirements (including equity and efficiency), and possible alternatives. This guide was shared with participants beforehand.

Participants were selected based on their significant experience in municipal public policy development and implementation, particularly concerning infrastructure and service financing. A total of 63 individuals were initially identified through referrals from key municipal associations (Fédération Québécoise des municipalités, and Union des municipalités du Québec) and the author's professional network, employing a snowball sampling technique to identify further potential interviewees. Thirty-five individuals agreed to participate (n=35), representing a sufficient sample for qualitative inquiry (Guest *et al.*, 2006). The sample included 18 elected officials, four of whom also served as Regional County Municipality (RCM) prefects, and 13 municipal officers from 23 local municipalities (two large, seven medium, 14 small) and eight RCMs and Capital Regional District (CDR). Four external experts (university professors, lawyers, and provincial government managers) were also interviewed. Though geographically dispersed across Québec (and one in British Columbia), all participating municipalities shared significant recent experience with major flooding events, primarily in 2017, 2019 and 2021. Contextual data on municipal characteristics (population size, growth, land use, etc.) were collected to explore potential associations with interviewee perspectives. Details are presented in the Appendix F.

Interviews, lasting approximately 60 minutes, were conducted between September 6 and November 22, 2024, either in-person (n=21) or via video conference (n=14). All interviews but one were audio-recorded with participants' consent. Recordings and transcripts of participants' opinions are kept confidential.

Interview transcripts were analyzed using thematic content analysis (Bardin, 2013 ; Merriam et Tisdell, 2015). Data were coded and categorized based on the research objectives, focusing on opinions regarding the contribution's effectiveness as a risk reduction incentive and implementation factors. Five main recurring themes emerged from the analysis and structured the presentation of results: incentive for action, equity, financial feasibility, citizen responsibility, and collaboration. Preliminary statistical analysis (Chi-Square, ANOVA) exploring relationships between participant/municipal characteristics and their expressed views on the contribution proposal did not reveal any significant associations, suggesting factors beyond the measured demographics or structural features likely shaped opinions. Detailed analysis is presented in the Appendix F.

5.3 Results

While participants generally acknowledged the lack of incentives for municipal risk reduction, the interviews did not confirm the core hypothesis that a risk-proportionate financial contribution would effectively incentivize such action. The proposal was primarily perceived as a "false good idea". An evident lack of consensus emerged: out of 35 participants, only five (14%) unequivocally supported the idea, 13 (37%) expressed openness but with significant reservations, and 17 (49%) were opposed. The prevailing sentiment was skepticism about the mechanism's ability to drive meaningful change in municipal behaviour, as illustrated by one participant: "*I am not sure that [a contribution] would really convince our elected officials to have the necessary political courage to adopt the required regulations*" [Translation by the author]. Table 5.1 illustrates the distribution of the participants’ opinion.

Tableau 5.1 Distribution of participants' opinion

(n = 35)	**Opposed**	**Skeptical**	**In favor**	**Total**
Elected	6	8	4	18
Officer	9	4	1	14
Other	2	1	0	3
	17	13	5	35

Note 1: Four elected officials are also prefects

5.3.1 Divergent Perspectives on the Proposed Contribution

The complexity of the issue and the diversity of viewpoints are summarized in Table 5.2, which organizes the main arguments into two groups, favourable and mixed and unfavourable participants across five recurring themes, such as: incentive for action, equity, financial feasibility, citizen responsibility and collaboration.

As indicated in table 5.2, the five supporters viewed the contribution as a tool to enhance municipal accountability, incentivize mitigation investments, foster collaboration, and ensure greater equity by aligning costs with risk. However, the majority of participants (those with mixed and opposing views) raised deep and multifaceted concerns regarding the feasibility and equity of such an approach, articulated around the effectiveness of the financial incentive and the concrete implementation challenges.

Tableau 5.2 Arguments collected during the interviews

Theme	Arguments from Supporters	Arguments from Mixed/Opposed Participants
Incentive for Action	A municipality that must contribute to flood damage costs will be more inclined to invest in risk reduction measures. Municipalities will become more aware of the importance of flood risk management. They will pay closer attention to information and expert recommendations.	Doubt about the effectiveness of contributions in incentivizing municipal action due to municipalities' limited power to act. Proposal to limit contributions solely to elements the municipality can control through local actions. Perceived as another transfer of responsibilities from the government to municipalities.
Equity	A form of risk mutualization, allowing costs to be distributed among municipalities and creating financial solidarity. Municipalities most exposed to risk should contribute more, reflecting the burden they place on current compensation mechanisms. Reward mechanisms for pro-active municipalities should be proposed.	Uncertainty and complexity in risk assessment could lead to disputes from municipalities regarding their contribution level. Contributions risk being a simple wealth transfer, affecting the most vulnerable populations. Contributions must consider past decisions and the impact of other municipalities' decisions.
Financial Feasibility	The financial contribution could be used to fund risk reduction measures. Contributions could help property owners increase their home's resilience (e.g., raising the ground floor). Introducing deferred contributions over time could mitigate municipalities' inability to pay.	An overly significant financial contribution could heavily burden the budget and prevent investment in other essential projects, particularly for small municipalities.
Citizen Responsibility	Communication and consultation with citizens are essential to ensure the social acceptability of prevention measures. Considering the importance of support and understanding citizens' motivations for living in flood zones.	Municipal contributions could translate into simply passing costs onto citizens, with no real incentive for risk reduction. The principle of compensating owners for flood damage is questioned. The idea of a sector-specific tax is raised ("user-pays" principle).
Collaboration	Contributions would promote collaboration and resource sharing among municipalities. Involving neighbouring municipalities in joint reflection would be beneficial.	Concerns were expressed about potential conflicts of interest among different actors. Closer collaboration between various government levels is necessary before adding complexity.

5.3.1.1 Incentive for Action

Most doubted the contribution's effectiveness, arguing that municipalities possess limited real power over key risk factors due to institutional constraints, historical land-use decisions ("inherited risk"), and provincial oversight. The measure was often perceived as an additional burden or responsibility transfer without corresponding means or authority, rather than a genuine incentive. Some suggested limiting contributions only to factors directly controllable by the municipality.

5.3.1.2 Equity

Major concerns were raised about fairness. Participants highlighted the difficulty and complexity of accurately assessing risk levels for contribution calculation, the potential for the contribution to become a simple wealth transfer penalizing historically disadvantaged or vulnerable populations, and the need to account for past planning decisions and the impact of actions by neighbouring municipalities. Supporters, conversely, saw it as a way to mutualize risk and make exposed municipalities contribute fairly.

5.3.1.3 Financial Feasibility

While supporters suggested contributions could fund mitigation, many participants, particularly from smaller communities, questioned the economic viability, fearing it would strain budgets already challenged by climate adaptation costs and impede other essential projects. Suggestions were made to adjust contributions based on fiscal capacity. Supporters proposed deferred contributions to ease the burden.

5.3.1.4 Citizen Responsibility

Concerns were expressed that municipalities might simply pass the cost onto citizens through increased taxes or stricter regulations, without fundamentally changing risk management practices. This concern led some to question the principle of compensating owners or to suggest targeted "user-pay" taxes for properties in flood zones. However, the equity implications of such taxes were also noted. Supporters emphasized the need for communication and consultation with citizens.

5.3.1.5 Collaboration

While supporters believed contributions could foster inter-municipal collaboration, others worried about potential conflicts of interest and argued for strengthening collaboration between government levels before adding another layer of complexity.

5.3.2 Implementation Challenges

Beyond the general perceptions, participants identified significant practical challenges to implementing a contribution mechanism, specifically related to the mode of participation and the complexities involved in calculating contributions.

5.3.2.1 Participation Mode

Two opposing visions emerged regarding which municipalities should contribute. One favoured universal, mandatory participation by all municipalities, regardless of direct risk level, to reflect climate change's broad impacts and ensure solidarity. The other advocated for a targeted approach, focusing contributions and efforts on the highest-risk municipalities for greater efficiency in risk reduction.

5.3.2.2 Contribution Calculation

Significant concerns were raised about how contributions would be calculated. The complexity of estimating damages, particularly using methods like depth-damage curves, was questioned regarding transparency and potential contestation. The quality and precision of underlying data, especially official flood maps, which often depict hazard but not vulnerability or exposure, were deemed insufficient. Participants also stressed the need to consider the influence of neighbouring municipalities' actions (watershed perspective) and argued that contributions should be limited to risk factors that municipalities can control.

Establishing fair appeal and revision procedures would be necessary but would add further complexity. As one participant cautioned, the technical challenge of the calculation tool is significant: "*Establishing the contribution will be one of the technical challenges, in fact. A winning condition too*" [Translation by the author].

5.4 Discussion

The specific political context during the interviews may have influenced participants' perceptions. The Québec government was proposing a new, stricter, permanent regulatory framework for flood zones, intended to replace the transitional regime since 2019. This proposed overhaul, involving redrawn maps and new zone classifications, generated significant reactions within affected communities.

Against this backdrop, the interviews did not support the study's central hypothesis—that risk-proportionate municipal financial contributions would incentivize municipalities to prioritize risk reduction. Most participants expressed reservations or opposition, arguing they have "little control over the risk" within the current governance model. This perceived lack of control was attributed more to institutional constraints and limited autonomy rather than the absence of direct financial liability.

However, this perception of limited control requires critical examination in light of legal precedents. Legal actions across various jurisdictions suggest that municipalities do possess a degree of control and accountability, particularly regarding drainage infrastructure maintenance and land-use planning. The potential for successful civil lawsuits from citizens following flood events, challenging the notion of municipal helplessness by imposing financial liability for damages, diminishes the credibility of claims that municipalities lack control over this problem. For instance, the City of Montreal's settlement agreement in 2023 with residents of the Rosemont borough for losses sustained between 2009 and 2011 (Sauvé, 2024), and the ongoing lawsuit against the municipality of Sainte-Marthe-sur-le-Lac following the 2019 floods (CBC, 2025), demonstrate judicial scrutiny of municipal flood management practices.

Ultimately, it is possible that the actors' responses strategically reflect a municipal desire to avoid an increased burden of responsibility, thereby shifting the financial weight of flood issues onto homeowners and higher levels of government. This strategic positioning could explain why participants then argue that the financial moral hazard argument becomes less relevant to their decision-making without effective levers for action.

This perspective diverges somewhat from literature suggesting that excluding municipalities from direct financial sharing of indemnity costs inherently creates moral hazard and disincentivizes prevention (Bernhardt *et al.*, 2020 ; Hudson *et al.*, 2019 ; Kousky *et al.*, 2021 ; Lavarde, 2024). While municipalities face flood-related costs (emergency measures, and infrastructure repair), the participants suggest other factors are more influential barriers to proactive risk reduction. Table 5.3 provides a comparative overview of key influential factors in flood risk management. It highlights areas where participants' perspectives converge with existing literature, such as the influence of current governance, inherited risk, and development objectives. Conversely, it also reveals divergences, notably regarding the perceived influence of moral hazard and risk perception, offering a nuanced understanding of the challenges involved.

Tableau 5.3 Key influential factors: A comparative analysis of participant opinions and the literature

Theme	Interviewee Position	Literature Position
Influence of Moral Hazard (Divergence)	The majority disagrees or opposes the idea that a financial contribution would incentivize risk reduction. The feeling of having "little control over the risk" in the current model makes the financial incentive less relevant. Other factors (governance, inherited risk, perception, development objectives) seem more influential.	Current compensation programs hinder risk reduction (cost/mitigation inconsistency) (Aerts et Botzen, 2011 ; Hudson *et al.*, 2019 ; Kousky *et al.*, 2021 ; Lavarde, 2024 ; Sandink *et al.*, 2015). Excluding municipalities from financial sharing creates moral hazard (Botzen, 2019 ; Davies, 2016 ; Davlasheridze et Miao, 2021 ; Kousky *et al.*, 2018 ; Thistlethwaite et Henstra, 2017) and insufficient prevention incentives. A municipal contribution could facilitate mitigation (Bernhardt *et al.*, 2020).
Influence of Current Governance (Convergence)	The current governance model is a significant obstacle. The legal framework limits autonomy and absolute power over land-use planning. A contribution would be an additional constraint with no positive effect on governance. Need for a multidimensional and collaborative approach.	Lack of coordination between government levels (Crosweller et Tschakert, 2021 ; Feltmate *et al.*, 2020a ; Hegger *et al.*, 2016b ; Henstra et Thistlethwaite, 2017b ; Hutter, 2016). Inconsistency in political discourse on local autonomy without real power transfer (Bisaro *et al.*, 2020 ; Bubeck *et al.*, 2018 ; Penning-Rowsell *et al.*, 2014). Risk management relies on shared multilevel governance (Lalancette et Charles, 2022). A collaborative structure is beneficial (Ansell *et al.*, 2020).

Theme	Interviewee Position	Literature Position
Influence of Inherited Risk (Convergence)	Historical land-use planning decisions hinder the implementation of risk reduction measures. This existing reality and social pressure condition current choices. The financial incentive of a contribution seems less decisive in the face of these challenges.	Historical urbanization of floodplains (Andrews, 1993 ; Cosens et Gunderson, 2021 ; Sécurité Publique Canada, 2022) and cultural/emotional attachment to place (Reese *et al.*, 2019 ; Scannell et Gifford, 2010, 2017 ; von Wirth *et al.*, 2016) create an inherited risk that is difficult to manage and resistance to change.
Influence of Risk Perception (Divergence)	Fear that a contribution would be poorly received by an unaware public (especially given the time elapsed since 2019). Difficulty and low inclination among elected officials to undertake this educational/awareness work.	Risk perception is a key factor influencing action. Existence of the "cycle of forgetting" (perception decreases over time). Strong link between citizen perception and public action (Grothmann et Reusswig, 2006 ; Van der Linden, 2015). Erosion of collective memory. False sense of security linked to protective infrastructure (Hanger *et al.*, 2018).
Influence of Development Objectives (Convergence)	Mention the frequent tension between economic development objectives (tax revenues) and risk reduction imperatives. Skepticism that a financial contribution would be sufficient to change priorities in the face of these pressures and habits.	Confirms the existence of tensions between economic development and risk reduction (Fruehauf, 2024 ; Van der Molen, 2018 ; Wiering *et al.*, 2018). Status quo bias (preference for maintaining existing practices) can reinforce resistance to change and the prioritization of development (Mendoza Leal *et al.*, 2024).

The interviews and literature highlight four key factors shaping municipal action, or inaction, on flood risk reduction: the influence of current governance, inherited risk, risk perception, and development objectives.

5.4.1 Influence of Current Governance

Participants strongly emphasized the current governance model as a significant constraint. They perceive the legal framework as limiting their autonomy and absolute power over land-use planning, a key driver of vulnerability. This opinion aligns with literature identifying a lack of coherence and coordination between government levels (Crosweller et Tschakert, 2021 ; Hegger *et al.*, 2016b) and criticizing the political discourse promoting local autonomy without transferring corresponding powers (Bisaro *et al.*, 2020 ; Penning-Rowsell *et al.*, 2014). From this perspective, a financial contribution would be merely an additional constraint, not a governance solution. Participants' call for a more multidimensional and collaborative approach resonates with concepts of multilevel risk governance, where responsibilities are shared and decisions are adapted locally (Ansell *et al.*, 2020 ; Lalancette et Charles, 2022).

5.4.2 Influence of Inherited Risk

Historical land-use decisions and the resulting settlement patterns in floodplains create a significant "inherited risk" that participants find difficult to manage. This opinion is consistent with literature recognizing the challenges posed by historical urbanization in flood-prone areas (Andrews, 1993 ; Cosens et Gunderson, 2021 ; Sécurité Publique Canada, 2022) and the strong cultural and emotional place attachment of riverside communities, which can create resistance to change (Reese *et al.*, 2019 ; Scannell et Gifford, 2010 ; von Wirth *et al.*, 2016). Participants felt current decisions are heavily constrained by this existing reality and associated social pressures, making a purely financial incentive seem less impactful than these deeply rooted challenges. Nevertheless, this constraint is potentially less significant for municipalities with more recent development or those with substantial undeveloped territory remaining.

5.4.3 Influence of Risk Perception

A divergence appeared regarding risk perception. Participants feared adverse public reaction to a contribution, especially given the time elapsed since the last major floods (mostly 2019) and expressed reluctance towards the extensive public education effort required. This lack of acknowledgment contrasts with literature emphasizing risk perception as a key driver for action (Grothmann et Reusswig, 2006 ; Van der Linden, 2015) and highlighting the "cycle of forgetting" where risk perception fades over time (Fanta *et al.*, 2019 ; Oppenheimer *et al.*, 2014). The potential for a false sense of security from protective infrastructure further complicates perception (Hanger *et al.*, 2018). The participants' hesitation suggests a potential barrier in translating risk awareness into politically feasible action at the local level.

5.4.4 Influence of Development Objectives

Participants acknowledged the frequent tension between municipal economic development goals (e.g., property tax revenues) and flood risk reduction imperatives. Their skepticism about the power of a financial contribution to shift priorities aligns with literature confirming these tensions (Fruehauf, 2024 ; Wiering *et al.*, 2018) and recognizing the role of status quo bias in reinforcing resistance to change in favour of established development patterns (Mendoza Leal *et al.*, 2024). Participants implied that the proposed financial incentive might not be strong enough to overcome these ingrained pressures and habits.

5.5 Conclusion

This research explored whether implementing a direct financial contribution from municipalities to post-flood compensation programs, proportional to risk, could enhance their proactivity in risk reduction. However, the findings from interviews with key municipal actors in Québec reveal significant reluctance towards this proposal. Far from achieving consensus, the idea of an additional financial contribution raised substantial concerns regarding its actual incentive effectiveness, operational feasibility, and equity, often perceived as an extra burden rather than a relevant lever for change. Consequently, the perceptions of these local actors refute the central hypothesis—that such a contribution would effectively incentivize municipalities to prioritize flood risk reduction.

This outcome, however, does not diminish the fundamental and essential role municipalities play in flood risk management. Their proximity to citizens and detailed knowledge of their territory remain critical assets for adapting mitigation measures to local realities. Therefore, the core challenge highlighted by this study lies in identifying and implementing alternative mechanisms that effectively empower and encourage proactive municipal action, without overburdening them financially or ignoring the significant constraints (budgetary, regulatory, and governance-related) they face.

Several alternative pathways, suggested by participants, warrant further exploration to shift from a logic of potential sanction towards one of support and valuing effort. These include notably:

- Conditional and targeted financial incentives: Rather than a generalized contribution to indemnities, increased financial support from higher government levels, conditional on adopting best practices or achieving risk reduction performance indicators (similar to some FEMA programs), could be more mobilizing. Another avenue is linking priority access to specific grant programs to implementing defined measures.

- Non-financial incentives: Public recognition, valuing municipal efforts through certifications or awards, and using high standards as communication and attractiveness tools can be powerful drivers of engagement and encourage emulation among municipalities.

These potential alternatives resonate strongly with the action priorities formulated by the interview participants themselves. They emphasized the need to focus on other crucial dimensions: 1) enhanced public engagement and risk communication; 2) stricter, better-enforced land-use and building regulations; 3) strengthened collaboration among all stakeholders; 4) increased technical and financial support for municipalities, especially the most vulnerable; and 5) a consistent prioritization of long-term community and infrastructure resilience. Detailed recommendations based on participant input regarding these priorities are presented in Appendix G.

The primary contribution of this research lies in its rigorous evaluation of the perceived feasibility and acceptability of a specific financial sharing mechanism, the municipal risk-proportionate contribution, and in illuminating, through the unique perspectives of municipal actors, the complex reasons for its rejection. Refuting the initial hypothesis, this study paves the way for a more nuanced reflection on action levers. It highlights the priorities and alternatives favoured by the municipal sphere to strengthen prevention.

Acknowledging the study's limitations, such as the inability to finely analyze all contextual influences (e.g., budget pressures, local politics), future research combining qualitative and quantitative approaches across different regions or flood types is needed to further investigate the suggested alternatives' effectiveness. Key questions remain regarding the appropriate balance between individual and collective responsibility, effective risk communication strategies, equitable compensation mechanisms for vulnerable populations, and ensuring coherent and fair governance structures.

Addressing these questions is crucial for progressing towards more sustainable and equitable flood risk management in Québec. Facing the climate emergency and intensifying extreme weather events, swift and concerted action is essential. Despite the challenges, municipalities must be supported and equipped to remain central to the efforts to build more resilient communities against future floods.

CONCLUSION

L'objectif général de cette recherche est de mieux comprendre les capacités d'agir des municipalités en matière de réduction du risque d’inondations fluviales, afin de contribuer à l'orientation des politiques publiques vers une gestion plus responsable, équitable et efficace de ce risque au Québec. Pour ce faire, l'étude explore spécifiquement si l'instauration d'une participation financière des municipalités québécoises aux mécanismes d'indemnisation existants pourrait renforcer leur proactivité. Les principales conclusions révèlent une réticence marquée du monde municipal face à cette proposition de contribution financière directe. L'hypothèse initiale selon laquelle un tel mécanisme agirait comme un incitatif suffisant est ainsi infirmée par la perception des acteurs de terrain. Bien que les municipalités aient exprimé des préoccupations quant à l'efficacité, la faisabilité et l'équité de ce type de contribution, la recherche souligne néanmoins leur rôle fondamental et incontournable dans la gestion du risque d’inondations. Elle met en évidence la nécessité d'explorer des mécanismes alternatifs financiers conditionnels et non financiers pour les encourager à adopter des mesures proactives.

Ces constats généraux s'appuient sur une analyse approfondie des différents facteurs qui influencent l'action municipale. Dans le chapitre 2, l'examen des mécanismes de gouvernance a permis de mettre en évidence comment la dépendance à l'aide financière externe, le manque d'incitations financières propres et la dilution des responsabilités peuvent contribuer à un sous-investissement dans la réduction du risque. Ces éléments illustrent les défis liés au manque d'imputabilité des décideurs et aux potentiels conflits d'intérêt au sein d'une gouvernance multi-niveaux. Parallèlement, l'étude des facteurs contributifs aux dommages, réalisée au chapitre 3, a révélé que les municipalités exercent une influence significative sur plusieurs de ces facteurs clés, notamment via l'aménagement du territoire, l’entretien des réseaux d’évacuation des eaux pluviales, et l'application des normes de construction. L'exploration de nouveaux modèles de partage du risque financier, réalisée au chapitre 4, a ensuite permis de proposer une contribution municipale proportionnelle au risque, calculée sur la base des dommages annuels moyens, et de constater que des mesures ciblées pourraient significativement atténuer l'exposition ou les coûts économiques. Enfin, le chapitre 5 permet d'analyser les perspectives municipales face à cette proposition, et ce travail a confirmé le scepticisme ambiant, tout en soulignant les limites perçues du pouvoir d'action municipal et les contraintes liées à l'historique de l'aménagement du territoire et au cadre réglementaire. Ces facteurs alimentent la perception d'un aléa moral où les coûts ne sont pas entièrement internalisés. En parallèle, le système de taxation municipale, qui dépend largement des revenus générés par les constructions sur le territoire, incite à préserver le statu quo foncier. Or, ce modèle n'est ni viable ni durable à long terme face aux défis posés par les changements climatiques.

Face à ces résultats et au rejet de l'idée d'une contribution financière directe comme principal levier, l'enjeu central réside dans l'identification et la mise en œuvre de mécanismes alternatifs permettant de responsabiliser et d'encourager l'action municipale, sans accabler financièrement les municipalités ou ignorer leurs contraintes. Plusieurs pistes, évoquées tant dans la littérature que par les participants, méritent d'être explorées, notamment des incitatifs financiers conditionnels à l'adoption de bonnes pratiques ou à l'atteinte d'indicateurs de performance, ainsi que des incitatifs non financiers comme la reconnaissance publique ou la certification de résilience. Ces approches font écho aux priorités d'action formulées par les personnes interviewées qui insistent sur un engagement accru du public, une réglementation plus stricte, une collaboration renforcée entre les parties prenantes qui favorise la concertation, un soutien technique et financier accru aux municipalités, et une priorité constante accordée à la résilience.

Concrètement, ces priorités d'action suggérées par les acteurs municipaux se traduisent par des pistes tangibles. Un engagement accru du public pourrait se matérialiser par le développement de plateformes web interactives sur les risques et l'organisation de consultations publiques régulières. Une réglementation plus stricte impliquerait de rendre obligatoire l'intégration de l'évaluation des risques dans tous les documents de planification municipaux et d'actualiser les codes de construction pour imposer des normes de résilience plus élevées. La collaboration renforcée passerait notamment par un soutien au regroupement des municipalités par bassin versant pour des projets d'atténuation régionaux et par la création de plateformes de partage de connaissances et de bonnes pratiques. Quant au soutien technique et financier accru aux municipalités, il pourrait prendre la forme de mécanismes de compensation ciblés pour les plus exposées ou d'une aide conditionnée aux efforts de réduction du risque, par exemple en augmentant les indemnisations du programme d'aide financière en cas de catastrophe du Québec (PGAF) pour les municipalités proactives. Enfin, accorder une priorité constante à la résilience signifierait, entre autres, la mise en place d'un « certificat de résilience » pour les propriétés et l'offre d'incitatifs concrets pour l'amélioration de la protection des bâtiments existants.

Au-delà de ces pistes, d'autres solutions complémentaires peuvent être considérées pour renforcer la gestion du risque d'inondations. Ces solutions incluent l'adoption de principes de « construire mieux » en imposant des normes de construction plus résilientes pour les nouvelles constructions et les réparations après sinistre. Un encadrement plus strict de l'utilisation et de l'occupation des sous-sols dans les zones à risque, ou même leur interdiction dans certains cas, est également une voie à explorer pour réduire les dommages et la vulnérabilité. Par ailleurs, l'utilisation des espaces de liberté dans l'aménagement du territoire, tels que les zones naturelles tampons, les espaces d'expansion des crues ou les parcs inondables, offre des solutions fondées sur la nature qui peuvent réduire la pression sur les infrastructures existantes (Mayer-Jouanjean *et al.*, 2022). Enfin, l'instauration d'un Fonds dédié au financement des mesures d'atténuation du risque, alimenté potentiellement par diverses sources (publiques, privées, voire des contributions indirectes), serait utile pour assurer une capacité d'investissement constante et planifiée dans la réduction du risque d'inondations à long terme.

Originalité

L'originalité de cette thèse réside non seulement dans son évaluation empirique rigoureuse auprès des acteurs municipaux québécois mais aussi dans l'exploration spécifique d'une contribution financière des municipalités aux mécanismes de partage des indemnités. De telles contributions municipales constituent une piste de solution négligée alors que la recherche actuelle se concentre principalement sur la participation financière des gouvernements centraux et des assureurs. En donnant la parole aux municipalités, cette recherche offre une compréhension inédite des freins réels à un tel mécanisme et, surtout, met en lumière les conditions et les alternatives privilégiées par les intervenants sur le terrain.

Elle comble ainsi une lacune en examinant comment l'implication financière des municipalités pourrait favoriser des mécanismes d'indemnisation plus équitables et durables. Au-delà de simplement identifier les facteurs influençant la décision municipale (gouvernance, incitatifs, et perception du risque), la recherche propose et analyse un modèle de partage des coûts qui intègre les municipalités comme parties prenantes actives, en se distinguant des approches centrées uniquement sur les incitatifs pour les particuliers. Ce modèle, qui envisage une contribution municipale proportionnelle au risque généré sur leur territoire, s'écarte des dispositifs visant principalement le transfert du risque. Il cherche plutôt à responsabiliser davantage les acteurs locaux en les impliquant directement dans le partage des coûts, mettant ainsi en lumière les enjeux d'équité et de financement municipal qui ne sont pas toujours alignés avec les objectifs de réduction du risque. Ce faisant, l'étude explore une voie novatrice pour améliorer la gestion des risques et réduire la vulnérabilité des communautés face aux inondations.

Limites de l’étude et pistes de recherches futures

Il importe toutefois de souligner les limites de cette étude. Si l'approche qualitative a permis une exploration en profondeur des perceptions, elle ne saurait rendre compte de toute la diversité des enjeux spécifiques (politiques, sociaux, et budgétaires) et des dynamiques propres à chaque contexte municipal québécois. De plus, la recherche se concentre sur les inondations fluviales au Québec. Des recherches futures, combinant des approches qualitatives et quantitatives et explorant différentes régions ou types d'inondations, sont nécessaires pour approfondir l'efficacité des alternatives suggérées. Des outils d’estimation des dommages à l’échelle du bâtiment sont également nécessaires pour mieux apprécier la résilience existante et proposer des analyses coûts-avantages crédibles. Finalement, il sera pertinent de poursuivre cette réflexion en établissant des liens avec les programmes de gestion du risque d'inondations et d’indemnisation (notamment le PRAFI et le PGAF). Une attention particulière pourrait également être portée à l'intégration des enjeux patrimoniaux dans ces modèles de gouvernance.

Au-delà des défis liés au partage du coût des indemnités, il est nécessaire de rappeler que les impacts des inondations dépassent largement les seuls dommages matériels directs. La littérature scientifique met en évidence des conséquences sociales significatives, telles que les déplacements de population, le démantèlement du tissu sociale et l'exacerbation des inégalités (Chakraborty *et al.*, 2022). À cela s'ajoutent d'importants dommages psychosociaux qui affectent durablement les sinistrés (Généreux *et al.*, 2020 ; Maltais *et al.*, 2023). Prendre en compte cette pleine mesure des impacts financiers, sociaux et économiques est essentiel pour développer des politiques de gestion du risque véritablement holistiques et équitables. Cela ouvre la voie à des questions de recherche encore plus larges :

- Comment garantir une gouvernance cohérente qui tienne compte des besoins et des capacités de chaque acteur face à ces impacts diversifiés ?
- Quel est le juste équilibre entre la responsabilité individuelle et la responsabilité collective face à l'ensemble de ces conséquences ?
- Quelles sont les meilleures stratégies de communication pour sensibiliser efficacement les populations au caractère multidimensionnel du risque ?

- Quels sont les mécanismes d'indemnisation et de soutien les plus aptes à assurer un rétablissement rapide et équitable, au-delà des seuls biens matériels ?
- Quelles stratégies spécifiques de financement (au-delà de la contribution directe) peuvent être développées et testées pour permettre aux petites et moyennes municipalités d'investir durablement dans des mesures d'atténuation à long terme ?
- Comment s'assurer que les mécanismes de partage des coûts répartissent équitablement le fardeau financier entre l'ensemble des contribuables et les citoyens les plus exposés ?
- Comment les municipalités peuvent-elles quantifier et intégrer les coûts indirects et intangibles des inondations (ex: impacts sur la santé mentale, perte de productivité économique locale, et dégradation environnementale) dans leurs processus décisionnels et leurs budgets d'atténuation ?

Face à l'urgence climatique et à l'intensification des phénomènes météorologiques extrêmes, une action rapide, équitable et concertée est indispensable. Les municipalités, malgré les défis, doivent être soutenues et outillées pour demeurer au cœur des efforts visant à bâtir des communautés plus résilientes face aux inondations futures au Québec.

ANNEXE A
CHAPTER 2 - DEFINITIONS USED IN THE PAPER

Centralization: the concentration of a government's coercive powers (De Vries, 2000).

Decentralization: transferring authorities and administrative responsibilities over public functions or policies from the national level to the local level (De Vries, 2000).

Exposure: the value of assets located in flood plains, including goods, infrastructure, cultural heritage, agricultural fields, and people (Balica *et al.*, 2012).

Flood hazard: the likelihood of loss of life, injury, or damage to physical assets resulting from flooding (Red Dragon Consulting, 2021a).

Flood risk management (FRM): a holistic and continuous societal management analysis, assessment, and reduction of flood risk (Schanze *et al.*, 2006).

Governance: the collective processes, both formal and informal, that determine how decisions are made, and social norms and institutions are elaborated (Hufty, 2011).

Governmental post-disaster financial assistance (GPDFA): financial assistance provided by federal and provincial governments to municipalities (as well as to individuals and businesses) to help finance recovery expenses that are usually not recoverable from other sources, namely private insurance (Henstra et Thistlethwaite, 2017a).

Overland flood insurance: insurance that covers damage from freshwater sources. Overland flooding usually occurs when bodies of fresh water, such as rivers and other watercourses, overflow onto dry land and cause damage. It can also happen when there is an intense rain storm and water accumulates rapidly, exceeding the ability of local stormwater drainage systems to divert it. Any claims related to coastal flooding, tsunamis, dam breaks and other saltwater sources are usually excluded (Insurance Bureau of Canada, 2019).

Policy instruments: legislative, financial, and social persuasion tools or mechanisms to steer target groups' behaviour and actions toward the desired direction (Glaus *et al.*, 2021).

Recovery programs: measures to restore economic, social, and ecological conditions and support the reconstruction and repair of damaged properties (United Nations Development Programme, 2023).

Residual risk: the amount of risk that remains after all efforts have been made to identify and eliminate or mitigate the risk (Slabotsky, 2017).

Risk identification: all actions taken to (1) evaluate the likelihood and the consequences of flooding, (2) share the knowledge among the actors, and (3) ensure the participation of all stakeholders (Red Dragon Consulting, 2021a).

Risk management strategies: prevention and mitigation of damage through (1) reducing the number of exposed people and assets by land-use planning and property buy-out programs, (2) building codes and standards, and (3) flood defence measures (Feltmate et Moudrak, 2021).

Sendai Framework for Disaster Risk Reduction 2015-2030: a global blueprint to prevent new and reduce existing disaster risks, outlining four priorities for action: (1) understanding disaster risk, (2) strengthening governance to manage disaster risk, (3) investing in disaster risk reduction for resilience, and (4) enhancing disaster preparedness for effective response and to "Build Back Better" in recovery, rehabilitation and reconstruction (United Nations Office for Disaster Risk Reduction, 2015b).

Vulnerability: the susceptibility of a given population, system or place to be harmed by a hazard (Balica *et al.*, 2012).

ANNEXE B
CHAPTER 2 - KEY LEGISLATIVE ACTS GOVERNING FLOOD RISK MANAGEMENT

	British Columbia	Québec
Municipalities	Local Government Act and Community Charter	Cities and Towns Act and Municipal Code of Québec)
	Municipalities Enabling and Validating Act	Municipal Powers Act
	Land Title Act and Land Act (1996)	Act respecting land use planning and development
Provinces	Emergency Program Act	Civil Protection Act
	Emergency Management Program Regulation	An act to establish a new development regime for the flood zones of lakes and watercourses, to temporarily grant municipalities powers enabling them to respond to certain needs and to amend various provisions, SQ 2021, c 7
	Environmental Management Act	Environment Quality Act
	Water Sustainability Act	Act to affirm the collective nature of water resources and to promote better governance of water and associated environments
	Flood Hazard Statutes Amendment Act	Watercourses Act
	Dike Maintenance Act	Dam Safety Act
	Drainage, Ditch and Dike Act	Protection Policy for Lakeshores, Riverbanks, Littoral Zones and Floodplains
Federal	Miscellaneous Statutes Amendment Act (No. 2)	
	First Nations Land Management Act	
	Emergency Management Act	
	Canada Land Surveys Act	
	Canada Water Act	

Sources: *Environmental protection and sustainability - Water Laws & Rules* (British Columbia Government, 2022); Ebbwater Consulting Inc. (2021); and *Tableau 4.2 – Lois, règlements et politiques* (Thivierge, 2021).

ANNEXE C
CHAPTER 2 - INDIVIDUAL FLOOD INSURANCE

According to national surveys conducted in 2019 and 2020 by the Insurance Bureau of Canada (IBC), overland flood insurance is available to about 90 percent of British Columbia and Québec residents, leaving 10 percent of the population ineligible because the risk of flooding is considered too high. However, flood risk management experts believe that the percentage of uninsurable properties is actually much higher. Historically, real estate development in both provinces clustered along streams and rivers. Each flood reduces the appetite of insurers for insuring properties that have been flooded. This is the case with farmers in the Abbotsford area of British Columbia following the November 2021 flood.

Overland flooding insurance for individual properties did not exist in Canada before 2015 and was introduced only in 2016 in British Columbia (and in Québec one year later) due to the federal pressures on the insurance industry. According to IBC, 42 percent of British Columbian residents are insured to the full value of the property, while residents in higher-risk areas can purchase lower amounts of coverage through optional endorsements.

Past floods have consequences for the future as well. Not only do certain properties become uninsurable, but because of the lack of insurance, using these properties as collateral to borrow money is virtually impossible, since insurance coverage is a requirement of financial institutions. In Québec, overland flood insurance for individual properties is available only through optional endorsements ranging from $10,000 to $50,000. Coverage is not available for any property located in zones subject to 20-year flood recurrence. In British Columbia, 15 insurance companies offer overland flood insurance, at significant cost differences (Red Dragon Consulting, 2021a) and 10 offer it in Québec.[30] The sub-limit restrictions in Québec explain why Québec government post-disaster financial assistance (GPDFA) overlaps insurance coverage, while insurance and GPDFA are mutually exclusive in British Columbia.

A 2016 survey involving 1,500 individuals, conducted by Vancouver-based insurance broker Square One, showed that 61 percent of British Columbians and 69 percent of Quebecers still mistakenly believe that flood protection is included in home insurance policies (Square One, 2016).

[30] Data provided by IBC Québec on December 16, 2021.

Six years after the introduction of overland insurance for individual properties, the flood insurance market penetration remains below 50 percent and coverage is not widely available in high-risk areas (Golnaraghi *et al.*, 2020). The low take-up rate of individual property flood insurance can be explained by (1) the continued availability of post-disaster financial assistance which reduces incentives for property owners to purchase coverage, (2) the need for better public education about overland flood insurance (Red Dragon Consulting, 2021b), (3) low risk perception of flooding and uncertainty about the benefits of flood insurance (Thistlethwaite et al. 2020: 265), (4) high costs when insurance is available (Ebbwater Consulting Inc, 2021), (5) the fact that most individuals are unaware that they should purchase flood insurance when it is available and that they would not be eligible for disaster assistance, and (6) uncertainty regarding the availability and the extent of flood insurance coverage, since each province has a different regulatory framework .

According to a recent study conducted by the insurance broker Aon, approximately 36 percent of natural disasters and 12 percent of flood disasters are insured worldwide (AON, 2021). Although overland flood insurance has met some of the requirements for economic viability in low-risk areas, high-risk areas remain underinsured, limiting most of the major benefits of using insurance to better manage the consequences of flood risks (Thistlethwaite, 2021).

ANNEXE D
CHAPTER 3 - EXPERT RANKING OF CONTRIBUTING FACTORS

Factors contributing to flood damage	Survey grouping	Mention rate (45 experts)	Ranking weighted method (35 experts)	Average method rank (35 experts)
Distance of building from a watercourse or ground elevation (land-use planning)	E36	31%	1	1
Flow, current and speed of rising water	E37	7%	2	2
Response time for mitigation work	C21	36%	3	3
Basement converted into living space	D32	40%	4	7
Obligation to comply with new building codes	D31	31%	5	5
Event duration	B10	49%	6	4
Design of sewer and water supply systems	A2	44%	7	14
Landscaping (topography, mineralization)	A1	49%	8	9
Readiness and competence of the municipality	C20	11%	9	8
Type of compensation program and settlement terms (public and private)	D29	13%	10	19
Inundation depth (height of water inside a building)	B11	n/a	11	10
Presence of contaminants	D33	13%	12	20
Site Access	D28	78%	13	12
Presence of private protective equipment	C25	64%	14	13
Time of year (season)	A5	33%	15	11
Quality of front-line intervention	E38	22%	16	6
Level of sewer and water system maintenance	A6	31%	17	21
Depth of the water table	C22	20%	18	22
Availability of claims adjusters	A4	24%	19	15
Presence of protective infrastructure	D34	13%	20	16
Quantity of debris generated from flood repairs (impact on repair costs)	E40	13%	21	23

Factors contributing to flood damage	**Survey grouping**	**Mention rate (45 experts)**	**Ranking weighted method (35 experts)**	**Average method rank (35 experts)**
Ice jams	B16	13%	22	17
Building structure and quality	E39	100%	23	18
Relocation and living expenses	D29	16%	24	30
Soil type (sandy, silty, clayey)	A7	47%	25	32
Claimant's previous experience	B17	31%	26	26
The extent (number of buildings) of damage	C24	18%	27	29
Water turbidity	C23	58%	28	27
First-floor height	B12	31%	29	25
Foundation type and anchoring	B18	29%	30	28
Level of general building maintenance	A8	33%	31	31
Area not served by municipal infrastructure	B14	27%	32	33
Year of construction	B09	49%	33	24
Type of occupation and content	B19	60%	34	36
Occupant status	C27	4%	35	34
Soil mineralization (urbanization, density)	D35	22%	36	37
Risk of riparian zone contamination	A3	9%	37	40
The role of public adjusters vs. insurers	B13	9%	38	38
System localization	C26	36%	39	35
Municipal by-laws	B15	29%	40	39

Note: The number of mentions of the contributing factor "Inundation depth" was not computed = (n/a)

Legend - Table columns

The Survey grouping column indicates which of the five categories each factor belongs to (see Legend-Categories). The number within this column represents the factor's original position in the Lime Survey questionnaire.

The Mention rate column refers to the frequency of experts mentioning this factor during consultations.

The Weighted Method Rank column indicates the hierarchy accorded to each factor by the experts.

Legend - Categories

Factors (1 to 8) = Drainage capacity (D)
Factors (9 to 19) = Building resilience (B)
Factors (20 to 27) = Intervention (C)
Factors (28 to 35) = Reconstruction and repair (D)
Factors (36 to 40) = Flood characteristics (E)

ANNEXE E
CHAPTER 3 - INTEGRATING THE TOP 10 FACTORS INTO DAMAGE ESTIMATES

While further research and data collection are needed to develop specific techniques, incorporating these factors into damage estimation tools can yield more accurate loss estimation and reduce uncertainty at the building level. These factors can be incorporated into damage estimations as coefficients, categorical variables, or additional parameters in the models, namely.

1. The distance from the watercourse/ground elevation factor could be incorporated by developing separate damage curves for different elevation zones or by including it as a continuous variable in a regression model.
2. The flow, current, and speed of rising water could be integrated by incorporating velocity as an additional parameter in the damage curve, with higher velocities leading to increased damage estimations, particularly at lower depths.
3. The response time for mitigation work could be included as a time-dependent variable, where longer response times lead to higher damage estimates. It could also be linked to factors like accessibility and contamination levels.
4. The basement converted into living space could be integrated as a categorical variable, with different damage curves or coefficients for finished and unfinished basements. Doyon and Jean [28] already incorporate the type of basement into their damage curves.
5. The obligation to upgrade to new building codes could be reflected by adjusting the damage estimates for older buildings to account for the potential costs of upgrading to current code requirements.
6. The event duration could be incorporated using a temporal extent, where longer durations result in higher damage estimations, reflecting the increased exposure to water and potential contaminants.
7. The design and state of sewer and water supply system maintenance could be integrated by incorporating different damage functions or coefficients for areas with varying levels of drainage capacity or maintenance standards.
8. The landscaping could be included by categorizing properties based on landscaping features that either direct water away from the building, potentially exacerbating flood damage, or by the percentage of land mineralization.

9. The readiness and competence of the municipality could be reflected by adjusting damage estimates based on the level of preparedness and the effectiveness of emergency response in different municipalities.
10. The type of compensation program and settlement terms could be integrated by incorporating the potential impact of compensation delays on homeowners' actual damage.

Coefficient application

This section illustrates how incorporating specific coefficients can enhance the accuracy of flood damage estimations derived from damage curves. Two examples are explored.

The soil type coefficient accounts for the influence of different soil types on building vulnerability, recognizing that certain soils (like clay) may increase the risk of damage compared to others (like sand). Since both soil type and year of construction function similarly in adjusting the damage rate, it was deemed sufficient to provide an example for one factor. This approach avoids redundancy while effectively conveying the methodology for applying coefficients to refine damage estimations.

The building value coefficient addresses the limitations of using municipal assessment values, which may not reflect the actual replacement cost of a building. By incorporating a building value coefficient, we can adjust damage estimations to reflect better the true actual value of the structure and its contents.

Coefficients can be applied to the damage rate (Txe) obtained from a damage curve at a given inundation depth (H). The adjusted damage rate (MTxe) is calculated as follows:

$$MTxe(H)=(C_1 \times C_2 \times \ldots \times C_i) \times Txe(H) \tag{1}$$

Where

- MTxe represents the adjusted expected damage rate, incorporating the influence of various factors.
- C_1, C_2, …, C_i are damage rate coefficients for specific factors.
- C_i > 100 % indicates an aggravating factor.
- C_i < 100 % indicates a beneficial factor.
- C_i = 100 % indicates a neutral factor.

Txe(H) represents the expected average damage rate obtained from existing damage curves at a given inundation depth (H). This average is calculated from a group of individual damage rates, each associated with a specific building impacted by the flood.

The above formula allows for integrating multiple factors that can influence the extent of damage, providing a more nuanced and accurate estimation of flood damage at the building level compared to traditional models that rely solely on inundation depth.

Soil type illustration

The experts assigned a damage rate coefficient (C1) of 120 % to clay soil, meaning that clay soil will likely cause 20 % more damage than sandy soil. For example, consider two identical buildings (One and Two) exposed to the same inundation depth. Building One is built on sandy soil while Building Two is on clay soil. Let us assume that from a given flood damage curve, the average damage rate Txe (H) at that inundation depth is 10 % for this group of two buildings. The average damage rate of 10 % is derived from two data points (Building One and Building Two). In this example, 50 % of the buildings are in sandy soil and 50 % in clay soil. Let Alpha be the proportion of sandy soil and (1-Alpha) the proportion of clay soil. The adjusted damage rate (MTxe) for building One located in sandy soil becomes:

$$10\% = Alpha * Txe(H) + (1- Alpha) * C1 * Txe(H) \tag{2}$$

Where

- $0.10=0.5 * Txe(H) + 0.5 * 1.2 * Txe(H)$
- MTxe(H) of Building One = 0.1 / 1.1
- MTxe(H) of Building One (sandy soil)=9.09% where the clay soil damage rate becomes:

$$MTxe(H) \text{ of Building Two} = C1 * MTxe(H) \text{ of Building One} \tag{3}$$

Where

- MTxe(H) of Building Two = 1.2 * 9.09%
- MTxe(H) of Building Two (clay soil)=10.91%

This example illustrates how the coefficient accounts for the relative influence of different soil types on building vulnerability. Furthermore, these coefficients help to explain the dispersion of individual building damage data points along the flood damage curves. By incorporating the influence of soil type, the adjusted damage estimates better reflect the observed variability in actual flood damage.

Building value illustration

The damage rate (Txe) represents the relationship between the estimated damage and the building's value. For example, Doyon and Jean [28] use municipal assessment value as the denominator of damage curves. The damage rate (Txe) is calculated as follows.

$$Txe = MAS^{\underline{PI}} \tag{4}$$

Where

- P.I. (Paid Indemnities): P.I. represents the aggregate financial assistance paid by the provincial government to flood victims to support the recovery of their buildings, including the structure, contents, and landscaping.
- MAS (Municipal Assessment Role): MAS is the assessed property value determined by the municipality for taxation purposes.

In this illustration, the expert assigned the building a median coefficient of 150 %. Consider a single-family home with the following characteristics.

- Municipal assessment value: $250,000 (Value not reflecting the current market value).
- Actual replacement cost: $375,000 (Cost of rebuilding the house at current market prices, including materials and labour).
- Estimated flood damage (in dollars): $40,000 (This is the estimated repair cost, determined by a professional assessment).

Scenario 1: Using municipal assessment value.

Damage Rate = (Damage in Dollars/Municipal Assessment Value) * 100 % (5)

Where

- Damage Rate = ($40,000/$250,000) * 100 % = 16 %

Scenario 2: Using actual replacement cost

Damage Rate = (Damage in Dollars/Actual Replacement Cost) * 100 % (6)

Where

- Damage Rate = ($40,000/$375,000) * 100 % = 10.7 %

Using the municipal assessment value results in a significantly higher damage rate (16 %) than the replacement cost (10.7 %). This difference highlights how the choice of building value in the denominator can drastically alter the perceived severity of the damage. When using the municipal assessment value, the damage appears more extensive relative to the building's worth, leading to an overestimation of the impact of the flood event and potentially skew risk assessments.

Using municipal assessment values to estimate building value can be problematic for several reasons. First, these values may not accurately reflect the replacement cost. Municipal assessments can be outdated, often lagging years behind current market conditions. Secondly, damage estimations are calculated at the time of loss, while outdated municipal assessments may not accurately capture the actual value of the building and its contents. Furthermore, it is also crucial to remember that municipal assessments typically focus only on the building structure itself, not its contents. This omission poses a significant challenge for accurate damage estimation, as the numerator in the damage rate calculation often includes losses to both the building structure and personal belongings.

This example demonstrates the importance of accurate and up-to-date building values when calculating damage rates. Using the actual replacement cost provides a more reliable picture of the financial impact, ensuring that both damage and building values are based on current market conditions. Construction costs and material prices fluctuate significantly, and outdated assessments may not capture these changes. Adjusting the municipal assessment role with a coefficient ultimately allows for a more precise understanding of the actual economic impact of flood events.

ANNEXE F
CHAPTER 5 - MUNICIPALITY PROFILE AND STATISTICAL ANALYSIS

Participating local municipalities

City / Municipality	Respondents	Permanent population 2024	Main rivers
Grand Forks	1 officer	4295	Rivières Granby et Kettle
Municipalité de La Visitation-de-l'Île-Dupas	1 elected	710	Archipel du lac St-Pierre (fleuve St-Laurent)
Municipalité de OKA	1 elected, 1 officer	6 059	Rivière des Outaouais et lac des Deux-Montagnes
Municipalité de Rivière-Beaudette	1 elected	2 651	Rivière Beaudette et le fleuve St-Laurent
Municipalité de Rivière-Ouelle	1 elected	1 017	Rivière Ouelle et le fleuve St-Laurent
Municipalité de Saint-Alphonse-de-Rodriguez	1 elected	3 487	Rivière l'Assomption et les lacs Pierre et Joly et Long
Municipalité de Saint-Ignace-de-Loyola	1 elected	2 122	Archipel du lac St-Pierre (fleuve St-Laurent)
Municipalité de St-Roch-de-l'Achigan	1 elected	5 631	Rivière de l'Achigan
Municipalité des Îles de la Madelaine	1 elected	12 428	Golfe du St-Laurent
St-Jean sur Richelieu	1 elected	99 494	Rivière Richelieu
Ville d'Amos	1 elected	12 757	Rivière Harricana
Ville de Contrecœur	1 elected, 1 officer	10 194	Fleuve St-Laurent
Ville de Deux-Montagnes	1 elected	18 347	Rivière des Mille Iles et lac des Deux-Montagnes
Ville de Fossambault-sur-le-Lac	1 elected	2 421	Rivière Jacques-Cartier et le lac St-Joseph
Ville de Papineauville	1 elected	2 257	Rivière des Outaouais
Ville de Portneuf	1 elected	3 461	Rivière Portneuf et le fleuve St-Laurent
Ville de Rigaud	1 elected	7 951	Rivière des Outaouais et rivière Rigaud
Ville de Shawinigan	1 elected	51 149	Rivière Saint-Maurice
Ville de Trois-Pistoles	1 elected	3 139	Rivière Trois-Pistoles et le fleuve St-Laurent
Ville de Trois-Rivières	2 officers	144 472	Rivière Saint-Maurice et le fleuve St-Laurent

Sources : Décret population Gouvernement Québec, Le bilan démographique du Québec 2024, Sommaires des rôles d'évaluation 2024, Recensement StatCan 2021, https://catalogue.data.gov.bc.ca/datasets

A statistical analysis was conducted to evaluate if there's a significant relationship between participants' positions regarding the contributions ("Pour, mitigé, contre" - a categorical variable) and characteristics of the participants or their municipalities.

The choice of statistical test (Chi-Square or ANOVA) was determined by the nature of the variables being compared. The Chi-Square test is used when examining the association between two categorical variables. It determines if the distributions of observed frequencies are significantly different from those expected if the variables were independent. ANOVA (Analysis of Variance) is used when comparing the means of a numerical (quantitative) variable across different groups defined by a categorical variable. It determines if the group means are statistically different. More details on statistical tests conducted on categorical variables can be found in (Agresti, 2013).

We examined whether the participants' positions regarding the contributions ("Pour, mitigé, contre ") is related to any of the following variables: Code Profession; Type (Mun, Ville, MRC); Population permanente 2024; Croissance population; Pourcentage d'utilisation du sol (résidentiel); Nombre d'unités d'évaluation permanente; Nombre de logements; Pourcentage de locataire vs propriétaire. Based on the statistical tests performed, none of the examined variables show a statistically significant relationship with participants' positions regarding the contributions ("Pour, mitigé, contre "). This suggests that the factors included in this analysis are not predictors of participants' stances on this topic, or that the dataset is too small to detect such associations.

Table 5.3 summarizes the results of the analysis between participants' positions (categorical variable) and various numerical or categorical characteristics of participants and their municipalities. For each variable tested, the table presents the statistical test used (Chi-square for categorical variables, ANOVA for numerical variables), the test statistic and the associated p-value, allowing for the assessment of the statistical significance of each relationship.

Other participating stakeholders

Organization	Categorie	Respondents
Capital Regional District, British Columbia	Capital Regional District	3 officers
Communauté Métropolitaine de Montréal (CMM)	Metropolitan Community	1 officer
Dentons, cabinet d'avocats	Law firm	1 lawyer
Ministère des affaires municipales et de l'habitation (MAMH)	Government of Quebec	1 officer
MRC de Vaudreuil-Soulanges	Regional county municipality	2 officers
MRC du Haut-Richelieu	Regional county municipality	2 officers
Université de Montréal	University	1 academic
Université du Québec à Montréal (UQAM)	University	1 academic

Statistical analysis

Variable	Test	Statistic	P-value	Detailed Conclusion
Code Profession	Chi-Square	9.1506	0.1653	The Chi-Square test analyzed the association between the position on funds and 'Code Profession' (a categorical variable). With a P-value of 0.1653 (> 0.05), there is no statistically significant relationship indicating that participants' professions are associated with their stance on the funds.
Type (Mun, Ville, MRC)	Chi-Square	10.8287	0.3710	The Chi-Square test examined the association between the position on funds and 'Type (Mun, Ville, MRC)' (a categorical variable). The P-value of 0.3710 (> 0.05) indicates no statistically significant relationship. The type of municipality (Municipality, City, MRC) does not appear to be associated with the position on the funds.
Population permanente 2024	ANOVA	1.5452	0.2389	ANOVA compared 'Population permanente 2024' (numerical) to the position on funds. The P-value of 0.2389 (> 0.05) means there is no statistically significant relationship. The population size in 2024 does not appear to significantly influence participants' positions regarding the funds.
Croissance population	ANOVA	0.2262	0.7997	ANOVA assessed the relationship between 'Croissance population' (numerical) and the position on funds. With a P-value of 0.7997 (> 0.05), there is no statistically significant relationship. Population growth does not appear to be linked to participants' positions.
Pourcentage d'utilisation du sol (résidentiel)	ANOVA	1.4535	0.2586	ANOVA compared 'Pourcentage d'utilisation du sol (résidentiel)' (numerical) to the position on funds. The P-value of 0.2586 (> 0.05) indicates no statistically significant relationship. The percentage of residential land use does not appear to influence the position on the funds.
Nombre d'unités d'évaluation permanente	ANOVA	1.8808	0.1798	ANOVA analyzed the relationship between 'Nombre d'unités d'évaluation permanente' (numerical) and the position on funds. With a P-value of 0.1798 (> 0.05), there is no statistically significant relationship. The number of permanent assessment units does not appear to be linked to participants' positions.
Nombre de logements	ANOVA	1.7587	0.1992	ANOVA compared 'Nombre de logements' (numerical) to the position on funds. The P-value of 0.1992 (> 0.05) indicates no statistically significant relationship. The number of housing units does not appear to influence the position on the funds.
Pourcentage de locataire vs propriétaire	ANOVA	0.2038	0.8174	ANOVA evaluated the relationship between 'Pourcentage de locataire vs propriétaire' (numerical) and the position on funds. With a P-value of 0.8174 (> 0.05), there is no statistically significant relationship. The percentage of tenants versus owners does not appear to be linked to participants' positions.

ANNEXE G
CHAPTER 5 - RECOMMENDATIONS FOR DECISION-MAKERS

Faced with the skepticism expressed regarding the effectiveness and feasibility of a direct financial contribution as the main incentive, the interviewees emphasized other dimensions deemed more fundamental or better suited to the municipal context for improving flood risk management. These recommendations, stemming from the concerns and suggestions of the interviewees, have been grouped under five principal axes: increased public engagement; stricter regulation; closer collaboration among stakeholders (concerted action); enhanced support for municipalities; and a priority on resilience. The government of Quebec defines resilience as the ability of a community exposed to floods to adapt, by resisting or transforming, to establish and maintain an acceptable level of functioning (Gouvernement du Québec, 2024a).

Recommendation 1. Raise Awareness, Involve, and Communicate

Effective flood risk management relies on awareness, active community involvement, and transparent communication. Raising public awareness of risks, informing them about protection measures, and involving them in decision-making promotes social acceptability, encourages responsible behaviours, and strengthens collective resilience.

Objective: Increase citizen responsibility

Actions	Responsible Actors	Resources Required
Develop user-friendly web and mobile platforms with interactive maps, risk information, protection measures, real-time alerts, and a discussion forum.	Government of Quebec, in collaboration with municipalities and experts in communication and technology.	Budget for platform development and maintenance, expertise in communication and technology.
Organize workshops and public consultations to raise public awareness. Distribute practical guides on flood preparedness.	Municipalities, emergency services, community organizations, and watershed organizations (OBV).	Staff will lead workshops, provide training materials, and emergency kits.
Create advisory committees composed of citizens, experts, and municipal representatives for decision-making.	Municipalities, MRCs, and OBVs.	Time and commitment from participants, as well as administrative support, are essential.

Support local risk reduction initiatives through funding, mentorship, and promotion of their actions.	Municipalities, community organizations.	Dedicated funds, support staff.
Implement effective alert systems using various communication channels (SMS, sirens, social media, radio).	Municipalities and emergency services, in collaboration with communication technology providers.	Technological infrastructure, budget for maintenance and regular testing.

Recommendation 2. Strengthen Regulation and Risk Assessment

Stricter regulation and holistic risk assessments are essential for proactive and effective flood risk management. Current building codes and regulations may be insufficient to ensure building resilience. Furthermore, the difficulty in enforcing specific regulations when issuing notices of violation limits municipalities' ability to act on risk. Finally, the absence of comprehensive risk assessments can lead to inconsistent land-use planning decisions and increase community vulnerability.

Objective: Reduce community vulnerability.

Actions	**Responsible Actors**	**Resources Required**
Establish a regulatory framework requiring municipalities to conduct comprehensive risk mapping, including riverine, pluvial, ice-jam floods, soil movements, earthquakes, and forest fires.	Government of Quebec.	Provincial funding, expertise in hydrogeology and natural risks.
Make it mandatory to integrate risk assessment into all municipal planning documents (master plans, land-use plans, water master plans, etc.).	Government of Quebec.	Training for urban planners and land-use planners, methodological guides.
Update building codes to impose stricter standards for flood resilience (e.g., building elevation, water-resistant materials, basement restrictions).	Government of Quebec.	Consultation with construction and architecture experts, impact studies.
Require real estate developers to integrate flood resilience measures into their projects.	Government of Quebec.	Control and inspection mechanisms, financial incentives.
Create a provincial registry of properties not complying with building standards in flood zones.	Government of Quebec.	IT system, staff for registry management.

Recommendation 3. Promote Collaboration and Resource Pooling

Flood risk management is a complex challenge that requires a collaborative approach and resource pooling. Collaboration among different actors (municipalities, government agencies, private sector, scientific community, insurers, etc.) promotes knowledge sharing, innovation, adoption of best practices, and optimization of financial resources.

Objective: Optimize resource utilization.

Actions	Responsible Actors	Resources Required
Encourage and financially support the grouping of municipalities by watershed for the implementation of regional mitigation projects.	Government of Quebec and watershed organizations (OBV).	Grants, financial incentives, and a project office.
Provide municipalities with modelling tools, mapping data, and financial support for hiring specialized staff.	Government of Quebec.	Online platforms, experts in hydrogeology and risk management, and training programs.
Organize workshops and conferences and create online platforms to facilitate knowledge and best practice sharing.	Government of Quebec, municipalities, universities, and research organizations.	Funding for event organization and development of online platforms.
Financially support collaborative research projects between universities, municipalities, and the private sector.	Government of Quebec, granting agencies, and foundations.	Research funds, scholarships.
Offer training programs on flood risk management to civil servants and municipal staff.	Government of Quebec, educational and training institutions.	Development of training programs and qualified trainers.
Encourage insurers to be more active in assessing and reducing flood risk.	Government of Quebec, insurance industry.	Incentive-based regulatory framework, working groups.
Facilitate the implementation of the national flood insurance program. Facilitate the federal role in assisting municipalities.	Government of Quebec, in collaboration with the federal government.	Expertise in insurance, funding from the federal government.

Recommendation 4. Support the Most Exposed Municipalities

Municipalities most exposed to flood risk, often those with low financial capacity, may face difficulties implementing effective mitigation measures. Providing financial and technical support promotes equity, reduces inequalities, and improves community resilience. Adequate support allows these municipalities to understand risks better, develop adapted mitigation plans, and implement appropriate prevention measures.

Objective: Reduce inequity.

Actions	Responsible Actors	Resources Required
Implement financial compensation mechanisms (low-interest loans, grants, direct aid) for the most exposed municipalities.	Government of Quebec.	Dedicated fund, expertise in municipal finance.
Increase investments in improving stormwater management infrastructure in vulnerable municipalities.	Government of Quebec, Federal Government (DMAF), and municipalities.	Funding, engineering expertise.
Formalize and financially support relocation or buyout programs for properties in high-risk areas.	Government of Quebec, municipalities.	Dedicated funds, expertise in real estate appraisal.
Provide targeted assistance to low-income households to help them adapt their homes and mitigate flood impacts.	Government of Quebec, municipalities, and community organizations.	Financial assistance programs and social support.
Increase the PGAF (Programme général d'indemnisation et d'aide financière) compensation cap for proactive municipalities in risk management and condition access to aid programs on risk reduction efforts.	Government of Quebec.	Reform of the financial assistance program and system for evaluating municipal efforts.

Recommendation 5. Prioritize Resilience and Risk Mitigation

Rather than simply compensating victims after a disaster, focusing on resilience and risk mitigation is necessary. Focusing on resilience involves reducing the vulnerability of the existing built environment, integrating risk management into land-use planning decisions, and promoting resilient construction practices. The goal is to create safer, more resilient communities that are better prepared for the challenges of climate change.

Objective: Reduce the consequences of floods

Actions	Responsible Actors	Resources Required
Implement a "resilience certificate" for residential properties, attesting to their level of protection against floods. This certificate could be mandatory during property sales or significant renovations.	MRCs, in collaboration with the Government of Quebec.	Regulatory framework, inspection system, database.
Offer grants, loans, tax deductions, partial tax holidays, and technical assistance to property owners for improving building resilience (elevation, flood-proofing, backwater valves, flood barriers).	MRCs, municipalities, in collaboration with the Government of Quebec and the federal government.	Grant programs, dedicated funds, and construction experts.
Delineate low-risk flood zones and offer incentives to attract investments there. Implement deterrent measures to limit construction in high-risk zones.	MRCs, municipalities.	Revision of urban planning schemes, fiscal tools, and regulations.
Offer attractive voluntary relocation programs for owners of buildings located in high-risk zones.	MRCs, municipalities, in collaboration with the Government of Quebec.	Funding and support for finding new housing.
Invest in restoring wetlands, riparian zones, and floodplains to improve natural water absorption.	MRCs, municipalities, and conservation organizations.	Funding and expertise in ecology and environmental restoration.
Improve drainage and stormwater management systems.	MRCs, municipalities.	Funding, engineering expertise.

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