Profitability of flood-related relocation with probabilistic cost-benefit analyses

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Abstract

Many regions are becoming subject to successive flooding and with climate change taking its toll, it is no surprise that we observe a growing interest for risk avoidance strategies such as relocation. Cost-benefit analysis is the dominant tool used by decision makers to assess flood risk avoidance projects and yet, few guidelines are available about how such an analysis should be implemented. This paper advocates for a probabilistic cost-benefit analysis and details a step-by-step procedure via a real-world example. The results show that relocation can be a cost-effective strategy for many high-risk properties and neighborhoods. The level of indemnities and the inclusion of intangible losses are two key drivers of profitability. Among other things, the analysis contrasts three distinct designs of relocation programs. The results reveal that proactive and innovative schemes, such as managed retreat and usufruct arrangements, constitute worthwhile alternatives to a more conventional post-flood design.

Keywords: flood risk management, financial modeling, cost benefit analysis, flood insurance and relocation, flood buyout programs

JEL Classification: D81, G22, H43, H84, Q54.

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“Increasingly, there is agreement that retreat from some areas will become an unavoidable option under intensifying climate change”

(Mach et al., 2019, p.5)

1. Introduction

Flooding is the most common and costly type of natural disasters worldwide. The Organization for Economic Cooperation and Development assesses that floods cause for more than $40 billion in direct damage annually (OECD, 2016). North America makes no exception: a significant proportion of U.S. and Canadian households are at risk of flooding and that proportion is expected to grow due to climate change and further developments in floodplains. Indeed, Wing et al. (2018) estimate that nearly 41 million people – approximatively 12% of the population – live in a 100-year floodplain in the United States. The situation is similar in Canada where the Insurance Bureau of Canada considers that 20% of households are at high risk and that about 10% are at very high risk of flooding (Canadian Underwriter, 2016).

Conventional strategies to address and manage flood risk combine risk attenuation and reduction measures with financing mechanisms such as insurance. These strategies are often cost-efficient when flood occurs occasionally. However, more and more areas are becoming subject to successive flooding (Dahl et al., 2017). In these areas, flooding is, or will soon be, a high-frequency-high-severity source of risk. Mechler et al. (2014) argue that such high-risk layers often exceed the adaptation capacity of the communities as well as the risk tolerance of private insurers. In these cases, public assistance can be the most efficient risk management option.

Post-disaster financial compensation to flooded households to help with the repairing and rebuilding is the most common form of public assistance. Yet, the increasing cost of flooding can jeopardize the financial viability of assistance programs. It can also bring into question the efficiency and social acceptance of compensations if households are to receive successive indemnities each time flood occurs. Given this context, it is no surprise that we observe a growing interest for publicly funded risk avoidance strategies such as relocation.[1] This rise in popularity is noticeable in the academic literature where more than twice as many papers discussing flood-related relocation were published between 2016 and 2020 (>200) than in the previous five years (about 100).

A handful of papers on relocation provide financial assessment or cost-benefit analysis of fictitious or real-world relocation projects. These studies reveal that relocation projects can be cost-effective public investments (André et al., 2016; Atoba, 2022; Creach et al., 2020; Pinter & Rees, 2021). The present paper complements this trend of literature by advocating for a probabilistic cost-benefit analysis (CBA) to estimate the profitability of relocation projects. Mechler et al. (2014) argue that CBA is the dominant tool used by decision makers in the context of flood risk management. At the same time, there are few guidelines available describing how one should implement CBA given the probabilistic nature of flood data. According to Mechler et al. (2014) the main challenges of conventional CBA approaches is the need to monetize all costs and benefits, and in particular the intangible ones. We address these shortcomings using a step-by-step approach detailing how the profitability of relocation projects can be estimated based on the type of information most likely available to them. We provide a real-world example of the estimation process using the context and data from a flood-prone area located in a sector of a municipality that is part of the Communauté métropolitaine de Montréal (CMM, thereafter, free translation: Montreal Metropolitan Community), Canada. Our inputs include monetary estimates of the intangible impacts of flooding coming from a concurrent research in which the impact of flooding on life satisfaction has been assessed using a subjective well-being approach (Bourdeau-Brien et al., 2022).

Our paper is most closely related to Boudreault & Bourdeau-Brien (2020) and Zarekarizi et al. (2020) who employ a probabilistic CBA to respectively examine the impact

[1] In this paper, relocation strategies include as synonym: home buyout, managed retreat, trans-locality, resettlement, property acquisition and induced displacement.

of a major overhaul in the province of Quebec's disaster financial assistance program and the optimal house elevation to prevent flood damage. We also draw on the insights of André et al. (2016) by comparing two public investment decisions, namely the decision to relocate and the one to offer post-disaster financial assistance and by comparing three distinct relocation scenarios:

(a) A conventional post-disaster scheme where households can obtain an indemnity to relocate after suffering from heavy damage;

(b) A managed-retreat option where relocation takes place before any flooding occurs;

(c) A civil-law inspired setting proposed by André et al. (2016) where the ownership right of flood-prone properties is acquired by public authorities from the start, but households are granted the right to use and derive profit from the property (a usufruct) until a flood occurs.

These three scenarios differ not only in terms of the timing of the cash flows, but also in terms of tangible and intangible damage of flooding.

The net present value (NPV) is the performance measure used at the core of our probabilistic CBA approach. The NPV is made of the difference between the present value of all cash inflows and the present value of all cash outflows of an investment project. As it is routinely done in many papers, we assess the merit of relocation projects from a societal perspective where the main cash outflows are the indemnities paid by public authorities to households to acquire flood-prone properties upon relocation. The main cash inflows are the prospective flood losses – both tangible and intangible – avoided following relocation.

We also investigate whether relocation is profitable from the perspective of households. From their point of view, governmental indemnities for relocation constitute a cash inflow while forfeited public financial assistance for rebuilding becomes an outflow, as well as the residual cost of the damage (or drop in property value) that are not compensated by the government. Taking into account the perspective of households is important given that many relocation programs are voluntary and households are more willing to accept relocation when it is financially viable (Frimpong et al., 2019).[2]

Flood-related losses are typically estimated using probabilistic modeling. More explicitly, in this paper we construct probability density functions of the submersion height based on available data for each residential property located in the study area. We acknowledge that a sizable degree of uncertainty comes with direct flood damage assessment. Thus, we follow Zarekarizi et al. (2020) and use two distinct models to consider this deep uncertainty. The first model is the depth-damage curves developed by Bonnifait (2005) and used by several papers studying flood risk in the Province of Quebec (Blin et al., 2005; Oubennaceur et al., 2019). The second model is inspired by Wing et al. (2018) who argue that flood losses are better approximated by beta distributions as usual depth-damage curves poorly fit empirical observations. In addition to property damage, our CBA considers damage to movable content, additional living expenses, intangible flood losses as well as climate change. Some expenses and losses are proportional to direct losses while the timing of the relocation decision affects others. We first implement our CBA at the individual property level and then group properties at the neighborhood level to examine the conditions under which relocation can be cost-effective.

The real-world example shows the advantage of using a probabilistic approach that informs not only on the expected financial benefit of relocation, but also on the likelihood of profitability. Of key importance, our simulations show the critical role of considering intangible costs and benefits in an analysis. Indeed, while relocation appears to be cost-effective for a handful of very high-risk houses and neighborhoods when cash flows are restricted to direct damage only, a far greater number of houses located in floodplains benefit from relocation with a more complete account of costs and benefits. In terms of

[2] Note that for simplicity, we assume that households relocate in areas at no risk of flooding. See Kim et al. (2020) or McGhee et al. (2020) for a discussion about where households choose to migrate following relocation in the U.S.

design of relocation programs, our CBAs reveal that proactive and innovative schemes such as managed retreat and usufruct arrangements can augment profitability even if these programs involve immediate major investments.

Given the importance of flood risk and of its consequences, we consider that this paper is of interest for a well-diversified audience embracing academics and practitioners from the fields of public administration, public policy, risk management and financial management. An auxiliary, yet important, contribution of this paper is to provide policymakers with a step-by-step CBA approach to assess the profitability of relocation decision that is applicable at both the individual and the neighborhood level. An adequate assessment of the cost-effectiveness of flood mitigation measures favors sound public decision-making and facilitates social acceptance. Among other things, the inclusion of intangible losses in the CBA is essential to capture the all-encompassing consequences of floods that could be diminished or avoided through mitigation projects to evaluate the effects of a project on the overall quality of life.

The rest of the paper is organized as follows. Section 2 briefly outlines important dimensions of flood-related relocation and summarizes the main takeaways from the academic literature. Section 3 discusses the area of study for the real-world example as well as the key input data. It also details a step-by-step procedure to implement a probabilistic CBA including additional living expenses, intangible flood losses as well as climate change. Section 4 describes and interprets the main results from our CBA while Section 5 concludes.

2. Context and literature review

The overarching goal of relocation is to reduce flood risk. The first step of such project entails a retreat strategy where households are urged to sell their property to public authorities and move away from the floodplains. Occasionally, homeowners are able to physically move their house to a flood-safe location. The second step consists in a risk avoidance strategy where the properties are typically demolished and the land is rezoned as recreational or green space to disallow future housing.

Relocation programs have been implemented in many countries over the last decades. Examples include Austria (Thaler, 2021), Canada (Doberstein et al., 2019), England (Thaler, 2021), France (Creach et al., 2020), Ireland (Tubridy & Lennon, 2021) and the United States (Bukvic & Borate, 2021). The characteristics of past relocation programs greatly differ from one to another. Households can be forced to relocate (compulsory relocation) through expropriation although in many instances, relocation is voluntary. Relocation projects can be instigated following a major flood (post-flood relocation) or be planned in advance in the absence of such event based on prospective risk modeling (pre-emptive relocation). In all cases, governments pay homeowners a compensation for acquiring the flood-prone properties. In addition, relocation programs can be limited to a house-buying component where households are free to use the financial compensation as they wish or they can include some form of support to help households in their quest to find a new home. Finally, relocation decision can be taken at the individual property level or involve entire communities.

The design of relocation programs seems to significantly affect its success. Among other things, McGhee et al. (2020) observe that a simple individual buy-back program – with no additional support to help with the relocation – force the large majority of households to move in a neighborhood of lower socio-economic quality. Furthermore, about 20% of the relocated households move to an area at risk of flooding. Also, Binder et al. (2019) note that individual programs negatively affect household resilience through the loss of social capital. On the good side, Koslov et al. (2021) notice that relocated households less frequently report mental health issues than households that choose to rebuild in floodplains following a major event. The situation is quite different for pre-emptive neighborhood-level relocation projects that also include household accompaniment. Indeed, Pinter & Rees (2021) observe that community relocation succeeds in reducing economic flood exposure by over 95% and these projects "*represent a tangible investment in future resilience*" (p.497).

Other strands of literature look at the popularity of voluntary relocation programs (Frimpong et al., 2019; Seebauer & Winkler, 2020), the implication of relocation on social and environmental justice (Dundon & Camp, 2021; Thaler, 2021) and the governance structure of public relocation programs (Iuchi & Mutter, 2020; Tubridy & Lennon, 2021). While interesting, these strands are only remotely related to the financial aspect of relocation, which constitutes the main subject of our study.

The next section presents the real-world data as well as the step-by-step approach to implement our probabilistic CBA.

3. Data and methods

3.1 Area of study

The real-world example of our CBA estimation procedure is based on a residential sector located on the bank of a river, in the south west of the Canadian province of Quebec. Because of its geography, the sector has been subject to flood damage several times in the past and remains at high risk of flooding.

We obtain high-resolution flood maps on the targeted sector from the CMM and combine these maps with Quebec's geolocated assessment roles (MAMH, 2021) to retrieve the location and characteristics of single-family properties. We identify 930 single-family properties inside the area of study. We start by grouping the properties by neighborhood using the 2021 Canadian census dissemination block boundaries.[3]

Next, we determine whether properties are at risk of flooding. For this preliminary risk assignment, we assume that a property is at risk when a 1000-year event brings

[3] Statistic Canada defines a dissemination block as "an area bounded on all sides by roads and/or boundaries of standard geographic areas". Dissemination block boundary files for the 2021 census are available online at https://www150.statcan.gc.ca/n1/en/catalogue/92-163-X (page consulted on May 20th, 2022).

overland water in the immediate surroundings of the house. We observe that 207 properties spread over 23 distinct neighborhoods exhibit some level of flood risk. For simplicity, we identify the neighborhoods included in our study with numbers from one to 23 based on the original dissemination block identifiers. As we are interested in assessing the profitability of relocation at both the individual and neighborhood-level, we recoup data on all single-family properties located in the 23 neighborhoods. Our study thus includes a total of 351 single-family properties. Figure 1 depicts the location of the neighborhoods.

[Insert Figure 1 around here]

3.2 Fluvial flood hazard

The fluvial flood maps obtained from the CMM contain detailed information on the submersion height at a spatial resolution of 50 cm x 50 cm over the entire study area. The maps[4], handed to us as raster image files, cover ten flood recurrence periods ranging from 2-year to 1000-year events.[5]

In order to associate water depths to each house, we first examine and correct the location of the centroids of each house. To do so, we manually input the latitude-longitude coordinates from the assessment role in Google Maps. When the coordinates fall noticeably away from the middle of the building footprint, we select the apparent centre of the footprint on Google Maps and update the coordinate accordingly. We then draw a 3-meter radius circle around the centroid of each single-family building and retain the highest water height in the circle for each reference period. We construct a complete probabilistic distribution of the water depth by interpolating between the ten available depth marks. We assume that the maximal depth for extremely rare floods equals that of a 1000-year event and that the minimal water depth corresponds to the elevation with respect to the nearest

[4] The report associated with this modeling is not included in the bibliographical references. Anyone interested should make a request by writing to info@cmm.qc.ca

[5] The 10 recurrence periods are: 2-, 5-, 10-, 20-, 50-, 100-, 200-, 350-, 500- and 1000-years.

level of the river based on a 10-meter digital elevation model produced by Quebec's Ministère des Ressources Naturelles et de la Faune (MRNF, 2007).

Figure 2 illustrates the water depth for the average property of our sample of 351 single-family houses (blue line) and for the average of the 207 properties at risk of flooding (red dotted line). The probabilities on the x-axis can be interpreted in terms of recurrence periods. A probability of 50% means that in a given year, there is a 50% chance that the water height will stay at 1.5m or less under the ground level of the average property (-0.47m for the average property at risk of flooding). Thus, we can expect such a level of submersion to occur no more than once every two years. Accordingly, the 50% probability corresponds to a 2-year recurrence period. Put differently, the annual exceedance probability (AEP) of flooding equals to one minus the probability on the x-axis. Panel A of Figure 2 presents the complete probability distribution of the average water depth. As floods are (should be) rare events, our focus is put on the right tail of the probability distribution that we present in Panel B. The x-axis on Panel B begins with the 95% probability that corresponds to a 20-year return period. The 100-year recurrence period is an often-important threshold that is used for various regulatory purposes as well as to estimate flood insurance rates in United States. This explains why we draw a vertical line at the 0.99 level on Panel B. In any given year, there is a 1% probability that such a level of submersion occurs. In these occasions, the owner of the average property at risk of flooding would see the water rise about 33 cm over the land. Figure 2 also exposes the variability of water depth across properties. The darker blue band shows the interquartile range (Q1-Q3) and the lighter blue band informs about the minimum and maximum (Min-Max) water depth. For a 100-year flood, the first (third) quartile indicates that water will stay at 1.39m below (0.46m above) ground level or less for 25% (75%) of the 351 properties included in the study. The lowest water depth for a 100-year flood is at 5m under ground level while the highest water depth is at 2.39m above ground level.

[Insert Figure 2 around here]

For simplicity, we assume that the probability distributions of water depth for all properties exhibit perfect positive spatial correlation meaning that in a given year, all properties in the study are subject to a similar event in terms of recurrence period (or equivalently of AEP). This assumption is necessary given that no data on spatial correlation is available to us. We acknowledge that spatial dependence is of utmost importance for the assessment of mitigation projects that affect large geographic areas. In our case, we believe that this assumption is reasonable given that the area of study is of a relatively small size (the most distant properties are less than 1.5km apart). Also, the most important source of flood risk for all of the area is linked to the water level and flow of the river bordering the sector under study.

3.3 Exposure and vulnerability

We make use of the available data to characterize flood risk exposure and vulnerability of single-family properties. In the context of this study, the exposure refers to the value of the single-family houses. Throughout the study, we refer to two distinct types of value. The first type is the values of the buildings as listed on the assessment role. Buildings' values are a proxy for the total reconstruction costs and are required to estimate direct flood damage. The second type is the total value of the property (building + land) that is needed to estimate residual losses when a damaged building is not rebuilt, as well as to determine the level of government relocation indemnities.

Several characteristics of buildings may exacerbate or lessen flood damage. Table 2 of Kaoje et al. (2019, pp.333-334) provide an interesting literature review of several relevant economic vulnerability indicators. Among the most commonly cited characteristics that influence the level of damage, we note the:

(1) First floor elevation;

(2) Number of storeys;

(3) Presence of a basement;

(4) Presence and height of basement windows;

(6) Use of first floor;

(7) Type of building material;

(8) Condition of the building.

Alas, few relevant information on the characteristics of the buildings in the study area are available. We employ items (1) to (3) of the list above in our CBA setup. We follow Bonnifait (2005) and assume that the elevation of the lowest floor is of -1.6 m for properties with a basement and of 0.3 m for properties without a basement. The first floor above the ground for properties with a basement has an elevation of 0.9 m. The number of storeys is collected from the assessment roles. We use a variety of sources to infer the presence or absence of a basement. First, we retrieve basement information on houses currently or recently listed for sale on real estate brokerage websites. We obtain basement information from real estate listings on 32 houses. Next, we ask two research assistants to review manually and independently the images on each of the 351 houses available on Google Street View and to best guess about basements. Our assistants have a high level of confidence about the presence or absence of basement for 144 additional houses. For the remaining properties, we exploit the intersection of Statistic Canada's dissemination areas and municipal neighborhood units[6] to surmise basement information based on the characteristics that we observe in other similar buildings located in the same areas/units. Table 1 presents a breakdown of the main property characteristics by neighborhood.

[Insert Table 1 around here]

We observe that about 70% of the properties are one-storey buildings and that a little more than half of the houses have a basement. The average total value of properties is of $276,142 but that average varies greatly between neighborhoods with some zones having an average value near $200,000 (e.g. neighborhood 15) and some other having

[6] Neighborhood units are developed for the purpose of municipal taxation. Units comprise properties that are close to each other and that have similar characteristics.

an average over $500,000 (e.g. neighborhood 9). Buildings are worth between 6% (for a house under reconstruction) and 80% of total property value with an average of 45%. Therefore, land is worth a little more than the building per se for the average property. We also provide some details about the flood depth for a 100-year event in Table 1. The median water depth for such a flood would reach 0.246 m above the ground level of the average property. Again, we observe large disparities between neighborhoods with some experiencing significant overland submersion (e.g., neighborhoods 8, 10 and 14). Interestingly, we do not see a clear-cut relationship between proximity to the river and median water depth for a 100-year event. This suggests that flood risk is not restricted to the riverbanks.

3.4 Estimation of flood damage

Damage resulting from flooding takes various forms. Merz et al. (2010) classify damage into four categories based on whether damage is direct or indirect, tangible or intangible. Direct damage occurs from the physical contact of water with humans or tangible assets, while indirect damage is due to flood but occurs farther away from the flooded zone or after the submersion. Tangible damage groups the consequences of flooding that can easily be expressed in dollars, while intangible damage is the opposite. A proper CBA needs to include costs and benefits that arise from all forms of damage. The following subsections describe the assumptions and methods we use to include the various forms of flood damage in our probabilistic CBA approach.

3.4.1 Direct tangible damage to properties and content

Damage to properties is the most recognized type of flood damage. A substantial academic literature is devoted to the prediction of flood damage and a variety of competing methods exist to assess the level of damage (e.g. Marvi, 2020). Still, even state-of-the-art methods come with a large amount of uncertainty (Wing et al., 2020) about the likely damage of prospective floods. We consider this “deep” uncertainty in our modeling and simultaneously use two distinct approaches in the spirit of Zarekarizi et al. (2020).

First, we use traditional depth-damage functions that link a deterministic level of damage to each level of water depth. We rely on functions that have already been used in several studies in the province of Quebec (Blin et al., 2005; Bonnifait, 2005; Oubennaceur et al., 2019) and that are estimated from empirical data originating from historical flood damage to residential properties. More precisely, the functions express the amount of damage as a percentage of the building values and are categorized based on the number of storeys (one or two) and the presence or absence of basement. Thus, the modeling relies on four distinct functions. Figure 3 depicts the percentage of building damage resulting from various levels of water depth according to the four depth-damage functions.

[Insert Figure 3 around here]

Interestingly, we observe that damage begins well before land submersion, even for properties without any basement. Bonnifait (2005) justifies that observation by stating that high level of underground water brings extreme humidity that damage floor joists.

The second approach builds on the insights of Wing et al. (2020) to infer flood damage to property. That approach acknowledges that flood damage is highly uncertain no matter the level of water depth. According to Wing et al. (2020), the level of damage is best described by beta distributions, where the parametrization shifts in stages as water depth increases so that the average level of damage also increases. We choose the parameters α and β of the beta distributions in order to match the hypothesized median and 95th percentile of water depth. Table 2 informs on the assumed median (P50) and the conjectured 95th percentile (P95) of the distribution of water depth for each stage and each type of property.

[Insert Table 2 around here]

Damage for properties with a basement begins when water reaches -1.6 m, the level of the lowest floor. Most of the time, the level of damage in that first stage is minimal with a median level fixed at 7% (one-storey) and 5% (two-storeys) of the building value.

In the second stage, water that finds its way into a basement often causes additional damage as it may reach the main electrical panel. In the third stage, it is much more difficult to prevent water from entering the house from the basement windows. More often than not, the basement gets entirely flooded and the first floor may be affected due to the excessive humidity. The medians of 35% and 25% corresponds to the theoretical value of basements on total building value for one-storey and two-storeys properties, respectively. The fourth stage involves a submersion with water level over the first floor of the house and the last stage entails over 2.8 m of water over the ground so that the first storey is almost completely submerged.

A similar progression of damage by stage is expected for houses without a basement. Small levels of damage begin to be observed in stage 2 when water is between -0.2 m and 0.3 m. The severity of flooding then rapidly increases in stage 3 when the level of water exceeds the level of the first floor. Stages 4 and 5 bring additional damage as it becomes implausible to keep the water out of the house.

We illustrate the resulting probabilistic distributions of flood damage by type of property and by stage in Figure 4.

[Insert Figure 4 around here]

However, floods not only damage buildings. They also destroy house contents. For simplicity, we assume that the value of the furniture, furnishings, home appliances and household effects is worth 40% of the value of the building. That percentage represents a commonly used assumption by actuaries to determine the total coverage (based upon conversations with Canadian actuaries on flood insurance pricing and underwriting).

In order to obtain the dollar amount of damage to property and content, we simply multiply the percentage of flood damage resulting from either the depth-damage functions or the beta distributions by the building values augmented by the value of house contents. These damages correspond to the amount required to restore the house to its pre-flood condition and buy new furniture and appliances.

3.4.2 Additional living expenses

Homeowners may be forced to leave their dwellings as a result of flooding. Under these circumstances, they incur additional costs to pay for a shelter, personal goods and meals. For temporary evacuation, the cost depends on whether homeowners find accommodation with relatives or friends, on the size of the household and on the duration of the displacement. Houses that need significant repairing demand a prolonged displacement.

We assume that the duration of the evacuation is somewhat proportional to the level of the damage.[7] Damage worth less than 2% of the building value warrants no evacuation. Damage accounting for between 2% and 10% of building value requires a 2-month displacement. Damage ratios between 10% and 25% mandate a 4-month displacement. Damage ratios between 25% and 50% necessitate a 8-month evacuation. A 12-month temporary moving is needed when damage accounts for more than 50% of the building value. Our calculations include additional living expenses of $2,500 per month of displacement. That amount is based on a cost of $1,750 for a dwelling that corresponds to the typical monthly rent for a two-bedroom apartment in the CMM territory as listed on popular rental websites, plus an allowance of $10 per day for food and other essential supplies for a household of 2.5 people.

3.4.3 Intangible losses

One of the main drawbacks of CBA is the difficulty to include intangible costs and benefits, as they are difficult to express in dollar terms. We use preliminary results from a concurrent research in which the monetary value of the impact of flooding on life satisfaction has been assessed using a subjective well-being approach (Bourdeau-Brien et al., 2022). Given that the research results are not yet publicly available, we describe

[7] The Federal Flood Mapping Guidelines Series presents estimates of the average residential displacement periods as a function of flood depth (see Table F-4 of Natural Resources Canada, 2021, p.66).

the empirical approach used to monetize flood-related intangible losses in Appendix 1. Intangible losses are therefore best approximated by the following equation:

$$ITG = \begin{cases} 0.05 \times DT^{1.741714} & DT < \$2{,}500 \\ 0.5254DT + 41420 & DT \geq \$2{,}500 \end{cases} \qquad eq. 1$$

where ITG stands for the intangible damage and DT is for the direct tangible damage arising from flooding.

3.5 Impact of climate change

Assessment of flood hazard resulting from flood mapping is not a static exercise. Flood risk varies as global warming affects the climate and as effective land use evolves. As our simulations are run over several decades, it is desirable to take into account the probable evolution of flood risk over time. Slack & Comtois (2016) review the most recent predictions of water levels on the St. Lawrence basin near the CMM territory and state that future levels should be "*within the margins of the historic range*" (p.50). Therefore, we implement one scenario that allows for more variable and extreme future climate, but with no long-term upward trend. More precisely, we add an exogenous shock to the submersion level modeled via the probability distribution of flood depth depicted in Figure 2. The importance of the shock is given by a random number drawn from a normal distribution with zero mean and a standard deviation that increases over time from zero to 50 cm.

We also include a second climate change scenario to investigate the sensitivity of our results to an increasing trend in flood risk. We build that scenario by shifting the probability distribution of water depth so that reaching a given water depth becomes more and more likely over time. More concretely, we assume that the AEPs progressively and linearly increase by a factor of 50% over 50 years. For example, the water depth associated to an event having a 20% (1%) AEP today has an AEP of 25% (1.25%) in 25 years and of 30% (1.5%) in 50 years.

3.6 Methodological approach to the CBA

Our probabilistic CBA approach is articulated over the simulations of plausible scenarios of flooding over time and follows a step-by-step procedure.

First, we generate 20,000 scenarios of 50 years. The length of a CBA is usually chosen to match the service life of the investment. In the case of relocation, the investment consists in removing buildings from the floodplain. Of course, such investment has no well-defined service life. Therefore, we opt for a somewhat long period of time of 50 years to capture the costs and benefits of the investment from the societal perspective. We reduce the length of the scenarios at 25 years when assessing the value of relocation from the perspective of households. This truncation reflects the fact that the duration of homeownership is usually much lower than 50 years. Indeed, Fontaine (2018) shows that two-thirds of homeowners have moved away from their house after 23 years. Beyond tenure duration, several studies emphasize the myopic behavior of households (Cardak & Martin, 2019; Pryce et al., 2011) so that households would tend to omit long-term cash flows in their appreciation of relocation. Given that most long-term incremental cash flows are associated with benefits arising from avoided flood losses, a shorter assessment length translates into less profitable projects from the perspective of households.

For each scenario and each year, we draw a random number uniformly distributed between zero and one and use that number to determine the magnitude (which is equivalent to the return period or the AEP) of the annual flood event. For simplicity, we assume a single flood event per year.

Second, we associate the water depth to each flood magnitude for each house. The resulting dataset contains 351 million observations of water depth.

Third, we assess the damage, in percentage of the building value, related to each water depth. For half of the observations, damage ratios are inferred from the depth-damage curves of Bonnifait (2005). For the rest of the observations, we generate damage ratios from the beta distributions as depicted in Table 2 and illustrated in Figure 4.

Fourth, we calculate the various forms of damage, in dollars, starting with the direct tangible damage to building and content. We do so by multiplying the damage ratios by the sum of building value and house content. Building value and content vary over time and we need to account for inflation given that we simulate damage over 50 years. Statistics on residential construction costs in Canada are only available from 2017. Therefore, we rely on two alternative sources of information and estimate future annual inflation rates for the next 50 years based on the observed historical averages. The first source is a special study from the U.S. National Association of Home Builders (Ford, 2020) that presents data on total construction costs between 1998 and 2019. A mean annual inflation rate of 4.22% can be inferred from that study. The second source of information is Statistics Canada's building construction price index for the Montreal metropolitan area. Data are available from 1981 to 2021. The main advantage of using that index is its geographical focus on an area similar to that of the CMM territory. However, the index provides the cost progression for non-residential buildings only. A mean annual inflation rate of 3.25% can be inferred from the index. In our calculations, we use the average of the two sources and assume that building values – and house contents and reconstruction costs – grow at a rate of 3.735%. The direct tangible damage is then used to estimate the additional living expenses and the indirect and intangible losses as described before in sections 3.4.2 and 3.4.3. Monthly ALE are assumed to grow at a rate of 2.23% that corresponds to the annual inflation rate for shelter in the province of Quebec between 1981 and 2021. Indirect and intangible losses are already proportional to the amount of direct tangible damage that are adjusted for inflation. Thus, they warrant no additional consideration. Finally, some calculations are based on total property value, which also vary over time. We assume an annual inflation rate of 6.66%. That rate parallels the average growth of single-family houses in the Montreal area according to MLS® home price index (CREA, 2022).

Fifth, we calculate the costs and benefits of three distinct relocation settings. The settings mainly differ in terms of when relocation takes place and how much is offered to relocated households. These two dimensions have an impact on the flood-related damages that are avoided by the relocation investments. It is important to remember that the analysis is performed on the incremental cash flows directly associated with the relocation projects. In other words, the cash flows that are included in the calculations arise from the difference between the outflows according to each relocation setting and the outflows of the status quo, without relocation (see Sections 3.7 and 3.8).

Sixth, we compute the NPV by discounting at time zero and summing all positive (benefits) and negative (costs) incremental cash flows that occur in the 50-year span of the project for each property and each scenario. Equation 2 shows the conventional NPV equation, that is,

$$NPV_h^s = \sum_{t=0}^{T}\left\{-I_{h,t}^s \times (1+k)^{-t} + ICF_{h,t}^s \times (1+k)^{-t}\right\} \qquad eq. 2$$

where NPV_h^s is the net present value of house h under scenario s. Each scenario spans $T = 50$ years and discount the incremental cash flows $ICF_{h,t}^s$ as well as the relocation indemnity $I_{h,t}^s$ that differs between houses and that vary across time t. As cash flows are expressed in nominal dollars, the discount rate k needs to be expressed in nominal terms.

We employ two distinct discount rates to value relocation depending on the perspective of the valuation. The valuation of relocation projects from the perspective of households entails that the discount rate must reflect the rate of returns that households will require on a similarly risky investment. Booth (2015) examines the appropriate forward-looking rate of return for the overall Canadian market. He recommends nominal compound rates of return between 7.3% and 8.3%. Accordingly, we choose the midpoint of the interval, that is k=7.8%, for valuing relocation investments from the perspective of households. [8]

[8] We acknowledge that the nature and the inherent uncertainty of the cash flows of relocation projects can hardly be compared to that of financial investments. Yet, the concept of discount rate is linked to the opportunity cost of an

The discount rate to use for the valuation from the societal perspective is a more complex issue. Most of the academic literature contends that discount rates should account for factors beyond the economic opportunity cost of funds such as the impact of a project on human health and the presence of social and environment externalities. However, the literature presents no consensus regarding the appropriate approach to estimate such social discount rate (Gollier & Hammitt, 2014; Groom et al., 2022). Although a review of the literature on social discount rates is outside the scope of this paper, we mention to interested readers the studies of Moore et al. (2004) and Boardman et al. (2010) who survey and analyze the most common estimation approaches of social discount rates and provide a Canada-oriented viewpoint to social discount rates. For the purpose of this paper, we employ the conventional, albeit controversial, simple Ramsey rule (Ramsey, 1928) and use data specific to the province of Quebec to estimate a nominal social discount rate of k=5.18%. As we calculate NPV separately for each scenario, we obtain a probabilistic distribution of possible NPV associated to all of the 351 properties. For the analysis by neighborhood, we sum the NPV_h^s over houses by sector to obtain the necessary distribution.

Last, we report the results of our probabilistic CBA calculations. We choose to rely mainly on the average NPV by property/neighborhood accounting for the fact that scenarios all have the same probability of occurrence. A positive average NPV denotes that the relocation project is cost-effective. We also leverage the full distribution of the NPV to analyze the range of possible values, as well as compute the probability of getting a positive NPV.

3.7 Losses under the status quo (no relocation)

Under the status quo, losses associated to each event are the sum of direct tangible damage (DT), additional living expenses (ALE) and intangible losses (ITG). We assume

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investment. Households opting out of a relocation project could choose to invest in financial assets and expect to earn an annually compounded rate of return of around 8% on their portfolio.

that households completely repair and rebuild their houses following a flood so that DT equals the cost of rebuilding and of purchasing new content. Hence, losses of each simulated year are independent from one another.

Under the societal perspective, we choose to ignore plausible post-disaster financial compensations offered to households by governments to help with the rebuilding. This choice aims at seeing more clearly the effect of relocation versus the non-intervention case where nothing is done.

The situation is different when we assess relocation under the perspective of homeowners. The very fact that we perform this assessment implies that relocation is voluntary. The most relevant base case for homeowners includes government financial assistance. We assume that government assistance provides compensation that equals 90% of the amount needed to rebuild and to purchase new content, up to a lifetime limit fixed at the minimum between building value and $200,000. Compensations are indexed to inflation. These assumptions are informed by the disaster financial assistance program in place in the province of Quebec (Boudreault & Bourdeau-Brien, 2020). Hence, the presence of government aid is a disincentive that reduces the propensity of households to accept a relocation offer.

The next section presents three designs of relocation programs. Most benefits arising from relocation are assumed to come from avoided flood losses.

3.8 Characteristics of three designs of relocation programs

Let us begin with a note of caution. It is clear that the cost-effectiveness of relocation is affected by how communities use properties left vacant by relocated households. Abandoned buildings in floodplains are typically demolished and previously built lots can be replaced by green spaces. On the first hand, the demolition, the changes of effective land use and the management of these activities can entail significant costs. On the other hand, green spaces increase rainwater infiltration and decrease peak runoff amounts, thus reducing flood risk. They can also augment the desirability of a sector and have a positive influence for quality of life and property value (McCord et al., 2014). However, we choose to remain agnostic about changes in land-use following relocation. Thus, we include no such costs and benefits in our calculation. This decision is alike to considering that the discounted benefits of prospective land use planning equals the discounted costs and investments.

In all cases, we assess the cost-effectiveness of relocation using three distinct level of government indemnities: (1) 75% of building value, (2) 100% of building value and (3) 100% of total property value. The indemnities increase over time at the same rate than the building (1 and 2) and property values (3). The indemnities constitute a negative cash flow from the societal perspective, but a positive cash flow from the household's perspective.

Last, we consider that the residential properties are valuable assets for both the societal and household perspectives. Demolitions occasion a loss of value and thus negative cash flows.

3.8.1 Post-disaster relocation

This first design is articulated on a relocation trigger that is inspired by that of the disaster financial assistance program in place in the province of Quebec. Homeowners have access to a governmental indemnity for a permanent relocation outside of a floodplain when, and only when, the discounted cumulative direct tangible damage from past floods exceed 50% of the value of exposed assets. When the trigger is reached, relocation takes place and all forms of flood losses linked to future floods are avoided.

However, before relocation, households experience the same losses that under the status quo. Households also suffer from losses associated with the flood event that triggers the relocation. That particular event requires special attention.

As the flooded house is meant to be demolished, the direct tangible costs correspond to the total property value instead of the cost of repairing the building. We also include the value of the destroyed content to the direct costs.

We acknowledge that post-flood relocation requires temporary displacement. Delays in the execution of relocations as well as time needed to identify a new suitable home and plan the move are assumed to require four months. Accordingly, 4 months' worth of ALE are included in the calculations. The corresponding incremental cash flows may be positive when relocation reduces the length of the temporary displacement or negative in the opposite situation.

The flood that triggers relocation is accompanied by a slightly lower amount of intangible losses than under the status quo. While homeowners still fully experience the event, they have the opportunity to leave the floodplain, which arguably reduces anxiety regarding future disasters. We fix the amount of intangible losses at 80% of that of the status quo. In terms of incremental cash flows, the lower intangible losses represent a positive cash flow.

3.8.2 Managed retreat (pre-emptive relocation)

In the managed-retreat design, the relocation decision is taken now (at time zero) before any flood episode. Accordingly, homeowners avoid all prospective flood losses.

From the societal perspective, the cost of relocation is the sum of the indemnity paid to the household and of the value of the property that will be demolished.

From a household's perspective, homeowners immediately receive a relocation indemnity in exchange for their property. The corresponding incremental cash flow is positive when the indemnity is more generous than the total property value or negative in the opposite situation. All future losses avoided represent positive incremental cash flow, but financial assistance offered by the government to help with rebuilding is also forfeited.

3.8.3 Conditional agreement to relocate (usufruct arrangement)

The last design is inspired by André et al. (2016). It is articulated on a legal agreement concluded now (at time zero) that dismembers the ownership right as allowed under the civil law. Public authorities buy the bare ownership of the property while the households keep a usufruct, which is the right to use and derive profit from the property. The usufruct agreement is written so that it ends the first time a property faces flood damage. More precisely, public authorities obtain the full ownership when a flood causes at least $1 of damage to the building.

Government indemnities for relocation are paid at two distinct moments. At time zero, the cost of buying the bare ownership of a property is fixed at 30% of the total indemnity as in André et al. (2016). When the first flood occurs, the cost to end the usufruct is set at 50% of the total indemnity. At the end of the day, households receive lower indemnities than under the two other program designs. However, they receive a significant amount at time zero without having to use that money immediately to purchase a new dwelling as they continue to enjoy their current home. That money can be invested on the financial market or can be used to purchase a vacant land in the prospect of a future relocation.

André et al. (2015) argue that such a design does not only reduce the cost for the government, but also promotes flood risk awareness and facilitates social acceptance of the relocation. The incremental cash flows associated with this design are as follows.

Upon the first flood, the direct tangible costs correspond to the total property value instead of the cost of repairing the building. We also include the value of the destroyed content to the direct costs. Although homeowners know that they are required to leave their house following the first flood, they do not know in advance when that event will happen. Chances are that they need a few weeks before moving into a new permanent house. We assume that households require a two months period of temporary displacement. The corresponding incremental cash flows may be positive when relocation reduce the length of the temporary displacement or negative in the opposite situation.

The first flood is accompanied by a significantly lower amount of intangible losses than under the status quo. While homeowners still fully experience the event, they know in advance that they have to leave the floodplain upon the first flood. The fact that households have the opportunity and some money to plan the moving reduces the non-market consequences of flooding. We set the amount of intangible losses at 20% of those under the status quo. In terms of incremental cash flows, the lower intangible losses represent a positive cash flow.

The next section portrays the simulated results.

4. Results

We present the results from our CBA in three stages. First, we display the actual level of flood risk by showing the expected discounted losses under the base case, as well as under two climate change scenarios. Losses are thus decomposed as direct tangible and intangible losses, as well as ALE. Second, we describe the cost-effectiveness of the three designs of relocation programs under the societal perspective and discuss the policy implications of the results. Last, we portray the cost-effectiveness of relocation from the perspective of households.

4.1 Flood risk without relocation (status quo)

Most houses located in the study area are at high risk of flooding. Accordingly, our base expectation is that the average level of flood risk, when assessed in dollars, corresponds to a high proportion of building values or of total property values. We calculate the average flood losses by property over the 20,000 scenarios and provide summary statistics on the distribution of flood losses across properties in Table 3.

[Insert Table 3 around here]

Over a 50-year period, and abstracting from the effect of climate change, we observe that total discounted flood flosses are worth, on average, 5.79 times current building values and 2.37 times current total property values.[9] The mere fact that these ratios are above one suggests that relocation could be a cost-effective risk management strategy for many houses of our study area.

[9] We employ a social discount rate of 5.18% to calculate the discounted value of flood losses in Table 3.

Table 3 also informs about the relative importance of the various forms of flood damage. We observe that ALE can be significant and account for more than a third of direct tangible damage. Most importantly, we see that intangible losses are the principal contributor to flood damage and explain about 60% of total losses. It means that CBA that omit ALE and intangible losses can significantly underestimate the value of mitigation projects. Indeed, while the mean discounted societal direct tangible damage remains above building values (ratio of 1.54), the mean direct damage falls under total property values (0.71). Median direct damage also sinks below building and property values (0.70 and 0.30, respectively).

Without surprise, both climate change scenarios bring additional losses, making relocation programs potentially more profitable. Whereas all properties become riskier, the relative impact remains somewhat moderate compared to the overall level of flood risk for both scenarios analyzed. Relocation therefore remains rarely profitable for properties at low risk of flooding as depicted by the 25th percentile of the distribution of losses across properties, and vice-versa for homeowners at high-risk of flooding.

The last column of Table 3 displays the discounted direct tangible damage from the perspective of households. These amounts are net of provincial disaster financial assistance (DFA) compensations. We observe that discounted direct damage to homeowners is about 80% lower than that from the societal perspective (mean of 28% of building value in the base case versus 154%) thus highlighting the generosity of the program for many households. However, a few very high-risk properties accumulate losses beyond the lifetime limit, therefore skewing the distribution of direct damage from the perspective of households in a way that the mean is higher than the 75th percentile.

For most homeowners, DFA compensations absorb the majority of the rebuilding costs. It suggests that the presence and generosity of government post-disaster aid could significantly and negatively affect homeowners’ incentive to accept a relocation offer. However, relocations are expected to remain cost-effective for most homeowners given the importance of intangible losses. Hence, homeowners facing a relocation decision need to be aware of the often-tremendous importance of the indirect and intangible consequences of flooding to make an informed decision. We believe that risk awareness relative to intangible losses is specifically critical when the decision to relocate is taken in calm period, as is the case in conventional managed-retreat programs.

4.2 Can relocation be profitable to the society?

Our simulations clearly show that the cost of relocation (foregoing a property and providing a compensation) is lower than prospective flood losses for many high-risk properties. Hence, flood risk management strategies based on relocation make economic sense. Indeed, relocation would be a cost-effective option for several individual properties and many neighborhoods in our study area. Table 4 provides a tally of the number of properties and neighborhoods (or sectors) with a strictly positive mean NPV over the 20,000 simulated scenarios.

[Insert Table 4 around here]

Without surprise, we see that the number of cost-effective relocations greatly increases when we consider flood losses beyond direct tangible damage (reading from the left to the right). Indeed, with an indemnity of 75% of the building value and under the base case, there would be 42 profitable relocations under the post-flood relocation arrangement if we only considered direct tangible damage whereas this number more than triples to 140 when we account for all sources of losses. Including ALE and intangible losses has a much more dramatic effect when the indemnity corresponds to 100% of the property value. We observe similar proportions across the other two relocation designs as well.

As expected, profitability is negatively impacted by the extent of government indemnities. Indeed, the number of profitable relocations drops significantly if the indemnity corresponds to the total property value instead of 75% of the building value.

This however increases profitability from the perspective of the homeowner and in turn makes it more likely that a homeowner opts for relocation in voluntary programs.

Interestingly, results are affected by the type of climate change scenario. Under an increased volatility of water depth, with no upward trend, the number of cost-effective relocations is slightly larger than under the base case scenario. However, we observe a material impact on the number of relocations under the second climate change scenario based upon a long-term upward trend in the average flood risk. Although we are not in a position to compare the realism of the two climate change scenarios, this result stresses that the choice and parametrization of climate change predictions must be carefully determined since their consequences are not straightforward.

Table 4 also compares the implications of three relocation program designs. Let us look at the base case with no climate change and with a relocation indemnity set at the total value of the property. If relocation is triggered by significant flood damage, public authorities should be entitled to offer a post-flood relocation option to about 25% of the homeowners in the study area (87 out of 351) as the societal benefits arising from the avoided future flood losses exceed the costs of relocating these homeowners. Surprisingly, a managed-retreat relocation program where relocation takes place immediately is a cost-effective option for a greater number of households. Indeed, public authorities should submit a relocation offer to about 47% of the homeowners in the study area (166 out of 351). The last program design involves a usufruct arrangement. We observe that a similar number of homeowners should be relocated under that design than under the managed-retreat program. Indeed, public authorities should negotiate such arrangement with about 49% of the homeowners (171 on 351) based on the CBA.

Although the managed-retreat and the usufruct designs entail a greater initial investment, additional flood losses avoided – and in particular intangible flood losses avoided – are large enough to offset the value of the investment, even accounting for the value of money. Programs requiring major damage to occur before triggering a relocation decision appear to be suboptimal designs.

Relocation programs can also be considered per neighborhood (or sector), instead of by property, meaning that homeowners of a neighborhood are collectively required to accept or reject a relocation proposal. From the public authorities' standpoint, a neighborhood approach to relocation makes sense as it facilitates the redevelopment or the naturalisation of the floodplain following the removal of the buildings. Among other things, it prevents a high-risk neighborhood from becoming full of 'holes' over a long horizon if some homeowners choose to relocate while some others choose to stay.

We model the neighborhood approach assuming that the event that triggers relocation is the same than in the property-level CBA. In the post-flood design, houses are relocated at different times given that the damage trigger is reached at various moments for individual houses. The situation is quite different in the managed-retreat design where all houses by sector are assumed to be relocated immediately. In the usufruct design, the bare ownership of all houses by sector is bought at time zero, but homeowners relocate at various times given that the first flood damage occurs at different points in time.

We observe that the number of neighborhoods where relocation is cost-effective is relatively small, between two and eight, when the CBA only considers direct tangible damage. However, the inclusion of ALE and intangible losses in the analysis explains that a neighborhood approach would be profitable in as many as 20 sectors out of 23. A usufruct arrangement leads to the highest number of profitable neighborhood-level relocation in most cases considered.

Relocation, although profitable on average for many houses and sectors, remains a risky strategy. One advantage of the probabilistic CBA approach is that it generates whole distributions of plausible NPVs by property or by neighborhood, rather than a single number representing the mean NPV. We can exploit these distributions to characterize the risk of relocation projects. As an example, in the context of limited resources, this characterization could be used by public authorities to plan the sequence of the relocation projects over time (say e.g., four years), starting with the properties or sectors where profitability is most likely. For the sake of the example, we order the sectors according to the likelihood of profitable managed-retreat relocations, with no consideration for climate change. Table 5 displays the result of this exercise.

[Insert Table 5 around here]

We observe that a pre-emptive relocation program would be cost-effective in all scenarios in eight sectors. Three additional sectors exhibit a mean positive NPV combined with relatively high likelihoods of profitability of 86%, 82% and 72%, respectively. The other 12 neighborhoods have negative mean NPV and are profitable in less than 50% of the simulated scenarios.

We further compare the merits of the three program designs in Figure 5. That figure shows the discounted costs and benefits of relocation over time for one property located in neighborhood 6 that we deem representative. The calculations are performed using indemnities set at the value of the buildings.

[Insert Figure 5 around here]

Panels A, B and C portray the evolution over time of the incremental cash flows and of the indemnity payments resulting from the post-flood, managed-retreat and usufruct designs, respectively. The blue (red) bands cover one standard deviation above and below the average incremental cash flows (indemnities). Panel D directly compares the total costs and benefits (incremental cash flows plus indemnities) of the three designs.

We observe that the managed-retreat (Panel B) and usufruct (Panel C) designs are characterised by a much lower uncertainty regarding the timing of relocation and of the related indemnity payment when compared to the post-flood (Panel A) arrangement. Indeed, most post-flood relocations happen between years five to ten while a large portion of the costs occurs in the first few years under the other designs. Hence, a relocation triggered by major floods is a suboptimal design for two reasons. First, it is deprived of significant benefits as homeowners suffer from flood losses before relocation (direct and indirect losses, as well as ALE). Second, as a significant part of the costs is linked to the value of the forfeited property and because property values increase faster than the social discount rate, the discounted costs of relocation are larger under that design.

4.3 Can relocation be profitable to households?

We repeat our CBA but this time investigate the cost-effectiveness of relocation from the perspective of households. We present the results of our simulations in Table 6.

[Insert Table 6 around here]

The profitability of relocation is primarily influenced by two factors, namely the level of indemnities and the inclusion of intangible losses in the analysis. Lower indemnities, set at 75% of building value, result in a lower number of profitable relocations. Conversely, generous indemnities, set at the total value of the properties, make almost all relocation financially viable from the perspective of the households. The consideration of intangible losses in addition to direct tangible damage also greatly improves the profitability of relocation.

Interestingly, our CBAs reveal that households can judge proactive designs of relocation programs favorably. As shown in Table 6, even with less generous indemnities, profitably of relocation at the individual level is more common in the managed-retreat and usufruct programs than in the conventional post-flood one. This result has important public policy implications as proactive designs have an almost immediate effect on land use which may help lessen the effect of climate change as well as reduce flood risk in nearby areas through the development of green and/or blue infrastructure.

5. Conclusion

The financial assessment of public investments requires special attention. These investments are often accompanied by various kinds of non-market effects that should be taken into account in a cost-benefit analysis. The same is true for investments in flood mitigation projects. However, flood risk is also characterized by heavy uncertainty, not only in terms of where, when and how much water covers the land, but also in terms of the nature and amount of losses related to overland flooding. These characteristics command a CBA that simultaneously considers that most of the necessary inputs are available as probability distributions and that significant costs and benefits are not readily expressed in monetary terms.

We stress that it is essential to capture the all-encompassing consequences of floods – including those needing to be monetized – to adequately value flood mitigation projects so that the analysis takes into account the project's impact on the overall quality of life of stakeholders. In turn, an adequate assessment of the cost-effectiveness of flood mitigation projects favors sound public decision-making and facilitates social acceptance.

This paper details to decision makers and risk managers how to perform a probabilistic CBA that takes into account intangible losses due to flooding in the context of a relocation project. The step-by-step procedure is accompanied by a real-world example based on the characterization of flood risk in an area located on the territory of the Communauté Métropolitaine de Montréal, in the Canadian province of Quebec.

The analysis shows the advantage of using a probabilistic approach that informs not only on the expected financial benefit of relocation, but also on the likelihood of profitability. Of key importance, the example displays the critical role of considering intangible costs and benefits in such a CBA. Indeed, while relocation appears to be cost-effective for a handful of very high-risk houses and neighborhoods when only accounting for direct damage, a far greater number of houses located in floodplains then benefit from relocation with a more complete account of costs and benefits.

Given that existing relocation programs often report low participation rates, public authorities should consider raising indemnities to the extent that relocation remains profitable from a societal perspective. Authorities should also initiate information campaigns to raise awareness not only on flood risk in general, but more specifically on the existence and importance of indirect and intangible consequences of flooding that may amount to nearly two-thirds of total losses.

Furthermore, the real-world example examines three distinct designs of relocation programs. The results reveal that proactive and innovative schemes, such as a managed-retreat strategy and a program articulated on a usufruct arrangement, constitute cost-effective alternatives to a more conventional post-flood design under some conditions.

Although climate change will likely increase the profitability of relocation programs in the future, its impact on the frequency and intensity of flooding should be carefully determined. It appears however that based upon the climate change scenarios investigated over the area of study, relocation should become moderately more profitable in the future.

Last, we emphasize that the probabilistic CBA approach presented in this paper is quite general and can be used to assess and compare a variety of flood mitigation options beyond relocation. The key practical difficulties reside in the adequate characterization of the natural hazard, of the damage to tangible assets and of the intangible losses. Given the often-overlooked consideration of intangible losses, an important first step would be to develop additional knowledge on the nature and monetary value of the intangible losses following flood events in order to overcome the most stringent limitation of most cost-benefit analyses.

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Figure 1 – Map of the neighborhoods included in the study

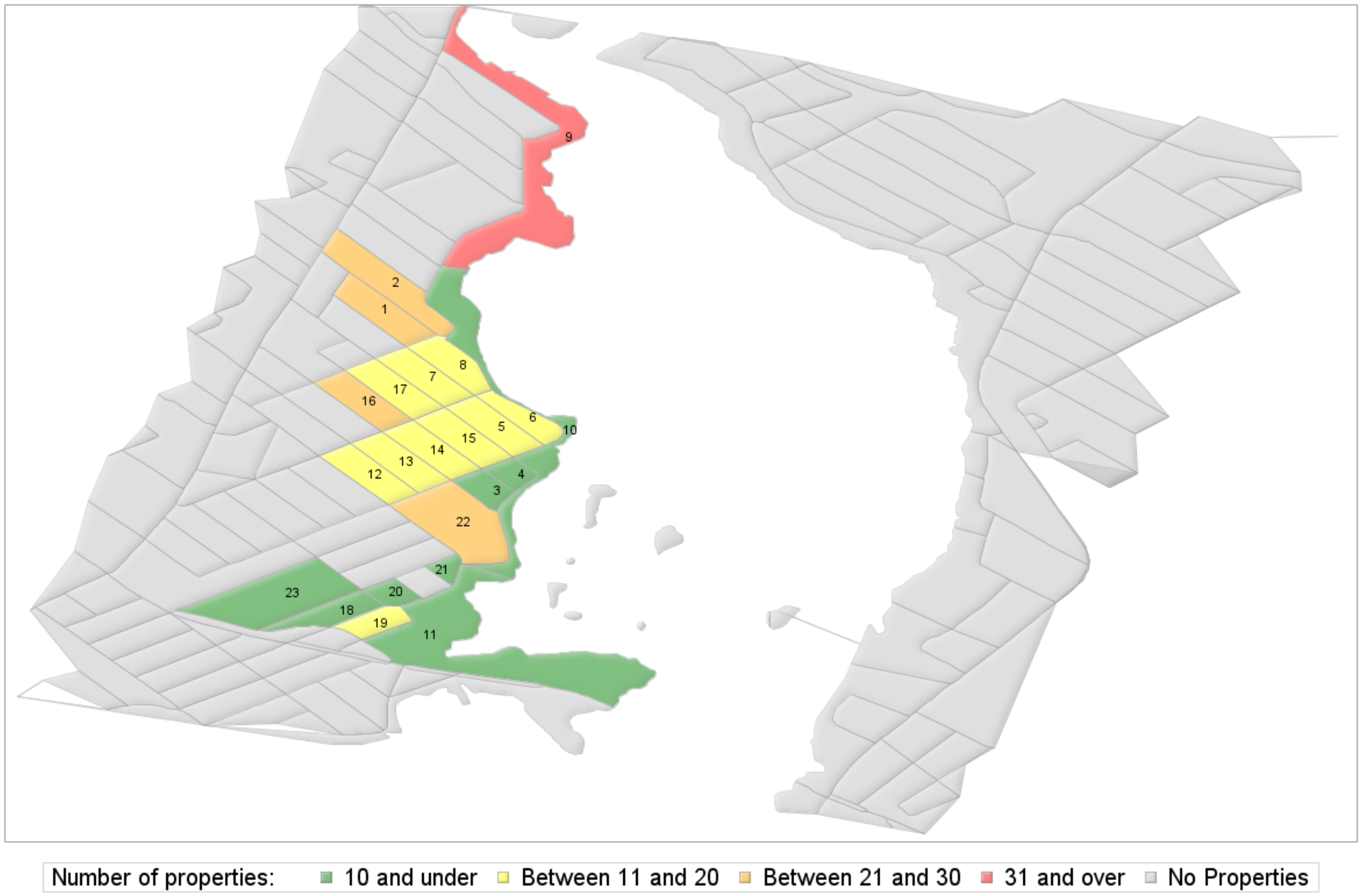

Figure 1 depicts the location of the neighborhoods (or sectors) included in the study. Between 3 and 40 individual properties are located in each neighborhood. Note that the map has been altered in order to preserve the privacy of the citizens.

Figure 2 – Probability distribution of flood depth for the average property

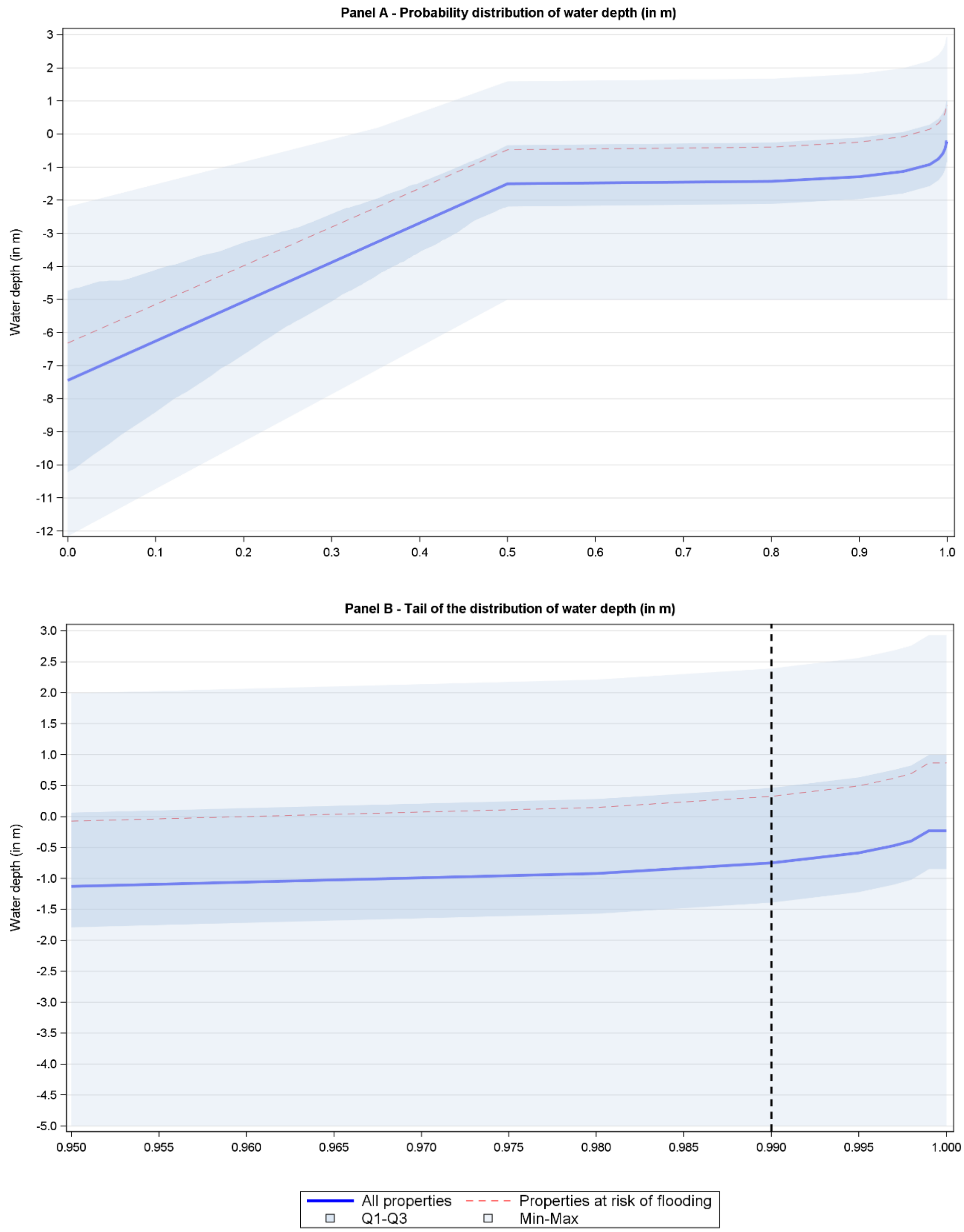

Figure 2 illustrates the water depth for the average property of our sample of 351 single-family houses (blue line) and for the average of the 207 properties at risk of flooding (red dotted line). Panel A presents the complete probability distribution of the average water depth. Panel B focuses on the right tail of the probability distribution. The darker blue band shows the interquartile range (Q1-Q3) and the lighter blue band informs about the minimum and maximum (Min-Max) water depth.

Figure 3 – Deterministic depth-damage curves from Bonnifait (2005)

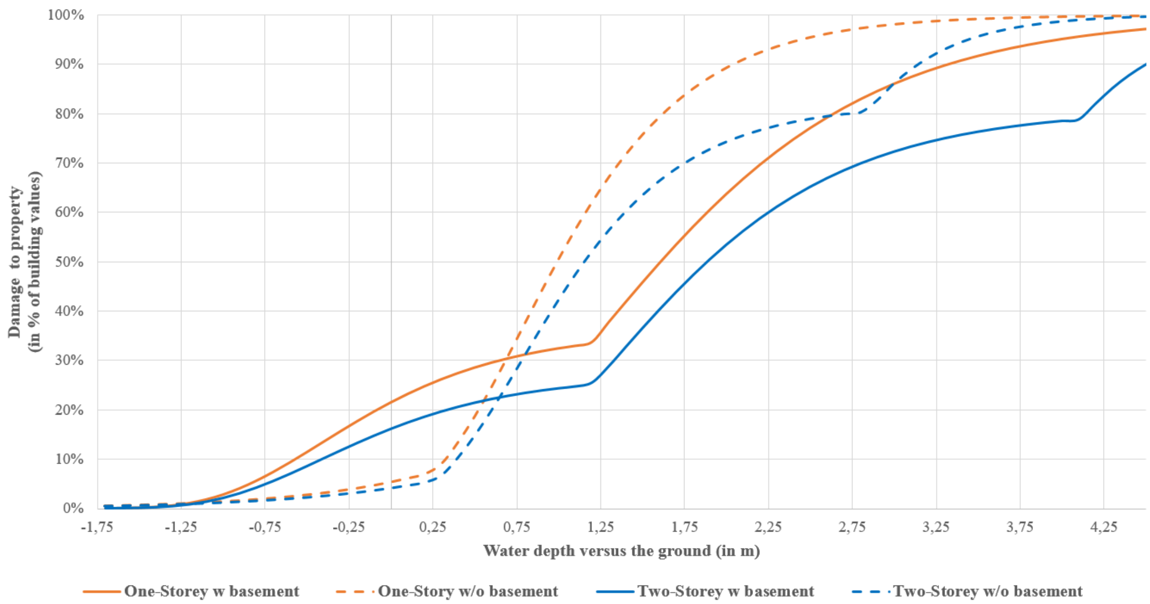

Figure 3 illustrates the deterministic depth-damage curves from Bonnifait (2005). The curves depict the percentage of building damage resulting from various levels of water depth. The solid red line presents the depth-damage relationship for one-storey properties with a basement. The solid blue line presents the relationship for two-storey properties with a basement. The dotted lines display the depth-damage function for one-storey (red) and two-storey (blue) houses without a basement.

Figure 4 – Stochastic damage curves inspired by Wing et al. (2020)

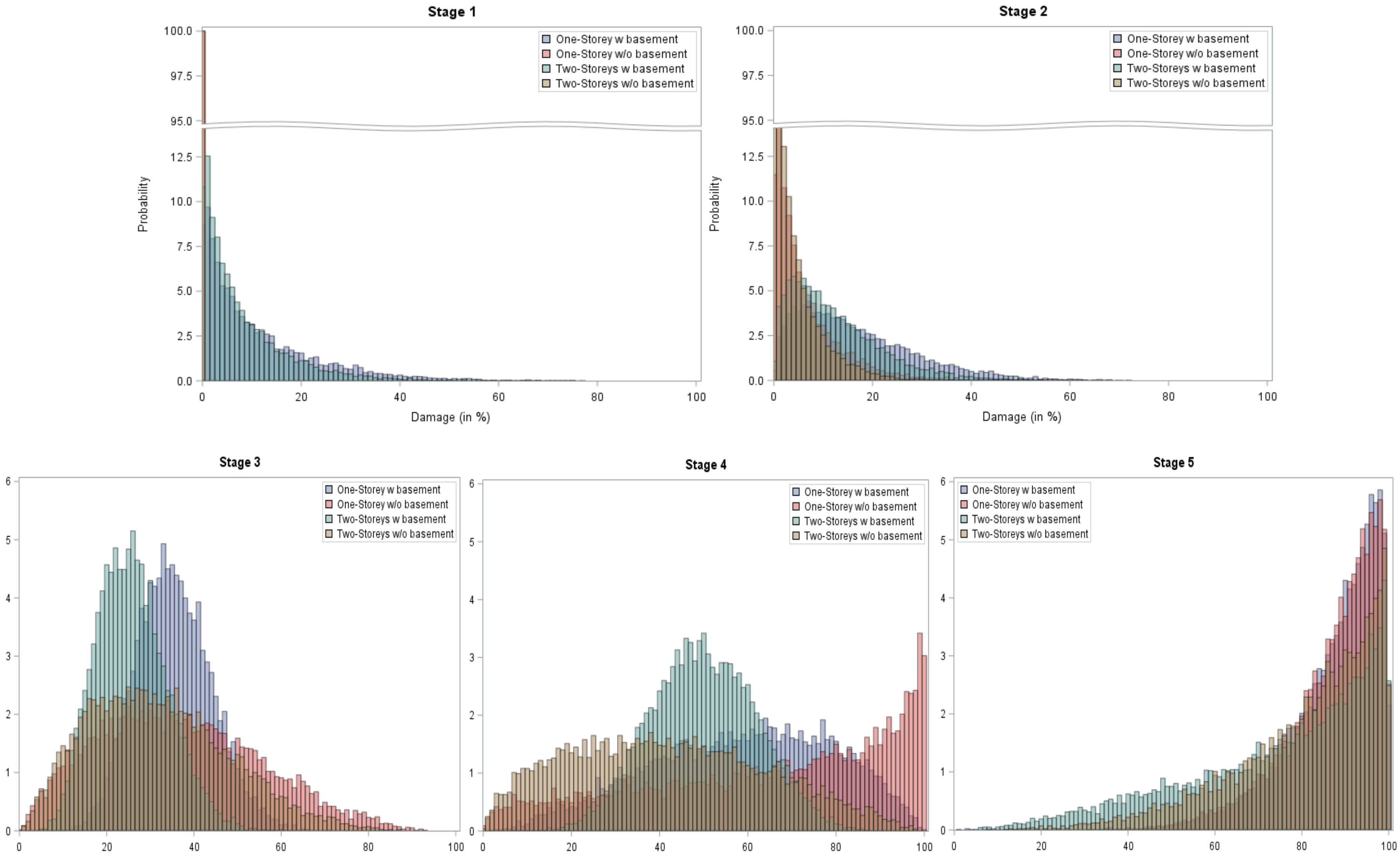

Figure 4 displays the probabilistic distributions of flood damage by type of property and by stage. The level of damage is described by beta distributions, whose parametrization shifts in stages as water depth increases so that the average level of damage also increases. The parametrization of the five stages can be found in Table 2.

Figure 5 – Timing of the costs and benefits according to the three relocation program designs

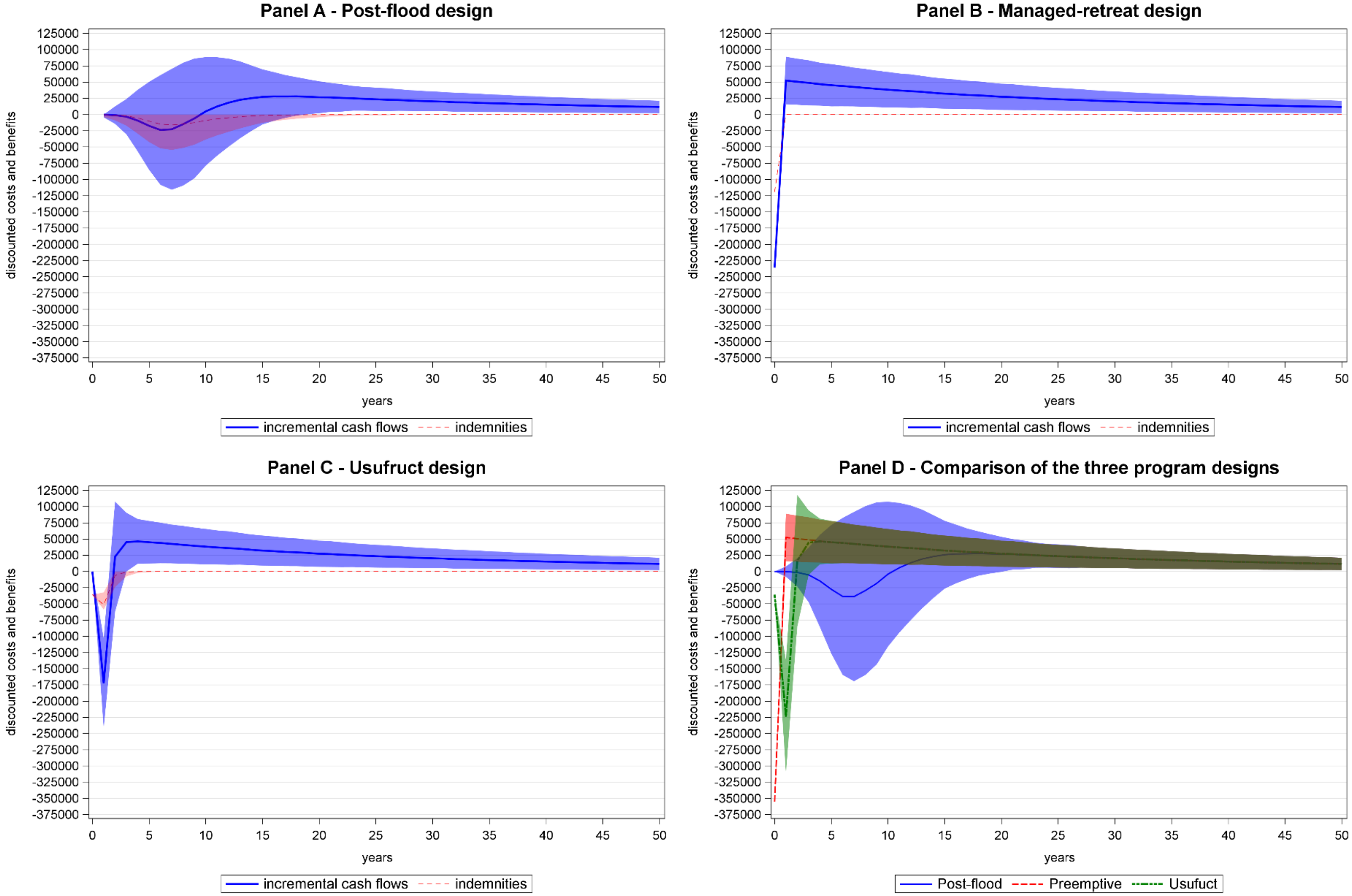

Figure 5 illustrates the distribution of the average discounted value of the costs and benefits of flood-related relocation over time. Panels A, B and C portray the evolution over time of the incremental cash flows (in blue) and of the indemnity payments (in red) resulting from the post-flood, managed-retreat and usufruct designs, respectively. Panel D compares the total costs and benefits (incremental cash flows plus indemnities) of the three designs. The blue (red) bands cover one standard deviation above and below the average incremental cash flows (indemnities).

Table 1 –Characteristics of properties and flood risk by neighborhood

Neighborhood	Number of properties	Proportion of properties			Average total value ($CAN)	Depth of submersion for a 100-year flood (in meter)		
		One-storey	Two-storeys	With basement		25th pctl	Median	75th pctl
1	24	0.833	0.167	1.000	245,492	-1.4050	-0.6240	-0.2750
2	25	0.800	0.200	1.000	279,576	-4.2800	-3.1400	-1.8800
3	9	0.222	0.778	1.000	263,289	0.0800	0.0840	0.3300
4	7	0.714	0.286	1.000	225,814	0.0720	0.3530	0.6510
5	19	0.579	0.421	0.000	217,479	0.3150	0.4540	0.6010
6	13	0.692	0.308	1.000	235,669	0.2910	0.4890	0.6420
7	19	0.789	0.211	1.000	235,537	-0.1940	0.2310	0.4400
8	16	0.438	0.563	0.500	235,175	0.4700	0.5900	0.7530
9	40	0.600	0.400	0.025	503,268	-1.7150	-0.8355	-0.1685
10	3	1.000	0.000	0.000	307,700	-0.1030	0.6480	0.6910
11	7	0.857	0.143	1.000	248,343	-1.4700	-1.0100	-0.1570
12	20	0.800	0.200	1.000	247,505	-4.4200	-1.7800	-0.7190
13	17	0.824	0.176	1.000	225,759	-0.1250	0.2440	0.6470
14	20	0.650	0.350	1.000	235,315	0.3425	0.6230	0.7540
15	16	0.625	0.375	0.000	208,675	0.4095	0.5445	0.6725
16	21	0.905	0.095	0.048	222,419	-5.0000	-5.0000	-1.7300
17	12	0.583	0.417	0.000	260,708	-0.7055	-0.1625	0.3340
18	8	0.875	0.125	0.875	256,500	-1.3450	-0.8245	-0.3815
19	12	0.583	0.417	0.000	286,700	-1.3850	-0.7565	-0.4160
20	4	0.250	0.750	0.000	381,275	-1.9250	-1.7650	-0.8420
21	5	0.600	0.400	0.000	246,660	-0.6460	-0.5220	-0.2430
22	25	0.840	0.160	0.000	262,976	-0.7700	-0.2510	0.4610
23	9	0.889	0.111	1.000	267,844	-2.1400	-1.6900	-1.3400
Area of Study	**351**	**0.707**	**0.293**	**0.533**	**276,142**	**-1.3900**	**-0.2460**	**0.4630**

Table 1 presents a breakdown of the main property characteristics by neighborhood.

Table 2 – Parametrization of the stochastic damage curves inspired by Wing et al. (2020)

Stage	Water depth	One storey with basement	One storey without basement	Two storeys with basement	Two storeys without basement
0	≤ -1.6m	P50: 0% P95: 0%	P50: 0% P95: 0%	P50: 0% P95: 0%	P50: 0% P95: 0%
1	]-1.6 to -0.2m]	P50: 7% P95: 35%	P50: 0% P95: 0%	P50: 5% P95: 25%	P50: 0% P95: 0%
2	]-0.2 to 0.3m]	P50: 14% P95: 40%	P50: 4% P95: 20%	P50: 10% P95: 30%	P50: 3% P95: 15%
3	]0.3 to 0.9m]	P50: 35% P95: 50%	P50: 35% P95: 70%	P50: 25% P95: 40%	P50: 30% P95: 60%
4	]0.9 to 2.8m]	P50: 60% P95: 90%	P50: 70% P95: 99%	P50: 50% P95: 70%	P50: 40% P95: 80%
5	>2.8m	P50: 90% P95: 99%	P50: 90% P95: 99%	P50: 80% P95: 99%	P50: 85% P95: 99%

Table 2 details the parametrization of the probabilistic distributions of flood damage by type of property and by stage. The level of damage is described by beta distributions, where the parametrization shifts in stages as water depth increases so that the average level of damage also increases. The table describes the level of damage, expressed in percentage of building value, for the median (P50) and the 95th percentile (P95) of the distribution of water depth for each stage and each type of property.

Table 3 – Distribution of discounted flood losses over 50 years

	Climate change scenario	Statistic	Discounted flood losses (societal perspective): Direct tangible damage	ALE	Intangible losses	Total	Direct tangible damage (household perspective)
Building Value	Base case	mean	1.54	0.76	3.50	5.79	0.28
		25th pctl	0.05	0.00	0.33	0.38	0.01
		median	0.70	0.29	2.40	3.38	0.07
		75th pctl	2.36	0.99	5.09	8.44	0.25
	Increased volatility of water depth	mean	1.62	0.78	3.53	5.94	0.29
		25th pctl	0.07	0.00	0.36	0.43	0.01
		median	0.93	0.31	2.40	3.64	0.09
		75th pctl	2.70	1.01	5.23	8.94	0.27
	Increased mean level of water depth	mean	1.87	0.91	4.10	6.87	0.36
		25th pctl	0.06	0.00	0.41	0.47	0.01
		median	0.85	0.34	2.82	4.02	0.09
		75th pctl	2.88	1.18	5.97	10.03	0.31
Total Property Value	Base case	mean	0.71	0.27	1.39	2.37	0.14
		25th pctl	0.02	0.00	0.15	0.18	0.00
		median	0.30	0.17	1.27	1.74	0.03
		75th pctl	1.07	0.42	2.40	3.88	0.11
	Increased volatility of water depth	mean	0.75	0.28	1.41	2.44	0.15
		25th pctl	0.03	0.00	0.18	0.21	0.00
		median	0.35	0.17	1.33	1.86	0.03
		75th pctl	1.13	0.44	2.41	3.98	0.12
	Increased mean level of water depth	mean	0.86	0.32	1.64	2.82	0.18
		25th pctl	0.03	0.00	0.19	0.22	0.00
		median	0.36	0.21	1.45	2.01	0.04
		75th pctl	1.30	0.50	2.82	4.62	0.13

Table 3 presents the mean, as well as the 25^{th}, 50^{th} and 75^{th} percentile of the distribution of flood losses across the 351 properties. The upper part of the table expresses flood losses as a proportion of the building value and the lower part of the table expresses flood losses as a proportion of the total value of the properties. The table also details the consequences of flooding according to the type of losses: direct tangible damage, additional living expenses (ALE) and intangible losses. Direct tangible damage differs depending on the perspective of the assessment. The first data column presents direct tangible damage from the societal perspective while the last column of the table presents direct tangible damage from the perspective of the households (net of compensations originating from disaster financial assistance programs). The calculations consider two climate change scenarios. The first brings additional uncertainty in the simulated water depth without affecting the mean level (increased volatility). The second scenario shifts the probability distribution of water depth so that reaching a given water depth becomes more and more likely over time (increased mean).

Table 4 – Number of profitable relocations from the societal perspective

	Climate change scenario	Indemnity	Number of profitable relocations (out of 351 properties) DT only	DT+ALE	DT+ALE+ITG	(out of 23 sectors) DT only	DT+ALE+ITG
Post-flood	Base case	75% of building value	42	67	140	5	18
		Building value	36	61	135	5	17
		Total property value	14	34	87	2	11
	Increased volatility of water depth	75% of building value	49	73	135	4	17
		Building value	40	67	132	4	16
		Total property value	16	35	89	2	10
	Increased mean level of water depth	75% of building value	61	85	151	8	20
		Building value	55	83	147	7	20
		Total property value	28	54	118	2	14
Managed-retreat	Base case	75% of building value	66	101	190	6	17
		Building value	58	91	183	3	17
		Total property value	33	63	166	2	11
	Increased volatility of water depth	75% of building value	69	110	193	7	17
		Building value	62	99	190	3	17
		Total property value	35	67	167	2	11
	Increased mean level of water depth	75% of building value	82	121	196	7	17
		Building value	72	112	192	7	17
		Total property value	47	76	176	3	13
Usufruct	Base case	75% of building value	66	102	196	6	19
		Building value	63	93	191	5	19
		Total property value	35	71	171	3	17
	Increased volatility of water depth	75% of building value	70	109	193	7	19
		Building value	67	101	189	6	19
		Total property value	40	73	168	3	17
	Increased mean level of water depth	75% of building value	85	123	206	8	19
		Building value	76	116	202	7	19
		Total property value	56	88	182	3	18

Table 4 details the number of properties and neighborhoods (or sectors) where relocation would be cost-effective from the societal perspective. The average net present value (NPV) of relocation is estimated over 20,000 simulated scenarios of 50 years for each property or neighborhood. The cost-effectiveness, or profitability, of relocation is obtained when the average NPV is strictly positive. Three designs of relocation programs are examined: a post-flood relocation, a managed-retreat approach, and a relocation articulated over a usufruct arrangement. Calculations are repeated for three levels of indemnities expressed in percentage of building value or of total property value. Incremental cash flows resulting from relocation are first restricted to direct tangible damage (DT) before encompassing additional living expenses (DT+ALE) and intangible losses (DT+ALE+ITG).

Table 5 – Cost-effectiveness of relocation and related public decision-making by sector

Rank	Sector	Mean NPV	Standard deviation of NPV	% of cost-effective scenarios	Relocation sequence
1	6	$893,724	$55,463	100.0%	Year 1
2	14	$815,975	$74,320	100.0%	Year 1
3	21	$808,404	$283,365	100.0%	Year 1
4	4	$641,233	$75,687	100.0%	Year 2
5	8	$514,677	$75,319	100.0%	Year 2
6	7	$508,524	$47,877	100.0%	Year 2
7	13	$474,517	$50,926	100.0%	Year 3
8	3	$421,696	$89,259	100.0%	Year 3
9	10	$236,082	$188,119	85.6%	Year 3
10	15	$131,377	$122,444	81.6%	Year 4
11	5	$184,490	$191,541	71.7%	Year 4
12	22	$-115,609	$165,456	49.8%	No Relocation
13	9	$-204,363	$284,446	45.2%	No Relocation
14	1	$-64,644	$101,664	44.6%	No Relocation
15	17	$-81,988	$121,486	42.4%	No Relocation
16	18	$-85,273	$152,667	41.0%	No Relocation
17	11	$-98,433	$91,698	18.5%	No Relocation
18	12	$-243,892	$41,214	0.0%	No Relocation
19	16	$-374,789	$43,951	0.0%	No Relocation
20	2	$-392,057	$36,811	0.0%	No Relocation
21	19	$-412,541	$158,068	0.0%	No Relocation
22	23	$-436,848	$35,864	0.0%	No Relocation
23	20	$-606,383	$138,981	0.0%	No Relocation

Table 5 displays the profitability-related uncertainty of neighborhood-level relocation. Neighborhoods (or sectors) are ranked based on the mean net present value (NPV) of relocation. Uncertainty related to the profitability of relocation is expressed both in terms of standard deviation and of the percentage of scenarios having a strictly positive NPV. The relocation sequence is an example of how, in the context of limited resources, a probabilistic cost-benefit analysis could be used by public authorities to plan the sequence of relocation projects over four years, starting with the properties or sectors where profitability is most likely.

Table 6 – Number of profitable relocations from the perspective of households

	Climate change scenario	Indemnity	Number of profitable relocation (out of 351 properties) DT only	DT+ALE	DT+ALE+ITG	(out of 23 sectors) DT only	DT+ALE+ITG
Post-flood	Base case	75% of building value	34	59	140	4	18
		Building value	41	69	146	5	18
		Total property value	205	226	250	23	23
	Increased volatility of water depth	75% of building value	34	61	134	4	18
		Building value	42	69	140	5	18
		Total property value	230	247	263	23	23
	Increased mean level of water depth	75% of building value	38	67	149	5	20
		Building value	50	77	155	7	20
		Total property value	205	219	251	23	23
Managed-retreat	Base case	75% of building value	38	76	190	3	17
		Building value	54	93	203	3	17
		Total property value	327	327	327	23	23
	Increased volatility of water depth	75% of building value	44	76	187	3	17
		Building value	55	94	202	3	17
		Total property value	334	334	334	23	23
	Increased mean level of water depth	75% of building value	49	86	195	3	17
		Building value	64	104	204	5	17
		Total property value	327	327	327	23	23
Usufruct	Base case	75% of building value	55	81	221	1	19
		Building value	63	92	240	1	20
		Total property value	178	209	342	11	23
	Increased volatility of water depth	75% of building value	53	82	221	1	19
		Building value	62	93	235	1	20
		Total property value	177	208	343	11	23
	Increased mean level of water depth	75% of building value	61	91	233	1	19
		Building value	67	98	251	1	20
		Total property value	182	222	342	12	23

Table 6 details the number of properties and neighborhoods where relocation would be cost-effective from the perspective of households. The average net present value (NPV) of relocation is estimated over 20,000 simulated scenarios of 50 years for each property or neighborhood. The cost-effectiveness, or profitability, of relocation is obtained when the average NPV is strictly positive. Three designs of relocation programs are examined: a post-flood relocation, a managed-retreat approach, and a relocation articulated over a usufruct arrangement. Calculations are repeated for three level of indemnities expressed in percentage of building value or of total property value. Incremental cash flows resulting from relocation are first restricted to direct tangible damage (DT) before encompassing additional living expenses (DT+ALE) and intangible losses (DT+ALE+ITG).

Appendix A

The empirical approach used by Bourdeau-Brien et al. (2022) is articulated over a survey that asks more than 600 individuals about their experience related to the 2019 spring flood in Quebec. The survey took place 18 months following the events so that the answers reflect the level of life satisfaction of the respondents after the bulk of the evacuation and rebuilding period.

The estimation approach relies on mediation analysis and a set of regression models are estimated simultaneously using a seemingly unrelated regression framework. The approach allows for the estimation of the direct effect of flooding on the general life satisfaction and considers the indirect effects of flooding on five subjective well-being domains (financial situation, family life, social life, health and home/living environment).

The monetisation of the total effect of flooding is obtained from the trade-off between income and subjective well-being. The main result from that study is that the average annual income required to compensate for changes in life satisfaction due to flooding is significant and grows with flood damage. As in Hudson et al. (2019), the intangible losses are extracted by subtracting the direct tangible flood impact from the required total compensations for the decline in life satisfaction.

Intangible losses are best approximated by the following linear equation:

$$ITG = 0.5254DT + 41420 \qquad eq. A.1$$

where ITG stands for the intangible damage and DT is for the direct tangible damage arising from flooding. However, the survey data does not allow the precise estimation of intangible losses for direct tangible damage of less than \$2,500. We address this issue by assuming that intangible losses when direct damages are worth less than \$2,500 follow a power function.