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Efficiency and Equity in Urban Flood Management Policies

A Systematic Urban Economics Exploration

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Abstract

Flood exposure is likely to increase in the future as a direct consequence of more frequent and more intense flooding and the growth of populations and economic assets in flood-prone areas. Low-income households, which are more likely to be located in high-risk zones, will be particularly affected. This paper assesses the welfare and equity impacts of three flood management policies—risk-based insurance, zoning, and subsidized insurance—using an urban economics framework with two income groups and three potential flood locations. The paper shows that in a first-best setting, risk-based insurance maximizes social welfare. However, depending on flood characteristics, implementing a zoning policy or subsidized insurance is close to optimal and can be more feasible. Subsidizing insurance reduces upward pressure on housing rents but increases flood damage, and is recommended for rare floods occurring in a large part of a city. Zoning policies have the opposite effect, avoiding damage but increasing housing rents, and are recommended for frequent floods in small areas. The social welfare impact of choosing the wrong flood management policy depends on the location of floods relative to employment centers, with flooding close to employment centers being particularly harmful. Implementing flood management policies redistributes flood costs between high- and low-income households through land markets, irrespective of who is directly affected. As such, they are progressive in terms of equity, compared to a laissez-faire scenario with myopic anticipations, in the more common scenario where poorer populations are more exposed to urban floods. But their impacts on inequality depend on flood locations and urban configuration. For instance, in a city where floods are centrally located and low-income households live in the city center, subsidized insurance would mitigate a surge in inequality, whereas a zoning policy could substantially increase inequalities.

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Efficiency and Equity in Urban Flood Management Policies: A Systematic Urban Economics Exploration

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1 INTRODUCTION

Flooding is one of the most damaging natural disasters. A recent study estimates that 1.47 billion people, or 19 percent of the world population, are directly exposed to substantial risks during a 1-in-100 year flood event[1] (Rentschler and Salhab 2020). In addition, flood exposure is likely to increase. In coastal cities with more than 1 million inhabitants, the total population exposed to floods will grow more than threefold between 2005 and 2070 (Hanson et al. 2011). Considering a set of 136 coastal cities, Hallegatte et al. (2013) show that average annual flood losses may increase from US$6 billion in 2005 to US$60 - 63 billion in 2050. This higher exposure results from more frequent floods and an increase in flood-prone areas (Hirabayashi et al. 2013) and the rapid growth of populations and economic assets in flood-prone areas (Jongman, Ward, and Aerts 2012).

But the risk is not equal for all urban populations. Low-income populations are more likely to live in high-risk zones; explanations for this include income levels, risk aversion, beliefs, access to information, and housing discrimination (Bakkensen and Ma 2020; Winsemius et al. 2018). Floods are also more damaging for low-income populations, whose low-quality dwellings are more likely to be destroyed due to poor construction materials, and who may not be able to access insurance or reconstruction programs (Jean-Baptiste et al. 2018).

It is therefore becoming increasingly important to study which public policies are most appropriate to mitigate the impacts of urban floods, with a particular focus on inequalities. Comparing three flood management policies—risk-based insurance, subsidized insurance and zoning—in an urban context, Avner and Hallegatte (2019) find that in a first-best setting, risk-based insurance maximizes social welfare, perfectly internalizing flood risks. But implementing this policy might be unrealistic for technical, social, or political reasons. First, the observed penetration rate of flood insurance remains low (Michel-Kerjan and Kunreuther 2011). Second, mandatory flood insurance would be technically difficult to implement, since it would require accurate assessment of risk levels in all areas and effective enforcement. And third, it would be politically difficult to implement, because people would have to accept a system where insurance premiums vary widely between neighborhoods based on models with high uncertainties.

When risk-based insurance implementation is unrealistic, Avner and Hallegatte (2019) show that subsidized insurance or zoning policies can be good alternatives. Land use zoning is close to optimal when flood-prone areas are small, floods are frequent, and housing quality is low. Zoning keeps total land value unchanged but transfers wealth from landowners in flood-prone areas to landowners in safe locations. Subsidized insurance is close to optimal when a large fraction of a city is flood-prone, floods are rare, and housing quality is high. And although it increases flood losses through the moral hazard effect, subsidized insurance encourages more construction, reducing housing rents and benefiting tenants regardless of where they live, especially in cities with large flood-prone areas.

This paper builds on a classical urban economics model (Fujita 1989) to investigate the effects of flood management policies in a theoretical monocentric city. Based on Avner and Hallegatte (2019), it compares three flood management policies (risk-based insurance, subsidized insurance, and zoning) and a laissez-faire situation with myopic agents with a situation with no floods. Enriching the framework by considering two income classes and different distributions of flood-prone areas, we investigate how flood management policies perform in terms of welfare, and explore distributional impacts for the different spatial distributions of flood-prone areas.

[1] A 1-in-100-year event is expected to occur once every 100 years on average (i.e. it has a probability of 1% of occurring in any given year).

The main challenge is to accurately represent high- and low-income households' housing decisions. Indeed, cities around the world display various spatial configurations. In some, low-income households tend to predominate in the city center, while in others, they tend to live in the outskirts. Urban economics, in its most standard form, where locational decisions are made by trading off commuting costs and living space (Fujita 1989), would fit best with a *low income-high income* pattern, where low-income households live in the city center and high-income households in the outskirts to enjoy larger dwellings and open space. This could be because monetary transport costs weigh more heavily on low-income households' budgets, while high-income households, with their higher purchasing power, are more strongly attracted by low housing prices in the suburbs. This phenomenon is observed in many American cities (Brueckner, Thisse, and Zenou 1999), although recent trends indicate that an opposite dynamic is occurring (Couture and Handbury 2020).

Urban economics can also explain the opposite pattern, where the wealthiest households live in the city center and the poorest in the outskirts, as observed in many European cities. This pattern can be explained by the presence of attractive amenities in city centers, which outweigh the extra costs of land and result in higher "central bids" for properties and land close to amenities from the richest, or by time having a very high opportunity cost for the richest households (Su 2022).

In this paper, we show that implementing flood management policies can reduce social welfare losses from floods compared to a myopic or laissez-faire situation in which economic agents do not anticipate flood occurrences and costs. As in Avner and Hallegatte (2019), risk-based insurance is the first-best policy in terms of maximizing social welfare, but subsidized insurance or zoning can be good options, depending on flood characteristics. Welfare losses from floods—and from implementing the wrong flood management policy—are particularly important when flooding takes place in the city center. Agreement between income groups on the hierarchy of flood management policies cautiously points to an absence of political economy issues that could lead to selecting a costly flood management option. Compared to a myopic scenario where households do not anticipate flood risks, flood management policies redistribute flood costs between high- and low-income households regardless of who is directly affected. Compared to a laissez-faire approach, flood management policies are therefore progressive or regressive, depending on who is directly impacted by the floods. In the most common setting, where poorer households are more exposed to floods, they are more progressive than a myopic scenario. The choice of flood management policy also impacts inequality levels throughout the urban area, but whether they increase or mitigate inequality depends on flood locations and city characteristics. When floods are close to employment centers and low-income households live nearby, land use zoning and risk-based insurance would deepen inequality levels, whereas subsidized insurance would mitigate them.

Section 2 presents the economic theory behind our simulation of a theoretical city and our modeling of floods and flood management policies. Section 3 presents the results of our urban flood simulations in terms of efficiency, social welfare, and equity. Section 4 discusses the implications of these results in terms of efficiency, equity, political economy, and in the context of climate change.

2 METHODS

2.1 URBAN ECONOMIC THEORY

We consider an idealized city, building on standard urban economics theory. The modeling framework is inspired by von Thünen's model (1826), adapted by Alonso (1964), Mills (1967), and Muth (1969), and comprehensively described in Fujita (1989). This model relies on the assumption that all jobs are located in a single location—the central business district (CBD)—and that households trade off between large and cheap dwellings per unit of space in the periphery, and smaller and more expensive dwellings in the city center with reduced commuting costs. Housing is supplied by landowners who choose where and how much to invest as a function of expected rents at each location. We place ourselves in a closed city with public land ownership configuration.

Each household is composed of one representative worker living at a distance r from the CBD. Each worker has to commute once a day to the CBD, at a cost $T(r)$. All households earn the same income Y and, at equilibrium, have the same level of satisfaction described by a utility function $U(z,q)$ that depends on the consumption of a composite good z and on the size of their dwelling q. The rent per square meter is $R(r)$ at each location in the city, and landowners' aggregate profits are recycled in the urban economy in the form of increased incomes corresponding to an amount of $\underline{L}$ per household (public ownership of land hypothesis). Each household maximizes its utility function under the budget constraint:

$$z + R(r)q + T(r) \leq Y + \underline{L} \quad (1)$$

In a first setting (*low income-high income* configuration), we consider that there are no amenities beyond the consumption of housing and a composite good. In this setting, the standard urban economics theory applies, and low-income households live in the city center (Brueckner, Thisse and Zenou 1999). A similar spatial pattern would emerge, if we assumed that amenities are higher in the suburbs than in the city center (for example, because of high city center density or crime rates).

$$U(z,q) = z^{1-\beta} q^{\beta} \quad (2)$$

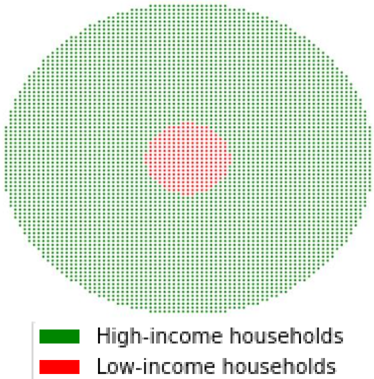
In a second setting (*high income-low income* configuration), we consider a city with a high level of amenities in the city center. With historical amenities, government investment in the city center, and the development of modern amenities, such as restaurants and theaters, this structure is typical of European cities (Brueckner, Thisse and Zenou 1999). We also consider that high-income households value amenities more than low-income households, a hypothesis supported by Couture and Handbury (2020), who show that high-income households' preference for restaurants, nightlife, and other such amenities explains the increase in proportion of high-income households living in city centers in the United States between 2000 and 2010.

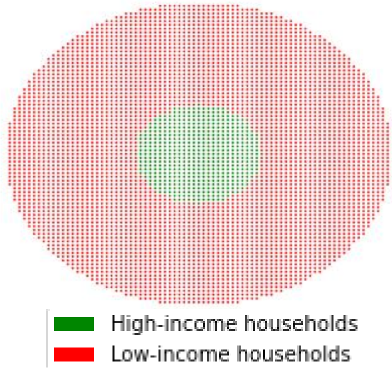
$$U(z,q,A) = z^{1-\beta} q^{\beta} A^{\gamma} \text{ with } \gamma_{rich} > \gamma_{poor} \quad (3)$$

Under this hypothesis—that high-income households' valuation of amenities dominates the conventional forces that attract them to the periphery (that is, that they value amenities over the increased housing consumption allowed by cheaper housing rents in the periphery)—high-income households live in the center and low-income households in the outskirts (Brueckner, Thisse, and Zenou 1999). This hypothesis can be verified in our model if the amenity level in the city center is high enough (appendix B). Figure 1 provides a graphical illustration of the difference between the *low income-high income* and *high income-low income* configurations.

Figure 1. Population distribution across the city (two settings)

Low income-high income **configuration**	***High income-low income*** **configuration**





Landowners supply the housing and choose how much capital $K(r)$ to invest at each distance from the CBD to produce a housing surface $H(r)$, assuming that they own a quantity of land $L(r)$ and that the housing production function is:

$$F(K, L) = AL^{a}K^{b} \text{ where } a, b > 0 \text{ and } a + b = 1 \tag{4}$$

Landowners maximize their profit function to identify the optimal amount of capital to invest at each location:

$$\Pi(r) = R(r)F\big(K(r), L(r)\big) - (i + \rho)K(r) \tag{5}$$

$$K(r) = argmax(R(r)F\big(K(r), L(r)\big) - (i + \rho)K(r)) \tag{6}$$

with i the interest rate and ρ the depreciation rate of capital. Due to the decreasing returns to capital, landowners will invest in tall buildings only when they anticipate rents that offset the extra building cost. At the edge of the city, the anticipated profit does not exceed the agricultural rent R_a, and landowners choose to rent their land to farmers instead of building dwellings. For simplicity, we assume that agricultural rent is null.

We calibrate our idealized city on the Paris agglomeration for illustrative purposes (table 1). To calibrate the parameters governing urban densities, rents, and population, we follow Viguié, Hallegatte and Rozenberg (2014). We consider two household groups with the same number of households, where the low-income group is the bottom 50 percent of the income distribution and the high-income group is the top 50 percent. Building on survey data from the National Institute of Statistics and Economic Studies' (INSEE) localized disposable income system, FiLoSoFi, there are 4.9 million households in the Paris agglomeration, with a median annual income of €37,232 for low-income households and €80,244 for high-income households (INSEE-DGFiP-Cnaf-Cnav-CCMSA 2015). Transportation costs include fuel and vehicle maintenance $t * r$, proportional to distance from the city center and identical for both household groups, and an opportunity cost of time (considering an average speed of 25 kilometers per hour) that is proportional to hourly salary and therefore higher for high-income households.

Table 1. Main parameters for our idealized city

Parameter	Symbol	Value	Obtention method and other relevant information
Housing production function scale	A	2.014	Calibrated based on data on the structure of Paris in 2008 (Viguié, Rozenberg and Hallegatte, 2014) using density data from INSEE (2008) and rent data from CLAMEUR.[2]
Elasticity of housing production with respect to capital	b	0.64	Calibrated based on data on the structure of Paris in 2008 (Viguié, Rozenberg and Hallegatte 2014), using density data from INSEE (2008) and rent data from CLAMEUR. The calibrated value of 0.64 is very close to the value of 0.65 found for France in Combes, Duranton and Gobillon (2021).
Share of household income net of transport costs spent on housing	β	0.3	Calibrated based on data on the structure of Paris in 2008 (Viguié, Rozenberg and Hallegatte 2014) using transport cost data from Hourcade and Nadaud (2009) and Rouchaud and Sauvant (2004), income data from Friggit (CGEDD, after INSEE[3]), and real estate data from CLAMEUR.
Interest rate: cost of capital	i	0.05	Assumed as a reasonable value. It is difficult to ascertain an interest rate that would reflect the annual financial burden of construction in an urban area that has developed over centuries.
Depreciation rate of capital	ρ	0.01	Assuming that structures last for 100 years on average, which is consistent with Hallegatte (2009).
Unitary transport cost: fuel and vehicle maintenance (euros per kilometer)	t	0.416	Established from the French tax perception center URSSAF's reimbursement calculations for using private vehicles for work, assuming an average annual mileage of 12,000 kilometers.
Fraction of land that can be built on (net or roads and public spaces)	s	0.62	Based on Corine Land Cover land use data.
Number of rich households (millions)	N_1	2.45	Assuming the population of the urban area of Paris is divided into two equal-sized groups.
Number of poor households (millions)	N_0	2.45	Assuming the population of the urban area of Paris is divided into two equal-sized groups.
Annual income of rich households (euros)	Y_1	80,244	Computed based on the FiLoSoFi database (INSEE-DGFiP-Cnaf-Cnav-CCMSA 2015).
Annual income of poor households (euros)	Y_0	37,232	Computed based on the FiLoSoFi database (INSEE-DGFiP-Cnaf-Cnav-CCMSA 2015).

2.2 FLOODS AND FLOOD MANAGEMENT POLICIES

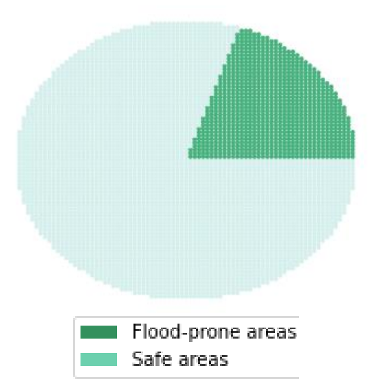
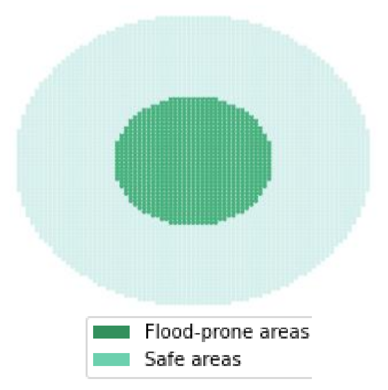
Our study of the impact of floods on this idealized city focuses on capital destruction. The model does not account for other consequences of floods, assuming, for example, that it is possible to avoid loss of life and injury through early warning systems. We consider that the agglomeration has two zones: a

[2] CLAMEUR (https://clameur.fr/) is an association of several public and private organizations that studies the evolution of rents in France.

[3] https://www.igedd.developpement-durable.gouv.fr/rubrique.php3?id_rubrique=138, accessed on January 13, 2023.

flood-prone zone representing a fraction θ of total available land, and a safe zone representing a fraction $1-\theta$. We consider three possible flood locations: city center, the periphery, or uniformly distributed across the city (Figure 2). In addition to the fraction of flood-prone areas (θ), we characterize floods by two parameters: return period (τ), which is the inverse of its frequency, and percentage of damage caused as a proportion of invested capital (δ). Our modeling considers various return times (from 1 to 50 years) and flood-prone areas (from 10 to 90 percent of the city), and we assume that the fraction of damaged capital in flood-prone areas is 40 percent. We take the number of inhabitants in the city (N) as given, corresponding to the classic "closed city" assumption.

Figure 2. Flood distribution across the city, where flood-prone area = 20 percent

Uniformly distributed	**In the city center**	**In the periphery**
		

We compare three flood management policies (described below) in terms of household utilities: risk-based premium insurance (P), subsidized insurance (S), and zoning (Z). Although we do not study investments in flood protection infrastructure per se as a policy, these can be reconciled with our modeling framework as they will impact return periods, flood damage, or flood areas. By systematically testing for variations of these three parameters, we allow for the possibility of investing in flood protection infrastructure.

Risk-based insurance premiums are paid by landowners and calculated as a function of the risk level in the considered lot. They are equal to local annualized flood costs, which depend on building location and cost. On average, flood insurance costs are therefore equivalent to an increase in building depreciation, and are modeled accordingly. Landowners account for flood risks in their profit maximization program:

$$K_p = (1-\theta)argmax\left(R_pF\left(K_{safe,P},L\right)-(i+\rho)K_{safe,P}\right) + \theta argmax\left(R_pF\left(K_{flood,P},L\right)-\left(i+\rho+\frac{\delta}{\tau}\right)K_{flood,P}\right) \quad (7)$$

With *subsidized insurance*, all households, irrespective of whether they are affected by floods, contribute to insurance proportionally to their income, and this insurance covers post-flood reconstruction needs. There is therefore no price signal incentivizing landowners to build less in flood-prone areas, and the landowners' maximization program remains unchanged (equation 6). However, household budget constraints include insurance payments and become:

$$z + R_s q + T \leq Y + \underline{L} - \underline{D} \quad (8)$$

with $\underline{D}_{poor} = D_S * \frac{Y_{poor}}{Y_{poor}N_{poor}+Y_{rich}N_{rich}}$, $\underline{D}_{rich} = D_S * \frac{Y_{rich}}{Y_{poor}N_{poor}+Y_{rich}N_{rich}}$ and $D_S = \frac{\theta\delta}{\tau} * \int_0^{rf} K_S(r)dr$ the total flood damage.

Zoning prevents people from building in flood-prone areas, so available land for construction is $L_Z = (1 - \theta)L$ and invested capital is:

$$K_z = (1-\theta)argmax(R_z F(K_z, L) - (i+\rho)K_z) \quad (9)$$

For benchmarking purposes, we also consider a scenario where no flood management policy is implemented and landowners and households are myopic to flood risks. They make construction and locational decisions as they would in a no-flood situation, incurring high costs in terms of structure destruction because of a lack of anticipation or adaptation. These costs are passed onto households, which need to finance the refurbishment of their dwellings. In this case, households and landowners solve the same program as in a scenario with no floods, but their utility is computed as:

$$U_M(z,q,A) = (z - (\frac{\delta}{\tau}K_{flood}/density))^{1-\beta} q^{\beta} A^{\gamma} \quad (10)$$

For the remainder of this paper, we call this the *myopic scenario*.

3 RESULTS

This section shows that results from Avner and Hallegatte (2019) are unchanged when we enhance the model with considerations of pre-existing heterogeneity across urban dwellers. We also provide additional insights, especially on the effect of floods and flood management on inequality within the city.

3.1 EFFICIENCY OF FLOOD MANAGEMENT POLICIES

In this section, we introduce a social welfare function equal to the sum of utilities $W = \Sigma U_i$ for $i = 1, \ldots, N$ to compare the efficiency of flood management policies in terms of total social welfare. Figure 3 shows the social welfare losses from floods under the three policy scenarios and the myopic scenario, compared to a situation with no floods, displaying results for the *low income-high income* configuration, where the low-income households live in the city center and the high-income households in the periphery. Because of the large number of situations studied[4] and to convey clear messages, the core text focuses on a subset of representative results: frequent floods in small areas and rare floods in large areas. We present heatmaps with results for a larger number of flood types in appendix D.

As in Avner and Hallegatte (2019), we observe that risk-based insurance minimizes social welfare losses for all flood types. Indeed, risk-based premiums that reflect the value of damage to structures perfectly internalizes flood impacts on housing prices. This leads to a reduced housing consumption in flood-prone areas, which maximizes social welfare.

Except in the case of very frequent floods (see appendix D), the cost of implementing the second-best instead of first-best is low. As in Avner and Hallegatte (2019), subsidized insurance is close to optimal in terms of welfare for rare floods in a large part of the city (with a 20-year return period and a flood-prone area covering 50 percent of the city). With subsidized insurance, landowners' construction decisions are not directly affected compared with the myopic scenario; rather, they are indirectly affected through a reduced household budget. So, housing stock is not dramatically reduced because of floods, and housing rents remain relatively low and similar to the myopic or no-flood scenarios. But subsidized

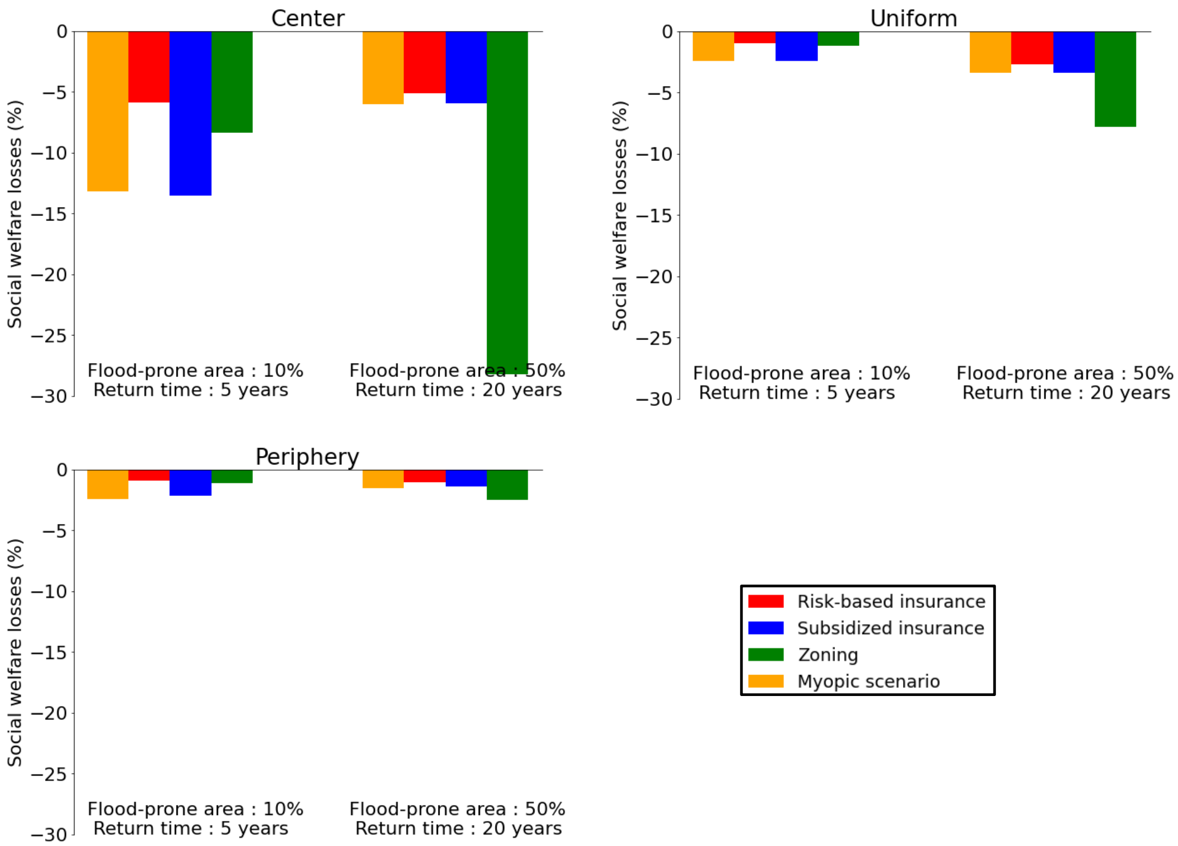
[4] As outlined in section 2, this includes 1) two urban configurations: *low income-high income*, where the low-income households are in the city center and high-income households in the outskirts, and *high income-low income*, where high-income households are centrally located and low-income households in the periphery; 2) three typical flood locations (central, peripheral, and uniformly distributed throughout the urban area); and 3) floods that vary by fraction of flood-prone area (10–90 percent of the city), and return periods (2–50 years). A systematic presentation of our results for all these cases would be overwhelming to the reader, so we focus on a representative subset of our results, highlighting the major trends and differences between studied cases.

insurance also leads to high damage to buildings from floods. A zoning policy is preferred for frequent floods that affect a small part of the city, as the loss of land for building purposes remains moderate and does not significantly affect rents and housing affordability.

The welfare impacts depend on flood locations relative to employment centers. Flooding in the city center has the highest impact on social welfare, even when implementing the first-best response. The center and its vicinity are the city's most valuable areas because they have the highest accessibility to employment and living there translates into commuting cost savings. They are also typically the most densely populated areas in the absence of floods. Implementing risk-based insurance in the presence of floods will lead landowners to modify their construction decisions, resulting in a large decrease in housing supply, an increase in rents in the rest of the city, and important flood damage. The welfare impacts of peripheral floods, and to a lesser extent of floods that occur uniformly across the urban area, are much smaller than for central floods, irrespective of the flood management policy implemented. Welfare loss differences across policies are also mechanically smaller in absolute terms.

The cost of implementing the wrong second-best policy also depends on a flood's location. For example, centrally located floods could lead to high welfare losses if the wrong policy is implemented. In particular, for rare floods affecting a large share of the urban area in the *low income-high income* configuration, implementing a zoning policy rather than a risk-based or subsidized insurance leads to high welfare losses. Figure 3 shows that in the *low income-high income* configuration, floods with a 20-year return period that cover half the urban area would lead to more than 25 percent welfare losses under a zoning policy, compared to just 4–5 percent under risk-based or subsidized insurance policies. Using risk-based or subsidized insurance to preserve the ability to build on the most valuable land in the urban area despite flood risks reduces housing rents and transport costs, outweighing the costs of structural damage. Conversely, by preventing building in a large and central area, a zoning policy results in accessibility losses and increased rents.

Figure 3. Social welfare losses from floods in the low income-high income configuration, considering three flood locations



The main results of this subsection also hold in the *high income-low income* configuration (figure A1, appendix A), where the first-best policy is also a risk-based insurance for all types of floods, and the cost of implementing the second-best instead of the first-best response is low except for very frequent floods. Subsidized insurance remains the second-best for rare floods occurring in a large part of the city, and a zoning policy is preferred for frequent floods that hit a small part of the city. The magnitude of welfare losses from floods is similar in both configurations. The exception is for city center floods, which are more damaging in the *high income-low income* configuration, when there are more amenities in the city center, which are not used or consumed when few people live close to the center.

3.2 FLOOD MANAGEMENT POLICIES, POLITICAL ECONOMY, AND THE DISTRIBUTION OF FLOOD COSTS

In this section, we focus on how flood management policies compare to the myopic scenario, how the hierarchy of policy options is similar across income groups, and how land and housing markets mitigate the costs that predominantly affect one income group or another. In table 2, we report the welfare losses compared to a no-floods scenario in the different configurations under the risk-based insurance, subsidized insurance, zoning, and myopic scenarios. We show the impact of floods on social welfare overall, and on high- and low-income households separately.

In section 3.1, we show that risk-based insurance is the first-best response when considering aggregate welfare. Table 2 shows that risk-based insurance is also Pareto optimal and the preferred policy for both high- and low-income households. Zoning is the second-best policy, in terms of each income group's welfare, for frequent floods in a small part of the city. However, for rare floods in a large part of the city, subsidized insurance is better than zoning for all income groups. When we consider high- and low-income households separately, the hierarchy of policies identified for total social welfare remains valid.

Although high- and low-income households generally agree on the second-best policy, in some rare cases, their preferences differ (appendix D). For example, under some circumstances,[5] low-income households favor subsidized insurance for central floods, as it allows them to keep living in the city center, with flood damage partly covered by high-income households. High-income households, on the other hand, prefer zoning. This points to possible, but nevertheless limited, political economy concerns in implementing the second-best policy that emerges from the social welfare function.

Table 2 shows that the myopic scenario leads to very unequal welfare outcomes across income groups. The income group living in the city center is much more affected than the other when floods occur in the city center, and less affected when floods occur in the periphery. By contrast, implementing flood management policies, which convey information about flood damage risks, allows for the costs of floods to be redistributed between high- and low-income households irrespective of who is directly affected. For example, when floods are in the city center and low-income households live in the city center, unanticipated frequent floods (myopic scenario) lead to direct utility losses of 27.3 percent for low-income households and 6.4 percent for high-income households, whereas land market mitigation limits the utility losses of low-income households to 7.1 percent and high-income households to 5.2 percent. In other words, functioning land markets that internalize flood risks also distribute flood costs across the population (through higher housing and transport costs) and prevent concentrated impacts on the affected population.

Land market mitigation can increase or decrease inequality, depending on who is directly affected by the floods. When mostly low-income households are affected, land market mitigation reduces their welfare losses, thus reducing inequalities compared to the myopic scenario. But when direct losses from floods affect mostly high-income households, land market mitigation can reduce the impact of floods

[5] 5-year return period / 30% of the city; 2-year return period / 70% of the city; 2-year return period / 80% of the city.

on high-income households at the expense of low-income households. In the more common scenario—where poorer populations are more exposed to urban floods (Bakkensen and Ma 2020; Winsemius et al. 2018)—internalizing flood risks in land markets and various flood management strategies are progressive and reduce inequalities.

Table 2. Utility losses from floods

Return period / coverage (area of city)	Myopic scenario (no flood information and no policy)			Risk-based insurance (after land market mitigation)			Subsidized insurance (after land market mitigation)			Zoning (after land market mitigation)		
	High-income	Low-income	Social welfare	High-income	Low-income	Social welfare	High-income	Low-income	Social welfare	High-income	Low-income	Social welfare
Low income-high income configuration												
5 years / 10% (center)	-6.4%	-27.3%	-13.2%	-5.2%	-7.1%	-5.9%	-13.5%	-13.6%	-13.5%	-7.5%	-10.1%	-8.4%
20 years / 50% (center)	-5.7%	-6.5%	-6.0%	-5.0%	-5.3%	-5.1%	-5.9%	-6.0%	-5.9%	-25.7%	-33.3%	-28.2%
5 years / 10% (uniform)	-2.6%	-2.2%	-2.4%	-0.9%	-1.0%	-0.9%	-2.3%	-2.5%	-2.4%	-1.1%	-1.2%	-1.2%
20 years / 50% (uniform)	-3.3%	-3.5%	-3.4%	-2.6%	-2.7%	-2.7%	-3.4%	-3.5%	-3.4%	-7.8%	-7.9%	-7.8%
5 years / 10% (periphery)	-3.6%	0%	-2.4%	-0.9%	-0.9%	-0.9%	-2.1%	-2.2%	-2.1%	-1.1%	-1.0%	-1.1%
20 years / 50% (periphery)	-2.2%	0%	-1.5%	-1.1%	-0.9%	-1.0%	-1.3%	-1.4%	-1.4%	-2.7%	-2.1%	-2.5%
High income-low income configuration												
5 years / 10% (center)	-26.6%	0%	-18.8%	-8.5%	-8.3%	-8.4%	-16.3%	-17.2%	-16.6%	-12.7%	-12.6%	-12.6%
20 years / 50% (center)	-6.5%	-6.0%	-6.3%	-5.4%	-5.5%	-5.4%	-6.0%	-6.4%	-6.1%	-37.7%	-38.5%	-37.9%
5 years / 10% (uniform)	-2.2%	-2.6%	-2.3%	-0.9%	-1.0%	-0.9%	-2.3%	-2.5%	-2.3%	-1.1%	-1.2%	-1.2%
20 years / 50% (uniform)	-3.5%	-3.3%	-3.4%	-2.7%	-2.8%	-2.7%	-3.4%	-3.7%	-3.5%	-8.0%	-8.1%	-8.0%
5 years / 10% (periphery)	0%	-4.6%	-1.4%	-0.5%	-0.7%	-0.6%	-1.3%	-1.4%	-1.3%	-0.7%	-0.8%	-0.7%
20 years / 50% (periphery)	0%	-2.2%	-0.7%	-0.5%	-0.7%	-0.6%	-0.7%	-0.8%	-0.8%	-1.2%	-1.3%	-1.2%

3.3 FLOOD MANAGEMENT AND INEQUALITIES

In this section, we further investigate the impact of the three flood management policies on inequalities, looking at how floods and flood management policies impact inequalities that are present even in the absence of floods. Figure 4 computes the efficiency (total welfare) and equity (Gini Index on household utilities) of the three policies, with each data point corresponding to one type of flood—that is, a combination of return period and flood-prone area. Figure 4 focuses on the *low income-high income* configuration with centrally located floods; other cases are documented in appendix A. The main results in terms of inequality will depend on where the poor and the rich live and whether flood-prone areas are: in the city center, uniformly distributed, or peripheral.

Figure 4. Inequality and welfare impact of the three policies when floods are located in the city center in the low income-high income configuration

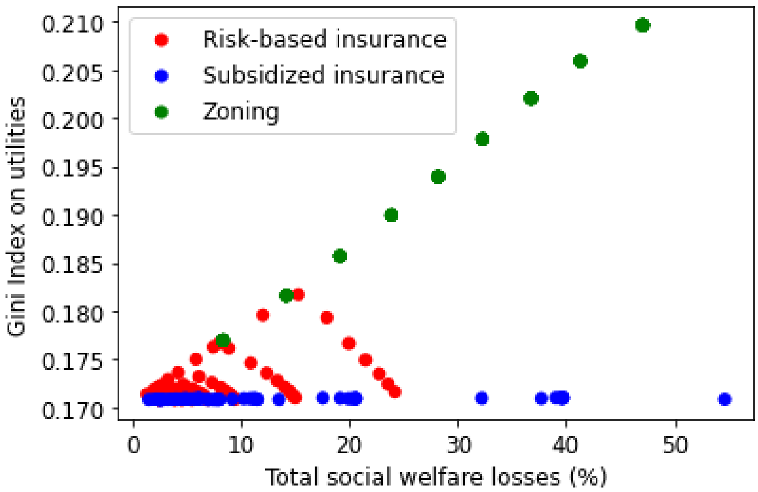


Figure 4 shows that, in the case of central floods and centrally located low-income households, zoning significantly increases inequalities, and subsidized insurance maintains inequality levels constant. Under subsidized insurance, everyone contributes to the insurance proportionately to their income, allowing low-income households to keep living in the city center with reasonable rents. Zoning forces low-income households away from the city center, increasing their transportation costs, which can become high compared to their income. In the case of frequent floods covering a small area, both types of households prefer zoning to subsidized insurance, although it increases inequalities between household types. This is an example of a partial efficiency-equity trade-off, with both income groups agreeing on the hierarchy of flood mitigation options, but experiencing relatively harsher/milder welfare outcomes that increase welfare inequalities. Risk-based insurance is the first-best policy in terms of social welfare, but increases inequalities in the *low income-high income* configuration; subsidized insurance, on the other hand, maintains the Gini Index constant in the *low income-high income* configuration for the three potential flood locations.

We can see that efficiency-equity trade-offs are more important for more frequent and larger floods. Figure 4 shows that subsidized insurance increases welfare losses and that zoning and risk-based insurance lead to higher increases in inequality when floods are more frequent or affect a larger share of the urban area.[6] Due to climate change, floods will increase in both extent and frequency (Hirabayashi et al. 2013), making the issue of efficiency and equity of flood management policies increasingly relevant.

[6] Floods that are more frequent or that affect a larger share of the urban area increase total social welfare losses and correspond to the dots on the right side of Figure 4.

4 DISCUSSION

This paper builds on Avner and Hallegatte (2019) in the analysis of the costs and benefits of three ex-ante flood management policies in an urban setting using a simple urban economics framework: risk-based insurance, subsidized insurance and land use zoning. It adds several important features to the previous paper: i) income heterogeneity, with both low- and high-income groups; ii) various locational configurations, where the high-income group resides in the city center or the periphery, depending on the presence and value of amenities; and iii) three locations for flood-prone areas: uniformly distributed (as in Avner and Hallegatte (2019)), centrally located, or peripheral. These additions allow for a richer set of analyses and the study of whether the choice of flood management policy leads to: i) political economy issues, with antagonistic preferences between high- and low-income households; and ii) efficiency-equity trade-offs.

As in Avner and Hallegatte (2019), risk-based insurance maximizes total social welfare. If implementing risk-based insurance is not feasible for technical, social, or political reasons, subsidized insurance for widespread and rare floods, or zoning in the case of frequent and localized flood events, are close to optimal. This result confirms that more feasible, second-best options need not come at large expense in terms of efficiency in aggregate. Zoning avoids structural damage but creates land scarcity for building purposes and drives housing rents up. Subsidized insurance—in the form of a flood compensation fund that every household contributes to—only conveys risk information indirectly and to a small extent and does not drastically reduce construction. And while it maintains a large building stock and consequently low housing rents, it also increases damage to structures in flood-prone areas.

The good news is that, with only a few exceptions for specific types of flood events, the hierarchy of flood management options coincides between high- and low-income groups, irrespective of urban configuration (high-income households living in the city center or the periphery) and flood location. This somewhat surprising result is important because it indicates that the choice of flood management type should not theoretically lead to political economy problems, where antagonistic preferences between household groups lead to a suboptimal solution being retained. However, the absence of political economy issues hinges on households of both income groups being able to recognize not only the direct effect of policies on flood damage, but also the indirect effects that take place through land and housing market adjustments.[7]

We also document that, compared to the myopic scenario—where landowners and households do not anticipate floods when making construction or locational decisions—flood management policies introduce flood risk information to a certain extent and therefore trigger land and housing market adjustments in the general equilibrium setting of classic urban economics that we employ here. Compared to the myopic scenario, these market adjustments redistribute costs between income classes, irrespective of who is directly affected by floods. As such, flood management policies can be progressive if the low-income group is hardest hit, or regressive if the high-income group is hardest hit. In most (but not all) cases, flood management policies would dominate the myopic scenario in terms of welfare outcomes for each income group and in aggregate.

We show that, although the hierarchy of flood management policies overwhelmingly coincides between income groups (and with aggregate social welfare by construction), it can nevertheless come at the expense of increased inequalities, compared to a no-flood scenario. Although both income groups prefer risk-based insurance, for central floods in the *low income-high income* configuration where low-

[7] This result holds if we assume that households succeed in properly assessing the full benefits of the policies. In practice, it is realistic to assume that households properly assess the benefits of the policies that are related to flood losses, but may be blind to the benefits of the policies that are related to housing costs.

income households live close to jobs, this type of insurance will deepen welfare inequalities across income groups compared to a no-flood situation. Whereas low-income households will be better off with risk-based insurance than any other policy in absolute terms, they will lose comparatively to high income groups. In this setting, only subsidized insurance, which taxes all households for flood damage in proportion to their income irrespective of whether they are at risk of floods, would maintain inequality levels constant across income groups. The situation would be reversed in the *high income-low income* configuration, where high-income households are directly hit by floods. In this case, risk-based insurance would lower inequality levels, while subsidized insurance would increase it, with the poorest effectively subsidizing risky location choices for the richest. These results point to a possible, though not systematic, equity-efficiency trade-off, and in some cases synergies.

The efficiency-inequality trade-offs (or synergies) are made more apparent as flood events are more damaging, either because of increased flood frequencies, increased flood-prone areas, or more intense events, all else equal. This result is relevant in the context of climate change (Hirabayashi et al. 2013). So, while the inequality impacts of flood management policies may appear as negligible for current climate conditions, they could prove much larger in the future. Considering the inertia displayed by structures and urban areas, and assuming that inequality levels can reach unsustainable levels from moral or political perspectives, irrespective of absolute welfare levels of each income group, it is important to take them into account today to avoid future widening of inequalities.

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Appendix A. Figures

Figure A1. Total social welfare losses due to floods in the high income-low income configuration

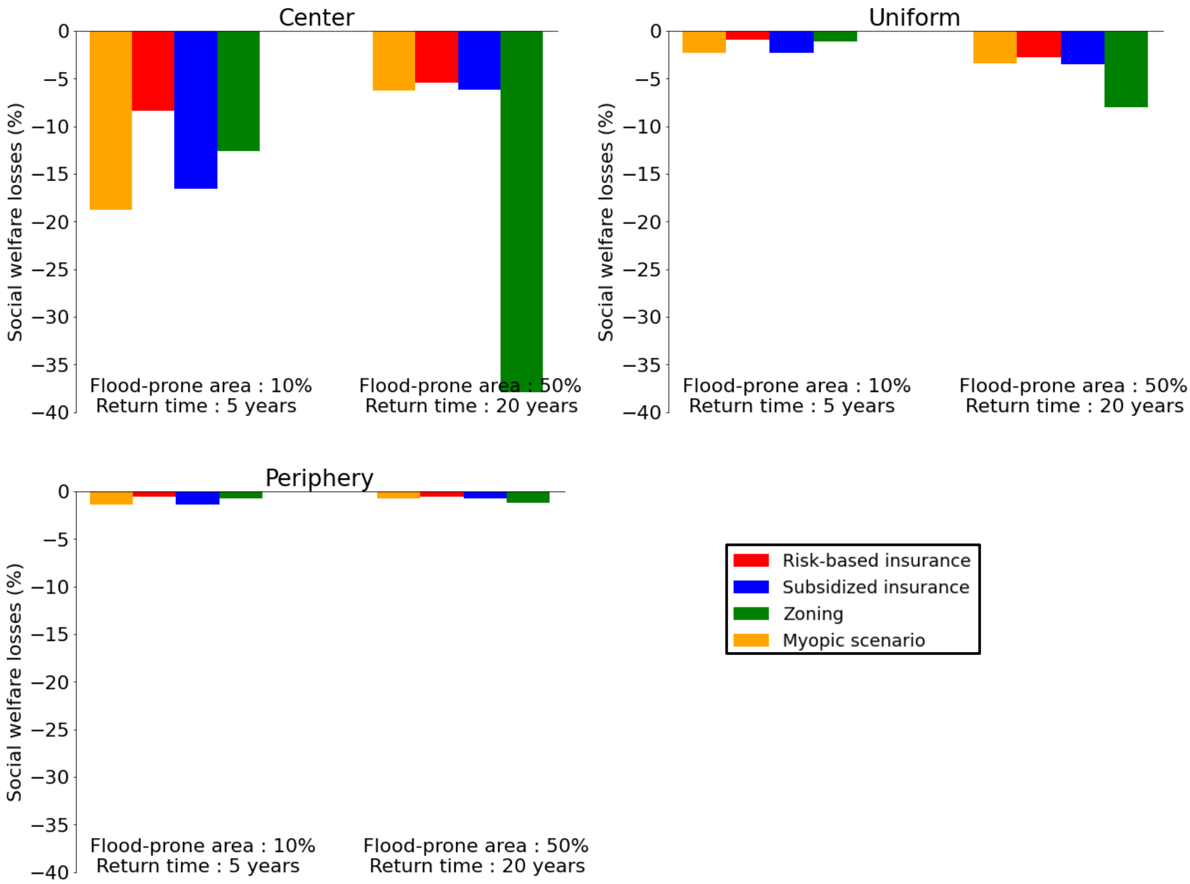
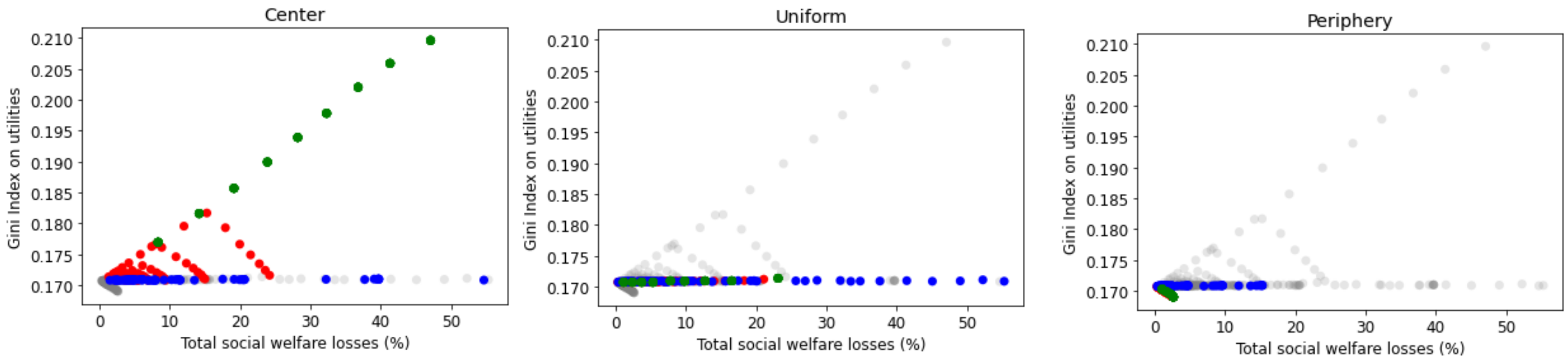
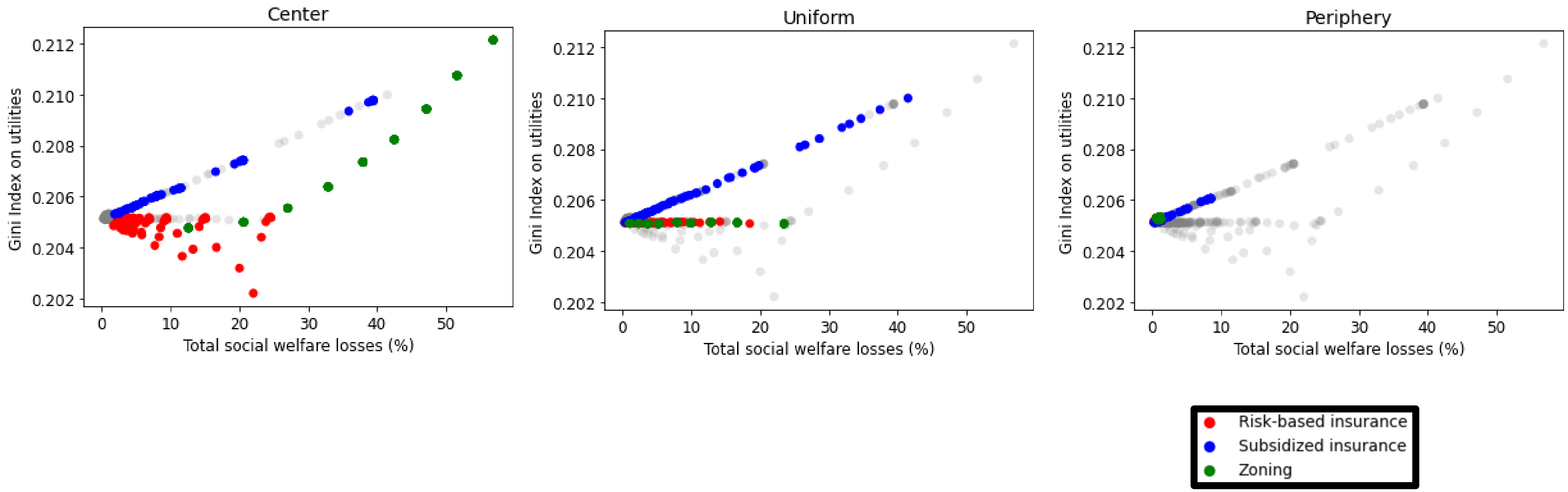


Figure A2. Inequality and welfare impact of the three policies in the two settings

a. Low income-high income configuration



b. High income-low income configuration



The impact of the three policies on inequality depends on flood location and urban configuration. Figure A2 provides comparable figures to figure 4 in the core text for all six cases: central, uniform and peripheral floods in cities where poor households live in center and those where they live in the outskirts. In summary, we find that:

- In the *low-income–high-income* configuration, subsidized insurance maintains inequality levels constant. Zoning increases inequality if floods are located in the city center, as it prevents low-income households from living in their preferred location, and decreases inequality if floods are located in the periphery, as it prevents high-income households from living in the periphery and enjoying large dwellings. A risk-based insurance stands between these two cases.

- In the *high-income–low-income* configuration, subsidized insurance increases inequality as low-income households subsidize the consumption of amenities by high-income households. When floods are in the periphery, their impact is extremely limited in terms of inequality and social welfare. When floods are distributed proportionally to the city center and zoning or risk-based insurance policies are implemented, an increase in the frequency or extent of floods has little or no impact on inequality, as both income classes are impacted by the floods, similarly to the *low income-high income* configuration. But when floods are concentrated in the city center and risk-based insurance is implemented, an increase in the extent and frequency of flooding decreases inequality because, even with land market mitigation, high-income households are more impacted by floods.

APPENDIX B. MATHEMATICAL APPENDIX

This appendix is largely derived from Brueckner, Thisse and Zenou (1999). We want to show that, assuming exogeneous amenities with more amenities in the city center, if the amenity gradient is steep enough, with our utility specification, high-income households live in the city center.

Two forces are at play in opposite directions:

1. Conventional forces push high-income households to the periphery.
2. Demand for amenities pushes high-income households to the city center.

Formally, we denote r the distance to the CBD, and consider an exogenous level of amenities at each distance from the CBD denoted $A(r)$. We consider two income classes: high- and low-income households. We denote Y_0 and Y_1 their incomes, assuming that $Y_0 < Y_1$, and T_0 and T_1 their transportation costs, assuming that $T_1 > T_0$. Households consume quantities of housing q_1 and q_0 with rents per unit of housing R_1 and R_0 and a composite good z_1 and z_0 with prices normalized at 1.

Utility is given by:

$$U(z, q, A) = z^{1-\beta} q^{\beta} A^{y}, \text{ with } \gamma_{rich} > \gamma_{poor}$$

$$s.c.\, q(r)R(r) + z(r) \leq Y - T(r)$$

We consider that high-income households live where their bid-rent is higher than the bid-rent of low-income households. Writing $\hat{r}$ the tipping point between high- and low-income households, high-income households live in the city center if the difference in the bid-rent slopes at $\hat{r}$ for the two groups is negative—that is, if:

$$R_1'(\hat{r}) - R_0'(\hat{r}) < 0 \qquad \text{(A1)}$$

Following Brueckner, Thisse and Zenou, equation (A1) rewrites:

$$\frac{T_0}{q_0(\hat{r})} - \frac{T_1}{q_1(\hat{r})} + A'(\hat{r})\left(\frac{v^A\,[Y_1 - T_1(\hat{r}),\ R_1(\hat{r}),\ A(\hat{r})]}{q_1(\hat{r})} - \frac{v^A\,[Y_0 - T_0(\hat{r}),\ R_0(\hat{r}),\ A(\hat{r})]}{q_0(\hat{r})}\right) \qquad \text{(A2)}$$

With $v[Y - T(r), R(r), A(r)]$ the indirect utility function and v^A the partial derivative of the indirect utility function with respect to A. Thus, v^A gives the marginal valuation of amenities after optimal adjustment of housing consumption.

What is the sign of (A2)?

- First, conventional locational effects, as embodied in the T/q ratio, are assumed to favor the suburban location of the high-income households. So, the first part of the equation is positive.
- Then, the gradient of amenities A' is assumed to be negative (that is, there are more amenities in the city center).
- We show in what follows that the valuation of amenities increases with income with our utility specification—that is, $\frac{v^A\,[Y_1 - T_1(\hat{r}), R_1(\hat{r}), A(\hat{r})]}{q_1(\hat{r})} - \frac{v^A\,[Y_0 - T_0(\hat{r}), R_0(\hat{r}), A(\hat{r})]}{q_0(\hat{r})} > 0$.

Denoting U^A and U^Z the derivatives of the utility function with respect to A and z:

$$U^A = \gamma\, z^{1-\beta} q^\beta A^{\gamma-1}$$

$$U^z = (1-\beta) z^{-\beta}\, q^\beta A^\gamma$$

$$q(r) = \beta(Y - T(r)) \,/\, R(r) \text{ and } z(r) = (1-\beta)\,(Y - T(r))$$

$$v^A/q = [(\gamma\, z^{1-\beta} q^\beta A^{\gamma-1}) \,/\, ((1-\beta) z^{-\beta}\, q^\beta A^\gamma)] \,/\, [\beta(Y - T(r)) \,/\, R(r)]$$

And thus $v^A/q = [\gamma\, z \,/(1-\beta)\, A] \,/\, [\beta(Y - T(r)) \,/\, R(r)]$

$$\Rightarrow v^A/q = [\gamma\,(Y - T(r))\, R(r)] \,/\, [A\,\beta(Y - T(r))] = \gamma\, R(r) \,/\, A\,\beta$$

As $\gamma_{rich} > \gamma_{poor}$, v^A/q increases with income, the marginal valuation of amenities rises with income and its rise is more rapid than the rise in housing consumption.

Conclusion: if the amenity gradient is steep enough, amenity demand dominates conventional forces and leads high-income households to live in the city center.

APPENDIX C. SENSITIVITY ANALYSIS

Robustness check 1 (fraction of damaged capital = 10%)

Risk-based insurance is the first-best option in terms of i) social welfare, ii) utility of high-income households, and iii) utility of low-income households.

The baseline results in terms of inequality are robust, but of a lower magnitude for risk-based and subsidized insurance.

Zoning is the second-best option for frequent floods in small areas and subsidized insurance is second-best for rare floods in large areas. But the tipping point between subsidized insurance and zoning has changed, with subsidized insurance preferred in a larger number of cases.

Robustness check 2 (fraction of damaged capital = 70%)

Risk-based insurance is first-best in terms of i) social welfare, ii) utility of high-income households, and iii) utility of low-income households.

The baseline results in terms of inequalities are robust, but of a higher magnitude for risk-based and subsidized insurance.

Zoning is second-best for frequent floods in small areas and subsidized insurance for rare floods in large areas. But the tipping point between subsidized insurance and zoning has changed, with zoning preferred in a larger number of cases.

Robustness check 3 (fraction of low-income households = 80%)

Risk-based insurance is first-best in terms of i) social welfare and ii) utility of low-income households.

High-income households living in the periphery prefer subsidized insurance in the case of floods in the periphery, but the difference between subsidized and risk-based insurance when high-income households prefer a subsidized insurance is extremely low (less than 1 percent).

The overall Gini Index is lower. The baseline results in terms of inequality and second-best are robust.

Robustness check 4 (fraction of low-income households = 20%)

Risk-based insurance is first-best in terms of i) social welfare, ii) utility of high-income households, and iii) utility of low-income households.

The overall Gini Index is higher. The baseline results in terms of inequality and second-best are robust.

Robustness check 5 (β = 0.7)

Risk-based insurance is first-best in terms of i) social welfare, ii) utility of high-income households, and iii) utility of low-income households in the *low income-high income* configuration.

But while risk-based insurance is also first–best for high-income households in the *high income-low income* configuration, for low-income households, either risk-based or subsidized insurance is first-best.

The overall Gini Index is lower. The results in terms of inequality and second-best are robust.

APPENDIX D. HEATMAPS

Table D1. Utility differential (%) between the first- and second-best policies

Interpretation: In the *low income-high income* configuration, when floods are in the city center, the flood-prone area is 20% of the city, and floods occur every 5 years, the second-best policy results in a utility loss of 5% for high-income households and of 7% for low-income households.

Low income-high income configuration

		High-income households									Low-income households								
		10	20	30	40	50	60	70	80	90	10	20	30	40	50	60	70	80	90
Flood distributed uniformly across the city	50	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0
	30	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0
	25	-0	-0	-0	-0	-1	-1	-1	-1	-1	-0	-0	-0	-0	-1	-1	-1	-1	-1
	20	-0	-0	-0	-1	-1	-1	-1	-1	-1	-0	-0	-1	-1	-1	-1	-1	-1	-1
	15	-0	-1	-1	-1	-1	-1	-1	-1	-1	-0	-1	-1	-1	-1	-1	-1	-1	-1
	10	-0	-1	-2	-2	-2	-3	-3	-3	-3	-0	-1	-2	-2	-2	-3	-3	-3	-3
	5	-0	-1	-1	-1	-2	-3	-5	-7	-8	-0	-1	-1	-1	-2	-3	-5	-7	-8
	2	-0	-0	-0	-0	-1	-1	-2	-3	-6	-0	-0	-0	-1	-1	-1	-2	-3	-6
	1	-0	-0	-0	-0	-0	-0	-1	-1	-3	-0	-0	-0	-0	-0	-0	-1	-1	-3
Flood in the city center	50	-0	-0	-0	-0	-0	-0	-0			0	-0	-0	-0	-0	-0	-0		
	30	-1	-1	-1	-0	-0	-0	-0			-0	-0	-0	-0	-0	-0	-0		
	25	-1	-1	-1	-1	-1	-1	-1			-0	-0	-0	-0	-0	-0	-0		
	20	-1	-1	-1	-1	-1	-1	-1			-0	-1	-1	-1	-1	-1	-1		
	15	-2	-2	-2	-2	-1	-1	-1			-1	-1	-1	-1	-1	-1	-1		
	10	-3	-4	-3	-3	-3	-3	-2			-2	-3	-3	-3	-3	-2	-2		
	5	-2	-5	-8	-9	-8	-8	-7			-3	-7	-8	-8	-7	-7	-7		
	2	-1	-2	-4	-6	-8	-11	-15			-1	-3	-6	-10	-15	-20	-21		
	1	-0									-0								
Flood in the periphery	50	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0
	30	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0
	25	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0
	20	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-1	-1	-1	-1
	15	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-1	-1	-1	-1	-1	-1	-1
	10	-0	-1	-1	-1	-1	-1	-1	-1	-1	-0	-1	-1	-1	-1	-1	-1	-1	-1
	5	-0	-0	-1	-1	-1	-1	-1	-1	-1	-0	-0	-0	-0	-0	-0	-0	-1	-1
	2	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0
	1	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	0	-0	-0	-0	-0	-0	-0

High income-low income configuration

		High-income households									Low-income households								
		10	20	30	40	50	60	70	80	90	10	20	30	40	50	60	70	80	90
Flood distributed uniformly across the city	50	0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0
	30	0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-1	-1	-0
	25	0	-0	-0	-0	-0	-1	-1	-0	-0	-0	-0	-0	-1	-1	-1	-1	-1	-1
	20	0	-0	-0	-1	-1	-1	-1	-1	-1	-0	-0	-1	-1	-1	-1	-1	-1	-1
	15	0	-1	-1	-1	-1	-1	-1	-1	-1	-0	-1	-1	-1	-1	-2	-2	-2	-2
	10	0	-1	-1	-2	-2	-3	-3	-3	-2	-0	-1	-2	-2	-3	-3	-3	-3	-3
	5	0	-1	-1	-1	-2	-3	-5	-7	-7	-0	-1	-1	-1	-2	-3	-5	-7	-8
	2	0	-0	-0	-0	-1	-1	-2	-3	-6	-0	-0	-0	-0	-1	-1	-2	-3	-6
	1	0	-0	-0	-0						-0	-0	-0	-0					
Flood in the city center	50	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0
	30	-0	-0	-0	-0	-0	-0	-0	-0	-0	-1	-1	-1	-1	-0	-1	-0	-0	-0
	25	-0	-0	-0	-0	-0	-1	-0	-0	-0	-1	-1	-1	-1	-1	-1	-1	-1	-1
	20	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
	15	-1	-1	-1	-1	-1	-1	-1	-1	-1	-2	-2	-2	-2	-2	-2	-1	-1	-1
	10	-3	-3	-2	-2	-2	-2	-2	-2	-2	-4	-4	-3	-3	-3	-3	-3	-3	-3
	5	-5	-8	-7	-7	-7	-7	-6	-6	-6	-5	-10	-9	-8	-8	-8	-7	-7	-7
	2																		
	1																		
Flood in the periphery	50	0	-0	-0	-0	-0	-0	-0	-0	-0	-0	0	0	0	-0	-0	-0	-0	-0
	30	0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0
	25	0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0
	20	0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0
	15	0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0
	10	0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0
	5	0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0
	2	0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0
	1	0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	-0	0	-0	-0	-0

Notes: X axis = proportion of flood-prone area (%); y axis = flood return time (years); proportion of damaged capital in flood-prone areas = 40%. Red cells correspond to high utility differentials between the first- and second-best policies, and green cells correspond to low utility differentials. In some cases, flood damages were too high for the model to converge (blank cells).

Table D2. Second-best flood management policy

Interpretation: In the *low income-high income* configuration, when floods are located in the city center, the flood-prone area represents 30% of the city, and floods occur every 5 years, zoning is the second-best policy for high-income households and subsidized insurance is the second-best policy for low-income households.

Low income-high income configuration

Flood distributed uniformly across the city

	High-income households									Low-income households									Total welfare								
50	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
30	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
25	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
20	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
15	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
10	Z	Z	S	S	S	S	S	S	S	Z	Z	S	S	S	S	S	S	S	Z	Z	S	S	S	S	S	S	S
5	Z	Z	Z	Z	Z	Z	Z	Z	S	Z	Z	Z	Z	Z	Z	Z	Z	S	Z	Z	Z	Z	Z	Z	Z	Z	S
2	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z
1	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z
	10	20	30	40	50	60	70	80	90	10	20	30	40	50	60	70	80	90	10	20	30	40	50	60	70	80	90

Flood in the city center

	High-income households									Low-income households									Total welfare								
50	S	S	S	S	S	S	S			S	S	S	S	S	S	S			S	S	S	S	S	S	S		
30	S	S	S	S	S	S	S			S	S	S	S	S	S	S			S	S	S	S	S	S	S		
25	S	S	S	S	S	S	S			S	S	S	S	S	S	S			S	S	S	S	S	S	S		
20	S	S	S	S	S	S	S			S	S	S	S	S	S	S			S	S	S	S	S	S	S		
15	S	S	S	S	S	S	S			S	S	S	S	S	S	S			S	S	S	S	S	S	S		
10	S	S	S	S	S	S	S			S	S	S	S	S	S	S			S	S	S	S	S	S	S		
5	Z	Z	Z	S	S	S	S			Z	Z	S	S	S	S	S			Z	Z	Z	S	S	S	S		
2	Z	Z	Z	Z	Z	Z	Z			Z	Z	Z	Z	Z	Z	S			Z	Z	Z	Z	Z	Z	Z		
1	Z									Z									Z								
	10	20	30	40	50	60	70	80	90	10	20	30	40	50	60	70	80	90	10	20	30	40	50	60	70	80	90

Flood in the periphery

	High-income households									Low-income households									Total welfare								
50	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
30	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
25	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
20	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
15	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
10	Z	S	S	S	S	S	S	S	S	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	S	S	S	S	S
5	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z
2	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z
1	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z
	10	20	30	40	50	60	70	80	90	10	20	30	40	50	60	70	80	90	10	20	30	40	50	60	70	80	90

High income-low income configuration

Flood distributed uniformly across the city

	High-income households									Low-income households									Total welfare								
50	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
30	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
25	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
20	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
15	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
10	Z	Z	S	S	S	S	S	S	S	Z	Z	Z	S	S	S	S	S	S	Z	Z	Z	S	S	S	S	S	S
5	Z	Z	Z	Z	Z	Z	Z	Z	S	Z	Z	Z	Z	Z	Z	Z	Z	S	Z	Z	Z	Z	Z	Z	Z	Z	S
2	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z
1	Z	Z	Z	Z						Z	Z	Z	Z						Z	Z	Z	Z					
	10	20	30	40	50	60	70	80	90	10	20	30	40	50	60	70	80	90	10	20	30	40	50	60	70	80	90

Flood in the city center

	High-income households									Low-income households									Total welfare								
50	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
30	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
25	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
20	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
15	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
10	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
5	Z	S	S	S	S	S	S	S	S	Z	S	S	S	S	S	S	S	S	Z	S	S	S	S	S	S	S	S
2																											
1																											
	10	20	30	40	50	60	70	80	90	10	20	30	40	50	60	70	80	90	10	20	30	40	50	60	70	80	90

Flood in the periphery

	High-income households									Low-income households									Total welfare								
50	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
30	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
25	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
20	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
15	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
10	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z
5	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z
2	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z
1	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z	Z
	10	20	30	40	50	60	70	80	90	10	20	30	40	50	60	70	80	90	10	20	30	40	50	60	70	80	90

Notes: S = subsidized insurance; Z = zoning; x axis = proportion of flood-prone area in the city (%); y axis = flood return time (years); proportion of damaged capital in flood-prone areas = 40%. In blue cells, the second-best policy is a subsidized insurance policy, and in orange cells, the second-best policy is a zoning policy. In some cases, flood damages were too high for the model to converge (blank cells).

Table D3. Utility differential (%) of choosing subsidized insurance instead of zoning

Interpretation: In the *low income-high income* configuration, when floods are located in the city center, the flood-prone area represents 20% of the city, and floods occur every 5 years, choosing a subsidized insurance policy over zoning results in a utility loss of 5% for high-income households and of 1% for low-income households.

Low income-high income configuration

	High-income households										Low-income households									
		10	20	30	40	50	60	70	80	90		10	20	30	40	50	60	70	80	90
Flood distributed uniformly across the city	50	0.8	1.8	3	4.4	6.9	9	12	17	27	50	0.8	1.8	2.9	4.4	6.9	9.1	12	17	27
	30	0.6	1.5	2.5	3.8	5.9	7.9	11	16	25	30	0.6	1.5	2.4	3.7	6	8	11	16	25
	25	0.6	1.3	2.3	3.4	5.5	7.4	10	15	24	25	0.6	1.3	2.2	3.4	5.5	7.4	10	15	24
	20	0.5	1.1	1.9	2.9	4.8	6.6	9.4	14	23	20	0.4	1.1	1.8	2.9	4.8	6.6	9.4	14	23
	15	0.3	0.7	1.3	2.1	3.7	5.2	7.8	12	20	15	0.2	0.7	1.2	2.1	3.7	5.3	7.9	12	21
	10	-0	-0	0.1	0.5	1.5	2.7	4.8	8.3	16	10	-0	-0	0	0.4	1.5	2.7	4.8	8.4	16
	5	-1	-2	-3	-4	-5	-4	-3	-1	5	5	-1	-2	-3	-4	-5	-4	-3	-1	5.2
	2	-4	-9	-12	-16	-19	-21	-22	-22	-19	2	-4	-9	-12	-16	-19	-21	-22	-22	-19
	1	-9	-18	-24	-30	-36	-39	-42	-43	-42	1	-9	-18	-24	-30	-36	-39	-42	-43	-42
Flood in the city center	50	6.5	12	18	25	31	38	47			50	9.5	18	27	36	46	57	70		
	30	5.5	11	17	23	29	36	45			30	8.5	17	25	34	44	54	67		
	25	5	10	16	22	28	35	44			25	8	16	24	33	43	53	66		
	20	4.3	9.3	15	20	27	33	42			20	7.3	15	23	31	41	51	64		
	15	3.1	7.6	13	18	24	31	39			15	6	13	20	29	38	48	61		
	10	0.7	4.2	8.6	14	20	26	34			10	3.5	9.4	16	24	33	43	55		
	5	-6	-5	-2	2.3	7.3	13	20			5	-4	-1	4.7	12	19	28	39		
	2	-27	-29	-26	-23	-19	-14	-9			2	-25	-25	-21	-16	-10	-3	5.3		
	1	-51									1	-50								
Flood in the periphery	50	0.8	1.3	1.7	1.9	2.1	2.2	2.3	2.3	2.3	50	0.6	0.9	1.2	1.3	1.4	1.4	1.5	1.5	1.5
	30	0.7	1.1	1.4	1.7	1.8	1.9	2	2	2	30	0.4	0.7	0.9	1	1.1	1.1	1.1	1.1	1.1
	25	0.6	1	1.3	1.5	1.6	1.7	1.8	1.8	1.8	25	0.4	0.6	0.7	0.8	0.9	0.9	1	1	1
	20	0.5	0.8	1.1	1.3	1.4	1.5	1.5	1.6	1.6	20	0.3	0.5	0.6	0.6	0.7	0.7	0.7	0.7	0.7
	15	0.3	0.6	0.8	0.9	1	1.1	1.1	1.1	1.1	15	0.1	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3
	10	-0	0.1	0.1	0.2	0.3	0.3	0.4	0.4	0.4	10	-0	-0	-0	-0	-0	-0	-0	-1	-1
	5	-1	-1	-2	-2	-2	-2	-2	-2	-2	5	-1	-2	-2	-2	-3	-3	-3	-3	-3
	2	-4	-5	-6	-7	-7	-7	-7	-7	-7	2	-4	-6	-7	-7	-7	-8	-8	-8	-8
	1	-8	-10	-12	-12	-13	-13	-13	-13	-13	1	-8	-11	-12	-13	-13	-13	-13	-13	-13

High income-low income configuration

	High-income households										Low-income households									
		10	20	30	40	50	60	70	80	90		10	20	30	40	50	60	70	80	90
Flood distributed uniformly across the city	50	0.8	1.8	2.9	4.4	7.1	9.2	13	17	28	50	0.7	1.8	2.9	4.3	7	9.1	12	17	27
	30	0.6	1.5	2.4	3.7	6.1	8.1	11	16	26	30	0.6	1.4	2.4	3.6	6	7.9	11	16	25
	25	0.5	1.3	2.2	3.4	5.7	7.5	11	15	25	25	0.5	1.3	2.1	3.3	5.5	7.4	10	15	24
	20	0.4	1.1	1.9	2.9	5	6.7	9.7	14	23	20	0.4	1	1.7	2.8	4.8	6.5	9.4	14	23
	15	0.3	0.7	1.3	2.1	3.9	5.4	8.1	12	21	15	0.2	0.6	1.1	1.9	3.6	5.1	7.7	12	21
	10	-0	-0	0.1	0.5	1.7	2.9	5.1	8.7	17	10	-0	-0	-0	0.3	1.3	2.5	4.6	8.2	16
	5	-1	-2	-3	-4	-4	-4	-3	-1	5.9	5	-1	-3	-4	-4	-5	-5	-4	-2	4.8
	2	-4	-9	-12	-15	-19	-21	-33	-33	-42	2	-5	-9	-13	-16	-20	-22	-31	-33	-38
	1	-9	-17	-23	-35						1	-9	-18	-25	-35					
Flood in the city center	50	12	23	34	45	56	68	83	100	123	50	12	23	34	46	58	70	87	105	131
	30	11	21	32	43	54	66	80	96	120	30	11	21	32	43	55	68	84	101	127
	25	10	20	31	42	53	64	79	95	118	25	10	20	30	42	54	66	82	100	125
	20	9.4	19	29	40	51	62	77	92	115	20	9	19	29	40	52	64	80	97	122
	15	7.8	17	27	37	48	59	73	89	111	15	7.3	17	26	37	49	61	76	93	118
	10	4.7	13	22	32	42	53	67	82	103	10	4	12	22	32	43	54	69	86	109
	5	-4	2	9.8	19	28	38	50	63	83	5	-5	0.9	8.8	18	28	38	51	66	87
	2										2									
	1										1									
Flood in the periphery	50	0.4	0.4	0.6	0.7	0.8	0.8	0.8	0.8	0.8	50	0.5	0.5	0.7	0.8	0.9	0.9	0.9	0.9	0.9
	30	0.3	0.3	0.5	0.6	0.6	0.7	0.7	0.7	0.7	30	0.4	0.4	0.5	0.6	0.7	0.7	0.7	0.7	0.7
	25	0.3	0.3	0.4	0.5	0.6	0.6	0.6	0.6	0.6	25	0.4	0.4	0.5	0.5	0.6	0.6	0.7	0.6	0.6
	20	0.2	0.2	0.3	0.4	0.4	0.5	0.5	0.5	0.5	20	0.3	0.3	0.4	0.5	0.5	0.5	0.5	0.5	0.5
	15	0.1	0.1	0.2	0.2	0.3	0.3	0.3	0.3	0.3	15	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3
	10	-0	-0	-0	-0	-0	-0	-0	-0	-0	10	-0	-0	-0	-0	-0	-0	-0	-0	-0
	5	-1	-1	-1	-1	-1	-1	-1	-1	-1	5	-1	-1	-1	-1	-1	-1	-1	-1	-1
	2	-2	-2	-3	-3	-4	-4	-4	-4	-4	2	-2	-2	-3	-4	-4	-4	-4	-4	-4
	1	-5	-5	-6	-7	-7	-7	-7	-7	-7	1	-5	-5	-6	-7	-8	-8	-8	-8	-8

Notes: X axis = proportion of flood-prone area in the city (%); y axis = flood return time (years); proportion of damaged capital in flood-prone areas = 40%. Red cells correspond to high utility differentials of choosing subsidized insurance instead of zoning, and green cells correspond to low utility differentials. In some cases, flood damages were too high for the model to converge (blank cells).

Table D4. Social welfare loss compared to a situation without floods

Interpretation: in the *low income-high income* configuration, when floods are in the city center, the flood-prone area is 20% of the city, and floods occur every 5 years, zoning results in a social welfare loss of -14%.

Low income-high income configuration

Risk-based insurance

		10	20	30	40	50	60	70	80	90
Flood distributed uniformly across the city	50	-0	-1	-1	-1	-1	-2	-2	-2	-2
	30	-0	-1	-1	-2	-2	-2	-3	-3	-4
	25	-1	-1	-1	-2	-2	-3	-3	-4	-4
	20	-1	-1	-1	-2	-3	-3	-4	-4	-5
	15	-1	-1	-2	-2	-3	-4	-5	-5	-6
	10	-1	-1	-2	-3	-4	-5	-6	-7	-8
	5	-1	-2	-3	-4	-6	-7	-9	-10	-13
	2	-1	-2	-3	-5	-7	-9	-11	-14	-18
	1	-1	-2	-4	-5	-8	-9	-12	-16	-21
Flood in the city center	50	-1	-2	-2	-2	-2	-2	-2	-3	-3
	30	-2	-3	-3	-4	-4	-4	-4	-4	-4
	25	-2	-3	-4	-4	-4	-4	-4	-5	-5
	20	-3	-4	-4	-5	-5	-5	-5	-5	-6
	15	-3	-5	-6	-6	-6	-7	-7	-7	-7
	10	-4	-6	-7	-8	-9	-9	-9	-9	-9
	5	-6	-9	-11	-12	-13	-14	-15	-15	-15
	2	-7	-12	-15	-18	-20	-22	-23	-24	-24
	1	-8								
Flood in the periphery	50	-0	-0	-1	-1	-1	-1	-1	-1	-1
	30	-0	-1	-1	-1	-1	-1	-1	-1	-1
	25	-0	-1	-1	-1	-1	-1	-1	-1	-1
	20	-1	-1	-1	-1	-1	-1	-1	-1	-1
	15	-1	-1	-1	-1	-1	-1	-1	-1	-1
	10	-1	-1	-1	-1	-1	-2	-2	-2	-2
	5	-1	-1	-2	-2	-2	-2	-2	-2	-2
	2	-1	-2	-2	-2	-2	-2	-2	-2	-2
	1	-1	-2	-2	-2	-2	-3	-3	-3	-3

Zoning

		10	20	30	40	50	60	70	80	90
Flood distributed uniformly across the city	50	-1	-2	-4	-5	-8	-10	-13	-17	-23
	30	-1	-2	-4	-5	-8	-10	-13	-17	-23
	25	-1	-2	-4	-5	-8	-10	-13	-17	-23
	20	-1	-2	-4	-5	-8	-10	-13	-17	-23
	15	-1	-2	-4	-5	-8	-10	-13	-17	-23
	10	-1	-2	-4	-5	-8	-10	-13	-17	-23
	5	-1	-2	-4	-5	-8	-10	-13	-17	-23
	2	-1	-2	-4	-5	-8	-10	-13	-17	-23
	1	-1	-2	-4	-5	-8	-10	-13	-17	-23
Flood in the city center	50	-8	-14	-19	-24	-28	-32	-37	-41	-47
	30	-8	-14	-19	-24	-28	-32	-37	-41	-47
	25	-8	-14	-19	-24	-28	-32	-37	-41	-47
	20	-8	-14	-19	-24	-28	-32	-37	-41	-47
	15	-8	-14	-19	-24	-28	-32	-37	-41	-47
	10	-8	-14	-19	-24	-28	-32	-37	-41	-47
	5	-8	-14	-19	-24	-28	-32	-37	-41	-47
	2	-8	-14	-19	-24	-28	-32	-37	-41	-47
	1	-8								
Flood in the periphery	50	-1	-2	-2	-2	-2	-3	-3	-3	-3
	30	-1	-2	-2	-2	-2	-3	-3	-3	-3
	25	-1	-2	-2	-2	-2	-3	-3	-3	-3
	20	-1	-2	-2	-2	-2	-3	-3	-3	-3
	15	-1	-2	-2	-2	-2	-3	-3	-3	-3
	10	-1	-2	-2	-2	-2	-3	-3	-3	-3
	5	-1	-2	-2	-2	-2	-3	-3	-3	-3
	2	-1	-2	-2	-2	-2	-3	-3	-3	-3
	1	-1	-2	-2	-2	-2	-3	-3	-3	-3

Subsidized insurance

		10	20	30	40	50	60	70	80	90
Flood distributed uniformly across the city	50	-0	-1	-1	-1	-1	-2	-2	-2	-2
	30	-1	-1	-1	-2	-2	-3	-3	-4	-4
	25	-1	-1	-2	-2	-3	-3	-4	-4	-5
	20	-1	-1	-2	-3	-3	-4	-5	-5	-6
	15	-1	-2	-3	-3	-4	-5	-6	-7	-7
	10	-1	-3	-4	-5	-6	-7	-9	-10	-11
	5	-2	-5	-7	-9	-12	-14	-16	-17	-19
	2	-6	-11	-16	-20	-26	-29	-32	-35	-38
	1	-10	-20	-27	-33	-41	-45	-49	-52	-55
Flood in the city center	50	-2	-2	-2	-2	-3	-3	-3	-3	-3
	30	-2	-3	-4	-4	-4	-4	-4	-4	-4
	25	-3	-4	-4	-5	-5	-5	-5	-5	-5
	20	-4	-5	-5	-6	-6	-6	-6	-6	-6
	15	-5	-6	-7	-7	-8	-8	-8	-8	-8
	10	-7	-9	-10	-11	-11	-11	-11	-11	-12
	5	-14	-18	-19	-20	-20	-20	-21	-21	-21
	2	-32	-38	-39	-39	-40	-40	-40	-40	-40
	1	-55								
Flood in the periphery	50	-0	-1	-1	-1	-1	-1	-1	-1	-1
	30	-1	-1	-1	-1	-1	-1	-1	-1	-1
	25	-1	-1	-1	-1	-1	-1	-1	-1	-1
	20	-1	-1	-1	-1	-1	-1	-1	-1	-1
	15	-1	-1	-1	-2	-2	-2	-2	-2	-2
	10	-1	-2	-2	-2	-2	-3	-3	-3	-3
	5	-2	-3	-4	-4	-4	-5	-5	-5	-5
	2	-5	-7	-8	-9	-9	-10	-10	-10	-10
	1	-9	-12	-14	-14	-15	-15	-15	-15	-15

High income-low income configuration

Risk-based insurance

		10	20	30	40	50	60	70	80	90
Flood distributed uniformly across the city	50	-0	-1	-1	-1	-1	-2	-2	-2	-2
	30	-0	-1	-1	-2	-2	-2	-3	-3	-4
	25	-1	-1	-1	-2	-2	-3	-3	-4	-4
	20	-1	-1	-1	-2	-3	-3	-4	-4	-5
	15	-1	-1	-2	-2	-3	-4	-5	-5	-6
	10	-1	-1	-2	-3	-4	-5	-6	-7	-8
	5	-1	-2	-3	-4	-6	-7	-9	-10	-13
	2	-1	-2	-3	-5	-7	-9	-11	-14	-19
	1	-1	-2	-4	-5	-8				
Flood in the city center	50	-2	-2	-2	-2	-3	-3	-3	-3	-3
	30	-3	-3	-4	-4	-4	-4	-4	-4	-4
	25	-3	-4	-4	-4	-5	-5	-5	-5	-5
	20	-4	-5	-5	-5	-5	-6	-6	-6	-6
	15	-5	-6	-6	-7	-7	-7	-7	-7	-7
	10	-6	-8	-9	-9	-9	-9	-9	-9	-10
	5	-8	-12	-13	-14	-15	-15	-15	-15	-15
	2	-11	-17	-20	-22	-23	-24	-24	-25	-25
	1									
Flood in the periphery	50	-0	-0	-0	-0	-0	-0	-0	-0	-0
	30	-0	-0	-0	-0	-0	-1	-1	-1	-1
	25	-0	-0	-1	-1	-1	-1	-1	-1	-1
	20	-0	-1	-1	-1	-1	-1	-1	-1	-1
	15	-0	-1	-1	-1	-1	-1	-1	-1	-1
	10	-1	-1	-1	-1	-1	-1	-1	-1	-1
	5	-1	-1	-1	-1	-1	-1	-1	-1	-1
	2	-1	-1	-1	-1	-1	-1	-1	-1	-1
	1	-1	-1	-1	-1	-1	-1	-1	-1	-1

Zoning

		10	20	30	40	50	60	70	80	90
Flood distributed uniformly across the city	50	-1	-2	-4	-5	-8	-10	-13	-17	-24
	30	-1	-2	-4	-5	-8	-10	-13	-17	-24
	25	-1	-2	-4	-5	-8	-10	-13	-17	-24
	20	-1	-2	-4	-5	-8	-10	-13	-17	-24
	15	-1	-2	-4	-5	-8	-10	-13	-17	-24
	10	-1	-2	-4	-5	-8	-10	-13	-17	-24
	5	-1	-2	-4	-5	-8	-10	-13	-17	-24
	2	-1	-2	-4	-5	-8	-10	-13	-17	-24
	1	-1	-2	-4	-5	-8				
Flood in the city center	50	-13	-21	-27	-33	-38	-42	-47	-52	-57
	30	-13	-21	-27	-33	-38	-42	-47	-52	-57
	25	-13	-21	-27	-33	-38	-42	-47	-52	-57
	20	-13	-21	-27	-33	-38	-42	-47	-52	-57
	15	-13	-21	-27	-33	-38	-42	-47	-52	-57
	10	-13	-21	-27	-33	-38	-42	-47	-52	-57
	5	-13	-21	-27	-33	-38	-42	-47	-52	-57
	2	-13	-21	-27	-33	-38	-42	-47	-52	-57
	1									
Flood in the periphery	50	-1	-1	-1	-1	-1	-1	-1	-1	-1
	30	-1	-1	-1	-1	-1	-1	-1	-1	-1
	25	-1	-1	-1	-1	-1	-1	-1	-1	-1
	20	-1	-1	-1	-1	-1	-1	-1	-1	-1
	15	-1	-1	-1	-1	-1	-1	-1	-1	-1
	10	-1	-1	-1	-1	-1	-1	-1	-1	-1
	5	-1	-1	-1	-1	-1	-1	-1	-1	-1
	2	-1	-1	-1	-1	-1	-1	-1	-1	-1
	1	-1	-1	-1	-1	-1	-1	-1	-1	-1

Subsidized insurance

		10	20	30	40	50	60	70	80	90
Flood distributed uniformly across the city	50	-0	-1	-1	-1	-2	-2	-2	-2	-2
	30	-1	-1	-1	-2	-2	-3	-3	-4	-4
	25	-1	-1	-2	-2	-3	-3	-4	-4	-5
	20	-1	-1	-2	-3	-3	-4	-5	-5	-6
	15	-1	-2	-3	-3	-5	-5	-6	-7	-7
	10	-1	-3	-4	-5	-7	-7	-9	-10	-11
	5	-2	-5	-7	-9	-12	-14	-16	-17	-19
	2	-5	-11	-15	-20	-26	-29	-32	-35	-37
	1	-10	-19	-27	-33	-41				
Flood in the city center	50	-2	-2	-3	-3	-3	-3	-3	-3	-3
	30	-3	-4	-4	-4	-4	-4	-4	-4	-4
	25	-4	-4	-5	-5	-5	-5	-5	-5	-5
	20	-5	-6	-6	-6	-6	-6	-6	-6	-6
	15	-6	-7	-8	-8	-8	-8	-8	-8	-8
	10	-9	-10	-11	-11	-11	-11	-12	-12	-12
	5	-17	-19	-20	-20	-21	-21	-21	-21	-21
	2	-36	-39	-39	-39	-39	-39	-39	-39	-39
	1									
Flood in the periphery	50	-0	-0	-0	-0	-0	-0	-0	-0	-0
	30	-0	-0	-1	-1	-1	-1	-1	-1	-1
	25	-0	-1	-1	-1	-1	-1	-1	-1	-1
	20	-0	-1	-1	-1	-1	-1	-1	-1	-1
	15	-1	-1	-1	-1	-1	-1	-1	-1	-1
	10	-1	-1	-1	-1	-1	-1	-1	-1	-1
	5	-1	-2	-2	-2	-2	-2	-2	-2	-2
	2	-3	-4	-5	-5	-5	-5	-5	-5	-5
	1	-5	-7	-8	-8	-8	-9	-9	-9	-9

Notes: X axis = proportion of flood-prone area (%); y axis =flood return time (years); proportion of damaged capital in flood-prone areas = 40%. Red cells correspond to large social welfare losses compared to a situation without floods, and green cells correspond to low social welfare losses. In some cases, flood damages were too high for the model to converge (blank cells).

Table D5. Gini Index computed on utilities

Interpretation: In the *low income-high income* configuration, when floods are in the city center, the flood-prone area is 20% of the city, and floods occur every 5 years, zoning results in a Gini Index of 18.2%.

Low income-high income configuration

Flood distributed uniformly across the city

Risk-based insurance

	10	20	30	40	50	60	70	80	90
50	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1
30	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1
25	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1
20	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1
15	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1
10	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1
5	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1
2	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1
1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1

Zoning

	10	20	30	40	50	60	70	80	90
50	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1
30	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1
25	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1
20	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1
15	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1
10	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1
5	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1
2	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1
1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1

Subsidized insurance

	10	20	30	40	50	60	70	80	90
50	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1
30	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1
25	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1
20	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1
15	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1
10	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1
5	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1
2	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1
1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1

Flood in the city center

Risk-based insurance

	10	20	30	40	50	60	70	80	90
50	17.1	17.1	17.1	17.1	17.1	17.1	17.1		
30	17.2	17.2	17.1	17.1	17.1	17.1	17.1		
25	17.2	17.2	17.2	17.1	17.1	17.1	17.1		
20	17.2	17.2	17.2	17.1	17.1	17.1	17.1		
15	17.3	17.2	17.2	17.2	17.1	17.1	17.1		
10	17.4	17.3	17.3	17.2	17.2	17.1	17.1		
5	17.5	17.6	17.5	17.4	17.3	17.2	17.2		
2	17.6	18	18.2	17.9	17.7	17.5	17.4		
1	17.7								

Zoning

	10	20	30	40	50	60	70	80	90
50	17.7	18.2	18.6	19	19.4	19.8	20.2		
30	17.7	18.2	18.6	19	19.4	19.8	20.2		
25	17.7	18.2	18.6	19	19.4	19.8	20.2		
20	17.7	18.2	18.6	19	19.4	19.8	20.2		
15	17.7	18.2	18.6	19	19.4	19.8	20.2		
10	17.7	18.2	18.6	19	19.4	19.8	20.2		
5	17.7	18.2	18.6	19	19.4	19.8	20.2		
2	17.7	18.2	18.6	19	19.4	19.8	20.2		
1	17.7								

Subsidized insurance

	10	20	30	40	50	60	70	80	90
50	17.1	17.1	17.1	17.1	17.1	17.1	17.1		
30	17.1	17.1	17.1	17.1	17.1	17.1	17.1		
25	17.1	17.1	17.1	17.1	17.1	17.1	17.1		
20	17.1	17.1	17.1	17.1	17.1	17.1	17.1		
15	17.1	17.1	17.1	17.1	17.1	17.1	17.1		
10	17.1	17.1	17.1	17.1	17.1	17.1	17.1		
5	17.1	17.1	17.1	17.1	17.1	17.1	17.1		
2	17.1	17.1	17.1	17.1	17.1	17.1	17.1		
1	17.1								

Flood in the periphery

Risk-based insurance

	10	20	30	40	50	60	70	80	90
50	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1
30	17.1	17.1	17.1	17	17	17	17	17	17
25	17.1	17.1	17	17	17	17	17	17	17
20	17.1	17.1	17	17	17	17	17	17	17
15	17.1	17	17	17	17	17	17	17	17
10	17.1	17	17	17	17	17	17	17	17
5	17.1	17	17	17	17	17	16.9	16.9	16.9
2	17	17	17	17	16.9	16.9	16.9	16.9	16.9
1	17	17	17	17	16.9	16.9	16.9	16.9	16.9

Zoning

	10	20	30	40	50	60	70	80	90
50	17	17	17	17	16.9	16.9	16.9	16.9	16.9
30	17	17	17	17	16.9	16.9	16.9	16.9	16.9
25	17	17	17	17	16.9	16.9	16.9	16.9	16.9
20	17	17	17	17	16.9	16.9	16.9	16.9	16.9
15	17	17	17	17	16.9	16.9	16.9	16.9	16.9
10	17	17	17	17	16.9	16.9	16.9	16.9	16.9
5	17	17	17	17	16.9	16.9	16.9	16.9	16.9
2	17	17	17	17	16.9	16.9	16.9	16.9	16.9
1	17	17	17	17	16.9	16.9	16.9	16.9	16.9

Subsidized insurance

	10	20	30	40	50	60	70	80	90
50	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1
30	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1
25	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1
20	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1
15	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1
10	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1
5	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1
2	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1
1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1

High income-low income configuration

Flood distributed uniformly across the city

Risk-based insurance

	10	20	30	40	50	60	70	80	90
50	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
30	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
25	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
20	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
15	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
10	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
2	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
1	20.5	20.5	20.5	20.5					

Zoning

	10	20	30	40	50	60	70	80	90
50	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
30	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
25	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
20	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
15	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
10	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
2	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
1	20.5	20.5	20.5	20.5					

Subsidized insurance

	10	20	30	40	50	60	70	80	90
50	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
30	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.6	20.6
25	20.5	20.5	20.5	20.5	20.5	20.5	20.6	20.6	20.6
20	20.5	20.5	20.5	20.5	20.6	20.6	20.6	20.6	20.6
15	20.5	20.5	20.5	20.5	20.6	20.6	20.6	20.6	20.6
10	20.5	20.5	20.6	20.6	20.6	20.6	20.6	20.6	20.6
5	20.5	20.6	20.6	20.6	20.6	20.7	20.7	20.7	20.7
2	20.6	20.6	20.7	20.7	20.8	20.8	20.9	20.9	21
1	20.6	20.7	20.8	20.9					

Flood in the city center

Risk-based insurance

	10	20	30	40	50	60	70	80	90
50	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
30	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
25	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
20	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
15	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
10	20.5	20.4	20.5	20.5	20.5	20.5	20.5	20.5	20.5
5	20.4	20.4	20.4	20.5	20.5	20.5	20.5	20.5	20.5
2	20.5								
1									

Zoning

	10	20	30	40	50	60	70	80	90
50	20.5	20.5	20.6	20.6	20.7	20.8	20.9		
30	20.5	20.5	20.6	20.6	20.7	20.8	20.9		
25	20.5	20.5	20.6	20.6	20.7	20.8	20.9		
20	20.5	20.5	20.6	20.6	20.7	20.8	20.9		
15	20.5	20.5	20.6	20.6	20.7	20.8	20.9		
10	20.5	20.5	20.6	20.6	20.7	20.8	20.9		
5	20.5	20.5	20.6	20.6	20.7	20.8	20.9		
2	20.5								
1									

Subsidized insurance

	10	20	30	40	50	60	70	80	90
50	20.5	20.5	20.5	20.5	20.5	20.5	20.5		
30	20.5	20.6	20.6	20.6	20.6	20.6	20.6		
25	20.6	20.6	20.6	20.6	20.6	20.6	20.6		
20	20.6	20.6	20.6	20.6	20.6	20.6	20.6		
15	20.6	20.6	20.6	20.6	20.6	20.6	20.6		
10	20.6	20.6	20.6	20.6	20.6	20.6	20.6		
5	20.7	20.7	20.7	20.7	20.7	20.7	20.7		
2	20.9								
1									

Flood in the periphery

Risk-based insurance

	10	20	30	40	50	60	70	80	90
50	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
30	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
25	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
20	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
15	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
10	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
2	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
1	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5

Zoning

	10	20	30	40	50	60	70	80	90
50	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
30	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
25	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
20	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
15	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
10	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
2	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
1	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5

Subsidized insurance

	10	20	30	40	50	60	70	80	90
50	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
30	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
25	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
20	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
15	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
10	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
2	20.5	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6
1	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6

Notes: X axis = proportion of flood-prone area (%); y axis = return time of floods (years); proportion of damaged capital in flood-prone areas = 40%. Red cells correspond to high Gini Indices, and green cells correspond to low Gini Indices. In some cases, flood damages were too high for the model to converge (blank cells).