Adaptation to Flooding and its Effect on the Urban Form

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January 31, 2023

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Abstract

Climate change raises the risk of floods in urban areas, often close to rivers. We examine how an increasing risk of flooding affects real estate markets, the urban form and welfare and triggers adaptation through reallocation. To this end, we develop an innovative approach to cast the monocentric city model in two dimensions (parallel and orthogonal to the river) and include flood costs. We, further, account for the amenity value of the river that additionally increases density in flood-prone areas. We calibrate the simulation to German data and show that the recently projected increase in flood risk leads to a welfare loss of 180 Euros per capita for a small German city of 20,000. The city shrinks along the river banks and extends around 20 percent further away from the river.

JEL codes: Q51, Q54, R31, R5

Keywords: climate risk, adaptation, urban form, floods, housing markets

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1 Introduction

Climate change is expected to lead to higher flood risk (cf. Seneviratne et al. 2021, Hattermann et al. 2014; Hattermann et al. 2016), very often in urban areas. We explore the effects of this higher flood risk on the spatial structure of cities, the real estate markets and welfare. Our results show that the risk shock leads to substantial reallocation of households, such that the city shrinks close to the river banks and extends further inland and away from the river. The spatial adjustment dampens the resulting net welfare loss: for a small-sized city such as Weilheim, Germany, (20,000 inhabitants), the welfare impact amounts to 180 Euros per capita.

For our analysis, we develop a new two-dimensional version of the monocentric city model[1] that allows us to distinguish a spatial dimension along the river and another denoting the distance from the river. Building on this setup, we incorporate flood costs in the capital cost of housing developers. Moreover, we account for the amenity value of coastlines and rivers (building on Wu (2006), who does not consider flood risk) that leads to more people settling in flood-prone areas.

We contribute to the literature on flooding in an urban economic setting. Filatova et al. (2009) use an agent-based modeling approach to study land markets within cities with agents having heterogeneous risk preferences and a CBD in some distance from the coastline. They find that people settle too close to the coast if they have heterogeneous preferences since risk-loving people do not evaluate the flood risk correctly. Avner et al. (2022) present a very useful first step in modeling cities that face flood risks and the effects of government policies on land values in a very stylized urban model where an exogenous share of the city area is subject to flood risk. Avner and Hallegatte (2019) use a similar approach to asses the effects of government interventions in the form of banning settlements in flood-prone zones and subsidizing insurances against flooding

[1] Cf. Alonso (1968), Mills (1967), Muth (1969)

damages. Our elaborate two-dimensional approach allows us to more deeply examine the effects on the urban form and land values at various locations and the interaction with the river amenity (cf. (Brown and Pollakowski, 1977; Lansford Jr and Jones, 1995; Leggett and Bockstael, 2000; Luttik, 2000; Wu et al., 2004; Gürlük, 2006; Chen et al., 2019; Gibbons et al., 2014)).

The paper proceeds as follows. Section 2 describes the underlying definitions and deducts the model which is the basis for this paper. It furthermore explains open and closed cities and the used scenarios. Section 3 presents the main results, mainly in terms of urban form and utility within Weilheim. In section 4 we discuss three extensions which we are currently working on. Finally, section 5 concludes.

2 Model

We develop a two-dimensional static monocentric city model in the tradition of Mills (1967), Alonso (1968), and Muth (1969) and include in it amenities and flood risk from rivers and other water bodies.[2]. The city's central business district (CBD) lies in a Cartesian plane at the coordinates $(\omega, \mu) = (0, 0)$. The μ coordinate denotes the distance to the river (of width zero) while the ω-value gives the distance of a location to the CBD along the river. The Euclidian distance $x(\omega, \mu)$ of a location to the CBD then is

$$x(\omega, \mu) = \sqrt{\omega^2 + \mu^2}. \tag{1}$$

[2]Particularly, linear water streams fit the model very well. However, the model can be adjusted to other geometric forms of waters as well.

2.1 Households

The households maximize utility by choosing their consumption of housing q and of a generic numeraire consumption good s.

$$\max_{c,q} u(c,q) = q^{\alpha} s^{1-\alpha} a(\mu)^{\gamma} \qquad s.t. \qquad p(\omega,\mu)q + s \leq y - t * x(\omega,\mu) \tag{2}$$

with exogenous household income y, housing price $p(\omega,\mu)$ and the driving cost per meter of distance and year t. We extend the utility function by a preference for the amenity value of the river $a(\mu)$ along the lines of Wu (2006):

$$a(\mu) = 1 + a_0 e^{-a_1|\mu|} \tag{3}$$

The amenity factor is highest $(1 + a_0)$ at the river bank ($\mu = 0$) and falls asymptotically to unity at higher distances, with the maximum additional amenity value a_0. The parameter $a_1 > 0$ describes how quickly the amenity value decreases with distance. The weight of the river amenity relative to consumption is given by the parameter $\gamma > 0$. The utility derived from housing and composite good consumption continues to have a Cobb-Douglas form. As the river amenity does not have a direct monetary price on its own, this allows households to spend fixed shares α and $1 - \alpha$ of their disposable income on housing and the composite good, respectively.

Per-capita income y consists of a fixed exogenous income y_0 and the endogenous excess land rent above the agricultural land rent r_{ag} divided by the city's population N:

$$y = y_0 + h * \frac{1}{N} * \iint_D r^*(\omega,\mu) - r_{ag} d\omega d\mu \tag{4}$$

Substituting the first-order conditions of (2) and rearranging, we obtain the bid price for housing:

$$p^*(\omega,\mu) = \alpha(1-\alpha)^{\frac{1-\alpha}{\alpha}} * \bar{V}(\omega,\mu)^{-\frac{1}{\alpha}} * (y - tx(\omega,\mu))^{\frac{1}{\alpha}} * (a(\mu))^{\frac{\gamma}{\alpha}} \tag{5}$$

We obtain the housing demand $q^*(\omega,\mu)$ in equation (6) by simply dividing the expenditure share by the bid price of housing from equation (5).

This derivation works because the amount of housing, respectively the housing size, is the residual of the expenditures of housing controlled for - i.e. divided by - the price of housing in the respective location.

$$q^*(\omega,\mu) = (1-\alpha)^{\frac{\alpha-1}{\alpha}} * \bar{V}(\omega,\mu)^{\frac{1}{\alpha}} * (y - tx(\omega,\mu))^{\frac{\alpha-1}{\alpha}} * (a(\mu))^{-\frac{\gamma}{\alpha}} \tag{6}$$

2.2 Housing production

Competitive housing developers rent land for the land rent $r(\omega,\mu)$ and employ capital $c(\omega,\mu)$ to build houses with demanded sizes of flats. They maximize profits π by choosing the floor space density $d^*(\omega,\mu)$ per square meter of land and take the equilibrium housing price $p^*(\omega,\mu)$ as given.

$$\max_d \pi = p(\omega,\mu)d(\omega,\mu) - r(\omega,\mu) - c(\omega,\mu) = 0 \tag{7}$$

Capital costs $c(\omega,\mu)$ are[3]

$$c(\omega,\mu) = (1 + f(\mu)) * d(\omega,\mu)^{\delta} \tag{8}$$

[3]This is a formulation of construction costs following Wu (2006). However, other papers use a formulation of construction costs which also involves a specific modulation of used capital and not only the density. Using exchange factors these two formulations are essentially equivalent. Since construction costs are convex in density, density is raised to the power of $\delta \in (1,\infty)$. The convexity of the construction costs in density follows the idea that taller buildings require additional construction measures, e.g., extra steel foundations etc. Brueckner (2011).

They depend not only on the size of the building d, but also on the flood risk $f(\mu)$ (df. Equation (9)) at the respective location:

$$f(\mu) = f_0 e^{-f_1|\mu|} \tag{9}$$

Without any flood damages, equation (8) equals the conventional construction costs. This term captures not only occurring flood damages, but also higher capital costs due the expectation of flood damages in the future. Similarly to the amenity function, the parameter f_0 denotes the maximum damage right at the river bank and parameter f_1 captures how fast flood risk decreases with a rising distance to the river. This structural form fits the empirical data pretty well. This empirical data process is described in more detail in Appendix A.

2.3 General equilibrium

The following equations (10) and (11) are the two fundamental equations describing the boundaries of the city in equilibrium. Equation (10) states that the land rent at all points of the city boundary $r(\bar{\omega}, \bar{\mu})$ must be the same as the exogenous agricultural land rent r_{ag}.

$$r(\bar{\omega}, \bar{\mu}) = r_{ag} \tag{10}$$

The second equation defining the city area ensures that the given population size N is equal to the integral over the building density $d^*(\omega, \mu)$ divided by the housing size $q^*(\omega, \mu)$ at each point of the city area.

$$\iint_D \frac{d^*(\omega, \mu)}{q^*(\omega, \mu)} d\omega d\mu = N \tag{11}$$

Thus, we further obtain the floor space density $d(\omega, \mu)$ at any point in the city. The density depends positively on the willingness to pay $p^*(\omega, \mu)$ at the respective location and negatively on the additional construction costs via the flood risk $(1 + f(\mu))$ there, since $\delta > 1$.

$$d(\omega, \mu) = (1 + f(\mu))^{\frac{1}{1-\delta}} * (\delta)^{\frac{1}{1-\delta}} * p^*(\omega, \mu)^{\frac{1}{\delta-1}} \tag{12}$$

2.4 Calculating the city boundaries

Modeling a two-dimensional closed city with amenities from a river is challenging because we can no longer rely on a circular city model, as in the standard case, since the river is a one-dimensional line rather than a single point in the center of the city. We use Equations (10) and (11) to calculate the city boundary.

The integrand of equation (11) is defined in equation (13). We use the density from equation (12) and the bid price from equation (5). We take the housing size from equation (6).

$$\frac{d^*(\omega, \mu)}{q^*(\omega, \mu)} = \left(\frac{\alpha}{\delta(1 + f(\mu))}\right)^{\frac{1}{\delta-1}} * \left(\frac{(1-\alpha)^{\delta*(1-\alpha)} * (y - t * x(\omega, \mu))^{\alpha+\delta-\alpha\delta} * a(\mu)^{\gamma\delta}}{\bar{V}(\omega, \mu)^{\delta}}\right)^{\frac{1}{\alpha(\delta-1)}} \tag{13}$$

Next, we transform equation (10), which states that the rent at the city boundary must equal the exogenously given agricultural rent. This way, we obtain the specified city boundary equation (14).

Equation (14) serves as the basis for calculating the limits of the double integral, which ensures that the number of people in a closed city matches the density at each point of the city. This double integral is formulated in equation (11) with the integrand specified in equation (13).

The city is symmetric along both axes - ω and μ. This is due to the specification that the

CBD is located in $(0, 0)$. Choosing this location is without loss of generality, assuming that the CBD is located on the river. Furthermore, we assume that the river is just a straight line with no further curvature crossing the CBD. These two specifications lead to symmetry properties. These symmetry properties allow us to focus on one quadrant, namely the upper right one. Later, this quadrant can easily be mirrored to compute the rest of the city.

$$r_{ag} = ((1 + f(\bar{\mu})))^{\frac{1}{1-\delta}} * p(\bar{\omega}, \bar{\mu})^{\frac{\delta}{\delta-1}} * (\delta^{\frac{1}{1-\delta}} - \delta^{\frac{\delta}{1-\delta}}) \tag{14}$$

Since we only calculate the city boundary for the upper right quadrant and the city is continuous[4], we know that the city boundary of this quadrant has to begin at some point at the μ-axis $(0, \mu_{end})$ and end at some point at the ω-axis $(\omega_{end}, 0)$. At this moment, both μ_{end} and ω_{end} are unknown. However, the lower limits of the double integral in equation (11) of both variables of integration ω as well as μ are already known and both are simply zero.

Now we would like to focus on the calculation of the upper limits. According to Fubini's theorem one of these two upper limits must be a number that defines the endpoint of the function. The other limit is a function that defines the boundary of one variable depending on the other one (Dineen, 2014).

The value of the ω-coordinate appears only once in the entire equation systems defined by equation (13) and equation (14), i.e. in equation (13) in the form of the distance to the CBD $x(\omega, \mu)$ which is defined in equation (1). Therefore, we are able to calculate the value of ω at the boundary in dependence on the value of μ. To do this, we take equation (14) and fill it with the bid price for housing equation (5), and the equation defining the distance to the CBD (1). After rearranging, we obtain the equation of $\bar{\omega}$ depending on μ at the city boundary. This equation (15) can be used later on as the

[4]This follows from the property that the amenity location and the river have a distance of zero, which makes sure that no urban sprawl exist, according to Wu (2006)

upper limit of ω in the double integral of the population in (11).

$$\bar{\omega}(\mu) = \sqrt{\left(\frac{y}{t} - \frac{((1+f(\bar{\mu})))^{\frac{\alpha}{\delta}} * \bar{V}(\omega,\mu) * r_{ag}^{\frac{\alpha(\delta-1)}{\delta}}}{(\delta^{\frac{1}{1-\delta}} - \delta^{\frac{\delta}{1-\delta}})^{\frac{\alpha(\delta-1)}{\delta}} * \alpha^{\alpha} * (1-\alpha)^{1-\alpha} * a(\bar{\mu})^{\gamma} * t}\right)^2 - \mu^2} \quad (15)$$

We know that the last and highest value of μ, which we call μ_{end}, is exactly at the point where the ω-axis is crossed. This property allows us to set ω equal to 0 in equation (15) to calculate the value of μ_{end}. In this way, we obtain equation (16), which specifies μ_{end}.

It is important to realize that $\bar{\mu}_{end}$ in equation (16) depends on itself. Since it appears as the exponent of an exponential function within a difference, we cannot simplify the equation in such a way that $\bar{\mu}_{end}$ is only on one side of the equation. This is an important reason why the equation system of equation (11) and equation (10) is not solvable analytically. This makes the method of numerical simulation necessary.

$$\bar{\mu}_{end} = \frac{y}{t} - \left(\frac{r_{ag}^{\frac{\alpha(\delta-1)}{\delta}}}{(\delta^{\frac{1}{1-\delta}} - \delta^{\frac{\delta}{1-\delta}})^{\frac{\alpha(\delta-1)}{\delta}} \alpha^{\alpha}(1-\alpha)^{1-\alpha} t}\right) * \bar{V} * \frac{(1+f_0 e^{f_1 \bar{\mu}_{end}})^{\frac{\alpha}{\delta}}}{(1+a_0 e^{a_1 \bar{\mu}_{end}})^{\gamma}} \quad (16)$$

The combination of equation (13), equation (15) and equation (16) into equation (11) gives equation (17). Equation (17) is the specification of equation (11) for this particular context with flooding costs and amenities in a two-dimensional space. It is a formula for calculating the population size and must be set equal to N to ensure that the city boundaries match the real population size.

$$\int_0^{\bar{\mu}_{end}} \int_0^{\bar{\omega}(\bar{\mu})} \Phi * \bar{V}^{\frac{\delta-2}{\alpha(\delta-1)}} * \left(\frac{(a(\mu))^{\gamma\delta}(y - x(\omega,\mu))^{\alpha+\delta-\alpha\delta}}{(1+f(\mu))^{\frac{1}{\alpha}}}\right)^{\frac{1}{\alpha(\delta-1)}} d\mu d\omega \quad (17)$$

with

$$\Phi = \left(\frac{\alpha(1-\alpha)^{\frac{\delta(1-\alpha)}{\alpha}}}{\delta}\right)^{\frac{1}{\delta-1}} \quad (18)$$

The reader may notice that in the double integral (17) the order of ω and μ are switched. Thus, ω is a function of μ and not vice versa, as originally defined. This is possible because the city boundary is an injective function of ω in μ, which means that in the domain $[0, \omega_{end}]$ each value has exactly one corresponding μ value in the domain $[0, \mu_{end}]$. This also allows us to express $\bar{\omega}$-values as a function of μ.

Equation (17) contains two unknowns. The unknowns are the level of average utility within the population of the city $\bar{V}$ and the end value of μ, which is μ_{end}. $\bar{V}$ must be the same for all individuals, otherwise people would move within the city until they all have the same utilities. This is implied by a model with homogeneous households in terms of their utility function and income. Therefore, $\bar{V}$ does not depend on the location.

μ_{end} gives us the maximum expansion of the city orthogonal to the river. Combining equation (17) with equation (16), we get an equation system with two unknowns and two equations. This equation system is, in general, solvable. However, it is not possible to obtain an analytical solution, as argued above. Nevertheless, it is possible to solve this equation system numerically, which is done using the Scipy command optimize.root (Virtanen et al., 2020). In doing so, we use the method of minimizing the last square roots by the Levenberg-Marquardt algorithm (Moré et al., 1980) which yields very accurate predictions when the starting values are within the 10% range of the real value (Gavin, 2019).

2.5 Open and Closed City

Closed and open city models show two extremes in terms of mobility - no mobility at all (closed city) and perfect mobility of citizens (open city) between cities. Please note that both models allow for perfect mobility within the respective city. This allows to see the upper limits of impacts in terms of welfare change and population decline due to increased flood risks. The reality probably lies somewhere in between these two extremes of the closed and the open city approach. The question of the extent of migration due to increased flooding events is still work in progress and is discussed in section 4.2.

The open city model assumes that the same level of utility exists throughout the world. This means that if the environment in an area changes in a way that affects utility negatively, this would be counteracted by migration out of the respective city. In contrast, if the utility increases, the migration would obviously move towards this city. Migration occurs until the same utility level in each city.

The closed city type assumes that the population within a city remains the same, regardless of changes in the environment of the city. However, this implies that changes in the environment that affect the utility function actually change the utility of all people living in the city and are not counteracted by migration flows.

2.6 Scenarios

The scenarios represent the amount of additional capital costs required to the construction of housing which are part of equation (9). Assuming perfect and unbounded rationality, risk-neutral agents, and a market for constructing houses that perfectly reflects the real costs, the additional capital costs due to flooding can be interpreted as the expected damage to housing due to flooding. A plausible interpretation of these additional costs is that construction companies pay an insurance on the house in question which gets completely passed to the tenants. The insurance is fair, meaning that it generates no profits for the insurance company and involves no transaction costs.

The first scenario corresponds to the base model with no additional costs due to flood risk. This could be the case because the relevant actors are highly myopic and do not internalize flood risks. It is equivalent to a case with only amenity as described in Wu (2006) for open cities.

The second scenario assumes that the construction costs reflect the current expected damage to residential buildings. To calculate the respective scenario flood risk maps of the Ammer river in Weilheim (LfUBayern, 2019) and data on damages caused by flooding events in Germany (Cammerer et al., 2013) are used. More details of the calculation can be found in the appendix A.

The third scenario reflects the expected damage to residential buildings that are expected due to climate change in the year 2100. The calculation is based on the costs of the previous scenario multiplied by the ratio of future expected flooding damages to current flooding damages in Germany from Hattermann et al. (2016). As with the second scenario, the detailed calculation can be found in the appendix A.

This results in three scenarios in order of the size of the additional costs on construction: i) No internalization of flooding, ii) Internalization of current flooding costs, and iii) Internalization of flooding costs in 2100.

Approximately, these scenarios can be interpreted as describing the presence, the medium-term future, and the long-term future of the urban form of cities in proximity to rivers.

3 Results

To give an impression of the model, we present a numerical simulation of it here. Calibrating the model on Weilheim, applying it on a closed city and on the three scenarios shows the resulting spatial structure and the fundamentals in a comprehensive way.

An overview of the fundamentals is given in table 1. The table shows that higher flooding costs lead to a vertical compression of the city. While the maximum distance of the city boundary to the river increases by about 19% from 0.60 km (no internalization of flooding costs) to 0.70 km (internalization of flooding costs in 2100), the horizontal length along the river decreases by about 17% from 3.61 km (no internalization of flooding costs) to 2.99 km (internalization of flooding costs in 2100). This process of compression is visualized in figure 3. Since the city simultaneously becomes smaller along the river and longer orthogonal to the river, the total city area changes only slightly by about 0.01 km^2.

The population remains constant under the assumption of closed cities. However, the utility decreases from 4,781 in the scenario without internalization to 4,770 in the scenario with current flooding costs, and finally to 4,745 in the scenario with climate change significantly increasing the flood risk. Therefore, in total the utility per individual decreases by almost 1% when the construction costs change from no internalization of flooding to 2100 flood risk. This loss of utility from non-internalization to internalization of 2100 flood risks is equivalent to a loss of utility from a reduction in disposable income by 180€ in the non-internalization scenario with unchanged prices.[5]

Land rent excluding agricultural land rent decreases by about 17% between no internalization of the flood risk and internalization of the flood risk. Land rents are the difference between price times density and construction costs. Clearly, construction costs are increased, which also reduces density and housing prices. This reduction in land rent can also be seen in figure 4.

The expected damages from a 100-yearly flood are about 1.5% lower if the current floods are internalized into capital costs of construction compared to no internalization. When comparing no internalization to internalization of flood risk for the year 2100, the expected damage is about 5% lower. This reduction can be explained by the fact that fewer people live directly on the river and more people live deeper in the land. This can be seen in figure 5. However, the change is rather small, although we assume a perfect internalization of flood risk. There are two reasons that explain this phenomenon. One reason is that a 100-yearly flooding event is still a rare event and therefore only to a

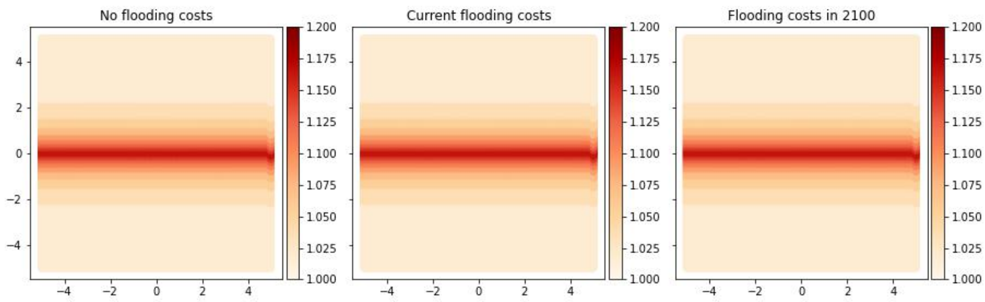
[5]Calculated using indirect utility and following the idea of equivalent compensation (EV) (Bockstael and McConnell, 1980).

small degree is represented in the expected flooding damage.[6] The second reason is that the additional capital costs of construction do not serve to actually counteract flooding, for example by constructing walls, but are merely 'useless' additional costs in this particular modeling approach. However, this assumption could easily be changed.

Variables	No internalisation flooding costs	Current flooding costs	Flooding costs in 2100
Max. dist. CBD along river	3.61 km	3.43 km	2.99 km
Max. dist. CBD orthogonal river	0.60 km	0.62 km	0.70 km
Utility level	4781	4770	4745
Population	22763	22763	22763
City area	1.14 km^2	1.14 km^2	1.15 km^2
Total income per capita	23,804€	23,798€	23,785€
Total land rents (excl. ag. rents)	2,575,838€	2,447,011€	2,436,568€
Land rents per capita (excl. ag. rents)	113€	107€	94€
Total damage 100-yearly flood	23,971,688€	23,606,815€	22,780,471€
Damage per capita 100-yearly flood	1,053€	1,037€	1,001€

Table 1: Closed city with land rents equally distributed among current population

Figure 1: Amenity distribution in closed city model with land rents being equally distributed among citizens in three scenarios (distances in km)



[6]In the case of current flooding it is represented to exactly 1% in the case of 2100 flooding costs to a higher degree but still low.

Figure 2: Proportion of additional capital costs on top of regular building costs due to flood risk in closed city model with land rents being equally distributed among citizens in three scenarios (distances in km)

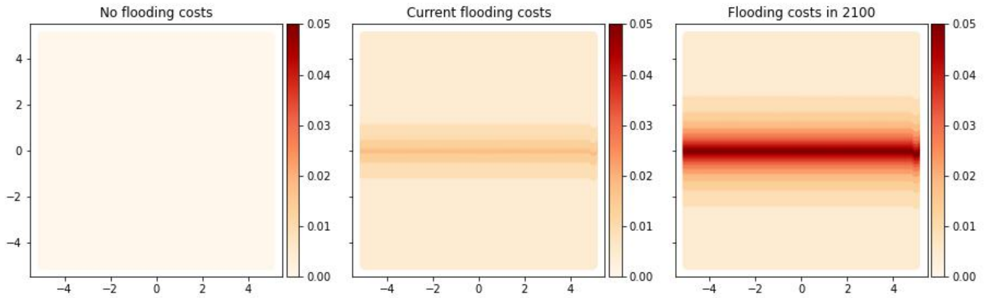


Figure 3: Density in people per m^2 in the closed city model with land rents being equally distributed among citizens in three scenarios (distances in km)

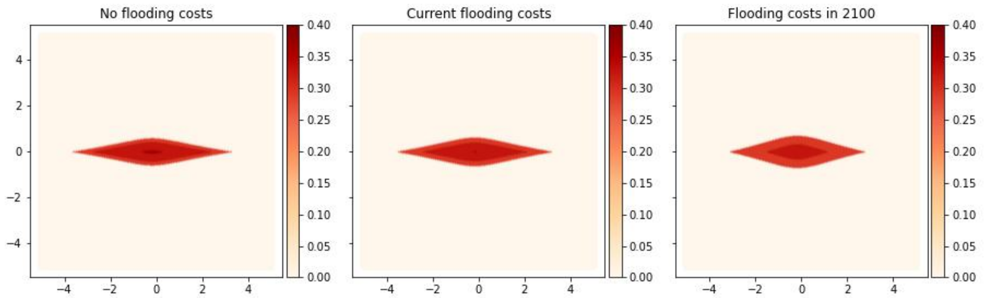


Figure 4: Land rent in € per m^2 in the closed city model with land rents being equally distributed among citizens in three scenarios (distances in km)

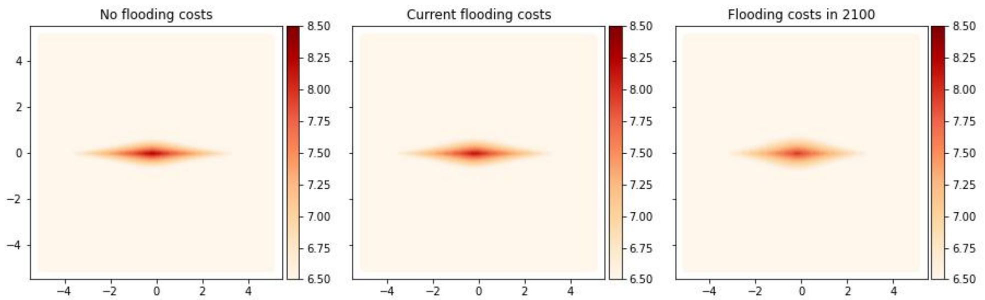
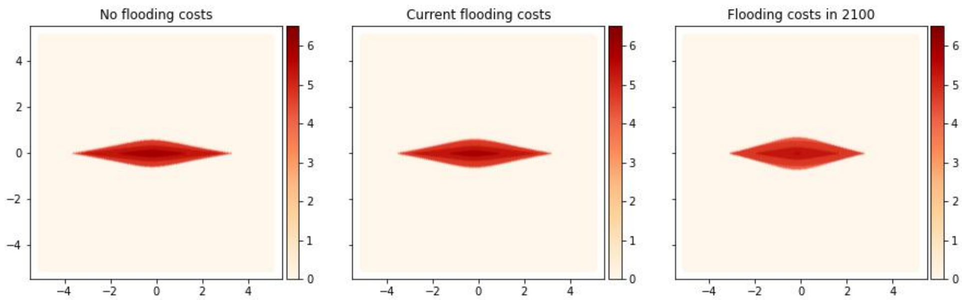


Figure 5: Expected damage in case of a 100-yearly flood (according to historical data) in € per m^2 in the closed city model with land rents being equally distributed among citizens in three scenarios (distances in km)



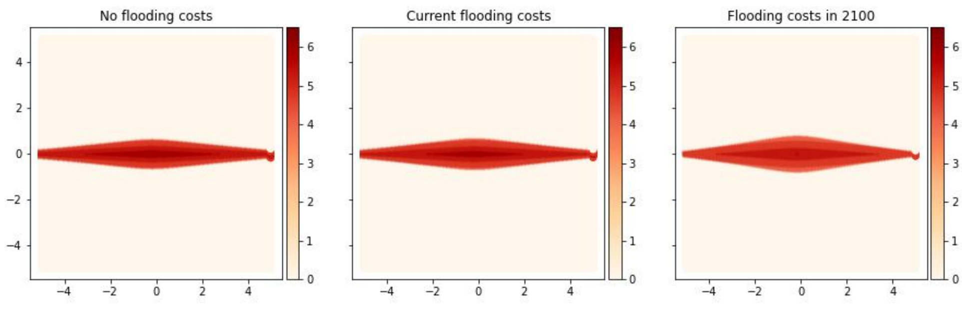
4 Discussion and Extensions

4.1 Economic growth

Our model is concerned with changes over long time periods of about 50 years. In this time period not only the flood risk will change but also other fundamental economic variables. We assume a yearly economic growth in Germany of 1.5% which results in doubling the wages after 50 years. By doing so, we can capture effects of general higher wealth levels on the housing market.

Furthermore, we include higher income growth within Weilheim than outside of Weilheim in our model. An annual growth of about 0.3% is expected due to a higher relative economic growth in Weilheim compared to the rest of Germany (LfS, 2023). Over a span of 50 years this results in a growth in population of about 15% without considering the increased flood risk. Figures 6 until 8 show that the increases in wealth make living close to the river more attractive since the utility increases in a concave way in the other goods. This results in a flatter city and the expected damage after the realization of a flooding event doubles as can be seen in table 2.

Figure 6: Density in people per m^2 in the closed city model with economic growth in three scenarios (distances in km)



Variables	No internalisation flooding costs	Current flooding costs	Flooding costs in 2100
Max. dist. CBD along river	7.4 km	7.03 km	6.06 km
Max. dist. CBD orthogonal river	0.65 km	0.69 km	0.80 km
Utility level	10,066	10,026	9,989
Population	22,763	22,763	22,763
City area	2.40 km^2	2.40 km^2	2.43 km^2
Total income per capita	50,101€	50,088€	50,058€
Total land rents (excl. ag. rents)	5,289,436€	4,993,984€	4,291,079€
Land rents per capita (excl. ag. rents)	232€	219€	189€
Total damage 100-yearly flood	50,376,226€	49,509,752€	47,800,211€
Damage per capita 100-yearly flood	2,213€	2,175€	2,100€

Table 2: Closed city with general economic growth

Figure 7: Land rent in € per m^2 in the closed city model with economic growth in three scenarios (distances in km)

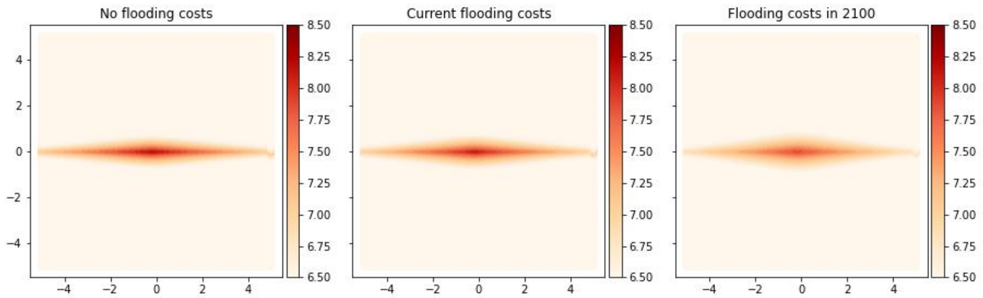
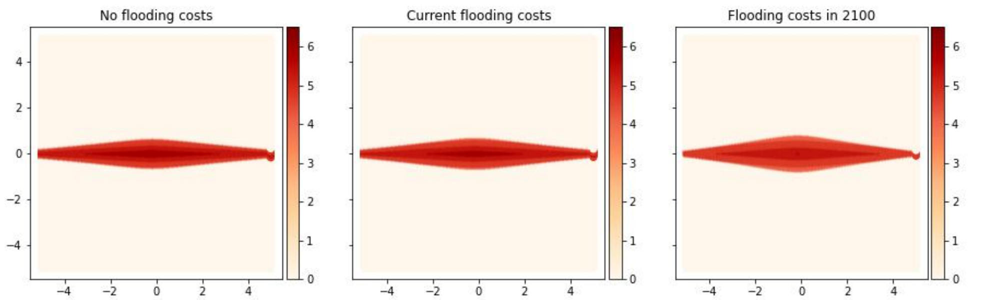


Figure 8: Expected damage in case of a 100-yearly flood (according to historical data) in € per m^2 in the closed city model with economic growth in three scenarios (distances in km)



4.2 Leaving costs

Closed and open cities model two extremes in terms of mobility between cities as discussed in section 2.5. We want to build a bridge between these two extremes by introducing moving costs or better leaving costs ϵ in the model. The basic idea of this modeling approach is to assume that people leaving the city will face a lower utility of $\bar{u} - \epsilon$ outside of the city compared to people already living outside who face their the equilibrium utility $\bar{u}$. The reason for this is that people who leave their hometown face extra costs, like transportation costs and losing their social network. These costs make them more reluctant to leave and only after the threshold $\bar{u} - \epsilon$ is reached these people will actually leave their original town.

Three equilibria are possible when economic growth as described in section 4.1 and leaving costs are considered. In the first equilibrium the leaving costs will not affect the equilibrium results of an open city if the respective city gains enough attraction by economic growth compared to the disadvantages by higher flood risk. In this case the city will grow in population in the same way as without leaving costs and will settle at a welfare level of $\bar{u}$ which is the same level of utility as outside of the respective city. If the city looses sufficiently high amounts of attractiveness by the higher flood costs, the city will settle at the smaller utility $\bar{u} - \epsilon$ and shrink in population until this point is reached. This is the second possible equilibrium. Lastly, it is possible that the effect on the utility over time is somewhere between these two equilibria. In this case, the population will stay constant and the city will behave like a closed city with a constant population and will end with a level of utility per individual between $\bar{u}$ and $\bar{u} - \epsilon$.

To give the reader an impression on the effect of the introduction of leaving costs, we apply the concept on our small-sized city of Weilheim. We still assume the economic growth described in the previous section 4.1. For the city to increase and therefore reach the first equilibrium we would need at least higher wealth levels of 104€ in Weilheim compared to the rest of the world for the current flood risk scenario. With the 2100 flood risk, we would need a higher wealth level in Weilheim of at least 337€ for an increasing population. This is not given, since the economic growth are only 57€. Therefore Weilheim will either stay constant or shrink.

In order for the city not to lose citizens and therefore end in the last equilibrium, we need leaving costs of at least 47€ for the current flood scenario and leaving costs of 278€ for the 2100 flood scenario. If the leaving costs are lower we end in the second equilibrium.

Determining an exact value for leaving costs is beyond the scope of this paper. Ransom (2022) finds leaving costs of 400,000$ in total for the USA which would be more than 10,000€ in annual terms. With moving costs that high, in all scenarios the population of Weilheim would stay constant and the open city with leaving costs would behave exactly like the closed city shown in subsection 4.1. If we assume that leaving costs are close to just transportation costs, the value would be probably close to 600€ which would be about 20€ annually. Having this low transport costs the city would in both scenarios behave like an open city and be settling on a lower level of utility of about 10,062 and a population of 20,831 with current flood costs, respectively 6,675 with 2100 flood costs.

4.3 Flash floods

So far, we model only pluvial flood (flooding from the river). However, pluvial floods gain in importance and are an important source of flooding as well. Flash floods do not only affect households living close to the river but also households in other locations, particularly households in valleys in proximity to heights.

Feldmann et al. (2023) provides us with geolocated data on flash floods which we will include in future work.

5 Conclusion

In this paper, we present an answer to the question: 'What happens to cities close to rivers if the flood risk increases?'. Higher flood risks are a very likely development for many cities due to climate change. The model presented by us includes higher flooding costs in the form of higher construction costs in areas close to the river.

Calibrated on a German small-sized town, the model shows a decrease in utility per person of approximately 1% and a relocation of people who lived along the river before land-inwards. In total, the width of the city along the city is reduced by about 17% comparing no internalization of flooding with the internalization of expected flooding damages due to climate change in the year 2100. However, this relocation only reduces the expected damages in a 100 yearly flooding event by about 5%. The land rent gets reduced by higher construction costs due to the internalization of flood risks.

In conclusion, increased flood risks due to climate change will significantly change smaller towns in Europe which are located nearby rivers. Policymakers should take these changes into consideration if they, e.g., decide on large infrastructure projects. It could very well be that such projects in cities close to rivers might not face the same demand in the future as now.

A Appendix

A.1 Calibration

This section is supposed to give an overview of all parameters, their values, and the method used to calibrate them can be found in tables 3 and 4. The values are chosen to represent the town of Weilheim and have to be adjusted for other cities.

Parameter	Description	Values	Calibration Method
a_0	Baseline additional amenity close to the river	0.18 in all cases with amenity; 0 in cases without amenity	Own calculations using housing price following regression analysis by Gibbons et al. (2014)
a_1	Rate of change of amenity by distance	-1 in all cases	Standard case taken from Wu (2006)
f_0	Baseline additional capital costs of building at the river	0 in scenario "No internalization of flooding costs"; 0.0161 in scenario "Internalization of current flooding costs"; 0.0539 in scenario "Internalization of 2100 flooding costs"	Own exponential regression using data on water depth after flooding events in Weilheim from LfUBayern (2019), water depth-damage relation from Cammerer et al. (2013); Multiplication of current flood risk with expected increase due to climate change from Hattermann et al. (2016)
f_1	Exponent of expected damage from flood events by distance	-1 in all cases	Own exponential regression using data on water depth after flooding events in Weilheim from LfUBayern (2019), water depth-damage relation from Cammerer et al. (2013)
r_{ag}	Exogenous agricultural land rent (everywhere outside of city)	For Weilheim 6,499,900 $\frac{€}{km^2}$	For Weilheim: average land rent in Bavaria from Weltagrarbericht (2019)

Table 3: Overview of parameters, including values and method of calibration; part 1

Parameter	Description	Values	Calibration Method
t	Transport costs to CBD from residence per km per year	$100\frac{€}{km}$	Calculated with Spritkostenrechner (2022) for car, 200 working days, back and forth, mileage: 7 liter per 100 km, 1.72€/liter
y	Disposable income per citizen	Weilheim: 23,691€ in models with external land owners; 23,691€ + endogenous determined land rent in models with land rents equally distributed among citizens	For Weilheim taken from Bundeswahlleiter (2019)
N	Population of city	For Weilheim: 22,76	For Weilheim taken from Bayernportal (2021)
α	Preference for Housing	0.24 in all cases	Taken from Marz and Sen (2022)
γ	Preference for amenity from river	0.18 in all cases	Set to be equal to a_0 like in Wu (2006); Own calculations using housing price following regression analysis by Gibbons et al. (2014)
δ	Exponent of construction costs to density	1.33 in all cases	Taken from Wu (2006) as ratio of housing value to the non-land construction costs
Φ	Basic to calculate population	0.00017 in all cases	Compression of variables, defined in (18)

Table 4: Overview of parameters, including values and method of calibration; part 2

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