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DOI
10.1016/j.ecolecon.2022.107682

Publication date
2023

Document Version
Final published version

Published in
Ecological Economics

Citation (APA)
Mutlu, A., Roy, D., & Filatova, T. (2023). Capitalized value of evolving flood risks discount and nature-based solution premiums on property prices. *Ecological Economics*, *205*, Article 107682. https://doi.org/10.1016/j.ecolecon.2022.107682

Ecological Economics 205 (2023) 107682

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Capitalized value of evolving flood risks discount and nature-based solution premiums on property prices

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ARTICLE INFO

Keywords:
Nature-based solutions
Flood Risk
Hedonic Price Method
Property Value

ABSTRACT

Nature-based solutions (NbS) are a cornerstone of climate change adaptation worldwide. Yet, evidence on their economic benefits is scarce, especially since the provided environmental amenities usually spatially correlate with climate-induced hazards, effects of which NbS aim to curb. This lack of empirical evidence creates obscurity regarding social acceptability of NbS, hindering their uptake and upscaling. We apply hedonic price models to estimate homeowners' willingness-to-pay for NbS, which offer flood safety and environmental benefits, while controlling for spatio-temporal changes in capitalized flood risk discounts due to the 1993-1995 floods in the Limburg Province, the Netherlands. We reveal a pre-flood effect of 5.6% (discounting on average -€12,753 for flood-prone properties), which rises to 10.9% (−€24,691 on average) immediately after the floods. However, the effect is only transitory. The flood discount of home values diminishes over time and eventually vanishes in 9–12 years, which coincides with the implementation of the largest and oldest NbS intervention in the Netherlands. Our analysis shows that NbS amenities provide a 15% (€33,687 on average) premium to nearby residential property prices. This evidence of the evolving flood risk discount and the stable NbS premium for individual homeowners could support the economic feasibility and wide acceptability of NbS for climate change adaptations.

1. Introduction

Effective flood risk management is vital to protect human life and reduce economic damages from extreme weather events exacerbated by climate change. Global financial losses from flood hazards constituted $105 billion in 2021, making them the costliest natural hazard (Aon, 2022). In particular, the 2021 European floods alone accounted for more than $13 billion in economic losses (Aon, 2022), highlighting how vulnerable urban areas are to such shocks. These extreme events once again remind us of the urgent need for transformative actions for climate change adaptation worldwide.

Nature-based solutions (NbS) are highlighted as a promising approach to adapt to adverse impacts of climate change during the first high-level global Climate Adaptation Summit[1] and the new EU Adaptation Strategy in 2021.[2] The concept of NbS is defined by the International Union for Conservation of Nature (IUCN) as "actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" (Cohen-Shacham et al., 2016). NbS are often referred to as "no regret" solutions due to their multiple co-benefits (European Commission, 2021). For example, urban parks can mitigate the urban heat island effect and provide comfort to nearby residents while improving air quality and increasing recreational value (Brown and Mijic, 2019).

There is growing evidence that NbS can effectively mitigate water-related risks while contributing to nature restoration and offering environmental benefits to local communities (Chausson et al., 2020; Kabisch et al., 2017; Narayan et al., 2016; Raymond et al., 2017). Such solutions can be applied to deal with various water-related hazards across, such as coastal flooding (e.g., mangroves), river flooding (e.g., floodplain restoration), intense precipitation (e.g., watershed vegetation), urban flooding (e.g., green urban roofs) and droughts (e.g., green walls) (Kabisch et al., 2017; Kapos et al., 2019; Ozment et al., 2019; Taylor and Druckenmiller, 2022; UNEP, 2021). Yet, the adoption of NbS

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[1] See more information about Climate Adaptation Summit: www.cas2021.com

[2] The 2021 EU Adaptation Strategy: https://ec.europa.eu/clima/sites/clima/files/adaptation/what/docs/eu_strategy_2021.pdf

https://doi.org/10.1016/j.ecolecon.2022.107682
Received 26 June 2022; Received in revised form 11 November 2022; Accepted 12 November 2022

differs regionally, with some countries exhibiting greater uptake than others (Chee et al., 2021). Many NbS are small-scale projects implemented to deal with local challenges. As a result, the body of knowledge is not sufficient to generalize the impacts of such efforts. Moreover, it is challenging to attract societal and political support for large-scale NbS implementation as the temporal and spatial distribution of ecological, economic, and social impacts among stakeholders are not clearly understood (Kabisch et al., 2017; Kapos et al., 2019; Seddon et al., 2020). One of the most well-known large-scale NbS projects is the "Room for the River" program in the Netherlands. The program ran from 2005 to 2019[3] and was implemented at approximately 30 river locations all over the country, with a budget of €2.3 billion (OECD Environment Policy Papers, 2020), it offers a rich ground for drawing lessons. Among the many cases within the "Room for the River" program, Grenmaas is one of the most successful NbS that addresses both the flood risk and local environmental quality problems. Therefore, we use Grensmaas as our case study to provide evidence on the economic impacts of a large-scale NbS project and its co-benefits.

Flood control is an important issue for the Netherlands, as due to its low elevation, approximately 70% of real estate properties are vulnerable to flooding (Kok et al., 2003). Sources of flooding in the Netherlands are widespread and include heavy rainfall, dike failures, and river or sea flooding. The country has been applying a mix of flood defense strategies consisting of structural engineered (e.g., dikes, embankments) and non-structural integrated solutions (e.g., natural coastal dunes, floodplain restoration) over the centuries to keep the low-lying areas free of water. After the two major river floods in the 1990s, there was a transformational shift in the Dutch flood management policy when, instead of a new cycle of raising the embankments, a sustainable and environment-friendly approach based on NbS was advocated (Klijn et al., 2018; Olsthoorn and Tol, 2001). NbS have become an important approach in the Netherlands to secure water safety by embedding natural processes in hydraulic engineering while taking the natural, social, and economic systems into account. However, to scale up NbS implementation to remedy water-related climate risks, it is crucial to understand whether and how the benefits of a project are felt in the urban environment it aims to protect. This is important since such benefits are likely to spatially overlap with floods risks, captilaized of effects which are reported to change with time elapsed after an adverse event (Beltrán et al., 2018). A quantitative assessment of both is important to evaluate the extent of flood damages and how these losses can be reduced through NbS.

Our analysis adopts a market-based valuation approach and focuses on revealing the economic impacts captured by the housing markets in the Netherlands. Towards this end, we employ the hedonic price method (Rosen, 1974), because it is one of the most precise methods to elicit actually capitalized values for various spatial attributes that people value (e.g. environmental amenities of an NbS or disamenities of flood-prone areas) (Bin et al., 2008a, 2008b; Bockarjova et al., 2020; Gibbons et al., 2014; Samarasinghe and Sharp, 2010; Veisten et al., 2012). Moreover the financial stability of the public and private sector is highly dependent on the strength of the housing market (Beltrán et al., 2018; Bishop et al., 2020). We decided to focus on the hedonic analysis of housing values instead of other revealed preference methods (e.g., travel costs typically used to assess effects on the touristic sector), since we focus on NbS applied to tackle climate change adaptation for general public in cities rather than the amenities provided by nature in (e.g., national parks). Specifically, we focus on two research questions for our case study in the Netherlands: (1) What is the spatio-temporal effect of floods on property prices? and (2) Do NbS for flood management capitalize in property prices? Towards this end, we employ the hedonic price method, which is commonly used to estimate the value people attach to environmental risk (Beltrán et al., 2018) and amenities (Bockarjova et al., 2020) – such as flood risk and NbS amenities. By analyzing property prices, the method elicits average willingness-to-pay for each housing attribute and reveals private economic benefits and costs to homeowners in impacted areas, possibly motivating acceptability of NbS. Using hedonic pricing, we investigate to what extent flood-prone properties were discounted following the large flooding events on the Meuse River in December 1993 and January 1995 in the Limburg Province, the Netherlands. Further, we use the hedonic price method to infer the price premium of residential properties located in Grensmaas where NbS aims to improve flood safety and local environmental quality along the Meuse River.

This paper contributes to the literature in three important aspects. First, to the best of our knowledge, this article is the first to estimate the temporal effects of flood risk discount on property prices in the Netherlands and is one of few in the literature (Atreya et al., 2013; Atreya and Ferreira, 2015; Bin and Landry, 2013) uniquely adding the non-US perspective. Second, besides identifying the persistence of the negative effect of floods on property prices over time, we investigate how NbS amenities capitalize into property prices and whether the effect is proximity-sensitive. Third, to strengthen our analysis, we estimate the effect of a traditional gray solutions flood management intervention implemented in response to the same flood events in the same province offering the same flood safety improvements. The most notable distinction between the two projects is that NbS provides additional nature amenities, while gray solutions do not. Hence, we attribute differences between willingness-to-pay for gray solutions and NbS to the co-benefits of NbS in addition to the safety improvement.

2. State-of-art-review

2.1. Flood risk effect on property values

The economic assessment of environmental risk is a prerequisite for planning public investment in protective infrastructures that mitigate the impact of environmental hazards. Economists routinely employ hedonic pricing methods to elicit capitalized risks or amenities, assuming that property prices reveal individual preferences regarding risk acceptance if homebuyers have complete information. Therefore, properties exposed to high hazard risk are expected to have relatively lower values than safe properties, all else being equal. On the contrary, improving safety and/or environmental amenities by investing in protective infrastructures should be positively reflected in property prices.

The hedonic pricing method is the primary method to measure the average individual willingness to pay for flood protection or willingness to accept flood hazards (Beltrán et al., 2018; Bin and Landry, 2013; Bockarjova et al., 2020; Daniel et al., 2009; Pope, 2008). Many studies investigate whether homebuyers consider and understand the given flood risk information by comparing the prices of equivalent properties within and outside the floodplain (Bin et al., 2008a, 2008b; Bin and Kruse, 2006; Carbone et al., 2006; Harrison and Smersh, 2001; Hino and Burke, 2021; Samarasinghe and Sharp, 2010; Speyrer and Ragas, 1991). The studies show that if flood insurance is not mandatory, the negative effect of flood risk on property prices is limited by the homebuyer's subjective assessment of the risk and loss from flooding (Samarasinghe and Sharp, 2010). Moreover, the literature evidence that actual flood events alter the capitalized flood risk discount (Atreya et al., 2013; Atreya and Ferreira, 2015; Bin and Landry, 2013; Bin and Polasky, 2004; Carbone et al., 2006; Kousky, 2010; Skantz and Strickland, 1987).

The majority of studies show that homebuyers perceive environmental disamenities caused by flood risk (Atreya et al., 2013; Atreya and Ferreira, 2015; Bin et al., 2008a, 2008b; Bin and Kruse, 2006; Bin and Landry, 2013; Daniel et al., 2009; Hino and Burke, 2021). Yet, empirical findings provide mixed evidence on whether the housing market

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[3] See the official website of the Ministry of Infrastructure and Water Management (Rijkswaterstaat) for more information: https://www.rijkswaterstaat.nl/water/waterbeheer/bescherming-tegen-het-water/maatregelen-om-overstromingen-te-voorkomen/ruimte-voor-de-rivieren - meer-water

efficiently capitalizes flood risk. The meta-analysis conducted by Beltrán et al. (2018) reveals that the impact of being in the floodplain on property prices ranges from −75.5% discount to a + 61.0% premium, whereas the average associated discount for inland flooding in a 100-year floodplain is −4.6% discount. The inconsistency in the estimates may arise due to the difficulty of separating the positive environmental benefits associated with water or benefits of publicly-funded post-flood restorations from adversities of being exposed to flood risks (Beltrán et al., 2018; Bin and Kruse, 2006; Bin and Landry, 2013). When registered, the discounts occur either due to the capitalized damages of a flood event, or additional flood insurance costs in places where flood insurance is risk-based and mandatory, or because homebuyers update their flood risk perception, which is registered even in the case of a nearly-missed flood event in the absence of the physical damage (Hallstrom and Smith, 2005). In either case, the properties within the floodplain experience a price discount, especially following a flood event (Atreya et al., 2013; Atreya and Ferreira, 2015; Beltrán et al., 2018; Bin and Landry, 2013; Bin and Polasky, 2004; Daniel et al., 2009; Kousky, 2010).

Fewer studies investigate the persistence of flood risk discounts over time. Bin and Landry (2013) and Atreya et al. (2013) find that floodplain properties experience a price decline immediately after the flood. Yet, the flood risk discount was transitory. Bin and Landry (2013) report that the price discount eventually disappeared five or six years after the flood in Pitt County, North Carolina, the US. Similarly, Atreya et al. (2013) find that the negative effect of the flood decays rapidly, vanishing four to nine years after the flood in Dougherty County, Georgia, US. A related study finds that the effect of flooding fade over time in the absence of additional flooding in Albany, Georgia, US (Atreya and Ferreira, 2015).

However, the limited number of studies from outside the US makes it difficult to draw broad conclusions on the impact of flood risk on property values elsewhere. The flood risk perception of homebuyers is likely to be influenced by multiple external factors such as flood management strategies of the government, laws and regulations on damage compensation, and insurance policies. For example, unlike the US, there is no mandatory flood insurance for flood-prone properties in the Netherlands[4] (van Doorn-Hoekveld, 2018). Therefore, we suspect that existing findings in the literature may vary across countries. The Netherlands with its 70% of residents located in flood-prone areas, while being the best protected country worldwide, constitutes an interesting case. Yet, to our knowledge, Daniel et al. (2009) is the only study conducted in the Netherlands that estimates the impact of flooding on property values. Specifically, their findings indicate, on average, a 9% price discount on the properties that were directly hit by the Meuse River floods in 1993 and 1995. Whether the increase in the price differentials identified by Daniel et al. (2009) was temporary or permanent is an open question. In this respect, our analysis differs substantially from Daniel et al. (2009) since our focus is on temporal dynamics of flood risk discount.

2.2. *Effect of nature-based solutions on property values*

A growing body of evidence suggests that many NbS offer to build climate-resilient pathways in a cost-effective and sustainable way compared to gray infrastructure-based alternatives. For example, Narayan et al. (2016) examine the costs and benefits of 52 coastal defense projects adopting NbS. Their findings indicate that NbS are two to five times more cost-effective at improving coastal defense than gray infrastructure. Moreover, research has shown that NbS can provide significant economic benefits (Bockarjova et al., 2020; Kok et al., 2021) beyond flood risk reduction, such as generating tourism and job opportunities (Kok et al., 2021), property market benefits (Bockarjova et al., 2020; McNamara et al., 2015), biodiversity conservation and restoration (Kabisch et al., 2016), recreational areas (Kabisch et al., 2017; Kapos et al., 2019; Seddon et al., 2020). For instance, restoring rivers by applying NbS to increase flood protection in Europe improved agricultural production, carbon sequestration, and storage, yielding a net economic benefit of approximately €1400 per hectare per year compared to unrestored rivers (Vermaat et al., 2016).

The hedonic literature estimating the NbS effect explores various types of amenities such as urban parks (Votsis, 2017), urban green roofs (Ichihara and Cohen, 2011; Veisten et al., 2012), wetland and river restoration (Lewis et al., 2008; Lupi et al., 1991). Bockarjova et al. (2020) provide an extensive meta-analysis of hedonic pricing studies that estimate the effect of green interventions, including multiple types of NbS, on property prices at different distances from the nature site. The study provides insights into the value homebuyers attach to ecosystem services provided by NbS, as is reflected in their willingness to pay a premium for properties exposed to positive externalities of the newly-generated environmental amenities. The results show that environmental amenities positively impact property prices in the nearby areas, and the effect decreases with distance, indicating a distance decay relationship. Moreover, they find that the effect differs based on the type of nature intervention. Specifically, homebuyers attach a higher value to the existence of a park or waterfront in the proximity of their house than other types of urban nature (Bockarjova et al., 2020). Even though there is a growing literature providing guidelines for implementing nature-based flood protection (OECD, 2020; World Bank, 2017), the empirical studies focusing on NbS introduced to remedy flood risk are limited. To our knowledge, Kousky and Walls (2014) is the only study in the hedonic literature that explicitly estimates the effect of NbS floodplain restoration on property prices in St. Louis County, Missouri, the US. However, their study does not particularly account for the recent flood occurrences in the study location, although it has a well-known flood history.

3. Methodology

3.1. *Case study*

In July 2021, the Limburg province in the Netherlands, the most protected country in the world, experienced a major flood. Despite the fact that most of the rainfall occurred in neighboring Germany and Belgium causing massive disruptions there, the economic costs of this relatively contained flood event in the Netherlands were still significant: in the order of 350–600 million euros (ENW, 2021). Notably, almost about 30 years earlier, in December 1993 and January 1995, the high-water levels in the Meuse River (Fig. 1.A) in Limburg almost led to a national catastrophe. Specifically, in 1993, the heavy rainfall caused the evacuation of 8000 people and affected 6000 houses, resulting in €200 million of damage. In 1995, the authorities evacuated >200.000 people and millions of livestock due to high river discharge. The total damage after the flood amounted to €125 million, with approximately 4500 houses reporting damage (ENW, 2021; Wind et al., 1999).

These consecutive floods have triggered a shift to a new flood protection policy in the Netherlands based on NbS, the famous ‘Room for

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[4] Insurance for river and coastal flooding is non-existent in the Netherlands due to its unique geographical conditions (van Doorn-Hoekveld, 2018). The government is responsible for flood management (Articles 21 and 133 of the Constitution, and Articles 1 and 2 of the Water Board Act, Waterschapswet), everywhere except the unembanked areas. Despite an attempt to introduce private flood insurance in the Netherlands in the 2000s, it was not supported due to presumably high insurance rates for homeowners (Ermolieva et al., 2017), lack of interest by insurers and reinsurers (Olsthoorn and Tol, 2001) and the presence of government compensation for major flooding events (Verbond van Verzekeraars, 2020). Only pluvial floods caused by heavy rainfall and not related to river or coastal floods are part of the general home insurance. In other words, there is no private flood insurance for river or coastal flooding available for Dutch homeowners. Consequently, there is no track record on its uptake or premiums.

the River' strategy. This approach was introduced in the early 2000s and aimed to reduce flood risk while simultaneously improving spatial planning and local environmental quality, with a strong focus on creating space for nature and ecosystems (Klijn et al., 2018; Olsthoorn and Tol, 2001; van Herk et al., 2015). The new strategy based on NbS was implemented in several locations, launching another Dutch innovation in managing the water. Here we focus on one of the most successful among the 'Room for the River' restoration projects: the Grensmaas Project.[5] Both the relatively recent occurrence of floods and the NbS response to flood management make this a useful case for the goal of this paper. The Grensmaas Project is the largest and oldest NbS-based river restoration project in the Netherlands that uniquely integrates flood protection and nature development in South Limburg (Fig. 1.C). Its implementation started in 2008 and will continue till 2027,[6] with a large part of the project already completed. Upon its completion, the Grensmaas NbS project will reduce flood risk from 1:50 to 1:250 years, and create approximately 1500 ha of nature development (Rijkswaterstaat, 2018; Wesselink et al., 2013).

Notably, just north of the NbS Grensmaas project, there is the Zandmaas Project which was developed in about the same period in response to the same flood events of 1993–1995 (Fig. 1.C). However, the Zandmaas project adopts a traditional flood management approach that also improves flood safety from 1:50 to 1:250 years (Rijkswaterstaat, 2018). To achieve this, the Zandmaas project relies on gray solutions such as constructing embanked high water channels and dikes along the Meuse River in North Limburg.[7] The key engineering constructions here took place between 2005 and 2015, with some work on dike reinforcement lasting until 2020. Hence, the Zandmaas project serves as a natural 'control' area to compare the effects of the NbS Grensmaas since it provides the same flood safety improvements (from 1:50 to 1:250 year flood) in response to the same hazard experienced by the population in 1993–1995. The key difference between the two projects is their environmental impact: Grensmaas improves ecosystem services and delivers additional environmental amenities, and Zandmaas does not. In the remainder of the paper, we refer to the Grensmaas and Zandmaas as the NbS and gray solution projects.

This unique case study allows us to tackle the two limitations highlighted in the previous section. First, it allows us to quantify the price differentials due to flooding over a period of time. Second, it enables us to quantify the perceived benefits of NbS as compared to gray solutions in a similar spatial and temporal context.

Note: Map A provides the combined flood inundation maps of 1993 and 1995; Map B depicts the house transaction data in North and South Limburg and highlights the housing transaction observations within the flood-prone area; Map C shows the locations and implementation timeline of the Grensmaas (nature-based solution for flood management) and Zandmaas (gray solutions for flood management).

3.2. *Hedonic housing price model*

To single out contributions (i.e., statistical effects) of various housing attributes (structural, location, and environmental characteristics) to the total property value, we employ the hedonic pricing method (Freeman, 2014; Rosen, 1974). The hedonic analysis reveals the average individual willingness-to-pay for a change in a housing attribute, holding all other attributes constant. We model the price of a property, P, as a function of its structural characteristics, ***S*** (e.g., number of rooms, construction year, square meters), location characteristics, ***L*** (e.g., distance to major roads), and consider its location with respect to the flood-prone area (*Floodprone*) and its distance to the river (***River***) that offers (or not) NbS as environmental characteristics.

Following the standard hedonic approach, we define two different treatments in Model 1 and Model 2 to answer our research questions. More specifically, we define Model 1 to examine whether flood-prone houses face a price discount before and after the Meuse River floods in 1993 and 1995 (see Eq. 1), and Model 2 to investigate how NbS and gray solutions based flood management strategies capitalize into property values (see Eq. 2). The hedonic price model is estimated by ordinary least squares (OLS), adopting a semi-logarithmic specification.[8] We use the squared transformation of the nondichotomous structural variables, such as total square meters of living space and number of rooms, assuming that the marginal effect of these attributes on house prices diminishes when the level of the attributes increases.

3.2.1. *Model 1: hedonic price model estimating price differential for flood-prone properties*

Eq. (1) assumes the dependent variable P_{ijt} to be the natural log of the sales price for each house transaction 'i' in municipality 'j' at time 't'. The variable ***S*** is a vector of structural characteristics, ***L*** is a vector of location characteris.

$$ln\left(P_{itj}\right) = \beta_0 + \beta_1 \boldsymbol{S}_{it} + \beta_2 \boldsymbol{L}_{it} + \beta_3 Floodprone_i + \sum_{r=1990-1993}^{2015-2017} \beta_4 Years_{i,r} + \beta_5 Floodprone_i{}^{*} Years_{i,r} + \beta_6 \boldsymbol{River_i} + f_j + g_t + \varepsilon_{itj} \tag{1}$$

To measure the flood risk and test its persistence over time, we use a quasi-experimental difference-in-differences (DiD) method. The method allows us to isolate the effects attributable to the flood hazard from the influence of other simultaneous changes (e.g., macroeconomic shocks, changes in local housing or labor market). In the standard DiD model to estimate flood risk, flood-prone properties are the treatment group and the outside properties are the control group. The variable *Floodprone* in

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[5] More information https://www.rijkswaterstaat.nl/water/waterbeheer/bescherming-tegen-het-water/maatregelen-om-overstromingen-te-voorkomen/maaswerken/grensmaas and http://www.grensmaas.nl/.

[6] The project was recently extended after the Europe Summer floods in 2021. The new end date is announced as 2027.

[7] Note that both projects were introduced in a top-down manner by Rijkswaterstaat and the waterboard of Limburg Province. Considering the central role of government in water management in the Netherlands, we do not expect major differences in risk and project communication with local residents. An extraordinary element of the Zandmaas/Grensmaas projects is the self-realization by sand and gravel companies. Flood protection measures combined with sand (Zandmaas) and gravel (Grensmaas) extraction to reduce the costs bearing on the national budget. This method has been adopted for a large proportion of the Grensmaas project and partially in the Zandmaas project. Besides the differences in financial and administrative aspects, the projects differ in approach because the topography of Zandmaas was not suitable to widen the river. In other words, it was not possible to give more room to the river. Please see the evaluation report from Rijkswaterstaat (2018) and https://www.rijkswaterstaat.nl/water/waterbeheer/bescherming-tegen-het-water/maatregelen-om-overstromingen-te-voorkomen/maaswerken/zandmaas for more information.

[8] The appropriate functional form for the hedonic price regression specification is arguable. In our dataset, the distribution of empirical price data is closer to the normal distribution in a logarithmic form (See Appendix A). This form also enables convenient coefficient interpretation as it permits estimating relative changes in price corresponding to each housing attribute rather than the absolute changes. In this analysis, therefore, the dependent variable is the natural log of the transaction price of the residential houses.

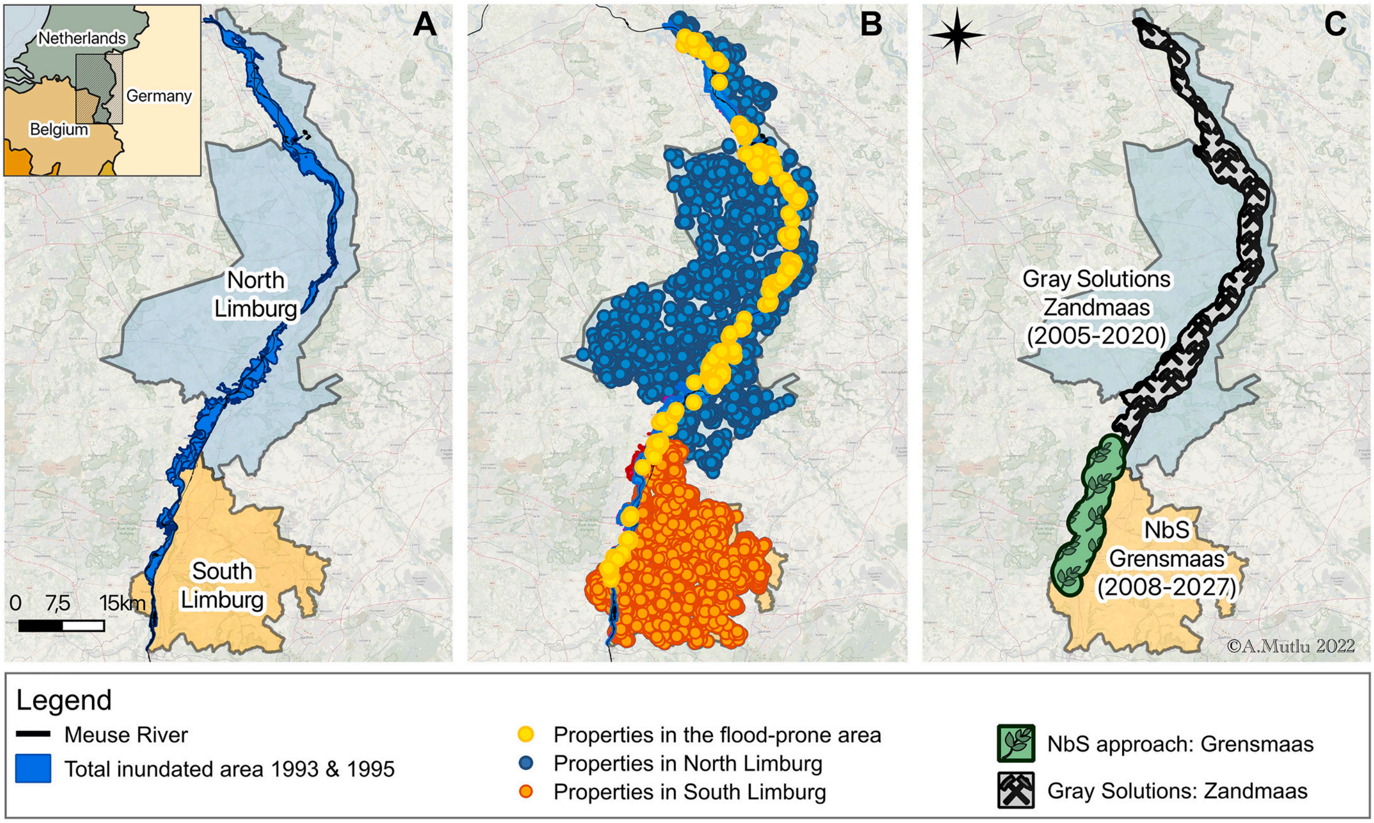

Fig. 1. Maps of floods, house transaction data, and flood management projects.

this model is a dummy variable equal to 1 if the property falls in the flood-prone area and 0 otherwise.

To detect whether the effect of the flood event decays with time, we generate a set of dummy variables *Years,* denoting a period of sale years in our dataset.[9] Each group in *Years* covers a period of four years.[10] Table A1 gives the number of flood-prone properties for each *Years* group (see Appendix A). A year group dummy variable equals 1 if the house was sold within the specified period. For example, *Year90_93* is equal to 1 if the house was sold between 1990 and 1993,[11] which is the period before floods[12] since the first flood happened in December 1993. Note that the variable *Years* itself is omitted in the regression results as it is a time-dependent variable which is essentially perfectly collinear with the year fixed effects.

The timing of the sales is critical for identifying the temporal decay effect of floods. We interact each temporal *Years* period variable with the spatial *Floodprone* variable to examine whether flood risk capitalizes into flood-prone property prices and how persistent this effect is. For instance, the interaction term *Floodprone*Year90_93* estimates the effect of floods on the flood-prone properties before the floods, whereas *Floodprone*Year94_97* is assumed to capture the immediate effect of floods on the flood-prone properties (the second flood happens only a year after the first one in January 1995). We use subsequent *Years* periods to investigate the temporal decay pattern of flood risk on properties located in flood-prone areas. Hence, these interaction terms are our key variable of interest to answer the first research question.

In line with the previous literature (Beltrán et al., 2018; Bin et al., 2008a, 2008b; Bin and Kruse, 2006; Bin and Landry, 2013; Daniel et al., 2009), we anticipate that the subjective risk of flooding could be partially compensated by the water-related amenities. For example, it has been proven that oceanview significantly increases house prices (Bin et al., 2008a, 2008b). Similarly, in the Netherlands, it has been shown that proximity to water increases housing value by roughly 5% at the most immediate proximities to water (Daniel et al., 2009). Yet, the added value of water in residential environments is highly context-dependent, and the water amenities are not limited to water views.

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[9] We experimented with single years and several different year period dummies. Even though the immediate flood effect is robust in all specifications, the temporal decay pattern is not clearly represented when we interact single years with the *Floodprone* variable. This could be due to the low number of observations per year. We therefore use four-year period dummies as the time decay pattern in the final specification. The results with single years are in Appendix B.

[10] Except for the last period dummy Year18_20, which contains the last three years: 2018, 2019, 2020. The variable is omitted from the regression results as it is the baseline category. In the context of our paper, the baseline category Year18_20 represents the "null effect of no flooding". One may choose a different baseline for other reasons; however, the performance of a linear model would be the same. In other words, the differences between the coefficient estimates of the categorical variables would be identical. See http://www.stata.com/manuals13/u25.pdf, Page 7 for more information on categorical variables.

[11] The variable Year90_93 includes the house transactions recorded between January 1990–November 1993; the month of December is not included because of the 1993 flood.

[12] One may expect that the flood discount could exist in the flood-prone properties even before the first flood due to an information effect, assuming that homebuyers are rational and fully informed about the flood risk. We estimate this effect by interacting the variable *Year90_93* and *Floodprone.*

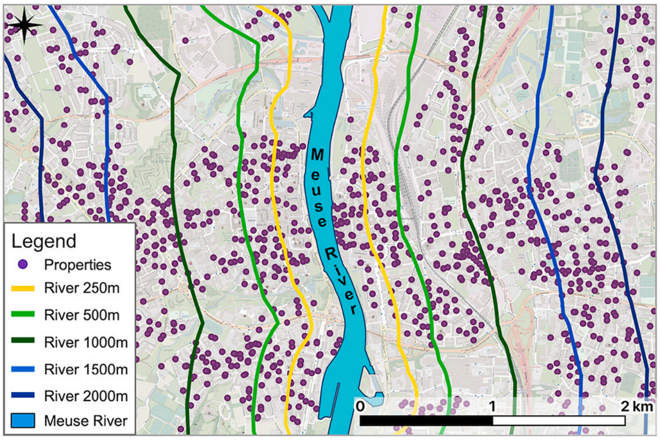

Fig. 2. An example of distance buffers to the river.

Houses which are closer to water may have a view of the water, but may also enjoy direct access to water thus providing recreational benefits (walking along the river, kayaking, etc.). Therefore, failing to control for water amenities may lead to biased estimates. We calculate the proximity to the Meuse River for five buffer zones at various distances from the river (Fig. 2) to capture the positive distance-decaying effect that may occur due to water-related amenities. Accordingly, we define five distance dummy variables for each buffer zone: *River250m, River500m, River1000m, River1500m*, and *River2000m.*[13] The variable ***River*** simply denotes the distance to river dummy variables in Eq. (2). Conventionally, the distance to major roads is assumed to affect housing prices due to the travel-price trade-off (Alonso, 1964; Muth, 1969). Hence, we include the distance variables, *Roads250m,* and *Roads500m*, as additional locational control variables, ***L***, in our analysis. We calculate all distances as the Euclidean distance in meters from the centroid of each property.

3.2.2. Model 2: Hedonic price model estimating the effect of flood management strategies: gray solutions and nature-based solutions

After estimating the flood risk effects and their possible variation over time using Model 1, we define Model 2 to examine whether the implementation of NbS and traditional gray solutions capitalize into nearby property values. In our study area, both NbS and gray solutions are launched in response to the same flood event, offering the same level of flood protection. We hypothesize that NbS flood management provides larger price premiums than gray solutions since the former offers additional benefits such as improving local spatial quality and contributing to nature development in the surrounding areas. However, we expect that the effect of environmental amenities provided by NbS on property prices decreases with distance from these amenities (i.e., distance from the river). To test our hypothesis, we use the property sales between 2000 and 2020 and estimate Eq. (2) separately for North Limburg and South Limburg, where gray solutions and NbS projects are implemented respectively (Fig. 1.C).

$$ln\left(P_{itj}\right) = \beta_0 + \beta_1 \boldsymbol{S}_{it} + \beta_2 \boldsymbol{L}_{it} + \beta_3 \boldsymbol{River}_i + \beta_4 Post_{Gray,NbS} + \beta_5 Post_{Gray,NbS} {}^{*}\boldsymbol{River}_i + f_j + g_t + \varepsilon_{itj} \tag{2}$$

The variable $Post_{Gray,\ NbS}$ is a time-dependent dummy variable which becomes equal to 1 after the start date of the corresponding project and 0 otherwise. Hence, the gray solutions dummy variable, $Post_{Gray}$, equals to 1 for any house sold after 2005 in North Limburg, where the Zandmaas project is constructed. The NbS dummy variable, $Post_{NbS}$, equals to 1 for any house sold after 2008 in South Limburg, where the Grensmaas project is implemented. Note that the variable $Post_{Gray,\ NbS}$ is omitted in the regression results as it is a time-dependent variable which is essentially perfectly collinear with the year fixed effects.

Model 2 estimates the effect of gray solutions and NbS on property prices within a 2 km distance to the river. The variable ***River*** indicates whether the property belongs to one of the five buffers at different distances from the river. We expect the effect of safety improvement provided by gray solutions or NbS intervention to be distance-agnostic since safety standards are the same in the entire dike ring. On the contrary, the effect of nature amenities provided by NbS is expected to decrease with an increase in distance to these amenities. Hence, our key variable of interest to answer the second research question is the interaction term between the two: $Post_{Gray,\ NbS}{}^{*}\boldsymbol{River}$, which examines the effect of the gray or NbS approach in flood management at specific distances to river.[14]

While the hedonic price method provides economically plausible and empirically tractable estimates on average willingness to pay for environmental risks and amenities, there are important caveats. One of the limitations of standard hedonic price model is that it assumes homogenous preferences. Under the assumption, market prices should reflect mean preferences when all households are identical. Bayer et al. (2007) demonstrate how heterogeneity manifests in a residential sorting equilibrium. When households are heterogeneous, in equilibrium, the hedonic price function reflects the marginal willingness to pay (MWTP) of one “marginal” consumer type, while the preferences of the remaining “infra-marginal” types are not directly reflected. On the one hand, if the attribute is in short supply, then MWTP for the marginal type will tend to exceed the population average MWTP. On the other hand, if the attribute is widely available, then the population average MWTP will tend to exceed the MWTP of the marginal type. For example, a new environmental policy or hazardous events such as floods may lead to changes in the distribution of amenity levels throughout a market and can induce resorting of households (Kuminoff et al., 2013). Individuals with higher valuations for environmental risks and amenities can sort to areas offering higher flood protection or richer natural amenities, which may cause house price functions to change over time. The key issue is not whether price functions change, but whether the changes are small enough to ignore (Bishop et al., 2020). Our case study area is populated by small-sized municipalities with populations ranging between 10.000 and 25.000. There are only four municipalities that are considerably larger in the Limburg Province; Maastricht, Heerlen, Sittard-Geleen, and Venlo which have approximately 100.000–120.000 inhabitants. Population and demographic statistics show that none of these municipalities significantly changed during our research period.[15] This indicates rather homogenous and static preferences of Limburg residents on location choice, even though some households more concerned about flood risk and environmental amenities may sort to different locations due to changes in environmental risks and amenities. Therefore, we believe that the effect of sorting is negligible and not a particular threat to the internal validity of our model.

Another important econometric issue in hedonic models is the potential spatial dependence in the error term. Neighboring properties often share common unobserved location attributes (e.g., school districts) and similar structural characteristics (e.g., alike design features)

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[13] We assume that the effect on properties located further from 2 km distance would be negligible. Therefore, we define a 2 km distance threshold presuming a maximum walking time of 25–30 min and an average walking speed of 4–5 km/h. Summary statistics of the properties located at different distances are reported in the Appendix C.

[14] One may question that the variable *Floodprone* is not in Model 2. The reason is that the distance variables to the river overlap with the flood-prone areas in many areas, especially for distances lower than 500 m. See Appendix D for more information.

[15] See Appendix E for population statistics in the Limburg Provience. More information can be found on the official website of Statistics Netherlands (https://opendata.cbs.nl/).

due to contemporaneous construction that may cause spatial dependence (Anselin and Bera, 1998). The presence of spatial dependence could make standard errors smaller than they should be, leading to biased or inefficient coefficient estimates (Bertrand et al., 2004). One of the most common strategies to control for omitted spatially varying covariates in the hedonic literature is adding spatial fixed effects (e.g., administrative boundaries, census tracts) (Kuminoff et al., 2010). In our analysis, we control for spatial autocorrelation by estimating Moran's I. We only detect weak spatial dependence for the samples used in Model 1 and Model 2 (See Appendix F for Moran's I estimates). Considering that our case study area is mainly populated by small towns, we assume that including spatial fixed effects at the municipality level is appropriate. Thus, the variable f_j denotes the spatial fixed effects that deal with the location-specific time-invariant unobserved components such as the geographical differences across 47 municipalities,[16] such as distance to big cities, national parks, and German and Belgian borders. In addition, g_t represents the year fixed effects that control for the temporal dynamics in the housing market, such as macroeconomic trends (e.g., inflation, supply/demand, the financial crisis of 2008, etc.), ε_{itj} is an error term representing other residual unobserved components.

Lastly, we use the Wald test to control for heteroskedasticity. We find that the test is statistically significant, indicating the presence of heteroskedasticity. However, we do not detect any pattern in the residual distribution, meaning that our analysis does not suffer from severe heteroskedasticity. We provide a graphical examination of the distribution of residual to control for heteroskedasticity in Appendix F. To account for spatial autocorrelation and heteroskedasticity, we cluster standard errors at the 6-digit postcode level.

3.3. Data

For our analysis, we rely on a house transactions dataset from the Dutch Association of Real Estate Agents (NVM[17]) for the province of Limburg (Fig. 1.B). The dataset provides detailed information on the transaction prices, date and a wide range of structural attributes such as the size, number of rooms, and maintenance quality. In addition, the dataset is spatially explicit, meaning that the X and Y coordinates and a 6-digit zip code are available for each transaction. In total, we have observations for 48 municipalities in the province of Limburg. Table 1 gives the definitions for all the variables considered in the analysis and Table 2 reports the descriptive statistics for the samples used in Model 1 and Model 2.[18]

We utilize the flood inundation maps of 1993 and 1995 provided by Rijkswaterstaat to determine the flood-prone areas. Since Olsthoorn and Tol (2001) state that the inundated areas in the province of Limburg were the actual floodplain, we are confident that the flood inundation maps are valid for making inferences regarding the capitalization of flood risks in property prices. We combine two inundation maps for the 1993 and 1995 floods because the inundated areas in both floods were almost identical (see Fig. 1.A) and identify the houses located within the flood-prone areas in Fig. 1.B. Hence, Model 1 measures flood risk using a sample of 68,247 single-family residential houses that were sold

Table 1
Variable definition for the full sample of the Dutch province of Limburg between 1990 and 2020 ($N = 68{,}247$) for the dependent variable (Price) and the four groups of independent variables (I.-IV.).

Variable	Definition
Price	Sale price of property, in Euro, adjusted to 2020 prices
I. Structural Characteristics ***(S)***	
LivingArea	Size of living area, in m2
Garden	Size of garden, in m2
Parcel	Size of parcel, in m2
Rooms	Number of rooms
Floors	Number of floors
InsideMaintenance	Index of inside maintanance (Min. Max: 1–9)
OutsideMaintenance	Index of outside maintanance (Min. Max: 1–9)
GardenQuality	Index of garden quality, (Min. Max: 1–5)
Lift	Dummy variable = 1 if property has a lift, else 0
Attic	Dummy variable = 1 if property has an attic, else 0
Monument	Dummy variable = 1 if property is classified as monument, else 0
Monumental	Dummy variable = 1 if property is classified as monumental, else 0
SwimmingPool	Dummy variable = 1 if property has a swimming pool, else 0
Parking	Dummy variable = 1 if property has a parking lot, else 0
ConstructionPeriod1	Dummy variable = 1 if property was built between 1600–1905, else 0
ConstructionPeriod2	Dummy variable = 1 if property was built between 1906–1930, else 0
ConstructionPeriod3	Dummy variable = 1 if property was built between 1930–1944, else 0
ConstructionPeriod4	Dummy variable = 1 if property was built between 1945–1959, else 0
ConstructionPeriod5	Dummy variable = 1 if property was built between 1960–1969, else 0
ConstructionPeriod6	Dummy variable = 1 if property was built between 1970–1979, else 0
ConstructionPeriod7	Dummy variable = 1 if property was built between 1980–1989, else 0
ConstructionPeriod8	Dummy variable = 1 if property was built between 1990–1999, else 0
ConstructionPeriod9	Dummy variable = 1 if property was built between 2000−2020, else 0
DaysOnMarket	Number of days property is listed on the market until sold, in days
II. Location Characteristics ***(L)***	
Roads250m	Dummy variable = 1 if property located in the 0-250 m buffer to the major roads, else 0
Roads500m	Dummy variable = 1 if property located in the 250-500 m buffer to the major roads, else 0
III. Flood Risk Discount & Its Temporal Decay *(Years)*	
Floodprone	Dummy variable = 1 if property located in the flood-prone area, else 0
Years90_93	Dummy variable = 1 if property sold before floods between 1990–1993, else 0
Years94_97	Dummy variable = 1 if property sold 0–4 years after floods between 1994–1997, else 0
Years98_01	Dummy variable = 1 if property sold 4–8 years after floods between 1998–2001, else 0
Years02_05	Dummy variable = 1 if property sold 8–12 years after floods between 2002–2005, else 0
Years06_09	Dummy variable = 1 if property sold 12–16 years after floods between 2006–2009, else 0
Years10_13	Dummy variable = 1 if property sold 16–20 years after floods between 2010–2013, else 0
Years14_17	Dummy variable = 1 if property sold 20–24 years after floods between 2014–2017, else 0
Years18_20	Dummy variable = 1 if property sold 24–27 years after floods between 2018–2020, else 0
IV. Environmental Amenities ***(River)***	
River250m	Dummy variable = 1 if property located in the 0-250 m buffer to the Meuse River, else 0

(*continued on next page*)

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[16] The number of municipalities in the Limburg Province has changed in the last decade due to the low number of inhabitants in some municipalities. The current number of municipalities is 33. However, in our analysis, we use the old municipal divisions to control for spatial heterogeneity since smaller scale division provides us more conservative results.

[17] The data used here cannot be shared due to the European General Data Protection Regulation and the conditions of data use agreed upon with the dataprovider - the Dutch Association of Real Estate Agents (NVM, https://www.nvm.nl/). Researchers interested in the data could contact NVM directly. We share our code here (https://github.com/asli-mutlu/Hedonic-Price.git)

[18] See Appendix G for the distribution of the mean house prices over the years between 1990 and 2020.

Table 1 (*continued*)

Variable	Definition
River500m	Dummy variable = 1 if property located in the 250-500 m buffer to the Meuse River, else 0
River1000m	Dummy variable = 1 if property located in the 500-1000 m buffer to the Meuse River, else 0
River1500m	Dummy variable = 1 if property located in the 1000-1500 m buffer to the Meuse River, else 0
River2000m	Dummy variable = 1 if property located in the 1500-2000 m buffer to the Meuse River, else 0
V. NbS and Gray Solutions	
$Post_{Gray}$	Dummy variable = 1 if property was sold in North Limburg after launching the gray solutions project in 2005, else 0
$Post_{NbS}$	Dummy variable = 1 if property was sold in South Limburg after launching the NbS project in 2008, else 0

between January 1990 and December 2020 in Limburg Province, with 1214 observations in the flood-prone area. The mean property sale price is €226,530 in 2020 prices.

Further, we specifically look at the sales in the 2000s to estimate the effect of two flood management projects implemented along the Meuse River: NbS Grensmaas in South Limburg and traditional gray solutions Zandmaas in North Limburg. We use the information provided by the Grensmaas Consortium and Rijkswaterstaat to determine the start and end dates of the projects and map the project locations (Fig. 1.C). We, therefore, estimate Model 2 using the observations in South Limburg to examine the effect of NbS flood management and the observations in North Limburg to measure the effect of the traditional gray flood management. Specifically, the sample for North Limburg in Model 2 uses 30,062 single-family house transactions, with a mean price of €246,306 in 2020 prices, and the sample for South Limburg in Model 2 uses 29,000 single-family house transactions, with a mean price of €225,481 in 2020 prices. We observe that other average property characteristics are almost identical in all samples (see Table 2).

Therefore, our analysis differs substantially from Daniel et al. (2009) in several aspects: (i) uses extended spatial and time coverage of the

Table 2

Summary statistics of the samples used in Model 1 and Model 2.

	Model 1 – Flood Effect		Model 2 – Flood Management Strategies			
	(N = 68,247)		Gray Solutions (*N* = 30,062)		NbS (*N* = 29,000)	
Variable	Mean	SD	Mean	SD	Mean	SD
Price (dependent var.)	226,530	89,112.610	246,306	85,122.810	225,481	93,786.910
I. Structural Characteristics ***(S)***						
LivingArea	136.072	48.096	135.124	35.621	136.153	62.631
Garden	95.592	118.712	118.144	123.767	98.531	116.817
Parcel	385.775	987.478	455.241	1329.059	337.48	570.735
Rooms	5.393	1.808	5.484	1.632	5.551	2.095
Floors	2.901	0.617	2.869	0.578	2.951	0.694
InsideMaintenance	6.869	1.022	6.956	0.940	6.755	1.086
OutsideMaintenance	6.896	0.934	6.959	0.879	6.814	0.960
GardenQuality	3.492	0.850	3.347	0.780	3.743	0.920
Lift	0	0.021	0.001	0.024	0	0.020
Attic	0.452	0.498	0.482	0.500	0.401	0.490
Monument	0.002	0.040	0.001	0.038	0.002	0.045
Monumental	0.003	0.050	0.002	0.047	0.004	0.059
SwimmingPool	0.007	0.082	0.010	0.098	0.006	0.077
Parking	0.661	0.473	0.675	0.468	0.633	0.482
ConstructionPeriod1	0.017	0.130	0.015	0.123	0.021	0.142
ConstructionPeriod2	0.047	0.211	0.029	0.168	0.070	0.254
ConstructionPeriod3	0.051	0.220	0.032	0.176	0.072	0.258
ConstructionPeriod4	0.135	0.341	0.113	0.317	0.164	0.370
ConstructionPeriod5	0.153	0.360	0.161	0.367	0.141	0.348
ConstructionPeriod6	0.212	0.409	0.236	0.425	0.165	0.371
ConstructionPeriod7	0.169	0.375	0.178	0.382	0.139	0.346
ConstructionPeriod8	0.112	0.315	0.133	0.340	0.102	0.303
ConstructionPeriod9	0.051	0.220	0.070	0.256	0.047	0.211
DaysOnMarket	155	236	184	273	156	217
II. Location Characteristics ***(L)***						
Roads250m	0.132	0.339	0.191	0.393	0.069	0.254
Roads500m	0.304	0.460	0.402	0.490	0.196	0.397
III. Flood Risk Discount & Its Temporal Decay (*Years*)						
Floodprone	0.017	0.129				
Years90_93	0.036	0.187				
Years94_97	0.056	0.229				
Years98_01	0.103	0.305				
Years02_05	0.129	0.335				
Years06_09	0.143	0.350				
Years10_13	0.111	0.314				
Years14_17	0.223	0.416				
Years18_20	0.198	0.399				
IV. Environmental Amenities ***(River)***						
River250m	0.009	0.094	0.005	0.071	0.013	0.114
River500m	0.019	0.136	0.016	0.125	0.021	0.143
River1000m	0.043	0.203	0.049	0.215	0.037	0.188
River1500m	0.046	0.210	0.041	0.199	0.049	0.216
River2000m	0.051	0.221	0.045	0.208	0.055	0.227
V. NbS and Gray Solutions						
$Post_{Gray}$			0.789	0.408		
$Post_{NbS}$					0.638	0.481

house transaction data resulting in 68,247 single-family residential houses with 1214 observations in flood-prone areas (Model 1) instead of 9505 observations with 246 in flood-prone areas in Daniel et al. (2009)), (ii) identifies flood-prone houses using official inundation maps rather than aerial photos, (iii) introduces spatial and time fixed effects to the hedonic model, and (iv) most importantly it explores temporal dynamics of flood risk discount.

4. Results and discussion

To address our two research questions, we estimate two hedonic models. First, we discuss the outcomes of Model 1 analysis implemented for the full sample (1990–2020) in the entire Limburg province to quantify whether and to what extent the risk of 1993–1995 Limburg floods has capitalized into the property prices and how stable this effect is. Model 1 includes all independent variables from groups I.-IV. in Table 1. Specifically, in Model 1 the coefficient estimates of the interaction term between the *Floodprone* and *Years* variables reflect the price variations in the flood-prone area over time.

Second, to quantify any possible effects of two policy interventions – NbS and gray flood solutions – we present the results of Model 2, where we focus on part of the sample between 2000 and 2020. We selected this time to have a considerable number of observations before the start date of the flood management projects. In addition, the results of Model 1 indicate that the flood discount in flood-prone properties diminishes between 2002 and 2005, and eventually disappears after 2005, which coincidence with the start date of the flood management interventions. Therefore, Model 2 presents price effects of three groups of independent variables, all groups I.-V. from Table 1, besides the *Years* dummy variables in group III. since the effect of the flood fully disappears by the launch of both the flood protection projects.

In both Model 1 and Model 2, we use the semi-log functional form for the price. Hence, to quantify the marginal effect of a unit increase in variable X one needs to multiply the expected value of house price by exp.($c\widehat{\beta}$). Further, for small values of $\widehat{\beta}$, the coefficient estimate is approximately $e(\widehat{\beta}) \approx 1+\widehat{\beta}$. Considering that estimated coefficients in our analysis are relatively small, each $\widehat{\beta}$ represents the expected percentage change in a house price for a unit increase in X. For example, Column 1 in Table 3 shows that the estimated discount in flood-prone properties for the given years is (−0.0563) x 100 = 5.6% change or (−0.0563) x €226,530 = €12,753 absolute monetary change, where €226,530 is the mean sales price for the sample used in Model 1 (See Table 2).

4.1. *Model 1: Capitalized flood risk discount and their dynamics across the Dutch Limburg Province*

4.1.1. *Flood risk discount in Limburg and its evolution over time*

In Model 1 (Column 1, Table 3), the coefficient estimate of the *Floodprone* variable provides the baseline effect attributable to the flood-prone disamenity for the 2018–2020 baseline period. We find no significant coefficient for the *Floodprone* variable, however the coefficient estimates of the interaction term between the *Floodprone* and *Years* variables reflect the price variations in the flood-prone properties over time, revealing the negative effect of flood events.

The overall pattern of the findings suggests that the properties in the flood-prone area in Limburg suffered from a price discount, even before the floods. In contrast to Daniel et al. (2009), we find evidence that residents in the Dutch Limburg Province seemed to be aware of flood risk in flood-prone properties in the pre-flood period, which we associate with a better attribution of flooded properties in our dataset and its wider spatio-temporal coverage. Specifically, the estimated coefficient for the first interaction term *Floodprone*Year90_93* indicates that the flood-prone properties suffer from a significant pre-flood price discount of about 5.6%, which is equivalent to €12,753 discount for an average house. Yet, the 1993–1995 flood events clearly amplified the price differential between properties within and outside the flood-prone area. We observe that the immediate effect of flooding – up to 4 years after the first flood in December 1993 – on property values located in the flood-prone location was €24,691 price discount, which was equivalent to roughly 10.9% reduction of impacted houses compared to the average property value. However, the flood discount was temporary, as evidenced in previous US studies (Atreya et al., 2013; Atreya and Ferreira, 2015; Bin and Landry, 2013). In the absence of recurring floods, the price differential diminished in subsequent periods, and this decline is non-linear. Namely, the price discount drops to 9% between 1998 and 2001, then approaches 6% between 2002 and 2005, i.e., €20,546 and

Table 3
Key estimation results of Model 1 and Model 2. (dependent variable: the logarithm of house price).

	Model 1 (1990–2020)	Model 2 (2000–2020)	
	Flood Effect	Gray Solutions	NbS
Variables	Limburg - Full	North Limburg	South Limburg
Flood Risk Discount & Its Temporal Decay			
Floodprone = 1	−0.0102		
	(0.0147)		
Floodprone*Years90_93	−0.0563*		
	(0.0303)		
Floodprone*Years94_97	−0.109***		
	(0.0233)		
Floodprone*Years98_01	−0.0907***		
	(0.0244)		
Floodprone*Years02_05	−0.0619***		
	(0.0223)		
Floodprone*Years06_09	−0.00529		
	(0.0245)		
Floodprone*Years10_13	−0.000383		
	(0.0274)		
Floodprone*Years14_17	0.00215		
	(0.0173)		
Environmental Amenities			
River250m = 1	0.128***	0.124***	0.0783***
	(0.0176)	(0.0359)	(0.0288)
River500m = 1	0.0961***	0.138***	0.0196
	(0.0134)	(0.0179)	(0.0242)
River1000m = 1	0.0908***	0.113***	0.0421**
	(0.0103)	(0.0195)	(0.0174)
River1500m = 1	0.0461***	0.0733***	−0.0169
	(0.00824)	(0.0129)	(0.0130)
River2000m = 1	0.0204***	0.0453***	−0.0141
	(0.00748)	(0.0145)	(0.0124)
NbS and Gray Solutions			
$Post_{Gray\ NbS}$*River250m		0.0309	0.0711***
		(0.0368)	(0.0274)
$Post_{Gray\ NbS}$*River500m		0.0107	0.0669***
		(0.0193)	(0.0239)
$Post_{Gray\ NbS}$*River1000m		0.0145	0.0646***
		(0.0147)	(0.0157)
$Post_{Gray\ NbS}$*River1500m		0.0215**	0.0625***
		(0.0109)	(0.0135)
$Post_{Gray\ NbS}$*River2000m		0.00200	0.0212*
		(0.0122)	(0.0117)
Constant	10.89***	11.06***	10.79***
	(0.0141)	(0.0223)	(0.0215)
Observations	68,247	30,062	29,000
R-squared	0.782	0.699	0.698
Number of Municipalities	47	27	20
House Characteristics	Yes	Yes	Yes
Municipality FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes

Notes: The structural and location characteristics (variables I. and II. in Table 1) are suppressed. The complete overview of the coefficients is reported in Appendix H. We clustered standard errors at the 6-digit postcode level in all specifications. Standard errors are in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

€14,022 discount correspondingly on average. Notably, the coefficient estimates for the years after 2005, which coincides with the beginning of the gray flood defense engineering works, are not significant. In other words, the flood discount disappears 9–12 years after the floods. The transitory effect suggests that homebuyers in our sample tend to forget the negative consequences of flooding over time or are being misinformed about flood risks. It might also be the case that the major flood safety improvements that followed the floods have reduced the public concerns about the hazard, and got capitalized in property prices delivering insignificant flood risk price discounts after 2005.

The estimated increase in price differential may indicate that fresh flooding experiences may update how homebuyers perceive flood risk and costs associated with flooding. Yet, this interpretation is only valid if the price discount occurred due to an information update regarding flood risk. Additionally, the revealed flood risk discount could reflect the structural inundation damage if the properties directly hit by the floods are not excluded from the analysis. Due to limits in data availability regarding structural flood damages on specific residential properties, our analysis cannot detect the observations with severe flood damage. However, Daniel et al. (2009) highlight that homeowners were generously compensated for the structural damages by the government. This gives us the confidence to argue that flooding damage is not confounding our results, and the estimated price discount is attributable to feelings of stress resulting from being at risk.

4.1.2. *Capitalized value of environmental amenities in Limburg*

In addition, Model 1 reports statistically significant and positive coefficients on distance to river, indicating that proximity to the river is desirable and serves as an amenity. The results capture the distance decay effect, i.e., the effect of distance to river on house prices diminishes as distance increases. For example, houses in close proximity to the Meuse River (up to 250 m) have an average of 12.8% higher sale prices, which corresponds to €28,995 premium for an average house. However, this effect declines further from the river, and drops to a 2% premium at a 2000 m distance, which is equivalent to €4612 premium for an average house.

4.2. *Model 2: The differentiated effects of gray solutions and nature-based solutions*

4.2.1. *Insignificant effect of gray solutions*

Model 2 (Column 2, Table 3) shows the estimated effects of post-flood gray solutions on property prices in North Limburg. We find some evidence on diminishing marginal returns for the proximity to river in gray solutions Model 2,[19] indicating that proximity to water is desirable. For instance, the properties within 500 m of the river are found to have on average a 13.8% price premium, whereas the premium is estimated as 4.5% at around 2000 m distance (equivalent to €33,990 and €11,157 correspondingly for an average house).[20] However, we find no significant effects associated with the start of the gray solutions project. Namely, the coefficients for the interaction terms of *Post*$_{Grey}$****River*** are insignificant, indicating that no significant impact can be attributable to traditional gray flood defenses within the 2000 m distance buffer to river. We note one exception in the interaction terms: properties located within 1500 m–2000 m buffer have approximately 2.1% or €5295 price premium on average after the implementation of gray solutions. However, the coefficient of *Post*$_{Gray}$**River1500m* is only weakly significant, and if it captures the true effect of gray solutions we would expect to see the effect in closer distances to the river as the properties nearby the river are more exposed. Therefore, there is not enough evidence to attribute this small positive effect to the implementation of the gray solutions. The interaction term might capture the effect of any other local improvement that coincided with the implementation of gray solutions.

4.2.2. *Positive effect of nature-based solutions*

NbS Model 2 (Column 3, Table 3) estimates the effect of NbS flood management on property prices in South Limburg. Most coefficients of the interaction terms *Post*$_{NbS}$****River*** are positive and statistically significant, indicating that improvement in the spatial quality and natural amenities provided by NbS flood management positively influence house prices in the surrounding areas. As expected, the magnitude of this effect decreases as the distance to river increases, revealing a distance decay relationship of the environmental amenity boosted by the NbS project. For example, properties within 250 m proximity to the river have approximately 7.8% higher prices (or €17,655 premium for an average house) after implementing NbS in addition to the 7.1% premium (i.e., €16,032 premium on average) that is attributable to the distance amenities within 250 m without the project. Therefore, the total effect of NbS amenities on the property prices within the 250 m buffer to NbS location is a €33,687 price premium on average.[21] This effect should be interpreted with caution as locations within the 250 m buffer to the river could also be flood-prone. As Model 1 reveals that the flood discount was still present in the flood-prone properties between the years 2000 and 2005, the estimates of *River250m* could partially absorb the negative effect attributable to flood risks. Hence, we suspect that the coefficient for *River250m* is underestimated.

We find that the positive effect of natural amenities becomes less pronounced when properties are further distant from the river. For the properties around 1000 m away from the river, we find a 6.5% increase in property values after the launch of the NbS project on top of the 4.2% premium provided by the environmental amenities within the 1000 m distance buffer, resulting in total of 10.7% or a €24,126 price premium. The NbS premium declines to 6.2% at 1500 m distance, which is equivalent to €13,979 of an average property price. As expected, the price premium caused by NbS further decreases at 2000 m from the riverbank and eventually becomes equivalent to €4780 of the average house price, which corresponds to a 2.1% premium for an average house.

The overall findings in Model 2 show that the NbS flood management approach capitalizes into property prices in the surrounding areas, in contrast to the traditional gray approach. Specifically, in North Limburg, where the traditional flood management project was implemented, we find that the homebuyers are indifferent to living near the gray flood defense, according to the revealed effects on housing prices. The results align with our expectations because the traditional approach is based on dike reinforcement and has no contribution to the local spatial and environmental quality. In contrast, our results show that NbS flood management significantly increases nearby property values. Keeping in mind that both NbS and gray solutions offer the same level of flood projection and were introduced as a response to the same flood event, we believe the price premium observed in nearby properties to the NbS project location in South Limburg primarily reflects the positive effect of nature amenities provided by NbS.

5. Conclusion

This study quantifies the time-varying effect of flood risk discount on property prices in the Netherlands and examines the impact of NbS on

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[19] With the exception in the coefficient estimates of *River250m*. Model 1 reveals that the flood risk discount on flood-prone properties is still present between the years 2000–2005. Therefore, we suspect that the coefficient estimates of *River250m* could partially capture the negative effect of being in the flood-prone area, and thus estimated value of *River250m* is lower than *River500m*.

[20] The premium for *River500m* is calculated as 0.138 x €246,306 = €33.990, where €246,306 is the mean sales price of the sample used in gray solutions Model 2. See Table 2.

[21] Calculated as (0.0783 + 0.0711) x €225,481 = €33.687, where €225,481 is the mean sales price of the sample used in NbS Model 2. See Table 2.

property prices compared to the traditional gray flood risk management. We use two case studies of flood management strategies – one based on NbS and another based on the traditional gray solutions – that were launched after the river floodings of 1993 and 1995 in the Dutch Province of Limburg. We employ hedonic price models to determine how persistently the housing market capitalized the effect of these flood events, while also exploring whether homebuyers are willing to pay a premium for the NbS flood management approach.

Our findings on the impacts of floods clearly indicate that the negative flood effect capitalized into flood-prone property prices reducing them by 10,9% on average. However, this discount diminishes over time and eventually vanishes within 9–12 years. In our case, the time period within which that discount disappears coincides with the launch of flood management projects. However, previous studies (Atreya et al., 2013; Atreya and Ferreira, 2015; Bin and Landry, 2013) found that the flood discount disappears regardless of whether or not there is any protective action taken, linking this phenomenon to evolving subjective risk perceptions that fade after a flood. Therefore, our findings suggest that with the lack of flood experience, housing markets do not efficiently capitalize flood risks, which is worrisome given the increasing probabilities and severity of floods exacerbated by climate change in the long run. This is of great interest to policymakers and private investors such as mortgage providers, insurances, as well as homeowners who are vulnerable to financial instability of housing markets in climate-sensitive areas.

Moreover, our analysis shows that the benefits of the NbS flood management approach capitalizes into property prices in the surrounding areas, in contrast to the traditional gray solutions. Specifically, in North Limburg, where the traditional flood management project was implemented, we find that the homebuyers are indifferent to living near the gray flood defense, according to the revealed effects on housing prices. The results align with our expectations because the traditional approach is based on dike reinforcement and has limited contribution to the local spatial and environmental quality. In contrast, our results show that NbS flood management significantly increases nearby property values by 15% on average. Keeping in mind that both NbS and gray solutions offer the same level of flood projection and were introduced as a response to the same flood event, we conclude that the price premium observed in nearby properties to the NbS project location in South Limburg primarily reflects the positive effect of nature amenities provided by NbS.

Nature-based solutions, when done well, can deliver many different benefits, including climate change adaptation and biodiversity conservation. They should therefore be planned, designed and implemented so as to deliver those benefits. The value and importance of nature need to be better reflected in economic and political decision-making and in a stronger integration between the biodiversity, climate change and development agendas. The estimated values for the NbS amenities studied here may give insights to public and private investors on the economic viability of NbS. However, it is important to recognize that the values calculated using the hedonic price model do not capture the total economic value of the amenities in question. Our results only quantify the extent of private co-benefits of NbS capitalized in prices of single-family homes within a 2 km surrounding area. Thus, the estimates do not capture how visitors or businesses benefit from the NbS amenities or how the latter contributes to the wider ecosystem services in surrounding areas. In addition, literature shows that the broader ecological benefits of NbS may not be directly perceived by the local residents such as reducing air pollution, improving water quality, or preserving natural habitats (Seddon et al., 2020). Considering these facts, we expect that public benefits of NbS to be higher than our estimated results.

This paper provides novel insights into the capitalized flood risk discount and its dynamics in the Dutch context. Also for the first time we elicit the capitalized premiums of the NbS flood project compared to the gray infrastructure flood defense carried out in about the same geographical region at the same time. These estimated values of the willingness to pay for flood risk reduction and for NbS amenities of an average homeowner in the Netherlands are valuable inputs for a cost-benefit analysis or other means to design climate-resilient policies. It is especially valuable in places where the pressure to develop housing in flood-prone areas aligned with climate change adaptation is high.

This work can be further expanded in a number of directions. First, it will be valuable to rerun the analysis to estimate the effects of the 2021 European floods. This could be realized after at least 3–5 years after the event (Bin and Landry, 2013; Bin and Polasky, 2004; Kousky, 2010). Second, while there is growing attention to preference heterogeneity in willingness to pay, mainly among the stated preferences studies (Schaafsma et al., 2012), exploring the influence of differences in spatial location preferences is still consistently named as a direction for future research (Knapp and Ladenburg, 2015; Ladenburg and Skotte, 2022) which we echo here. Third, besides not fully accounting for individual heterogeneity in preferences for risks, amenities and housing attributes, the fundamental assumptions of hedonic analysis include full information and perfect rationality. Yet, flood-prone markets are known to exhibit information asymmetry (Pope, 2008; Votsis and Perrels, 2016). Alternative decision-making models under risk - beyond the Expected Utility theory - such as Prospect Theory (Kahneman and Tversky, 1979; Slovic et al., 2004) and Protection Motivation Theory (Rogers, 1975) gain attention and are consistently applied to study risk perceptions, risk communication and drivers of individual adaptation behavior (Bubeck et al., 2012; Mol et al., 2020; Noll et al., 2022; Seebauer and Babcicky, 2020). Indeed, individuals exhibit preferences heterogeneity and bounded rationality under incomplete information. Alternative theoretical stands (reviewed by e.g., Machina and Viscusi (2013)) and new empirical evidence on loss aversion, framing, reference point, the role of information and learning, non-stable risk preferences and other deviations from perfect rationality emerging in the vast and growing literature on experimental and behavioral economics (Cartwright, 2018; Machina and Viscusi, 2013; Plott and Smith, 2008), could serve as a guide for specifying alternatives heuristics for decision-making in housing markets prone to flood risks. Furthermore, the analysis could go beyond capitalized losses or benefits of an average homeowner and could consider the distributional impacts of hazards and of NbS climate adaptations for various socioeconomic groups explicitly.

Lastly, stated preference methods such as surveys, choice experiments, and stakeholder interviews can uncover the complexity of subjective risk perceptions and enhance flood risk communication and motivate individuals to take adaptation actions that strengthen socioeconomic resilience to floods (Lechowska, 2018; Osberghaus, 2015; Rollason et al., 2018). In addition, the disaggregated data obtained using stated preference methods can be used in micro-simulation models, such as agent-based models (Arthur, 2021), and can further be compared to the results of the hedonic analysis. Such combinations of traditional economic techniques (revealed and stated preferences methods) and agent-based simulations (de Koning et al., 2017) can be used in future research to explore how individual experiences and interactions lead to the evolution of opinion dynamics on flood risk perception and preferences for NbS amenities under various assumptions about behavior under risk. Disaggregating average patterns across specific socioeconomic groups in a simulated synthetic society will help trace distributional impacts of climate-induced hazards and of adaptation efforts, identify (soft) adaptation limits (Mechler et al., 2020) and quantify an adaptation deficit (Gawith et al., 2020) imposed by behavioral biases. Simulations are also known to scale up behavioral patterns observed in data - such as hedonic analysis reveals - for large populations, over time to also trace the out-of-equilibrium dynamics, and across geographical space where hazards under different climate scenarios could be tested (de Koning and Filatova, 2020). Pursuing these future research directions will help to amplify the impact of empirical evidence provided by hedonic analysis, and to design actionable policies that account for individual behavior under risks and economic motives for individual acceptability of NbS, supporting their wide uptake.

Declaration of Competing Interest

Declaration of Competing Interest could have appeared to influence the work reported in this paper.

Data availability

The data used here cannot be shared due to the European General Data Protection Regulation and the conditions of data use agreed upon with the dataprovider - the Dutch Association of Real Estate Agents (NVM, https://www.nvm.nl/). Researchers interested in the data could contact NVM directly. We share our code here (https://github.com/asli-mutlu/Hedonic-Price.git)

Acknowledgments

The authors are thankful to NVM, Brainbay and the Amsterdam School of Real Estate for the provision of the house transaction data used for this analysis. This work was supported by the Dutch Research Council NWO grant number 17596, and the NWO VIDI grant number 191015 . We are thankful to Stefan Kuks, Matthijs Kok, and Frans Klijn for the insightful discussions about the history of the projects, and to the two anonymous reviewers for their valuable comments.

Appendix A

Table A1
Number of observations sold in the flood-prone area per year group.

Years	N
1990–1993	39
1994–1997	64
1998–2001	103
2002–2005	133
2006–2009	127
2010–2013	113
2014–2017	288
2018–2020	280
Total	1147

Table A2
Number of observations in the flood-prone area each year per municipality. Note that the municipalities that have zero observation in the flood-prone area are not reported in the table.

Year	Municipality ID																				Total
	885	889	893	907	914	933	934	935	938	944	957	971	975	983	993	1507	1670	1711	1883	1937	
1990	0	0	0	0	0	0	0	1	0	0	1	0	0	3	2	0	0	0	0	0	7
1991	0	0	0	1	0	0	0	2	1	1	2	0	0	0	0	0	0	2	0	0	9
1992	0	0	1	0	2	0	0	2	0	0	2	0	0	3	0	0	0	3	0	0	13
1993	0	0	0	0	0	0	0	2	0	0	6	0	0	2	0	0	0	0	0	0	10
1994	1	0	1	0	0	0	0	5	0	0	1	1	0	3	0	0	0	0	0	0	12
1995	0	0	0	1	1	0	0	8	0	0	0	0	0	4	0	0	0	4	0	0	18
1996	1	0	2	0	0	1	0	3	0	0	1	2	0	7	0	0	0	3	0	0	20
1997	1	0	1	1	1	0	0	4	0	0	1	0	0	3	0	0	0	2	0	0	14
1998	0	0	1	0	0	1	0	6	0	1	4	0	0	5	0	0	1	1	0	0	20
1999	0	0	1	1	1	0	0	5	0	1	4	0	0	4	0	0	0	2	0	0	19
2000	0	0	2	0	0	0	0	10	2	1	4	1	0	6	2	1	0	3	0	0	32
2001	3	0	1	2	1	0	0	8	0	0	9	1	0	7	0	0	0	0	0	0	32
2002	3	0	3	0	0	0	0	5	0	0	4	6	0	6	2	0	0	4	0	0	33
2003	4	0	2	0	1	1	0	4	2	0	7	5	0	7	1	0	0	1	0	0	35
2004	5	0	2	1	0	1	0	10	0	3	8	1	1	0	0	0	0	3	0	0	35
2005	5	0	1	0	0	0	0	11	0	1	6	2	0	2	0	2	0	0	0	0	30
2006	1	0	3	1	1	0	0	8	0	0	12	1	0	1	2	2	0	1	0	0	33
2007	0	0	6	3	1	0	0	6	2	2	7	0	0	3	1	0	0	0	0	0	31
2008	3	0	5	1	0	0	0	5	0	1	10	0	0	4	1	0	0	3	0	0	33
2009	2	0	3	2	1	0	0	4	1	1	7	0	0	5	2	0	0	2	0	0	30
2010	2	0	0	2	0	0	0	8	2	0	4	0	0	3	3	0	0	1	0	0	25
2011	1	2	5	3	3	0	0	6	0	0	5	1	0	0	2	0	0	4	0	0	32
2012	2	0	3	3	0	0	0	3	0	1	8	0	0	3	4	0	0	1	0	1	29
2013	5	0	1	1	0	0	0	7	0	1	4	0	0	5	3	0	0	0	0	0	27
2014	4	1	2	2	0	0	0	7	0	0	13	3	0	10	3	1	0	0	0	0	46
2015	6	0	3	1	1	0	0	5	0	0	12	3	0	14	3	0	0	3	0	0	51
2016	9	0	5	1	1	1	0	7	2	2	14	1	0	25	7	1	0	6	1	0	83
2017	15	0	9	4	2	1	0	15	1	2	18	4	0	29	5	1	0	2	0	0	108
2018	17	0	6	1	3	1	0	15	0	2	12	2	0	21	12	0	0	1	1	0	94
2019	13	0	7	6	2	2	1	5	2	1	17	1	0	30	4	1	0	3	1	0	96
2020	14	0	8	1	2	0	0	13	0	1	18	2	0	18	7	0	0	6	0	0	90
Total	117	3	84	39	24	9	1	200	15	22	221	37	1	233	66	9	1	61	3	1	1147

Appendix B

When we use single years, we detect a 2.5% discount in the flood-prone properties in 1991 (−0.151 + 0.126 = 2.5) and this discount seems to increase after the first flood event in 1993 (−0.151 + 0.106 = 4.5). However, the number of houses sold in the flood-prone area per year and municipality is quite low to have meaningful estimates.

Table B1
OLS results of Model 1 with single-year interactions.

	Flood Effect
VARIABLES	Limburg - Full
Flood Risk Discount & Its Temporal Decay	
Floodprone = 1	−0.151***
	(0.0460)
Floodprone*Year1991	0.126**
	(0.0561)
Floodprone*Year1992	0.0846
	(0.0629)
Floodprone*Year1993	0.106**
	(0.0538)
Floodprone*Year1994	0.0251
	(0.0525)
Floodprone*Year1995	0.00348
	(0.0541)
Floodprone*Year1996	0.0596
	(0.0476)
Floodprone*Year1997	0.0365
	(0.0686)
Floodprone*Year1998	0.0728
	(0.0581)
Floodprone*Year1999	0.0729
	(0.0713)
Floodprone*Year2000	0.00249
	(0.0608)
Floodprone*Year2001	0.0702
	(0.0573)
Floodprone*Year2002	0.0646
	(0.0529)
Floodprone*Year2003	0.122**
	(0.0609)
Floodprone*Year2004	0.0855
	(0.0597)
Floodprone*Year2005	0.0375
	(0.0609)
Floodprone*Year2006	0.0912
	(0.0557)
Floodprone*Year2007	0.183***
	(0.0671)
Floodprone*Year2008	0.132**
	(0.0604)
Floodprone*Year2009	0.140***
	(0.0542)
Floodprone*Year2010	0.0900
	(0.0636)
Floodprone*Year2011	0.199***
	(0.0766)
Floodprone*Year2012	0.181***
	(0.0633)
Floodprone*Year2013	0.0749
	(0.0678)
Floodprone*Year2014	0.124**
	(0.0552)
Floodprone*Year2015	0.130**
	(0.0565)
Floodprone*Year2016	0.155***
	(0.0511)
Floodprone*Year2017	0.148***
	(0.0511)
Floodprone*Year2018	0.0992*
	(0.0511)
Floodprone*Year2019	0.169***
	(0.0495)
Floodprone*Year2020	0.154***
	(0.0525)

(*continued on next page*)

Table B1 (*continued*)

	Flood Effect
VARIABLES	Limburg - Full
Environmental Amenities	
Meuse River (0 - 250 m)	0.129***
	(0.0175)
Meuse River (250 - 500 m)	0.0961***
	(0.0134)
Meuse River (500 - 1000 m)	0.0907***
	(0.0103)
Meuse River (1000 - 1500 m)	0.0460***
	(0.00825)
Meuse River (1500 - 2000 m)	0.0203***
	(0.00748)
Constant	11.06***
	(0.0141)
Observations	68,247
R-squared	0.702
Number of Municipalities	47
House Characteristics	Yes
Municipality FE	Yes
Year FE	Yes

Appendix C

Table C1
Summary statistics of properties located at different distances to the river.

	River250m		River500m		River1000m		River1500m		River2000m	
	($N = 614$)		($N = 1280$)		($N = 2944$)		($N = 3150$)		($N = 3512$)	
Variable	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Price (dependent var.)	281,251.64	117,910.67	252,528.31	101,762.51	246,507.23	94,520.54	240,384.73	86,618.41	231,593.25	90,716.961
I. Structural Characteristics (S)										
LivingArea	141.322	51.395	140.482	50.389	141.018	39.862	138.101	41.528	136.431	34.702
Garden	93.767	138.595	85.997	113.153	98.771	121.823	83.153	103.559	86.114	111.989
Parcel	308.752	284.804	297.047	221.15	333.108	314.653	312.51	370.298	305.555	300.908
Rooms	5.223	2.203	5.248	2.031	5.455	2.079	5.176	1.964	5.264	1.988
Floors	2.889	0.779	2.888	0.682	2.913	0.672	2.887	0.655	2.881	0.705
InsideMaintenance	6.746	1.299	6.880	1.057	6.856	1.082	6.933	1.102	6.766	1.088
OutsideMaintenance	6.796	1.201	6.909	0.986	6.886	0.986	6.96	0.988	6.831	0.986
GardenQuality	3.401	0.849	3.485	0.853	3.504	0.886	3.449	0.844	3.383	0.841
Lift	0	0	0.001	0.028	0.001	0.026	0.001	0.025	0	0
Attic	0.345	0.476	0.401	0.490	0.443	0.497	0.439	0.496	0.437	0.496
Monument	0.010	0.098	0.005	0.068	0.002	0.041	0.007	0.081	0.003	0.058
Monumental	0.024	0.155	0.016	0.124	0.005	0.071	0.007	0.085	0.002	0.041
SwimmingPool	0.003	0.057	0.009	0.092	0.007	0.082	0.007	0.083	0.004	0.063
Parking	0.533	0.499	0.602	0.490	0.638	0.481	0.658	0.474	0.63	0.483
ConstructionPeriod1	0.117	0.322	0.064	0.245	0.040	0.195	0.017	0.131	0.021	0.142
ConstructionPeriod2	0.070	0.255	0.059	0.235	0.050	0.219	0.050	0.218	0.034	0.181
ConstructionPeriod3	0.070	0.255	0.057	0.232	0.051	0.221	0.052	0.222	0.052	0.223
ConstructionPeriod4	0.156	0.363	0.120	0.325	0.166	0.372	0.143	0.350	0.156	0.363
ConstructionPeriod5	0.062	0.241	0.117	0.322	0.182	0.386	0.102	0.303	0.193	0.395
ConstructionPeriod6	0.039	0.194	0.122	0.327	0.166	0.372	0.119	0.324	0.227	0.419
ConstructionPeriod7	0.106	0.308	0.221	0.415	0.097	0.296	0.201	0.401	0.117	0.321
ConstructionPeriod8	0.230	0.421	0.117	0.322	0.113	0.316	0.158	0.365	0.06	0.237
ConstructionPeriod9	0.029	0.169	0.026	0.159	0.055	0.228	0.070	0.255	0.055	0.228
DaysOnMarket	133.215	193.189	125.962	190.831	138.721	209.876	128.284	192.804	136.909	202.601
II. Location Characteristics (L)										
Roads250m	0.018	0.133	0.027	0.163	0.071	0.257	0.162	0.368	0.058	0.233
Roads500m	0.064	0.244	0.087	0.282	0.196	0.397	0.325	0.468	0.253	0.435
III. Flood Risk Discount & Its Temporal Decay (*Years*)										
Floodprone	0.143	0.351	0.207	0.405	0.065	0.246	0.009	0.096	0	0.017
Years90_93	0.036	0.186	0.041	0.199	0.04	0.197	0.036	0.186	0.049	0.216
Years94_97	0.042	0.202	0.076	0.265	0.06	0.238	0.075	0.263	0.069	0.254
Years98_01	0.13	0.337	0.105	0.306	0.106	0.308	0.112	0.315	0.112	0.316
Years02_05	0.173	0.378	0.159	0.366	0.134	0.341	0.157	0.364	0.149	0.356
Years06_09	0.153	0.36	0.141	0.348	0.154	0.361	0.156	0.363	0.155	0.362
Years10_13	0.116	0.32	0.089	0.285	0.117	0.321	0.11	0.312	0.123	0.328
Years14_17	0.194	0.396	0.202	0.401	0.205	0.404	0.192	0.394	0.2	0.4
Years18_20	0.156	0.363	0.188	0.39	0.183	0.387	0.163	0.37	0.142	0.349

Appendix D

One could suggest that Model 2 can use an interaction variable between the *Floodprone* and $Post_{Gray,NbS}$ to measure the price change in flood-prone property prices after launching the flood management projects. We specify this in Eq. (3) and report the results in Table D2. Note that the key estimated results represented in the coefficients of $Post_{Gray,\ NbS}$ * *River* are very similar to the results in Table 3. However, we do not prefer this model because the variable River measures the distance to the river, and therefore, it usually overlaps with the flood-prone area, especially for distances smaller than 500 m (See Fig. D1). This makes it difficult to interpret the coefficients and estimate the effect of the projects precisely.

$$ln\left(P_{itj}\right) = \beta_0 + \beta_1\boldsymbol{S}_{it} + \beta_2\boldsymbol{L}_{it} + \beta_3 Floodprone_i + \beta_4 Post_{Gray,NbS} + \beta_5 Floodprone_i{}^{*}Post_{Gray,NbS} + \beta_6\boldsymbol{River}_i + \beta_7\boldsymbol{River}_i{}^{*}Post_{Gray,NbS} + f_j + g_t + \varepsilon_{itj} \tag{3}$$

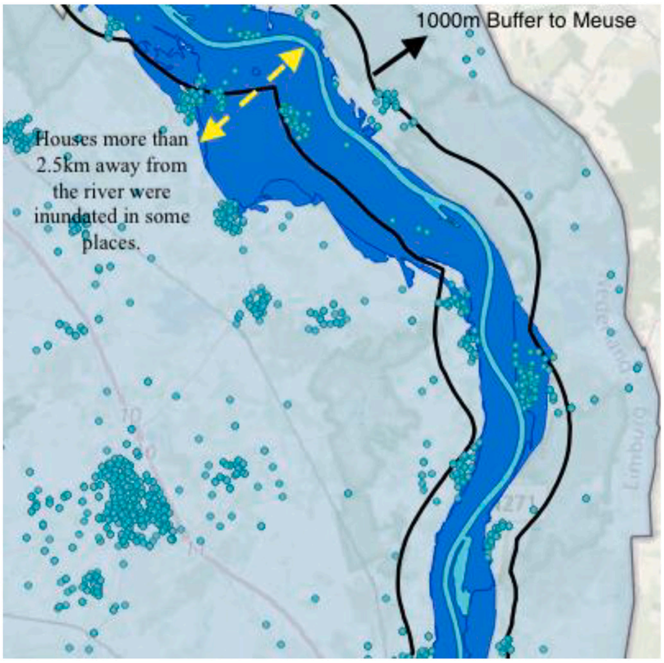


Fig. D1. Distance to Meuse River vs. flood-prone area (Source: own analysis.)

Despite that, using the variable *Floodprone* and distance to *River* together is statistically possible. One may argue that this would cause multicollinearity. We test this using the variance inflation factor (VIF). In Table D1, VIF is smaller than 10 for *Floodprone* and distance to Meuse variables meaning that they are not correlated and safe to use in the regression together. And actually, we do use them together in Model 1. However, the focus in Model 2 is on the effect of flood management projects on property prices at different distances to the river, i.e., the distance to the project location. Since using two alike interaction variables will make the interpretation complicated, we prefer not to add *Floodprone* and $Post_{Gray,\ NbS}$ interaction to the main body of the paper.

Note that we measure the distance to the river, not the distance to the flood-prone area. This is because we are interested in the effect of water-related amenities and flood management projects applied along the river. If we use the distance to the flood-prone area instead of the river, we cannot attribute this to the effect of water amenities because the width/size of the floodplain differs along the river.

Table D1
Collinearity Diagnostics using VIF (Floodprone and Distance to Meuse).

Variable	VIF	SQRT VIF	Tolerance	R-Squared
Floodprone	1.06	1.03	0.9410	0.0590
River250m	1.01	1.01	0.9882	0.0118
River500m	1.05	1.02	0.9530	0.0470
River1000m	1.01	1.01	0.9858	0.0142
River1500m	1.01	1.00	0.9933	0.0067
River2000m	1.01	1.00	0.9925	0.0075

Table D2
Model 2 with Floodprone*Post(Gray, NbS) interactions.

	Model 1 (1990–2020)	Model 2 (2000–2020)	
	Flood Effect	Gray Solutions	NbS
VARIABLES	Limburg - Full	North Limburg	South Limburg
Flood Risk Discount &Its Temporal Decay			
Floodprone = 1	−0.0102	0.00665	−0.216***
	(0.0147)	(0.0206)	(0.0271)
Floodprone*Years90_93	−0.0563*		
	(0.0303)		
Floodprone*Years94_97	−0.109***		
	(0.0233)		
Floodprone*Years98_01	−0.0907***		
	(0.0244)		
Floodprone*Years02_05	−0.0619***		
	(0.0223)		
Floodprone*Years06_09	−0.00529		
	(0.0245)		
Floodprone*Years10_13	−0.000383		
	(0.0274)		
Floodprone*Years14_17	0.00215		
	(0.0173)		
Environmental Amenities			
River250m = 1	0.128***	0.122***	0.115***
	(0.0176)	(0.0358)	(0.0288)
River500m = 1	0.0961***	0.135***	0.0585**
	(0.0134)	(0.0187)	(0.0256)
River1000m = 1	0.0908***	0.111***	0.0628***
	(0.0103)	(0.0194)	(0.0175)
River1500m = 1	0.0461***	0.0718***	−0.00826
	(0.00824)	(0.0129)	(0.0131)
River2000m = 1	0.0204***	0.0446***	−0.00990
	(0.00748)	(0.0144)	(0.0125)
NbS and Gray Solutions			
$Post_{Gray\ NbS}$*Floodprone		0.0378*	−0.0689**
		(0.0209)	(0.0294)
$Post_{Gray\ NbS}$*River250m		0.0280	0.0879***
		(0.0370)	(0.0257)
$Post_{Gray\ NbS}$*River500m		0.000279	0.0812***
		(0.0205)	(0.0248)
$Post_{Gray\ NbS}$*River1000m		0.0128	0.0756***
		(0.0148)	(0.0151)
$Post_{Gray\ NbS}$*River1500m		0.0225**	0.0628***
		(0.0109)	(0.0135)
$Post_{Gray\ NbS}$*River2000m		0.00262	0.0212*
		(0.0122)	(0.0117)
Constant	11.06***	11.19***	10.93***
	(0.0141)	(0.0221)	(0.0213)
Observations	68,247	30,062	29,000
R-squared	0.702	0.668	0.688
Number of Municipalities	47	27	20
Clustered SE PC6	Yes	Yes	Yes
House Characteristics	Yes	Yes	Yes
Municipality FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes

Appendix E

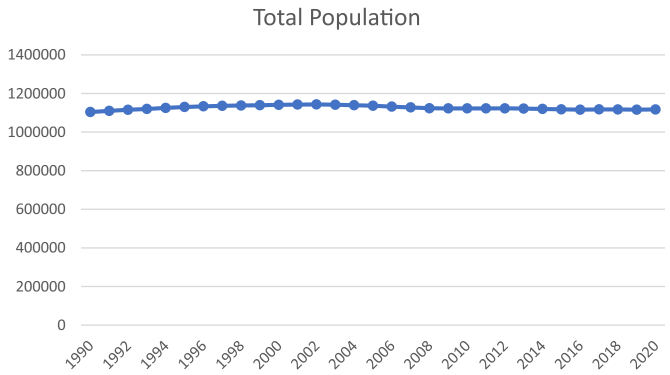


Fig. E1. Total Population in Limburg Province between 1990 and 2020. Data source: Eurostat (NUTS2: NL42).

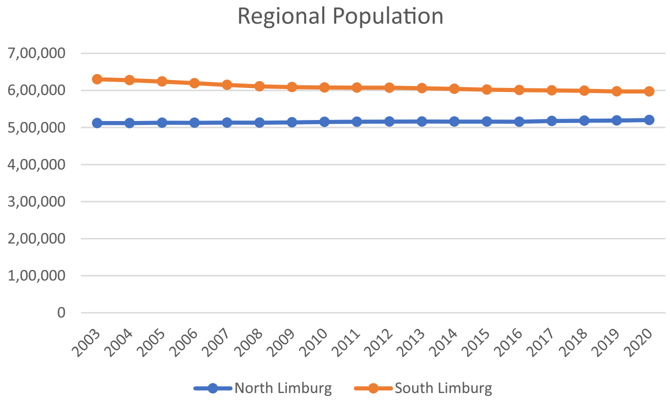


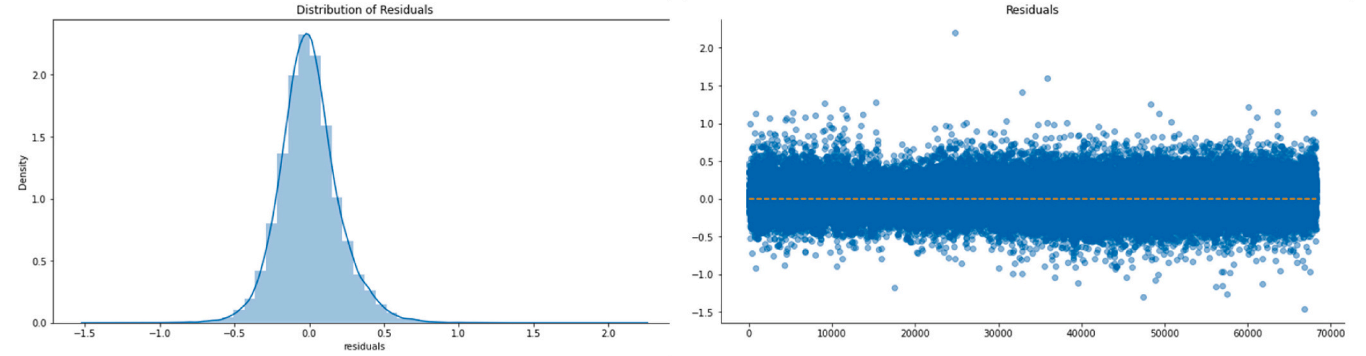
Fig. E2. Regional Population in Limburg Province between 1990 and 2020. Data source: Eurostat (NUTS3: NL421, NL422, NL423).

Appendix F

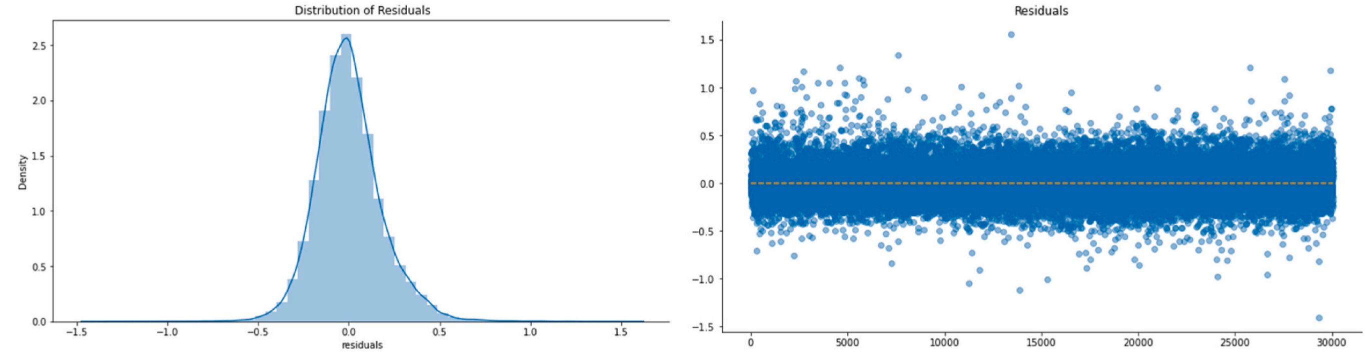
Appendix F provides information on heteroskedasticity and spatial autocorrelation tests used in the analysis.

First, we use residual plots to investigate heteroskedasticity visually. Fig. F1 shows that the residuals (histograms on the left) follow a normal distribution and have random distribution (residuals against fitted values on the right) in all samples. Therefore, we do not detect any pattern indicating heteroskedasticity.

Model 1 – N: 68,247 (full sample of Limburg Province (1990-2020))



Model 2 (Gray Solutions) – N: 30,062 (North Limburg (2000-2020))



Model 2 (NbS) – N: 29,000 (South Limburg (2000-2020))

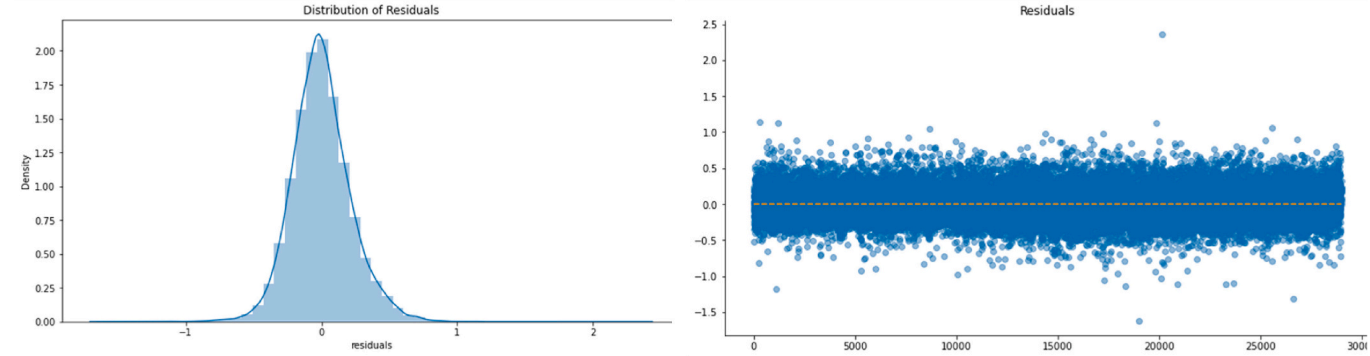


Fig. F1. Residual Plots.

Second, we use statistical test to detect heteroskedasticity. Table F1 gives the Wald test statistics,[22] where Chi squared is distributed under the null hypothesis of homoskedasticity. Since the *p*-values are statistically significant, we reject the null hypothesis. Therefore, we detect heteroskedasticity in our samples.

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[22] We use **xttest3** module in Stata 17. For more information see Christopher (2001)

Table F1
Wald test for groupwise heteroskedasticity.

Sample	N	Chi2	P-Value
Model 1	68,247	1094.86	0.000
Model 2 (Gray)	30,062	81.16	0.000
Model 2 (NbS)	29,000	344.48	0.000

Third, we control for spatial autocorrelation. Table F2 represents the Moran's I estimation for the samples used in this paper. We observe that Moran's I is positive and statistically significant in all samples. However, the estimate is lower than 0.50 meaning that spatial autocorrelation is weak. To account for potential spatial autocorrelation of the error term, we use clustered standard errors. We tested clustering errors at different spatial aggregation levels such as 6-digit postcode level, neighborhood, municipality, or property ID level. In both Model 1 and Model 2, the results were robust to all specifications. We only detect one exception. In Model 2, clustering standard errors at the municipality level make the standard errors approximately 4–5 times higher, thus, making the estimated coefficients insignificant. Considering that the number of clusters at the municipality level is around 20–25 in Model 2, we suspect that standard errors are likely to be overestimated due to low number of clusters and higher level of spatial aggregation (see (Angrist and Pischke, 2009)). Hence, we use cluster standard errors at the 6-digit postcode level, which corresponds to the street level, to control for heteroskedasticity and spatial autocorrelation.

Table F2
Moran's I estimations.

Sample	N	Moran's I	P-Value
Model 1	68,247	0.25	0.001
Model 2 (Gray)	30,062	0.19	0.001
Model 2 (NbS)	29,000	0.19	0.001

Appendix G

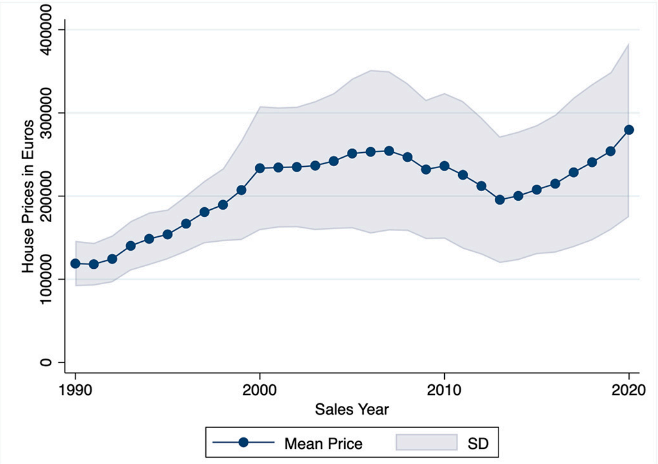

Fig. G1. Mean house prices in the full sample of Limburg Province ($N = 68{,}247$) and its standard deviation in each year (adjusted to 2020 prices in Euros).

Appendix H

Table H1 presents the extended version of Table 3 including the coefficient estimates for all variables.

Table H1
Hedonic OLS results including all variables.

	Model 1 (1990–2020)	Model 2 (2000–2020)	
	Flood Effect	Gray Solutions	NbS
Variables	Limburg - Full	North Limburg	South Limburg
Flood Risk Discount & Its Temporal Decay			
Floodprone = 1	−0.0102		
	(0.0147)		
Floodprone*Years90_93	−0.0563*		
	(0.0303)		

(continued on next page)

Table H1 (*continued*)

	Model 1 (1990–2020)	Model 2 (2000–2020)	
	Flood Effect	Gray Solutions	NbS
Variables	Limburg - Full	North Limburg	South Limburg
Floodprone*Years94_97	−0.109***		
	(0.0233)		
Floodprone*Years98_01	−0.0907***		
	(0.0244)		
Floodprone*Years02_05	−0.0619***		
	(0.0223)		
Floodprone*Years06_09	−0.00529		
	(0.0245)		
Floodprone*Years10_13	−0.000383		
	(0.0274)		
Floodprone*Years14_17	0.00215		
	(0.0173)		
Environmental Amenities			
River250m = 1	0.128***	0.124***	0.0783***
	(0.0176)	(0.0359)	(0.0288)
River500m = 1	0.0961***	0.138***	0.0196
	(0.0134)	(0.0179)	(0.0242)
River1000m = 1	0.0908***	0.113***	0.0421**
	(0.0103)	(0.0195)	(0.0174)
River1500m = 1	0.0461***	0.0733***	−0.0169
	(0.00824)	(0.0129)	(0.0130)
River2000m = 1	0.0204***	0.0453***	−0.0141
	(0.00748)	(0.0145)	(0.0124)
NbS and Gray Solutions			
$Post_{Grey\ NbS}$*River250m		0.0309	0.0711***
		(0.0368)	(0.0274)
$Post_{Grey\ NbS}$*River500m		0.0107	0.0669***
		(0.0193)	(0.0239)
$Post_{Grey\ NbS}$*River1000m		0.0145	0.0646***
		(0.0147)	(0.0157)
$Post_{Grey\ NbS}$*River1500m		0.0215**	0.0625***
		(0.0109)	(0.0135)
$Post_{Grey\ NbS}$*River2000m		0.00200	0.0212*
		(0.0122)	(0.0117)
Structural Variables			
Parcel	0.000112***	9.30e-05***	0.000236***
	(5.60e-06)	(4.27e-06)	(1.62e-05)
$Parcel^2$	−2.15e-09***	−1.60e-09***	−8.30e-09***
	(3.07e-10)	(1.92e-10)	(1.40e-09)
Garden	0.000275***	0.000297***	0.000239***
	(2.12e-05)	(2.96e-05)	(3.06e-05)
$Garden^2$	4.25e-08	1.93e-08	−6.19e-08
	(3.48e-08)	(4.54e-08)	(5.36e-08)
LivingArea	0.00437***	0.00393***	0.00438***
	(6.20e-05)	(0.000180)	(8.81e-05)
$LivingArea^2$	−3.84e-06***	−3.24e-06***	−3.85e-06***
	(6.72e-08)	(4.94e-07)	(8.53e-08)
Rooms	0.0158***	0.0340***	0.00490*
	(0.00209)	(0.00258)	(0.00254)
$Rooms^2$	−6.94e-05	−0.000930***	0.000283
	(0.000158)	(0.000181)	(0.000190)
Lift	0.0755**	0.0156	0.136**
	(0.0346)	(0.0384)	(0.0584)
Attic	−0.00577***	0.00426	−0.0176***
	(0.00197)	(0.00274)	(0.00310)
InsideMaintenance	0.0498***	0.0424***	0.0622***
	(0.00161)	(0.00228)	(0.00240)
OutsideMaintenance	0.0116***	0.0133***	0.0145***
	(0.00176)	(0.00250)	(0.00273)
Monument	0.123***	0.114***	0.101*
	(0.0336)	(0.0376)	(0.0525)
Monumental	0.0836***	0.0113	0.0951***
	(0.0285)	(0.0430)	(0.0363)
SwimmingPool	0.132***	0.124***	0.120***
	(0.0113)	(0.0144)	(0.0190)
Parking	0.118***	0.108***	0.115***
	(0.00245)	(0.00317)	(0.00390)
DaysOnMarket	−3.70e-05***	−1.85e-05***	−6.93e-05***
	(3.99e-06)	(4.73e-06)	(6.72e-06)
GardenQuality = 2	−0.0177	−0.0244	−0.00556
	(0.0126)	(0.0172)	(0.0199)
GardenQuality = 3	0.0502***	0.0443***	0.0734***
	(0.00654)	(0.00786)	(0.0124)

(*continued on next page*)

Table H1 (*continued*)

	Model 1 (1990–2020)	Model 2 (2000–2020)	
	Flood Effect	Gray Solutions	NbS
Variables	Limburg - Full	North Limburg	South Limburg
GardenQuality = 4	0.129***	0.135***	0.154***
	(0.00679)	(0.00820)	(0.0130)
GardenQuality = 5	0.0972***	0.0927***	0.122***
	(0.00672)	(0.00805)	(0.0128)
Floors	−0.0116***	−0.0231***	0.00639**
	(0.00203)	(0.00290)	(0.00289)
ConstructionPeriod1	−0.00415	0.0138	−0.0102
	(0.00955)	(0.0145)	(0.0138)
ConstructionPeriod2	−0.0793***	−0.0106	−0.104***
	(0.00716)	(0.0128)	(0.00922)
ConstructionPeriod3	−0.0180***	0.0316***	−0.0353***
	(0.00676)	(0.0115)	(0.00907)
ConstructionPeriod4	−0.0359***	−0.0238**	−0.0539***
	(0.00530)	(0.00942)	(0.00705)
ConstructionPeriod5	−0.0430***	−0.0531***	−0.0459***
	(0.00502)	(0.00884)	(0.00706)
ConstructionPeriod6	−0.0176***	−0.0402***	0.0194***
	(0.00501)	(0.00879)	(0.00696)
ConstructionPeriod7	−0.0107**	−0.0165*	−0.00167
	(0.00514)	(0.00905)	(0.00730)
ConstructionPeriod8	0.0993***	0.0962***	0.102***
	(0.00589)	(0.00973)	(0.00851)
ConstructionPeriod9	0.164***	0.144***	0.180***
	(0.00691)	(0.0104)	(0.0111)
Location Characteristics			
Roads250m	−0.00784*	−0.0239***	0.0373***
	(0.00466)	(0.00550)	(0.00952)
Roads500m	−0.0145***	−0.00369	−0.0335***
	(0.00335)	(0.00440)	(0.00554)
Constant	11.13***	10.88***	10.54***
	(0.0193)	(0.0262)	(0.0263)
Observations	68,247	30,062	29,000
R-squared	0.782	0.699	0.698
Number of Municipalities	47	27	20
House Characteristics	Yes	Yes	Yes
Municipality FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes

Notes: We clustered standard errors at the 6-digit postcode level in all specifications. Standard errors are in parentheses.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2022.107682.

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