Living on the Edge:
How does Your House Price Respond to Urban Hazard Risks?

Sofia F. Franco
Nova School of Business and Economics
Universidade Nova de Lisboa
Portugal
sfranco@novasbe.pt

Jacob L. Macdonald
Nova School of Business and Economics
Universidade Nova de Lisboa
Portugal
jacob.macdonald@novasbe.pt

Final Draft

October 31, 2018

Abstract

This work considers the capitalization of urban hazard information via the residential real estate market of Lisbon, Portugal. We employ a spatial hedonic framework to estimate the impact of being located across zones in the municipality with a heterogeneity of urban flooding risks or seismic hazards. Special attention is given to the heterogeneity of these influences within and between these zones as influenced by local amenities and relative location in the city. We employ a geographic regression discontinuity to ensure that our results are not sensitive to underlying locational features of a dwellings location, and complement our results with a quantile regression to explore the impact of these hazard zones across the distribution of dwelling prices.

Results indicate that the residential real estate market responds to hazard information with lower dwelling prices observed in areas with very high risks in the range of 3.5% for flooding and 1.1% for seismic risk. The largest response occurs due to urban flooding which is highly publicized and a relatively common occurrence for residents in comparison to seismic activity. Results suggest further that the combined effect of being subject to multiple hazards yield larger price reductions in the order of 3.8%, highlighting the importance of considering local contexts and interactive behaviour for policy discussion and mitigation planning. Flooding risk zones are heterogeneous in their impacts with ecological amenities such as greenery or urban forests mitigating this negative impact while impervious surfaces and higher neighborhood crime compound the negative effect.

Keywords: Urban Geohazards; Hedonic Pricing; Geographic Regression Discontinuity; Spatial Econometrics; Flooding Risk; Seismic Risk

1 Introduction

As population increasingly take up residency in urban areas and create denser living areas, a growing number of individuals are exposed to a variety of environmental hazard risks on a daily basis. Earthquakes, floods, landslides, avalanches and tsunamis are all examples of such hazards impacting cities across the globe and presenting severe threats to humans, property and the natural or built environment. Landslides can be caused by any number of factors including heavy rainfall and floods, earthquakes, or human activities, and are the most common natural hazards on land. In terms of casualties however, earthquakes and floods are often considered to be among the most significant. Tsunamis, many times a by-product of seismic events, are another type of geohazard that are relatively rare but as the 2004 deadly Indian Ocean tsunami tragically illustrated, their impacts can be devastating.[1]

In 2002, across the globe over 500 natural disasters were recorded with a total estimated direct damage of $55 billion and $13 billion in insurance losses, further killing 10,000 people and impacting 600 million more (United Nations 2004). The risk of being exposed to environmental hazards vary greatly according to location, climate, topography and the built environment. Cities must obey the particularities of their urban risks as they vary across the globe and consider these factors as they design and implement resilient policies, assess costs and support the local community. Each time these natural hazard events and their devastating losses occur, however, the same questions arise about the necessity of better managing urban development in areas prone to natural hazard.

The need to account for geological factors in land-use planning has often been urged by the United Nations. This is especially the case in coastal lowlands and more so for urban centers, most of which are located in earthquake zones or other hazard prone areas. Today, as more than half of the world's population live in urban areas, and coupled with the impacts of climate change, risk reduction strategies in urban areas are key to building resilient communities. The reach and potential impacts of natural hazards increase significantly in denser and growing urban areas and have important consequences for public policies supporting infrastructure, safety, mitigation strategies, cleanup or rebuilding (Lall and Deichmann 2010; Gencer 2013). Furthermore, many urban areas are confronted with a multitude of natural hazard risks and anthropogenic hazards such as accidents, pollution, explosions and fire. For instance, using a sample of 52 European cities representing 15% of the EU population, the PanGeo-project shows that an average sized European city could have four different types of geohazards covering an area of 186 km^2 and, exposing 626,000 people. Compressible-ground was identified by the PanGEo-project as the largest urban geohazard, by area, affecting the sampled European cities.[2] This is

[1] Geohazards are conditions relating to geology that have the potential to cause harm and damage, often involving some form of ground motion or instability. Examples include earthquakes, volcanic eruptions, landslides, flooding and tsunamis.

[2] Certain types of ground contain layers of very soft materials like peat and clays. These layers are often likely to compress if they are loaded by overlying structures, or if the groundwater level changes around them. This compression may result in depressions appearing in the ground surface or under structures, potentially damaging

not surprising considering that most European cities have grown near rivers or coasts where compressible sediments and alluvium often accumulate. Therefore, identifying the spatial distribution and concentration of hazard risks in urban areas is crucial to understanding where and how preventative and corrective actions can reduce levels of vulnerability and exposure of urban inhabitants.

The goal of this paper is to study the effects of localized natural hazard vulnerability on housing prices. In particular we aim to examine the direct effects that hazard risk zones (flooding or seismic) have on housing prices from 2007 in Lisbon, Portugal, and further whether there exists any interactions with local amenities or any spillover effects. We examine how these impacts are valued differently across the conditional distribution of house prices and, for completeness, we compare our estimated residential price differentials between risky and less risky zones to the present value of future insurance premiums.

While many direct costs can be measured in relation to cleanup efforts, the estimated economic impact of these urban hazard events often omit important effects such as persistent influences on the real estate market. When the location and occurrences of these events can be predicted and publicly made available to the general population through hazard risk maps or the media, urban residents can supposedly react accordingly and these risks may illicit important behavioral responses with impacts on the real estate market. In general, the market absorbs these behavioral responses through the price that households and firms are willing to pay for real estate in a particular location. Existing housing price studies on urban natural hazards usually deal with the effect of a single hazard and show that the residential real estate market responds to a natural hazard with depressed property prices in flood zones (Rajapaksa et al. 2016; Rajapaksa et al. 2017a; Rajapaksa et al. 2017b; Bin and Landry 2008; Bin and Landry 2013) and in areas with high seismic risk (Naoi et al. 2009; Naoi et al. 2010; Hidano et al. 2015).

Yet, to the best of our knowledge, no research has examined the spillover effects of high-risk areas on nearby real estate values nor the price impacts of multiple natural hazard risks and their interactions with local amenities and the built environment. This is surprising as many urban properties are vulnerable to multiple hazards and the continuous nature of spatial interactions yield contagion effects from high-risk areas to low-risk areas within close proximity. In addition, the variability of local amenities within hazard zones may mitigate or exacerbate the effects of their risks, translating to effects in their property value.

Finally, the degree of capitalization into property prices of different and multiple types of natural hazards can reveal not only the residents' risk beliefs but also the perceived potential private property damage of these urban dis-amenities. Even if hazard risk maps are publicly made available and media mentions occur, residents may still be apt to underestimate or even ignore these risks. For instance, people can feel either apathetic or optimistic about their risk of death, injury, or property damage due

foundations and infrastructure. There are a number of problems that may affect properties built in such types of ground, including structural damage to foundations and to the fabric of the building, strains or break in service connections to water, gas and electricity or, cracks in walls, floors or ceilings of a building.

to a natural hazard (Bakkensen and Barrage 2018), or act as if a very low probability of an extreme event is zero by simply believing that it will not harm them or their property (Lindell 1997). Moreover, residents may expect that they will be provided with disaster relief from governments and nonprofit organizations in case a natural disaster occurs (Burby 1998; Jackson 1997). Therefore, understanding the capitalization into housing prices of natural hazard risks can help local governments to be more aware of their residents' risk beliefs and behavior with regards to urban natural hazards and how mitigation measures may contribute to housing prices. It can also provide valuable information to value insurance contracts, to design resilient development strategies and to determine future urban development locations.

Lisbon provides an interesting context for studying the impact of natural hazard risks in an urban setting given its topography, coastal location and climate. Flooding occurrences are yearly events in the city and with its varied topography, with many valleys and hills, the areas of high flooding risk in Lisbon are not constrained to the riverfront like in many cities. On the other hand, seismic events are far less common, though the risk is still present and supposedly known to many residents. The country's history inflects on the date of the devastating category M9 Great Lisbon Earthquake of 1755, and this event remains much ingrained in modern culture and urban planning.

As such, the within city spatial heterogeneity of seismic and flooding risks is expected to be capitalized into Lisbon´s residential property prices. Moreover, the expected reduction in value for properties located in delineated flooding or seismic hazard zones relative to those units outside should equal the present value cost of all future hazard insurance premiums.

Though Lisbon is a city prone to natural hazards, insurance penetration against these hazards is still low, especially in terms of seismic risk coverage. Since homeowners are not required by law to acquire hazard insurance against flooding or earthquake, the negative evaluation effect of these hazard risks are subjective to the buyers' assessments of the risk loss from a particular hazard event. In such a context, the present value of the cost of hazard insurance (e.g. flooding or earthquake) may be viewed as the upper limit, rather than the expected value, of housing value reduction associated with a particular hazard or set of hazards. In addition, because of the limitations on available hazard insurance and the property owners' desire of additional coverage, property values for high-end units may be further depressed by this non-insurable component of a natural hazard risk.

We employ a spatial hedonic framework to decompose the price of a residential dwelling into its value bearing attributes, paying particular attention to location within the city of Lisbon and relative to amenities and important areas of the city. The variability of georeferenced dwellings across zones of different risks in the city allows for the estimated impact of being located in areas of a municipality exposed to greater hazards. If the residential real estate market capitalizes on these risks, then we would expect negative impacts on prices for dwellings located within or near such zones.

Our empirical specification is chosen based on spatial diagnostics from the Moran's I and Lagrange multiplier statistics which test the spatial heterogeneity of the dependent variable and spatial autocorrelation of the error term. Results indicate the presence of significant spatial influences which may impact standard ordinary least squares (OLS) results, and thus a spatial error (SEM) specification is employed to mitigate this potential bias.

Our analyses further take spatial influences and locational spillovers into consideration in a number of ways. First, in constructing measures of location and neighborhoods, we forgo the use of pre-defined administrative boundaries and rather construct our own proper measures based on distances reflective of how residents perceive their neighborhood. This mitigates potential biases from the modifiable aerial unit problem, which may arise by using inconsistently sized administrative boundaries to represent neighborhood and locational realities which may be delineated according to political or topographic considerations.

Second, to ensure that the estimated effects are not driven by underlying locational features, we make use of a geographic regression discontinuity (GRD) framework whereby the boundaries of areas with greater natural hazard risks are used as a geographic threshold. Results on the inside of the zones can thus be considered as treatments, while those located nearby on the other side of the boundary and in a non-hazard zone may be considered valid controls. We further employ a propensity score matching to find valid control properties conditional on key locational features, and show that results are robust when considering a range of potential underlying locational mechanisms which may be driving the estimates.

Our estimates indicate that the residential real estate market in Lisbon responds negatively to areas of increased natural hazard risk. Being located in areas with very high flooding potential or damage from seismic risk yields a reduction in dwelling prices on average of 3.5% and 1.1%, respectively. Our evidence also suggests that residents respond to the severity of the potential impacts with larger estimates for very high risk areas compared to high risk areas. While the potential damage effect of seismic events is significantly greater than flooding events, the estimated housing price impacts tends to be smaller. This signals that the Lisbon real estate market underestimates the potential risk of this type of geohazard event, likely due to their scarcity relative to flooding events which are seasonal occurrences. Further, given the topography of the city it is possible to have areas which are subject to both high seismic and high flooding risks. As expected, these joint hazard zones have stronger negative impacts on dwelling prices in the range of 3.8%. Using a quantile regression, we further identify that the impact of flood risk is the largest for higher priced dwellings. Dwellings priced above the 70^{th} percentile are more negatively impacted by these hazard risks, with those located at the 80^{th} percentile having negative price impacts of around 4.2%.

Another contribution of this work is related to capturing the heterogeneity of hazard zones, not only conditional on the variability of local amenities within the zones which may mitigate or exacerbate their impact, but also conditional on the relative location between zones across the city. We find that the impact of proximity to flood zones yield negative effects on housing prices which is mitigated when dwellings have greater accessibility to local urban green spaces. Urban green infrastructure has important implications for a city's storm water and flood management strategies as they help absorb rainfall and localized riverine floods, preventing water from overwhelming pipe networks and pooling in streets or basements. The negative impact of being located in flood zones however is compounded by nearby lakes and increased impervious surfaces in the neighborhood. Being located in seismic risk zones on the other hand has marginally less of a negative impact conditional on the built and demographic characteristics of the neighborhood, with mitigating effects coming from having more low-rise buildings and more owners or educated residents, which may serve as a signal for how well taken care the dwellings in the zone are.

Crime levels are found to have significant influences for dwellings located in flooding or seismic hazard zones, with worse price impacts if general crime levels or thefts in the neighborhood are higher. In the case of extreme flooding events specifically, when buildings are vulnerable to looting the occurrence of floods may provide opportunity for these crimes and thus residents respond negatively to flooding in areas of higher crime.

Not only does the within variation of local amenities influence the relative effect of hazard risks on housing prices, but it is important to consider the location of the hazard zones across the city and their spillover effects to nearby areas. While being located in flooding zones yield negative average price effects on dwellings, this is dependent on location in the city. Coastal properties have a net positive impact, even after controlling for the multitude of flood zones in these areas. This positive price effect of being located near the Tagus river suggests that residents believe that the amenity value of riverfront proximity outweighs the potential flood risk and associated damages.

To our knowledge, this is the first comprehensive study of the heterogenous impact on the residential real estate market of both flooding and seismic risks at a micro level within a municipality. We employ a range of spatial measures to accurately capture the locational realities of each observation and employ self-constructed spatial fixed effects to mitigate potential spatial biases and measurement error. The use of a GRD framework ensures the robustness of results to locational influences. When these spatial influences are not taken into consideration the resulting estimates may be biased. The special topography and climate of Lisbon allow for the analysis of simultaneous multiple natural hazards, and if there is heterogeneity across different types of natural hazard risks, or heterogeneity within a specific risk zone due to locational amenities, it is important to capture these and better understand how urban natural hazards interact with or are conditioned by a resident's local environment. By accounting for spillover influences across space and the relative location across the city, our results give credence to the notion that residents trade off the risk of urban natural hazards for other aspects of their locality.

The structure of this paper is as follows. Section 2 explores the previous literature of urban natural hazards with an emphasis on flooding and seismic events or risks. Section 3 describes the study region and these hazards in the context of Lisbon, Portugal, and presents the data. Section 4 outlines the empirical strategy emphasizing the importance of considering spatial influences in the variable measurement and estimation. Results are presented in section 5 with discussions related to the insurance premiums in section 6. Final conclusions are presented in section 7.

2 Literature Review

There is a range of literature on the impact that urban hazards and information plays into dwelling prices and the decision making process of residents. This can broadly be categorized into two types, with some works focusing on the impact of individual geohazard events and others accounting for the information regarding geohazard risk zones. The valuation of specific seismic or flooding events are common, however these likely underestimate the true impact if the potential reoccurrence of these events cause behavioral changes in other markets that are not accounted for. In general, results indicate that the real estate market responds negatively to potential risk due to urban natural hazards and prices are depressed in such zones of higher hazard risk, and can thus be used to inform on true economic impacts of these event risks.

Given the prominence of flooding events across the globe, a number of works have focused on the impact that flooding risk, flooding occurrences and flash floods have on the real estate market. Many works value the *ex-ante* effect of how flooding risk information is taken into account and influences property values, however, there are further many *ex-post* studies which focus on the economic impact due to occurred flooding events.

In North Carolina, Bin and Landry (2008) and Bin and Landry (2013) highlight both the estimation of impacts from flood risk information and the impact of specific events. The average effect of being located in a flood plain is estimated to be an approximate discount of 7.3% when evaluated using a spatial error hedonic specification (Bin and Landry 2008). Using the events of major hurricanes in the area however, Bin and Landry (2013) estimate the impact of being located in flooding plains while controlling for spatial influences from positive amenity values related to water proximity. In particular, the authors use distance measures of proximity to the water in their estimations. Following recent hurricane and flooding events, the authors estimate that prices decreased 5.7% following Hurricane Fran and 8.8% following Hurricane Floyd.

Atreya and Czajkowski (2016) disentangle the countervailing impacts of flood risk and water-related amenities by interacting distance to the nearest coastline and flood risk to account for these impacts acting jointly on housing sale prices in Galveston County, Texas. They further vary flood return periods to allow for an interaction between negative and positive amenities related to proximity to water. The study shows that properties located in high-risk areas command a price premium up to 146% for up to nearly a quarter mile from the nearest coastline and the expected distance effects vary by flood risk type. In particular, housing premiums to higher risk homes decay at a faster rate the further one moves away from the water.

Rajapaksa et al. (2016) employ a difference-in-difference methodology to identify the impact of flood risk information and flood occurrences on housing prices in Brisbane, Australia. The authors conduct both OLS and spatial maximum likelihood estimation which accounts for significant spatial dependence in housing prices, making use of temporal variation in regards to when flood hazard information was made available and when actual floods occurred. This work uses the impact of the release of flood risk map information in 2009 and the impact of actual flooding events which occurred in 2011, comparing the sale time of dwellings and their spatial exposure to each. Estimates indicate that the impact of public flood information being released led to price depressions in flood zones between 1 to 4% while actual flooding occurrences had impacts on prices by detracting between 18 and 19%.

Rajapaksa et al. (2017a) further explore whether the impact due to flood risk areas are conditional on locational or sub-market attributes. Using a spatial quantile regression under the difference-in-difference framework, the variation of risk impact conditional on areas of high value or low valued homes is explored. Flood risk is found to have the largest impacts on high valued property sub-markets in the range of a 4% to 8% decrease in prices while little to no significance was found to indicate that flood risk impacted lower value properties.

Also under a spatial quantile regression framework, Zhang (2016) find that in the North Dakota and Minnesota area, the average impact of being in a flood zone on dwelling prices is around 6% while lower-valued properties are more impacted than higher valued properties. Using the time of flooding events and time of sale, the author further concludes that the impact of a flood event depresses dwelling prices, but that this effect dissipates over time.

Along the lines of exploring heterogeneity, Rajapaksa et al. (2017b) highlight the importance of considering proximity to major waterways in terms of flood risk capitalization. Using a semi-parametric model allows the authors to capture the non-linearity of impacts over space as they relate to proximity to the river. The estimated average impact of flooding zones is a depression of 5% of prices in these areas, however the benefits of being closer to the river outweighs potential risks of urban hazards and the effect is non-linearly related to proximity to the river.

Using similar methodologies the impact of seismic risk zones has been studied by exploiting discontinuities in time or over space as they pertain to known hazard zones, seismic activities and the impact on dwelling prices. While regular seismic activity is relatively uncommon in any municipal area, unlike flooding occurrences which can be yearly events, the housing market in the few areas with significant risk capitalizes on the risk of living in zones with higher potential damage.

With regular seismic activity and occurrences in Japan, much research has been dedicated to understanding the influence of hazard information on property values in this region. Naoi et al. (2009) find that the price impact of seismic zones on dwellings is larger following a large seismic event and thus that the real estate market potentially undervalues the impact of these events until they occur. While seismic activity is negatively capitalized in the real estate market, the effect is heterogeneous according to local characteristics. The negative impact of seismic risk is significantly influenced by dwelling characteristics, age and the local built environment (Naoi et al. 2010).

Using a two-dimensional spatial regression discontinuity, Hidano et al. (2015) value the difference between areas with high seismic risk or high risk of building collapse and their respective low risk areas. Under such approach, the authors find a dwelling premium for those that are located in low risk areas ranging from ¥13,970 to ¥17,380.

While natural seismic activity is rare, new on land technologies have been introduced in recent decades that have exacerbated seismic events, primarily to facilitate oil and natural gas extraction. These induced seismic activities have become a standard by-produce of human ground interventions, and have important consequences on the real estate market in line with natural seismic occurrences.

Metz et al. (2017) use the spatial and temporal variation of these events to identify the impact of drilling-induced seismic activity in Oklahoma. The effect translates to an approximate decrease in prices of 3.09% in affected areas, and the authors show that this result is robust using a number of spatial sub-setting of the data conditional on important locational characteristics. In the Netherlands, Koster and van Ommeren (2015) compare earthquakes felt by residents with those which have not been felt by residents to identify the impact of induced seismic activity. Dwellings which have experienced a noticeable earthquake sold on average at a price reduced by 1.9%.

3 Study Region and Data

3.1 Lisbon, Portugal, and Urban Hazards

The capital city of Lisbon, Portugal, is one of the oldest cities in the world founded on the banks of the Tagus river. Today, Lisbon maintains its status as an economic and cultural hub in Europe and is currently the largest city in the country with a population of almost 2.8 million individuals and 311,000 firms located in the greater metropolitan area. The city is broadly organized into 53 civil parishes, or *freguesias*, covering its 100.05 km^2 area, which broadly align with residents' neighborhoods and are defined as conglomerations of census tracts.[3] These areas are distinguished based on the historic and cultural evolution of the city with each *freguesia* having a distinct character and aesthetic, and residents in particular areas of the city strongly identifying with their *freguesia*.

Lisbon has two predominant central business districts (CBD). The primary and historic CBD is known as *Baixa Pombalina* and made up of twelve *freguesias* bordered by the Tagus river in the south. In 1998, Lisbon leveraged it's hosting of the World Expo to redevelop a previously idle area into a secondary CBD, known as *Parque das Nações* (Park of the Nations or "Expo"), located further inland along the riverfront which is now an active commercial and residential area of the city.

The name *Baixa Pombalina* is in reference to the *Pombaline* style of architecture and urban design, widely introduced in the area during the rebuilding which followed the Great Earthquake of 1755. Previously narrow medieval streets were rebuilt as open avenues, and buildings were constructed in a

[3] In 2012 the municipal council approved the reorganization from 53 *freguesias* to 24. However, geographic housing and census data are representative and ordered according to previous delineations and we thus make use of the original 53 administrative divisions.

specific design to allow more flexibility in the case of a repeated seismic event. This caged-style building design is one of the first widespread architectural seismic policy initiative in a major urban area. Though a vast majority of the city was destroyed during the earthquake and subsequent tsunami, Portuguese history emphasizes this period due to the events importance as a catalyst to implement a wide range of frontier urban designs from the time in redesigning the city.

The devastation of the 1755 Earthquake is still evident in modern Lisbon through the stock of historically significant buildings, churches, palaces and amenities which have survived and remain a testimony to the past.[4] Estimates of the impact of this singular event on Portuguese history is massive, with a value ranging from 32% to 48% of GDP at the time, and a lower bound estimate of almost 23,000 completely destroyed or substantially damaged buildings (nearly 70% of Lisbon´s dwellings at the time) and 30,000 – 40,000 lives lost by the combined effects of the quakes, fire and tsunami (Pereira 2009). Under current housing stock and urban design, an earthquake of that magnitude and characteristic would have an impact of approximately €11.4B, or 8% of GDP (Tang et al. 2012).

The 1755 earthquake was not, however, the first devastating earthquake to hit the city. The Tagus river follows a fault line, and large earthquakes can and do occur along it. In 1531, the city was hit hard, when an earthquake along this fault struck the center of Portugal, east-northeast of Lisbon, with an estimated magnitude of M7. There was also a severe earthquake in 1321, again with widespread destruction, and other significant quakes occurred in 1147 (also leaving the city, just captured from the Moors, in ruins), 1334 (destroying the cathedral roof) and 1356. In 1909, a quake hit north-east of Lisbon, with a magnitude of M6.5.

Since 1909, the region has been seismically calm, though occasionally there are earthquakes of much lower magnitude that are briefly felt throughout the city. Recent examples include the M4.3 quake in the region of Sobral de Monte Agraço on August 17th, 2017, and the M6 earthquake located near the St. Vicent Canyon, offshore to the south-west coast of Portugal on December 17th, 2009.

While there have been many discussions of the chances of a re-occurrence of the 1755 event, such an event may only occur once every 5,000 years or so, leaving imminent danger out of the mindset of the local population. However, a more immediate danger is a potential repeat of those medieval quakes in the near future. In addition, the more critical source of concern is the Lower Tagus Valley region, which could produce a magnitude M6 to M7 earthquake with a return period as short as 150 to 200 years. This seismic source zone, with its proximity to Lisbon, the large number of old masonry buildings and a fraction of reinforced concrete frames designed with limited lateral resistance, presents the most significant potential for large scale loss from a seismic event.

[4] The Carmo Convent (located in *Baixa Pombalina*) for example now houses an archeological museum and stands out as a defining feature of the city skyline. The main drawing point of this site however is the partially destroyed arches and surviving pillars of the ancient church caused by the earthquake, which serves as a reminder to locals and tourists alike of the events destruction.

The city’s intimate history with earthquakes, and awareness of their significance and destructive capacity, has thus become ingrained in the current culture. The residential population is therefore aware of the inherent risks that come with living in certain areas of the city with higher potential hazard occurrences and subsequently larger damages.

While seismic activity tends to be few and far between, flooding is a regular occurrence in the city.[5] Yearly, during the rainy winter months, many parts of Lisbon experience sometimes severe flooding. The rugged topography of the city means that these flooding occurrences are not limited to the riverfront and we thus observe heterogeneity of this urban risk across the city.

Catastrophic flooding events are not frequent, however, from time to time Lisbon suffers extreme meteorological events such as heavy rains that cause severe flash flooding and landslides. The two most well-known extreme rainfalls include Lisbon’s flooding of November 25th, 1967, and February 18th, 2008. In particular, the floods of November 25th, 1967, claimed 464 lives, making it the worst natural disaster to hit Portugal since the earthquake of 1755 and the fourth deadliest flash flood in world history. The severity of flooding events occurring in the city is expected to escalate with the rising of sea level and more severe rainfall patterns due to climate change.

The risk of these hazard events therefore are likely to be realized by residents at some point in their lifetime, and act as dis-amenities to specific areas of the city where the risks and potential for damages are greatest. The value of these urban dis-amenities can be estimated by geo-locating dwellings inside of these zones and comparing prices while controlling for other important locational features which vary across the city.

Figure 1. Flood and Seismic Risk in Lisbon

Panel A: Flood Risk *Panel B: Seismic Risk*

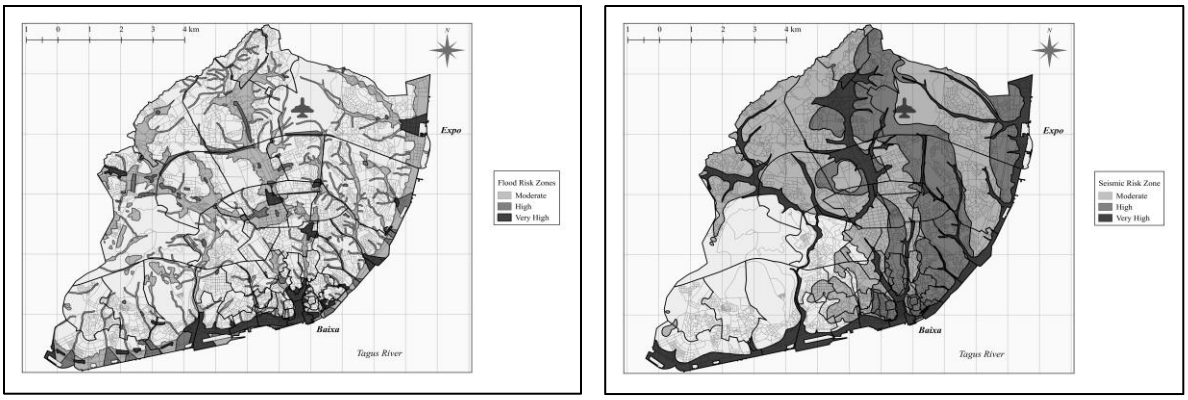


Figure 1 shows Lisbon´s flood and seismic risk zones maps. Much of the flooding and seismic risk zones appear near the Tagus riverfront or are linked to the city’s topography, and thus distance to the river and elevation are important aspects to take into consideration along with urban hazards. About 6% of the city is zoned under the high or very high flood risk categories, while 24% of the city falls into the high or very high seismic risk categories. While different properties across an earthquake prone area

[5] Since 2007 Portugal has experienced twelve seismic events of varying magnitude (four in the Lisbon region), while in 2014 alone there were a total of 1,336 flooding incidents reported throughout the city.

are equally likely to experience the same large earthquake, there is significant local variation in the likely damage that would result from that earthquake over small distances due to variation in soil geology. In terms of the number of dwellings, around 45% of the homes in our data set locate within high and very-high seismic risk zones while, 14% of the homes locate in high and very-high flood risk zones. There are 11% of the homes located within areas with high risk of both hazards.

3.2. Home Insurance Market

In Portugal there are two types of home insurances that can be purchased: fire insurance or a multi-risk (MR) insurance. Buildings on horizontal property are required by Portuguese law to have basic fire insurance. This should cover each autonomous fraction, as well as the common parts of a property against fire-related damages such as explosions due to gas leaks and fires due to short circuiting or spontaneous combustion. Natural disasters such as floods and earthquakes are not covered by basic home fire insurance policies.

On the other hand, a MR home insurance policy is not mandatory but is more comprehensive in terms of the risks covered and includes fires and other common and not-so-common damages, such as domestic explosions, lightning, thefts, water related damages (except for cases related to flooding from damaged plumbing infrastructure) and sometimes flood damages from extreme weather conditions. If a house is located in an area where floods are common, a special flood protection policy may be necessary, however, because rebuilding a home after a severe flooding event can be very expensive, certain locations in Lisbon, as for instance in *Baixa Pombalina*, may not be insurable for flood coverage.[6] Nevertheless, a MR insurance guarantees greater coverage of risks related to the house and its contents, and may also include civil liability coverage for accidents that may happen at the home or at the hands of the homeowner or his relatives within the dwelling premises.

Like in the case of home fire insurance, claims due to seismic events are excluded from the MR insurance coverage. It is possible to obtain earthquake-specific protection for a property and its belongings by purchasing a separate insurance policy that can be attached as a supplement to any MR insurance or to the fire insurance policy. Besides the *Associação Portuguesa de Seguros* (APS) risk zone, the annual insurance seismic premium depends also on the dwelling´s construction year, the home structure insurance value component (the home contents value component is excluded), the coverages selected and the deductible.[7]

Home insurance in general covers two key components, structure and contents. The home structure insurance component covers the cost for reconstruction of the parts of the property (core structure excluding land) that are damaged or destroyed (usually upon application of an inflation

[6] *Baixa Pombalina* is a historic part of the city of Lisbon located by the Tagus river as thus is a zone that is highly exposed to sea level rise and urban flash floods.

[7] The APS zones divides Portugal´s territory into 5 zones, A, B, C, D and E, in descending order in terms of the vulnerability of seismic risk. The evaluation of the seismic risk of built-up areas is associated to the level of seismic hazard, building vulnerability and level of exposure.

factor or a cost index) and is not based on the market value of the house. The contents insurance component typically protects personal belongings (e.g. furniture, home appliances or clothes) from certain risks. Scheduled personal property, often referred to as a rider, can also be purchased as an optional coverage to provide additional protection for certain valuables such as art, antiques, furs, jewelry or musical instruments. The valuation of home contents is decided as per their market value after depreciation.

Homeowners can insure both the core structure (such as floors, walls and pillars) as well as the possessions, while tenants can buy content insurance to cover their possessions. In addition, both can opt for additional insurance for risks associated with seismic events as well as expenses towards rent in case an alternate accommodation is required. Thus, the overall annual premium of a dwelling's insurance often depends on what it would cost to replace the house along with any additional endorsements or riders attached to the policy. Specifically, the actual premium that someone will pay for home coverage depends on the specific location of the dwelling as well as factors such as the area (in m^2), cost of reconstruction (per m^2) which is sometimes adjusted for the quality of materials used in construction, the way the house is constructed and the estimated value of possessions.

Though Lisbon has areas considered to be of high and very high seismic risk (as seen in figure 1) and economic losses from moderate and severe earthquakes can be very high, insurance companies do not make spatial distinctions with respect to seismic risk across the city. Hence, home insurers typically classify homogeneously all homes located in the metropolitan area of Lisbon as being under the APS zone B category (the second highest zone in terms of seismic risk in the APS national map).[8] Even so, insurance companies require an earthquake deductible, that is, an amount paid out-of-pocket before the insurance begins, of around five percent of the structure's insured value.

On the other hand, with regards to flood insurance, home insurers take into account the specific location of the dwelling within the city as Lisbon is not uniformly exposed to flood risks because of sub-city local characteristics (e.g. topography or proximity to the riverfront). Home insurance premiums for flood coverage can therefore range from frighteningly expensive to downright cheap. Premium costs depend mostly on a property's flood risk level according to the city´s risk mapping data, but also on factors such as whether the property has undergone any renovation that may mitigate flooding damage or on the elevation level of the home in relation to the base flood elevation level. Typically, homes that fall into the high or very high risk flood areas tend to have their insurance premium tailored to their property, with premiums sometimes aggravated up to 100% depending on the level of flood risk exposure, flood occurrences and, in certain cases, insurance companies can even decline to write or simply not offer flood coverage for certain locations within the flood zone.

[8] The metropolitan area of Lisbon is considered one of the regions in the country with highest seismic risk because of the high concentration of population, infrastructures and economic activities and also buildings in need of repair and lacking seismic construction protection.

According to a 2007 report by *Autoridade de Supervisão de Seguros e Fundos de Pensões* (ASF, The Portuguese Insurance and Pension Funds Supervisory Authority), 65% – 70% of homes in Portugal were covered by some sort of home insurance, either a dwelling fire policy or a MR insurance. Even though around 91% of homes in the APS zone B had a MR insurance, only 18% of those policies covered seismic events. Among those with seismic coverage, only 24% had a total insured value that would include protection on both home structure and its contents. Most of the seismic insured values, around 61%, included only home structure insurance.[9]

Despite the nationwide positive, yet very moderate, evolution in the penetration rates for residential MR insurance since 2016, insurance penetration rates for flood and more specifically for seismic risks remain low in 2018. For instance, nationwide only 15% of houses purchased with a bank loan have seismic coverage (*Negócios*, 28 March 2018). It is also estimated that nearly 60% of the housing stock in the city of Lisbon does not have seismic coverage and, that around 30% of the homes in Lisbon either just have fire insurance or simply no coverage.[10]

A possible explanation for the very low penetration rates for seismic coverage may be related to the very low relative frequency of these natural hazards when compared to flooding events. Moreover, because coverage against natural disasters is not mandatory and Lisbon is generally considered a risky area in terms of earthquakes and flooding from extreme weather events, insurance premiums for houses located in the city tend to be very expensive. As a result, the majority of the property owners in Lisbon choose not to include additional coverages for these types of natural hazards in their policies. In 2010, the public debate discussed the creation of a national seismic fund to provide means for property owners to protect themselves financially from earthquake events and cut seismic premiums by 30% – 40%. After the wildfires and floods of 2017, the public debate has moved towards the creation of a national fund that covers several natural disasters such as hurricanes, wildfires, severe floods and earthquakes. Yet, a careful study of the viability and implementation of such a national program is still yet to exist.

3.3. Data Sources

Residential property data from 2002 to 2007 is obtained from *Confidencial Imobiliário*, with the large majority of observations coming from 2007.[11] While we include year fixed effects to capture variability in housing prices over time, it is important to note however that the data is a pooled cross-section without repeated observations. The database contains the list price, structural characteristics and

---

[9] The 2007 ASF report can be found at:
http://www.portugal.gov.pt/pt/GC18/Documentos/MFAP/ Consulta_Fundo_Sismico.pdf.

[10] Personal communication with Ricardo Beja, an ASF registered Insurance Mediator, October 2018.

[11] While some residential real estate sub-markets in the United States and Europe underwent a significant bubble in 2007, Augusto Mateus & Associados (2011) conclude that Portugal remained insulated, and the residential market of Lisbon experienced no similar structural changes. Of the 32,420 observations 65.9%, or 21,353 observations, are from 2007 with 0.3%, 0.9%, 2.4%, 7.5% and 23.1% of the data from 2002 to 2006 respectively.

location identifiers for 32,420 dwellings which allow us to assign each observation to a neighborhood or hazard zone.

The municipality of Lisbon, *Câmara Municipal de Lisboa* (CML), maintains a wide range of publicly available geo-referenced data regarding local amenities, ecological characteristics, transportation infrastructure, urban hazards and the city's built environment. The municipal urban planning strategy (*Plano Diretor Municipal*) provides the size and location of urban hazard zones in the city, which are classified hierarchically based on the potential risk to residents as seen in figure 1. Areas of the city can be categorized according to the severity of risk (moderate, high or very high) of either hazard, providing heterogeneity of these potentially impacts across space.

The location of hazard zones in the city are determined by CML. In the case of seismic risk, studies from the city highlight these areas according to soil quality and type, fault lines, topography and the potential for damages in terms of the built and population density. Seismic studies led to the development of the seismic risk map in 2001, informing the public of these locations (Instituto Superior Técnico 2005). Given the regular occurrences of flooding, the areas of high flooding risk are easily determined and heavily influenced by the slope and elevation of the city. Online platforms and active local authorities make it easy for residents to report flooding occurrences with the municipality keeping a logged archive of these floods for recent years.[12]

The locations of urban amenities in Lisbon come from the city's open data platform. Using these GIS databases, we can measure proximity to employment centers and other areas of the city such as the riverfront, determine proximity to and neighborhood concentrations of transportation infrastructure and public open spaces such as parks or forests. We use Census 2011 data to capture neighborhood level socio-demographic and building stock variables.

Our MR insurance premium quotes were obtained using the DECO online home insurance premium calculator. These MR quotes do not include seismic coverage, and so we calculate the supplemental seismic premium to be added to the annual MR premium based on the 2018 commercial seismic insurance rates for zone B on home structure applied by all home insurers in the market. The reconstruction cost per m^2 was set at €799.86 as stated on the insurance policy descriptions obtained from the DECO home insurance simulations. This value is a national average reconstruction cost per m^2 for a property with an average construction quality in region I (which includes the city of Lisbon). We also include in the calculation of the MR premium quotes the three most common amounts insured on contents, €15,000, €30,000 and €50,000, provided by home insurers in Portugal.

We consult the *Agência Portuguesa do Ambiente* for data on the elevation in relation to the mean-sea level and topographical profile of the city. Our measure of elevation then also conveys the flood risk by measuring elevation relative to the sea level. To measure greenness of a resident's neighborhood

[12] Geo-referenced data on reported flood locations is only available for recent years since 2011, and thus cannot be merged with dwelling observations from 2007.

we the Normalized Difference Vegetation Index (NDVI) as calculated from aerial photography in Franco and Macdonald (2017). Crime data for general crime levels and thefts for each *freguesia* in 2007 is obtained from João (2009). Variables and descriptive statistics for key variables are presented in table 1 with all variables presented in table A1 of the Appendix.

Table 1. Key Descriptive Statistics

	N	***Mean***	***St. Dev.***	***Min***	***Max***
Price	32,420	243,500 €	148,503	25,000	2,500,000
Locational Characteristics					
Located within 3 km of the Riverfront	32,420	0.480	0.500	0	1
Located 100 m from Tagus Riverfront	32,420	0.007	0.084	0	1
Located 500 m from Tagus Riverfront	32,420	0.116	0.320	0	1
Located 500 m outside of an Area of Very High Seismic Risk	32,420	0.633	0.482	0	1
Located 500 m outside of an Area of Very High Flooding Risk	32,420	0.408	0.491	0	1
Open Spaces and Ecological Urban Hazards					
Located in an Area of High or Very High Seismic Risk	32,420	0.454	0.498	0	1
Located in an Area of High or Very High Flooding Risk	32,420	0.140	0.347	0	1
Located in an Area of Very High Seismic Risk	32,420	0.196	0.397	0	1
Located in an Area of Very High Flooding Risk	32,420	0.062	0.242	0	1

4 Empirical Analysis

4.1 Spatial Hedonic Specification

Our empirical specification is built on the seminal work of hedonic valuation from Rosen (1974). If a household has preferences across local amenities, the implicit value of these amenities can be imbedded in real estate prices. A hedonic estimation is therefore able to decompose the price of a dwelling into its value bearing attributes. Using a wide range of GIS databases, we enhance the standard set of structural characteristics for each dwelling with local neighborhood amenities, locational attributes, and the areas ecological and topographical profile.

We extend the standard hedonic model with important considerations for potential underlying spatial dependence. Such dependence in the data may influence the estimation associated with dwelling prices which are closely related to their neighbors or commonly influenced by omitted neighborhood characteristics. The most general form of our framework decomposes housing prices into its value bearing attributes as follows:

$$P_{it} = X_i\beta_1 + H_i\beta_2 + S_i\beta_3 + T_t\beta_4 + D_H \cdot A_i\beta_5 + H_i \cdot L_i\beta_6 + \rho \mathbb{W} P_{it} + u_{it} \quad (1)$$

$$u_{it} = \lambda \mathbb{W} u_{it} + \varepsilon_{it} \;\; ; \qquad \varepsilon_{it} \sim iid(\mathbf{0}, \sigma^2 \mathrm{I_n}) \quad (2)$$

where (log) price, P_{it}, for an observation at location i and time t is decomposed into a vector of time-invariant covariates, X_i, including the constant and a range of structural characteristics or neighborhood attributes. When appropriate, concentrations of local neighborhood attributes are calculated using individual buffer radii surrounding each dwelling so as to limit any influences from the modifiable aerial unit problem (Franco and Macdonald 2018). Census tract neighborhood characteristics are measured as the area weighted concentration within 500 meters of a dwelling. Our variable of interest is captured in the vector H_i which includes a dummy variable for whether a dwelling is located in an area of respective flood, seismic or a jointly hazardous zone, as well as spillover effects occurring to directly adjacent dwellings.

We include fixed effects for both year, T_t, and space, S_i. We include S_i to mitigate potential biases due to omitted locational factors resulting from time-invariant unobserved neighborhood characteristics that contribute to dwelling prices, however, it is important to consider the scale of these units in order to appropriately capture these underlying influences. The introduction of spatial fixed effects using administrative boundaries (e.g. civil parishes or *freguesias*) may provide an inconsistent definition of one's neighborhood and inaccurately capture the influence from the concentration of local amenities or the locational realities at an observation point. The size of administrative *freguesia* boundaries varies greatly and using these units as controls for a location in the city may not be refined enough to be effective. Moreover, if dwellings are on the edge of the spatial unit, they may further receive some spillover from a neighboring unit's unobserved characteristics. As in Franco and Macdonald (2018), we introduce our unit spatial fixed effects S_i according to a dwellings location in a constructed 500 meter by 500 meter grid superimposed over the city. This improves the model specification by more accurately capturing very localized potentially omitted spatial influences while addressing the modifiable areal unit problem. Appendix figure A1 presents the comparison of Lisbon *freguesias* and the constructed grid.

Including a large range of spatial fixed effects at such detailed resolution is feasible given the size of the data, and further relegates neighborhood and locational characteristics to these spatial controls. This limits the need to control for an abundance of locational characteristics such as distance to all types of local urban amenities or proximity to CBD's. An additional benefit of this methodology is the reduction of multicollinearity which may come from controlling, for example, for distance to the main CBD and important urban amenities which may be located in this area such as the river.[13]

Although our spatial fixed effects capture omitted location influences across the city, spatial dependence in prices or the error term of the models may have significant effects if the chosen fixed effect units do not accurately reflect or align with the underlying data generating process (Anselin and Arribas-Bel 2013). It is therefore important to test and incorporate, where necessary, spatial dependence in the form of either the spatially lagged dependent variable, $\mathbb{W}P_{it}$, with coefficient ρ, or modeling the error u_{it} as an autoregressive error term accounting for spatial correlation, $\mathbb{W}u_{it}$, with coefficient λ.

The general econometric specification in (1) nests multiple spatial models where the chosen empirical models are decided on via the results of the spatial diagnostics. From this specification, when $\rho = 0$ we have a spatial error model and with $\lambda = 0$ a spatial autoregressive model. $\mathbb{W}$ represents the $n \times n$ weight matrix defining the extent and strength of spatial spillovers between dwellings. We specify six weights ranging from quite local to more spatially broad to ensure estimates are not the product of the chosen matrix. These spatial weights include a binary weighting schemes to indicate all

[13] To ensure no multicollinearity concerns, the variance inflation factor for the estimates of interest is below 10.

neighbors within 500 meters (SW1); an inverse distance weight for all neighbors within 500 meters (SW2); an inverse squared distance weight for all neighbors within 500 meters (SW3); a binary weighting scheme to indicate all neighbors within 100 meters (SW4); neighbors based on the 100 nearest dwellings (SW5); and neighbors based on the 10 nearest dwellings (SW6). Table A2 of the Appendix summarizes the properties of these weights.

4.2 Identification and Robustness of Results

Although the estimation of spatial hedonic models may alleviate estimation biases, it does not address concerns regarding the identification of impacts. The locations of hazard zones are exogenously determined via ecological and topographical processes, and thus not conditional on dwelling prices, however there may exist some significant underlying locational influences driving the estimated impacts near these areas.

We check the robustness of our estimates via a geographic regression discontinuity (GRD) framework, a type of regression discontinuity with a geographic treatment assignment comparing treated (hazard prone) properties to valid control properties nearby but not in a hazard risk zone.[14] The methodology behind our GRD framework and choosing valid treated and control properties in nearby geographic sub-sets is highlighted in figure A2 of the Appendix for the example of flood risk areas.

We homogenize the data by sub-setting around hazard zone boundaries. In the relevant geographic subset, all other locational attributes such as accessibility to the CBD, accessibility to the riverfront, and other natural amenities are likely to be similar and thus provides a quasi-experimental design. The locational similarity of properties in all other aspects will be greater for bordering dwellings located at the geographic boundary that separates the two zones.

We test the use of a variety of spatial sub-setting thresholds, conditional on the hazard zone of interest which include sub-setting to all properties within 500 meters from very high risk flood zones and 500 meters from very high risk seismic zones. We further subset the data conditional on being located within 3 kilometers of the Tagus riverfront, and estimate our parametric GRD hedonic pricing model again to ensure that the impacts from these hazard zones for example are not being driven by properties being located near to the Tagus river.

While this methodology ensures that we are estimating impacts from a relatively homogeneous set of observations from which potentially important neighborhood effects are not driving the results, it may be the case that relative location along the hazard zone boundary also has significant variability.

[14] The GRD methodology has previously been employed to study area wide impacts from media market zones on political turnout (Keel and Titiunik 2015), police surveillance zones on crime (MacDonald et al. 2016) and historic conservation areas on property values (Franco and Macdonald 2018). One of the prerequisites for a GRD is to identify the geographic boundary where a discontinuity exists in how the treatment is assigned. We use municipal defined boundaries representing the locations of high flood risk or high seismic risk as our regression discontinuities, where the treatment jumps discontinuously along these geographic borders. Another prerequisite is that we compare similar properties in the control and treatment groups on either side of the geographic boundary and that enough variability along that boundary exists.

To compensate, we also use a propensity score match to examine distance as defined by covariates and homogenize the data by finding controls conditional on important locational characteristics.

Figure A3 of the Appendix highlights the geographic discontinuity in prices occurring at either hazard boundary. These figures suggest that dwellings within hazard zones sell at a lower price with dwelling prices increasing as we move from these boundaries. The discontinuity at the flood risk boundary suggest some indication of higher prices the further inside very high risk flood zones. Since the majority of the very high risk flood zones are located along the Tagus river however, this figure highlights the importance of distinguishing between the negative zonal effect of being in an area of higher flood risk and the positive amenity value of being closer to the riverfront.

4.3 Within and Between Heterogeneity of Urban Hazard Zones

This research concerns itself with capturing not only the direct effect of how urban hazard zones impact residential property prices, but further how this effect is conditioned on the heterogeneity of local amenities found across the different zones, the relative location of these hazard zones across the city, and how the impact of these zones may depend on the distribution of dwelling prices.

We thus estimate our baseline empirical model with and without the inclusion of the terms $D_H \cdot A_i$ which represents the within variation, and $H_i \cdot L_i$ which represents the between variation. Here D_H measures the accessibility to a hazard zone as the distance to the border of the nearest hazard risk, while A_i represents a range of local amenities, and L_i represents a dummy for being located in notable areas of the city.

Since we measure the impact from flooding risk and seismic risk through proximity of the dwelling to the boundary of hazard zones, dwellings located inside these zones and in particular if located at the center of the zone, are exposed to larger external effects. However, as we move towards the boundary (if located inside) or away from the boundary (if located outside) we expect the negative effects of these dis-amenities to decline. The rational for our measurements is hence based on the fact that housing externalities decline in distance (Rossi-Hansberg et al. 2010). Hence the measure D_H captures the relative strength of being located further inside either of these hazard areas. In particular, dwellings located outside of a hazard area take a positive geographic distance value while those located inside a hazard area take a negative geographic distance value.

On the other hand, the within variation is interpreted relative to the global average impact of being in a hazard zone, H_i. We estimate the average marginal impact of being closer to a hazard zone border as conditioned by local amenities. A positive estimate of β_5 would therefore signal marginally higher house prices further away from a hazard zone conditional on higher levels of the local amenities, and thus an exacerbating effect, while negative values would indicate a mitigating influence of local amenities with marginally higher prices for dwellings closer to hazard zones conditional on higher levels of the local amenities. If residents trade off the urban dis-amenity value from hazard zones according to benefits coming from other local urban amenities, we expect there to be variation in the estimate of β_5 according to the type of local amenities considered.

This measure of variation in H_i focuses on how the heterogeneity of a dwelling's local amenities can mitigate or exacerbate the impact of proximity to these zones. We focus on how the interaction between proximity to hazard zones and urban green areas, the local built environment or neighborhood crime levels influence a dwellings price. If these local amenities or dis-amenities can be used to make an otherwise risky zone marginally better, or worse, then we expect this interaction influence to capture this effect and the residential real estate market to respond.

The between variation captures how the relative location of these hazard zones in a city can influence their impact on housing prices. If housing prices are representative of a bundle of attributes, then residents may give more or less importance to urban hazard zones if the local area compensates in other aspects. While the location of flood and seismic risks are in many cases concentrated along the river and in the downtown core, the amenity value of proximity to the river may outweigh the negative dis-amenity of being in a flood zone. Interacting dummy variables to represent whether a dwelling is located in a hazard zone while simultaneously in direct proximity to the riverfront would thus capture this potential impact representing the relative costs and benefits that residents accept by living in certain areas of the city.

We further interact this hazard indicator with dwellings which are simultaneously located in historically preserved conservation areas which are also located along the riverfront and in historically important areas of the city. These historic areas of the city are preserved for their historic charm and the combination of aesthetically pleasing buildings, open spaces and neighborhood allure. If these areas are more preserved relative to other areas nearby, then the benefit of living here may outweigh the cost of being in a zone of increased urban risk. In the case of these between hazard zone effects, it is important to consider the net effect coming from $\beta_2 + \beta_6$ when $L_i = 1$.

5 Results

Our baseline results focus on three categories of models of urban hazards for flooding risk, seismic risk and jointly hazardous areas (simultaneously in a zone of flooding and seismic risk), each introduced separately so as not to introduce conflicting impacts in the effects on housing prices. All models include structural characteristics with magnitudes in line with previous literature and all providing positive price effects on dwellings, the largest impact coming from its size with a price effect of 0.86% per percentage increase in square meterage, and more luxury type amenities such as pools, air conditioning or a view of the Tagus river drawing premiums of 15.9%, 12.5% and 5.8% respectively.

We test all models for spatial dependence of the dependent variable and spatial autocorrelation of the error term. Diagnostic results from the spatial tests are presented in table A3 of the Appendix. Global results on the Moran's I statistic indicate significant spatial dependence influencing the estimates which should be accounted for. Using the Lagrange multiplier (LM) tests to better identify the source of the spatial influences indicate that a SEM is appropriate to control for the underlying spatial autocorrelation in the error term, while no significant spatial influence is found from the spatially lagged dependent price variable. Therefore, according to our empirical model specification presented in section 4, we conclude that $\rho = 0$ and there is no significant spatial lag effect, while λ is a significant parameter and a SEM specification should be estimated. Results from a spatial Breusch-Pagan test indicate the presence of heteroscedasticity, and thus robust standard errors are presented.

Using the AIC model selection criteria, SEM models outperform their OLS counterpart and further all have reduced sum of squared errors (SSE). Diagnostics suggest, based on a combination of the AIC, SSE, robust LM tests and variable significance, the preferred model is the SEM with weight matrix using all properties within 100 meters as neighbors (SW4), and subsequent analyses use this specification. We note also that SEM coefficients of hazard covariates are smaller than in OLS models, showing the bias induced by not controlling for spatial autocorrelation.

5.1. Flood and Seismic Risks Average Price Impacts

Spatial hedonic results presented in table 2 indicate that the residential real estate market negatively capitalizes on hazard risks. All specifications include an interaction effect between elevation and distance to the riverfront so as to ensure that the price impact for location in a hazard risk zone is not biased by these important locational features. Often homes located in high risk zones are also the most desirable in terms of their proximity to the water. Thus it is important to allow for the joint impact of the potential negative housing price effects of higher risk (whether flood, seismic or both) and the potential positive housing price effects of living close to the water. Moreover, there is an inherent variation in flood risk within a given region that can be associated to the elevation in relation to the sea-level. This measure of elevation has its zero value at the level to which stormwater flows, and from where water would pool in a flooding event. Thus, we use elevation in relation to the sea-level in addition to a flood risk indicator variable to account for the spatially inherent variation of topography within a risk zone.

While dwelling prices are positively influenced by being at a higher elevation, this effect is stronger the closer a dwelling is to the riverfront. The negative coefficient estimate on the interaction term indicates that dwelling prices increase as the distance to the river decreases, and this effect is stronger for dwellings at higher elevations. This may be associated with better access to water-related amenities and views while having a lower flood risk from being located at higher elevation in relation to the base flood elevation level. We further control for average distance to all parks and gardens in the city as a form of concentration of green spaces, as well as the number of urban forests nearby, with results indicating that these green amenities are also positively valued by residents.

The per dwelling price impact of being located in a designated very high risk flood zone (*Model 1*) is a decrease of approximately 3.5%. For an average priced dwelling, this corresponds to an approximate price discount of €8,500. The price impact due to flooding risk is the largest taking into consideration the other different urban hazards studied in this paper. This is likely due to the fact that flooding is a common occurrence in the city and happens yearly. Residents looking to purchase or sell their dwelling are well aware of the relative hazard risk of their neighborhood when it comes to flooding, given the nearby slopes, elevation, whether it is in a valley or near the river.

Table 2. SEM (SW4) Urban Hazard Estimates

Dependent Variable: ln(Price)	***Model 1***	***Model 2***	***Model 3***	***Model 4***	***Model 5***	***Model 6***
Nº. of Urban Forests in 500 m	0.01540**	0.01520*	0.01535**	0.01587**	0.01590**	0.01548**
	(0.00781)	*(0.00780)*	*(0.00780)*	*(0.00781)*	*(0.00781)*	*(0.00781)*
ln(Average Distance to all Parks)	-1.19597***	-1.17027***	-1.18900***	-1.15547***	-1.18652***	-1.16523***
	(0.16812)	*(0.16747)*	*(0.16861)*	*(0.16752)*	*(0.16805)*	*(0.16744)*
Elevation	0.00130***	0.00139***	0.00149***	0.00156***	0.00143***	0.00142***
	(0.00028)	*(0.00028)*	*(0.00027)*	*(0.00027)*	*(0.00027)*	*(0.00027)*
ln(Distance to Tagus River)	-0.03037*	-0.02392	-0.02499	-0.02109	-0.03000*	-0.02578
	(0.01769)	*(0.01736)*	*(0.01767)*	*(0.01733)*	*(0.01771)*	*(0.01732)*
Elevation × ln(Distance to Tagus River)	-0.00054**	-0.00062**	-0.00064**	-0.00067***	-0.00056**	-0.00062**
	(0.00026)	*(0.00025)*	*(0.00025)*	*(0.00025)*	*(0.00026)*	*(0.00025)*
	Flood Risk		***Seismic Risk***		***Joint Hazards***	
	Very High	***High***	***Very High***	***High***	***Very High***	***High***
Urban Geohazard Risk	-0.03513***	-0.01612**	-0.01114*	-0.01118*	-0.03786***	-0.02474***
	(0.01128)	*(0.00731)*	*(0.00647)*	*(0.00631)*	*(0.01419)*	*(0.00802)*
Lambda	0.15503***	0.15801***	0.16021***	0.16128***	0.15532***	0.15600***
	(0.03744)	*(0.04114)*	*(0.01360)*	*(0.02077)*	*(0.03940)*	*(0.03389)*
Year F.E.	Yes	Yes	Yes	Yes	Yes	Yes
500 m F.E.	Yes	Yes	Yes	Yes	Yes	Yes
Structural Characteristics	Yes	Yes	Yes	Yes	Yes	Yes
AIC	-3990.9	-3984.6	-3982.7	-3982.9	-3987.6	-3989.0
$AIC_{SEM} \div AIC_{OLS}$	*1.00500*	*1.00520*	*1.00540*	*1.00550*	*1.00500*	*1.00510*
Log Likelihood	2241.5	2238.3	2237.3	2237.4	2239.8	2240.5
$L.L._{SEM} \div L.L._{OLS}$	*1.00490*	*1.00510*	*1.00520*	*1.00530*	*1.00490*	*1.00500*
SSE	1652.5	1652.8	1652.9	1652.9	1652.7	1652.6
$SSE_{SEM} \div SSE_{OLS}$	*0.99897*	*0.99897*	*0.99891*	*0.99891*	*0.99903*	*0.99897*
Residual Std. Error	0.22577	0.22579	0.22580	0.22580	0.22578	0.22578
$Res.\ Error_{SEM} \div Res.\ Error_{OLS}$	*0.99572*	*0.99572*	*0.99572*	*0.99572*	*0.99572*	*0.99572*
Adj. VIF for Hazard Variable	1.99	2.01	2.07	2.54	2.10	2.04
Spatial Breusch-Pagan	1208.6***	1205.2***	1206.9***	1208.1***	1207.5***	1208.3***
Wald Test	17.15***	14.75***	138.87***	60.28***	15.54***	21.18***
Likelihood Ratio Test	21.70***	22.70***	23.28***	23.65***	21.78***	22.07***
Observations	32,420	32,420	32,420	32,420	32,420	32,420

*Notes: ***Significance at 1 % level; **Significance at 5 % level; *Significance at 10 % level.*
Robust Standard Errors

The impact on housing prices for being located in designated flood risk zones is sensitive to the strength of the risk, with very high flood risk zones yielding significantly larger impacts than the more dispersed combination of high or very high flood risk zones, with negative impacts of 3.5% and 1.6% respectively (*Model 1 and Model 2*). This suggest that on average residential prices reflect differently to the relative variability and strength of flooding risk areas across the city.

Seismic risk on the other hand, yields smaller magnitude price discounts in the order of 1.1% (*Model 3*) with little difference between the impact of being located within a designated very high seismic risk zone relative to being located within a high risk or very high seismic risk combined zone. Seismic activity in Lisbon is quite rare. Even if a property is located near a fault line and the potential for damage is catastrophic, the low magnitude of our estimate likely stems from the undervaluation of seismic risk that residents have given the scarcity of these events and low chances of any occurrence on the same magnitude as in the past, even if located in a seismic zone. Evaluated at an average priced dwelling, the impact of being within designated seismic risk zones on property values detracts from prices by approximately €2,700.

Although these price estimates are relatively conservative, given that they are per-dwelling effects and a potentially large number of dwellings are located in these areas, the total effect of urban hazards on the residential market of Lisbon is potentially quite large. Within our sample, 6.2% of the homes are located in an area of very high flooding risk while 19.6% of homes are located in areas of very high seismic risk. The aggregate effect across all dwellings exposed to these risks therefore is large.

Given the heterogeneity and overlap of these urban hazard risks across the study region, it is possible to examine the impact of being jointly in designated areas of flooding risk and seismic risk. Dwellings located in both types of very high risk zones have a negative impact on prices on the order of 3.8%, or around €9,250 evaluated at the value of an average priced dwelling (*Model 5*). While the market responds to urban natural hazard risks, there seems to be heterogeneity across how the risk from different types of natural hazards are capitalized into dwelling prices.

Hazard Risk Zone Spillover Effects

We consider the price impact of hazard zones in table 3 in terms of the spillover effect that they have. While there is a negative price impact of being located in a hazard zone, this effect is not restricted to the boundaries of the hazard zone itself. Results suggest that the negative effect of flood risk zones extend beyond the boundary of the zone and impact properties adjacent and within 50 or 100 meters of the boundary as well. For dwellings located just outside a very high risk zone (whether in terms of flood, seismic or both), there is a negative effect on price of approximately 1.5%. This effect is driven by properties that are located adjacent to very high risk flood zones and simultaneously located in a non-risk area (*Model 7 and 8*).

This suggests that nearby dwellings capitalize on the dis-amenity value of being located near to high risk flood zones, with no significant impact coming from seismic zones. Flooding is regular in the city and the path of storm water runoff is not limited to any boundaries, and thus we would expect these negative direct spillovers to occur for flooding events and not for seismic events.

These spatial spillover results also reveal that hazard zones compound each other and that being located in areas of high concentrations of either types of hazards impact housing prices. When a dwelling is located in a high flood risk zone which is adjacent to a very high flood risk zone, it is surrounded by these risk areas and residents perceive the combined effect of these zones together. Prices in high risk zones that are directly adjacent to very high risk zones are detracted by approximately 13.3% (*Model 9*), indicating that being in and around many flood-prone areas provides even higher dis-amenity values. These compounded spillovers also occur between flood risk and seismic risk zones with negative impacts of 4.2% for dwellings adjacent to very high risk flood zones which are simultaneously located in high risk seismic zones (*Model 10*).

Table 3. SEM (SW4) Hazard Zone Spillover Effects

Dependent Variable: ln(Price)	*Model 7*	*Model 8*	*Model 9*	*Model 10*	*Model 11*	*Model 12*	*Model 13*
In V. High Risk Flood Zone	-0.04424*** *(0.01259)*	-0.05174*** *(0.01344)*	-0.04533*** *(0.01258)*	-0.05279*** *(0.01326)*			
50 m from V. High Risk Flood Zone	-0.01422* *(0.00806)*	-0.01132 *(0.00820)*	-0.01414* *(0.00805)*	-0.01197 *(0.00810)*			
In V. High Risk Seismic Zone					-0.01048 *(0.00911)*	-0.00588 *(0.00933)*	-0.0115 *(0.00912)*
100 m from V. High Risk Seismic Zone					0.00072 *(0.00709)*	0.00836 *(0.00799)*	0.00500 *(0.00742)*
100 m from V. High Risk Flood Zone × In a Non-Flooding Risk Zone		-0.01496* *(0.00889)*					
100 m from V. High Risk Flood Zone × In High Risk Flood Zone			-0.13299* *(0.07532)*				
100 m from V. High Risk Flood Zone × In High Risk Seismic Zone				-0.04200** *(0.01842)*			
100 m from V. High Risk Seismic Zone × In a Non-Flooding Risk Zone						-0.01593** *(0.00803)*	
100 m from V. High Risk Seismic Zone × In High Risk Seismic Zone							-0.02150* *(0.01098)*
Lambda	0.15404*** *(0.02346)*	0.15312*** *(0.03819)*	0.15280*** *(0.02619)*	0.15429*** *(0.02090)*	0.16035*** *(0.03373)*	0.16116*** *(0.02915)*	0.15891 *(0.10038)*
Year F.E.	Yes	Yes	Yes	Yes	Yes	Yes	Yes
500 m F.E.	Yes	Yes	Yes	Yes	Yes	Yes	Yes
AIC	-3991.9	-3992.8	-3991.6	-3995.9	-3980.7	-3982.2	-3982.3
$AIC_{SEM} \div AIC_{OLS}$	*1.00490*	*1.00480*	*1.00480*	*1.00490*	*1.00540*	*1.00550*	*1.00530*
Log Likelihood	2243.0	2244.4	2243.8	2246.0	2237.4	2239.1	2239.1
$L.L._{SEM} \div L.L._{OLS}$	*1.00480*	*1.00470*	*1.00470*	*1.00480*	*1.00520*	*1.00530*	*1.00520*
SSE	1652.4	1652.2	1652.3	1652.1	1652.9	1652.7	1652.7
$SSE_{SEM} \div SSE_{OLS}$	*0.99903*	*0.99903*	*0.99903*	*0.99903*	*0.99891*	*0.99891*	*0.99891*
Residual Std. Error	0.22576	0.22575	0.22576	0.22574	0.2258	0.22578	0.22578
$Res. Error_{SEM} \div Res. Error_{OLS}$	*0.99572*	*0.99572*	*0.99572*	*0.99572*	*0.99572*	*0.99563*	*0.99568*
Mean Adj. VIF for Hazard Variables	1.82	1.83	1.73	1.81	2.54	2.38	2.33
Max Adj. VIF for Hazard Variables	2.23	2.39	2.24	2.33	2.94	3.04	2.94
Spatial Breusch-Pagan	1212.2	1212.5	1212	1212.3	1207.2	1210.5	1206.7
Wald Test	43.11***	16.07***	34.03***	54.51***	22.60***	30.57***	2.51
Likelihood Ratio Test	21.35***	21.12***	21.18***	21.43***	23.30***	23.62***	23.00***
Observations	32,420	32,420	32,420	32,420	32,420	32,420	32,420

*Notes: ***Significance at 1 % level; **Significance at 5 % level; *Significance at 10 % level.*
Robust Standard Errors

The direct spillover effect from seismic zones is less pronounced than flood risk zones, yet suggests that being adjacent to very high risk seismic areas while simultaneously in high risk seismic areas has a compounded negative price effect of 2.2% (*Model 13*). Being adjacent to a seismic zone which has no risk of flooding further indicates a negative price impact of 1.6% highlighting that these dis-amenity values are not constrained directly to the boundaries of the zones and, dwellings located nearby, even without and direct risk themselves, are further subject to the impact stemming from natural hazards.

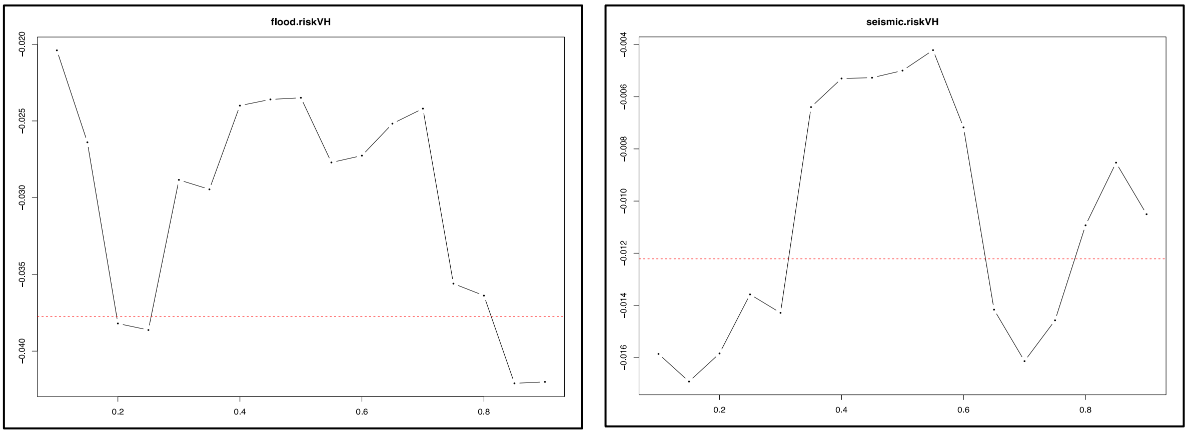
5.2. Hazard Risks Quantile Price Effects

To capture the potential impact of natural hazards conditional on the distribution of dwelling prices, we further estimate a quantile regression for *Model 1* and *Model 3* with results plotted in figure 2. This allows us to further examine whether specific portions of the distribution of housing prices are more or less impacted from the very high risk of natural hazards. Dwellings at different points in the distribution of housing prices may have coefficient values which vary from the average if properties are inherently more susceptible to these risks or more sensitive to the dis-amenity value.

Results for very high flood risk areas suggest that dwellings at the higher end of the distribution, above the 70th percentile, are more negatively impacted by these hazard risks. For these priced dwellings, large floods have the potential to have more relative damaging costs and residents in such properties capitalize more on these perceived risks and costs. For a resident in a higher priced dwelling located in a very high flood risk, their potential for loss is greater than for cheaper dwellings. Above the 85th percentile, the impact on dwelling prices increases significantly to approximately 4.2%, compared to the average value estimated under *Model 1* at 3.5%. At the 10th percentile of dwelling prices on the other hand, the impact of flood risk reduces to 2.0%. While flood risk impacts differently dwelling prices at different ends of the distribution, we find little evidence that seismic risk has similar heterogeneous effects.

Figure 2. Very High Flood and Seismic Risk Quantile Estimates

Panel A: Flood Risk *Panel B: Seismic Risk*



5.3. House Price Response to Hazard Risks Conditional on Other Urban Features

Within Variation of Hazard Risks

If residents value differently hazard zones conditional on local amenities, then we would expect there to be within variation in very high flood risk or very high seismic risk areas. It is important to capture this heterogeneity across areas conditional on their local context to better understand the interaction of hazard zones with broader municipal infrastructure and amenities. We estimate *Model 1* and *Model 3* with a range of local dwelling amenities and neighborhood attributes which relate to each respective risk. The results are presented in tables 4a and 4b below.

In general, results indicate that local green infrastructure plays an important role in mitigating the dis-amenity value of being located in high risk flood zones. The average marginal impact of being closer to very high risk flood zones is mitigated if a dwelling has a higher concentration of urban forests nearby or a higher average level of neighborhood greenery as determined by the NDVI (*Model 15 and 16*). Urban forests and large tree stands are important aspects of a city in terms of storm water runoff management and flood mitigation strategies, and general vegetation also plays a similar role. These urban green amenities provide ample pervious surfaces that allow excess water to drain off easily and thus cause less flood dis-amenity to residents.

Table 4a. SEM (SW4) Flood Risk Interaction Effects

Dependent Variable: ln(Price)	*Model 14*	*Model 15*	*Model 16*	*Model 17*	*Model 18*	*Model 19*	*Model 20*
Located in V. High Risk Flood Zone	-0.03489*** *(0.01128)*	-0.03507*** *(0.01128)*	-0.03569*** *(0.01129)*	-0.03601*** *(0.01128)*	-0.03208*** *(0.01129)*	-0.02660** *(0.01156)*	-0.02748** *(0.01154)*
Distance to V. High Flood Risk Zone × Nº. of Lakes in 100 m	0.01008** *(0.00435)*						
Distance to V. High Flood Risk Zone × Nº. of Urban Forests in 100 m		-0.02492** *(0.01144)*					
Distance to V. High Flood Risk Zone × Average NDVI in 100 m			-0.14395* *(0.08410)*				
Distance to V. High Flood Risk Zone × ln(Average Slope in 100 m)				-0.00598*** *(0.00228)*			
Distance to V. High Flood Risk Zone × ln(Length of Roads in 100 m)					0.00551*** *(0.00152)*		
Distance to V. High Flood Risk Zone × Crimes per Person						1.02605*** *(0.36522)*	
Distance to V. High Flood Risk Zone × Thefts per Person							1.14986*** *(0.43905)*
Lambda	0.15388*** *(0.02309)*	0.15431*** *(0.03935)*	0.15489*** *(0.06793)*	0.15299*** *(0.02869)*	0.15238*** *(0.02569)*	0.14771*** *(0.03245)*	0.14764*** *(0.01926)*
Year F.E.	Yes	Yes	Yes	Yes	Yes	Yes	Yes
500 m F.E.	Yes	Yes	Yes	Yes	Yes	Yes	Yes
AIC	-3993.5	-3991.0	-3992.5	-3996.3	-3999.7	-3997.5	-3996.4
$AIC_{SEM} \div AIC_{OLS}$	*1.00490*	*1.00490*	*1.00490*	*1.00480*	*1.00480*	*1.00440*	*1.00440*
Log Likelihood	2243.7	2242.5	2243.3	2245.2	2246.9	2245.8	2245.2
$L.L._{SEM} \div L.L._{OLS}$	*1.00480*	*1.00480*	*1.00480*	*1.00470*	*1.00470*	*1.00430*	*1.00440*
SSE	1652.3	1652.4	1652.3	1652.2	1652.0	1652.1	1652.2
$SSE_{SEM} \div SSE_{OLS}$	*0.99903*	*0.99903*	*0.99897*	*0.99903*	*0.99903*	*0.99909*	*0.99909*
Residual Std. Error	0.22576	0.22576	0.22576	0.22575	0.22573	0.22574	0.22575
$Res. Error_{SEM} \div Res. Error_{OLS}$	*0.99577*	*0.99572*	*0.99572*	*0.99577*	*0.99572*	*0.99577*	*0.99577*
Mean Adj. VIF for Hazard Variables	2.39	1.92	3.85	2.66	4.79	3.85	3.54
Max Adj. VIF for Hazard Variables	2.79	1.99	5.71	3.33	7.58	5.62	5.01
Spatial Breusch-Pagan	1208.6***	1208.9***	1210.8***	1207.7***	1204.0***	1207.5***	1208.3***
Wald Test	44.42***	15.38***	5.20**	28.44***	35.19***	20.73***	58.78***
Likelihood Ratio Test	21.37***	21.58***	21.65***	21.14***	20.91***	19.45***	19.51***
Observations	32,420	32,420	32,420	32,420	32,420	32,420	32,420

*Notes: ***Significance at 1 % level; **Significance at 5 % level; *Significance at 10 % level.*

While urban green infrastructure can mitigate some of the negative dis-amenity values associated with being in an area of high flooding risk, compounding negative effects come from being located nearby to lakes and impervious surfaces (*Model 14 and Model 18*). The pooling of storm water can be significant in these areas and result in high surface runoff and reduction in lag time.[15] Dwellings with higher concentrations of lakes or a denser road network nearby therefore have higher prices for being located further away from flood risk zones with prices increasing with higher concentrations of these amenities further away from the hazard.

The built environment can therefore have profound influence on how residents value the relative impact of these urban hazards, and thus has important implications for municipalities and developers to create more amenities which may mitigate the negative impact of urban natural hazards. If neighborhoods in risky areas of a city can be developed in such a way as to provide residents with these mitigating amenities, then our results suggest that this is captured and capitalized by the residential real estate market.

[15] Surface runoff is water, from rain, snowmelt, or other sources, that flows over the land surface, and is a major component of the water cycle. Lag time is defined as the time difference between peak runoff and the mass center of rainfall excess.

Table 4b. SEM (SW4) Seismic Risk Interaction Effects

Dependent Variable: ln(Price)	*Model 21*	*Model 22*	*Model 23*	*Model 24*	*Model 25*
Located in Very High Risk Seismic Zone	-0.00044* *(0.00026)*	-0.00058** *(0.00026)*	-0.00074*** *(0.00026)*	-0.00061** *(0.00025)*	-0.00061** *(0.00025)*
Distance to Very High Seismic Risk Zone × % Neighborhood Property Owners	-0.26412*** *(0.06317)*				
Distance to Very High Seismic Risk Zone × % Neighborhood Educated		-0.18500** *(0.09163)*			
Distance to Very High Seismic Risk Zone × % Buildings with 1 or 2 Stories			-0.33073*** *(0.11074)*		
Distance to Very High Seismic Risk Zone × Neighborhood Crimes per Person				0.99184* *(0.53180)*	
Distance to Very High Seismic Risk Zone × Neighborhood Thefts per Person					1.27597** *(0.64370)*
Lambda	0.16013*** *(0.04145)*	0.16114*** *(0.01857)*	0.15865*** *(0.01717)*	0.15370*** *(0.04421)*	0.15333*** *(0.05597)*
Year F.E.	Yes	Yes	Yes	Yes	Yes
500 m F.E.	Yes	Yes	Yes	Yes	Yes
AIC	-4001.1	-3985.1	-3991.3	-3984.6	-3985.1
$AIC_{SEM} \div AIC_{OLS}$	*1.00540*	*1.00540*	*1.00520*	*1.00490*	*1.00480*
Log Likelihood	2247.6	2239.6	2242.7	2239.3	2239.6
$L.L._{SEM} \div L.L._{OLS}$	*1.00520*	*1.00530*	*1.00510*	*1.00480*	*1.00470*
SSE	1651.9	1652.7	1652.4	1652.8	1652.7
$SSE_{SEM} \div SSE_{OLS}$	*0.99897*	*0.99897*	*0.99879*	*0.99909*	*0.99915*
Residual Std. Error	0.22573	0.22578	0.22576	0.22579	0.22578
$Res.\ Std.\ Error_{SEM} \div Res.\ Std.\ Error_{OLS}$	*0.99572*	*0.99568*	*0.99563*	*0.99577*	*0.99577*
Mean Adj. VIF for Hazard Variables	4.22	4.11	6.00	2.46	2.37
Max Adj. VIF for Hazard Variables	6.29	6.07	9.90	2.77	2.60
Spatial Breusch-Pagan	1215.4***	1218.1***	1218.7***	1215.9***	1215.5***
Wald Test	14.92***	75.34***	85.37***	12.09***	7.50***
Likelihood Ratio Test	23.30***	23.58***	22.82***	21.24***	21.05***
Observations	32,420	32,420	32,420	32,420	32,420

*Notes: ***Significance at 1 % level; **Significance at 5 % level; *Significance at 10 % level. Robust Standard Errors*

In terms of seismic risk zones, neighborhood characteristics have important mitigating behaviors. In neighborhoods where there is a higher percentage of owner-occupiers or educated individuals (*Model 21 and Model 22*) the dis-amenity value of being located nearer to seismic risk areas is attenuated. These indicators may serve as a proxy to indicate how well homes in an area are maintained with property owners specifically having a larger incentive to provide protection for their properties and for themselves and their relatives against such risk. Moreover, in general educated people tend also to be better informed about general topics including urban hazards and thus, be potentially more engaged in preparedness activities such as collecting survival items such as food and water, undertaking mitigation actions such as retrofitting buildings, securing household items, making a household emergency plan or simply learning survival skills.[16]

In terms of the built environment, our results seem to suggest that there is a price premium for being located closer to seismic risk zones in which there are higher percentages of low-lying buildings with

[16] It should be noted that the infrequent nature of seismic hazard events means that people often also lack personal experience of such a hazard (Becker et al. 2017). They will, however, have indirect experience (e.g. experience of small seismic events that did not impact them directly), vicarious experience (e.g., media reports of national or international events, accounts of prior events from relatives), and challenging life event experience (e.g., of accidents, crime etc.), all of which could play independent and interdependent roles in future preparedness decision making and actions.

one or two stories (*Model 23*). This result should be interpreted with caution as it may be related to the residents' perception that in the case of an earthquake, these buildings tend to be the most stable with higher risks coming from larger structures or high-rise buildings. However, damages during an earthquake results from several factors including strength and length of the shaking, type of soil and type of building. Buildings of different heights tend to respond differently in an earthquake. Aside from architectural constraints (i.e., how well built the structure is) the particular resonance of an earthquake can knock down a small building and spare the skyscraper.[17] Small building are more affected, or shaken, by high-frequency waves (short and frequent). On the other hand, large structures or high rise buildings are more affected by long period, or slow shaking.

For both very high seismic and very high flood risk zones, there is exacerbating negative price impacts for being closer to these hazard areas if a resident lives in a neighborhood with higher crime levels as determined by the general amount of crime and level of thefts (*Models 19, 20, 24 and 25*). In the case of an extreme urban hazard, uplifting cooperation follows community disasters, but so do looting, sexual assaults, acts of domestic violence and fraud (Frailing et al. 2015). It is all too commonly understood (from either anecdotes or systematic evidence) that certain individuals in disaster areas turn to anti-social activities, including crime. Criminals may take advantage of these hazard events for their own gain, especially if it comes to looting in the wake of disasters that force many residents away from their homes and businesses. This may be most evident in the case of extreme flooding events where ground-level shop fronts are often targeted during the commotion for quick gains. These additional risks appear to be capitalized in the residential real estate market with residents aware of the increased risk from chaotic urban hazard events when living in areas with significantly higher crime levels.

Between Variation of Hazard Risks

While the average price impact of hazard zones is negative, residents may trade off this risk if other aspects of their location have benefits which outweigh these risks. In table 5, we interact dwellings which are located in very high risk areas with indicators to represent being located in attractive areas of the city as determined by proximity to the riverfront or historic conservation areas. If the benefits of these zones outweigh the costs, then we would expect a mitigating effect on the price impact risk of urban hazards.

[17] The resonance is the oscillation (up-and-down or back-and-forth motion) caused by a seismic wave. During an earthquake, buildings oscillate. If the frequency of this oscillation is close to the natural frequency of the building, resonance may cause severe damage.

Table 5. SEM (SW4) Locational Interaction Effects

Dependent Variable: ln(Price)	***Model 26***	***Model 27***	***Model 28***	***Model 29***
Located in Very High Risk Flood Zone	-0.04069*** *(0.01173)*	-0.03680*** *(0.01132)*	-0.05462*** *(0.01604)*	
Located in Very High Risk Seismic Zone				-0.01509** *(0.00673)*
Located in Very High Risk Flood Zone × Located in Conservation Area	0.04246* *(0.02537)*			
Located in Very High Risk Flood Zone × Located 100 m from Tagus Riverfront		0.09123* *(0.05540)*		
Located in Very High Risk Flood Zone × Located 500 m from Tagus Riverfront			0.03798* *(0.02141)*	
Located in Very High Risk Seismic Zone × Located in Conservation Area				0.03581* *(0.02005)*
Lambda	0.15216*** *(0.05108)*	0.15407*** *(0.04272)*	0.15421*** *(0.05458)*	0.15806*** *(0.01841)*
Year F.E.	Yes	Yes	Yes	Yes
500 m F.E.	Yes	Yes	Yes	Yes
AIC	-3993.0	-3992.9	-3992.5	-3984.9
$AIC_{SEM} \div AIC_{OLS}$	*1.00470*	*1.00490*	*1.00490*	*1.00520*
Log Likelihood	2243.5	2243.5	2243.3	2239.5
$L.L._{SEM} \div L.L._{OLS}$	*1.00470*	*1.00480*	*1.00480*	*1.00510*
SSE	1652.3	1652.3	1652.3	1652.7
$SSE_{SEM} \div SSE_{OLS}$	*0.99903*	*0.99903*	*0.99897*	*0.99897*
Residual Std. Error	0.22576	0.22576	0.22576	0.22578
Res. Std. $Error_{SEM} \div$ Res. Std. $Error_{OLS}$	*0.99577*	*0.99572*	*0.99572*	*0.99568*
Mean Adj. VIF for Hazard Variables	1.66	1.69	2.51	1.86
Max Adj. VIF for Hazard Variables	2.06	2.00	2.79	2.16
Spatial Breusch-Pagan	1212.6	1211.1	1210.0	1209.1
Wald Test	8.88***	13.00***	7.98***	73.72***
Likelihood Ratio Test	20.87***	21.43***	21.44***	22.63***
Observations	32,420	32,420	32,420	32,420

*Notes: ***Significance at 1 % level; **Significance at 5 % level; *Significance at 10 % level.*
Robust Standard Errors

Conservation areas are shown to positively mitigate the dis-amenity value of both flooding and seismic risk. These areas are maintained by the municipality in order to preserve their charm and character, and thus are likely to be more prepared for the eventual floods which occur each year and with priority clean ups occurring after significant events. Even with these significant hazard risks, the net effect of being located in a simultaneous flood hazard and conservation area is 0.2%, or approximately €500 (*Model 26*). This effect is more pronounced for seismic risk zones with a net effect of approximately 2.1% (*Model 29*).

While flooding risk is highest near the riverfront, it is important to disentangle the impact due to the dis-amenity value of the urban hazard risk and the amenity value of the riverfront, which is sought after by residents. If the benefits of being located nearer to the riverfront, for recreational or aesthetic purposes, outweigh the costs of being in a risk zone, then we would expect this trade-off to be capture in dwelling prices.

We find a very localized effect coming from dwellings directly at the riverfront and located within 100 meters of the Tagus. The positive impact of being on the riverfront outweighs the negative cost associated to being in a very high risk hazard zone with a net benefit of approximately 5.4% (*Model 27*). Residents therefore capitalize on direct proximity to the riverfront even if these areas have inherently large risk, a result consistent with the previous literature. These results however appear to be fairly localized with net negative impacts still occurring if a dwelling is only located within 500 meters of the riverfront (*Model 28*). This suggests that the amenity value of the riverfront is strongest for those directly in the line of sight, and residents are willing to trade-off the risk of flooding to be in this zone.

5.2. Geographic Regression Discontinuity Robustness

From our baseline results, we check the robustness of our estimates by considering spatial subsets around each type of hazard zone boundary. The results for the GRD estimates are presented in table A4 of the Appendix and show that the estimated price impacts of being located within a designated flood risk or seismic risk zone is consistent and robust to a variety of spatial subsets.

We consider the effects from very high hazard risks (*Models 1, 3 and 5* in table 2), and consider a subset of properties 500 meters outside of the respective hazards geographic boundary as our control group. Nearby properties should have similar local amenities and underlying influences, and by removing properties located at some farther distance of the geographic boundary we remove potential locational influences which may be driving the results. We further directly consider the clustering of hazard zones near the river, by showing that the estimated effects are robust to considering a subset of dwellings 3 kilometers from the riverfront. This, along with explicitly including covariates measuring proximity to the river and its interaction with our elevation measure ensures that the price impacts of flood risk are not driven by significant locational characteristics which may be attributed to proximity to the Tagus.

The choice of distance outside a boundary to consider in a GRD however may be subjective, and so we further draw control properties using a propensity score matching process to match properties located in hazard zones to those located outside of these areas conditional on important locational influences. We match flood prone properties to non-flood prone properties based on their distance to the nearest urban green infrastructure in the form of urban forests, on neighborhood population density, and on the amount of impervious road surface within 100 meters of an observation. Seismic risk properties on the other hand are matched conditional on the average slope within 100 meter of a dwelling. By comparing similar properties in these respects, we are removing potential mechanisms which may be related to and influence the estimated price impact of being in such hazard zones.

6 Insurance Considerations

We compare the predicted house price differentials in each of the housing price quantiles to the present value of the annual MR insurance premium estimates for homes located within designated high and very high (flood or seismic) zones. Any difference in these two measures could be a premium resulting from the perception that insurance does not fully compensate the loss.

Our results are presented in table 6 with full characteristics of our hypothetical house for each housing price quantile in table A5 of the Appendix. All the values are expressed in 2018 monetary values and the reported annual MR insurance premium for each type of house is based on the market insurance rates (through the DECO online simulator) in October 2018. The online MR insurance premium estimate represents a base cost quote for a primary residence located in Lisbon, with the simulated premium cost for each representative home price quantile depending on the value of the insured structure and contents, year of construction and area of the dwelling. All the online MR premium estimates include flood coverage for a dwelling located at least 150 meters from water.[18]

Table 6. Insurance Premiums and Hazard Dis-Amenity Values by Quartile

	Price € (2018)	Multi-Risk Insurance Premium €			P.V. of Annual Insurance €			Hazard Impact €
		Flooding	Additional Seismic	Total	3% Discount	5% Discount	7% Discount	
High (and Very High) Seismic Risk Zones (N = 14,733)								
0-10th	137,759.36	66.35	39.82	106.17	3,539.14	2,123.48	1,516.77	-1,540.15
10th-20th	183,826.38	76.09	50.39	126.48	4,215.99	2,529.59	1,806.85	-2,055.18
20th-30th	208,310.03	81.43	56.08	137.51	4,583.63	2,750.18	1,964.41	-2,328.91
30th-40th	234,202.16	108.09	60.14	168.23	5,607.75	3,364.65	2,403.32	-2,618.38
40th-50th	262,935.02	115.22	67.46	182.68	6,089.24	3,653.54	2,609.67	-2,939.61
50th-60th	299,029.56	124.57	77.21	201.78	6,726.00	4,035.60	2,882.57	-3,343.15
60th-70th	340,068.88	130.8	83.71	214.51	7,150.40	4,290.24	3,064.46	-3,801.97
70th-80th	403,871.54	140.94	94.28	235.22	7,840.59	4,704.35	3,360.25	-4,515.28
80th-90th	490,856.15	196.43	107.28	303.71	10,123.71	6,074.23	4,338.73	-5,487.77
90th-100th	765,323.43	229.42	143.04	372.46	12,415.39	7,449.24	5,320.88	-8,556.32
High (and Very High) Flooding Risk Zones (N = 4,547)								
0-10th	139,727.95	66.35	-	66.35	2,211.67	1,327.00	947.86	-2,252.41
10th-20th	191,985.87	76.92	-	76.92	2,564.00	1,538.40	1,098.86	-3,094.81
20th-30th	224,677.70	83.96	-	83.96	2,798.67	1,679.20	1,199.43	-3,621.80
30th-40th	254,135.36	115.22	-	115.22	3,840.67	2,304.40	1,646.00	-4,096.66
40th-50th	288,373.69	123.01	-	123.01	4,100.33	2,460.20	1,757.29	-4,648.58
50th-60th	329,164.10	129.24	-	129.24	4,308.00	2,584.80	1,846.29	-5,306.13
60th-70th	376,822.72	140.94	-	140.94	4,698.00	2,818.80	2,013.43	-6,074.38
70th-80th	438,496.39	187.74	-	187.74	6,258.00	3,754.80	2,682.00	-7,068.56
80th-90th	538,970.88	200.53	-	200.53	6,684.33	4,010.60	2,864.71	-8,688.21
90th-100th	883,530.68	240.03	-	240.03	8,001.00	4,800.60	3,429.00	-14,242.51

Notes: Premium Values and Results Obtained via the DECO Simulator (2018)

However, because the estimated and paid premiums may differ depending on the exact location of the dwelling and other factors, especially when flood coverage is added, we create scenarios where the estimated premium changes and may increase either a significant amount as much as 100% or a gradual increase depending on the type of property (low, medium or high-priced home). The calculations under these adjusted premium scenarios are presented in table A6 of the Appendix.

The forth column of table 6 reports the supplementary premiums to be added to the base MR annual cost if seismic coverage is purchased and added to the policy. This value is calculated based on the 2018 commercial seismic insurance rates for structures in zone B applied by all participating home insurers in the market adjusted by an administrative cost factor.[19] The fifth column of table 6 then

[18] It should be noted that the online premiums estimates are simulated premium costs for a representative property in each of the price quantiles. There can be a difference between these online estimated and the paid premium values depending on the dwelling exact location in the area (e.g. zip code), its structural features (e.g. floor, roof, construction materials) and other mitigation features set in place to protect the dwelling.

[19] The 2018 tabulated commercial rates and corresponding administrative cost factor were provided by Ricardo Beja, an ASF registered Insurance Mediator, in October 2018.

reports the total annual premium as the sum of the base premium (which includes flood coverage) and the supplemental seismic premium.

The discounted value of the MR insurance payments is calculated assuming alternative discount rates, in perpetuity, ranging between 3%, 5% and 7%. The last column on table 6 reports the monetary value that the estimated impact of being located inside of a very high risk hazard has on dwellings in that price quantile.

MR Insurance Premiums for High (and very High) Seismic Risk Zones

For houses located in designated high and very high seismic risk zones we calculated a total MR premium that includes seismic coverage as this is the most relevant likely natural hazard in these locations. In general we find that our two measures tend to align when a 7% discount rate is applied.

Preliminary calculations of the present value of the additional seismic coverage with a 3% discount rate reveal that this value is quite comparable to the negative price differential in dwellings located in a hazard zones only for those with prices up to the 60th percentile. However, because seismic insurance cannot be purchased separately but only as a supplement to the MR policy, we proceeded with our analysis by comparing the price differentials and the present value of the total annual MR premiums when this supplement is included to the base premium. Because the total annual MR premium includes coverage for several home hazards other than just floods and earthquakes, it is not surprising that the discount rate that now makes the two measures comparable is higher. The 7% discount rate reflects the extra risks covered in the MR premium.

Using a 5% discount rate or lower, we find that the negative impact from hazards zones are in general a lot lower than the present value of the total MR insurance premiums except for the very high-valued homes (on the 90th percentile). At 7% discount rate, we find that for all house price quantiles the price differentials are larger than the present value MR total insurance premiums. However, while the magnitudes of the two measures are quite comparable at 7% for house prices up to the 90th percentile, the opposite occurs for the extremely high-priced homes (so above the 90th percentile). This may thus suggest that nonmonetary losses that cannot be covered by the MR insurance seem to be relevant for extremely higher valued homes. Another possible explanation is the limited coverage and deductibles that MR insurances with seismic supplements have.

MR Insurance Premiums for High (and very High) Flooding Risk Zones

On the other hand, for houses located in designated high and very high flooding risk zones we use MR premium estimates without supplemental seismic coverage as now flooding is the most likely environmental hazard in these areas. In this context the total annual premium and the annual base premium coincide.

It is interesting to note that using a 3% discount rate, we find that for high and very high-priced houses the price differentials due to the hazard effect are considerably larger than the present value of

MR insurance premiums whereas they are more comparable for moderate and lower-priced homes. This result may be related to floods being yearly natural events in these areas of the city and therefore individuals and insurers have less uncertainty regarding the occurrence and potential losses from these natural events from their own personal experiences. Moreover, because flood losses can be very severe and costly, it can be difficult for the private sector to insure floods, particularly in very risky zones. When private coverage is available it can be expensive yet still limited in coverage. Our findings for the high and very high-priced homes in risky flood zones may further indicate that for individuals who own more expensive houses, the payment from the insurance company would not fully compensate for the expected loss which may include the inconvenience of being displaced while repairs are being made or the loss of personal content with sentimental value. Thus, if these individuals cannot obtain adequate insurance, they will rationally reduce their offering price to account for this uninsurable component of flood risk.

Insurance premiums in very risky flood zones can nevertheless be increased up to 100% (when compared to low and moderate risk flood areas) and can also vary within the same risk zone depending on the insured structure and contents and exact location. Moreover, not all homes within flood zones require the same level of catastrophe insurance. Therefore, we have also explored the scenarios where the base premium bluntly increases 100% in these risky areas or gradually increases based on the type of insured house, with pricier houses subject to higher premium increases than moderate or lower-priced houses. The results in table A6 in the Appendix reveal that a progressive risk-based approach with a 3% discount rate provides quite comparable price differentials between inside and outside risky flood zones with the present value of MR premiums for all price quantiles. However, if a blunt 100% premium increase is set, then the two measures are just comparable at 5% discount rate for all price quantiles except the 90^{th}-100^{th} quantile.

Even though the valuation effect of flood hazards from 2007 to 2018 on residential housing asking prices may be also attributable to an increase in nominal house prices, the large gap observed for the two measures for the high priced properties in high and very high risky areas suggests that the Lisbon housing market is still not aligned with insurance costs. Yet, we should note that the current study focused exclusively on housing prices and on a valuation snapshot of different sources of environmental hazards and not appreciation rates. It is possible that the pattern of house price appreciation could vary systematically along environmental dimensions. For example, as market participants become more aware of the valuation implications of the environmental amenities, appreciation or depreciation patterns across say flood zone categories may differ. While this issue is beyond the scope of the current study, it is indicative of other potential future research avenues.

Finally, our analysis also provides some insight into the ongoing debate about home insurance affordability by examining MR premiums that include coverage for several natural hazard risks. Though our back-of-the-envelope calculations show that the housing price discounts related to natural hazards (which represent the personal expectation of the losses from these hazard occurrences) are in general higher than the present value cost of insurance that includes coverage for individual or multiple natural hazards, current statistics show that only a small percentage of homeowners in Lisbon have seismic insurance or choose to include flood coverage in their MR policies. High cost and limited coverage may be two possible deterrents to purchasing MR policies that include coverage for these natural hazards. Moreover, and in contrast to floods, given the low frequency of earthquakes individuals may take seismic coverage for granted until they experience a significant earthquake. In such a context, mandatory seismic insurance requirements in very high seismic areas may be one possible way to increase participation rates.

7 Conclusions

This work investigates the capitalization of urban natural hazards on residential property values in Lisbon, Portugal, with specific emphasis on spillover effects and the heterogeneity within and between areas of urban hazards. Results indicate that housing prices are negatively impacted by being located in areas of very high flooding risk or very high seismic risk, however these results may be mitigated or exacerbated conditional on a dwellings local environment.

While locational in a flood zone detracts from housing prices, this effect is found to be mitigated by proximity to urban green spaces and greenery and exacerbated by nearby lakes and impervious surfaces. Seismic risk on the other hand is significantly mitigated by characteristics of the neighborhood in terms of more owner-occupiers and educated individuals, and more low-lying buildings. In addition to the physical environment and neighborhood, both types of risks are enhanced when considered in regards to crime levels, with higher crimes having increased negative impacts in hazard risk zones.

Further, although being located in an urban hazard zone has negative impacts we find that not only are there negative spillover effects to nearby non-risk areas, but residents may trade off the dis-amenity value from flood zones for the benefit of being located in desirable areas of the city, namely at the riverfront or in historically protected zones.

Although the location of hazard risk zones in the city are not driven by housing prices, there may be some underlying influencing impacting the estimates. In implementing a GRD design, we ensure that the estimated impacts of hazard zones are not being driven by significant locational differences. Sub-setting the data around hazard borders removes locational or neighborhood differences that could potentially be a driving mechanism from which the estimates are obtained. The GRD design shows that our results are robust and not driven by this heterogeneity.

These results have important policy implications for municipalities. Not only does it provide a value for how the risk of these events impact residential real estate markets, and subsequently property tax collection, but further provides an indication as to what amenities and neighborhood characteristics either attenuate or compound the negative effects of natural hazard risks. As the risk of these hazard events capture their persistence and local residents' exposure, better understanding the true value of their impacts is important.

By showing that the impact of flooding zones is conditional on urban green infrastructure, our results provide an indication that the variability in flood risk zone is conditional on local green amenities. Such amenities could thus be implemented in high risk flooding zones to attenuate the negative effects experienced by residents. Similarly, considering the types of buildings in high risk seismic areas should be a priority for developers and the municipalities' point of view, with low-lying structures not only safer in the event of seismic activity, but also valued by local residents.

Our estimates suggest that the per dwelling average price impact of being located in a flood risk zone or a seismic risk zone is €8,500 and €2,700 respectively. This effect however, especially for flood risk areas, is not the same across the distribution with higher priced dwellings having a stronger impact. These properties appear to react to the threat of flood risk more than seismic risk, and higher valued properties may be relatively more damaged with greater price influences in the case of floods. Aggregated across all residents exposed to such risk suggests that the overall impact of these natural hazard risks are quite large. By understand the impacts that these hazards can have on the real estate market, the municipality and planners are better able to prepare and plan for the occurrences of these hazards and better respond to the needs of residents.

References

Anselin, Luc, and Daniel Arribas-Bel. 2013. "Spatial fixed effects and spatial dependence in a single cross-section." *Papers in Regional Science* 92, no. 1: 3-17.

Atreya, Ajita, and Jeffrey Czajkowski. 2016. "Graduated Flood Risks and Property Prices in Gaveston County." *Real Estate Economics:* 1-38.

Augusto Mateus & Associados. *A Actualidade do Sector Imobiliário Residencial: Ajustamentos e desfios*. November 2011.

Bakkensen, Laura A., and Lint Barrage. 2018. "Flood Risk Belief Heterogeneity and Coastal Home Price Dynamics: Going Under Water?" *NBER Working Paper 23854.*

Bin, Okmyung, and Craig E. Landry. 2013. "Changes in implicit flood risk premiums: Empirical evidence from the housing market." *Journal of Environmental Economics and Management* 65: 361-376.

Bin, Okmyung, and Craig E. Landry. 2008. "Flood Hazards, Insurance Rates, and Amenities: Evidence from the Coastal Housing Market." *The Journal of Risk and Insurance* 75, no. 1: 63-82.

Burby, Raymond J. 1998. *Cooperating with Nature: Confronting Natural Hazards with Land-Use Planning for Sustainable Communities.* Joseph Henry Press.

Frailing, Kelly, Dee Wood Harper Jr., and Ronal Serpas. 2015. "Changes and Challenges in Crime and Criminal Justice After Disaster." *American Behavioral Scientist* 59, no. 10: 1278-1291.

Franco, Sofia F., and Jacob L. Macdonald. 2017. "Measurement and valuation of urban greenness: Remote sensing and hedonic applications to Lisbon, Portugal." *Regional Science and Urban Economics* In Press.

Franco, Sofia F., and Jacob L. Macdonald. 2018. “The effects of cultural heritage on residential property values: Evidence from Lisbon, Portugal.” *Regional Science and Urban Economics* 70: 35-56.

Gencer, EA. 2013. *Natural disasters, urban vulnerability, and risk management: a theoretical overview*. In: *The interplay between urban development, vulnerability, and risk management a case study of the istanbul metropolitan area*, Mediterranean Studies 7. Berlin: 7-43.

Hidano, Noboru, Tadao Hoshino, and Ayako Sugiura. 2015 “The effect of seismic hazard risk information on property prices: Evidence from a spatial regression discontinuity design.” *Regional Science and Urban Economics* 55: 113-122.

Instituto Superior Tecnico. 2005. “Estudo Sectorial sobre Risco Sísmico.” *Instituto de Engenharia de Estruturas, Território e Construção.*

João, Paulo. 2009. “Model preditivo da criminalidade – georreferenciação ao concelho de Lisboa.” Instituto Superior de Estatistica e Gestão de Informação – Master’s Thesis.

Koster, Hans R. A., and Jos van Ommeren. 2015. “A shaky business: Natural gas extraction, earthquakes and house prices.” *European Economic Review* 80: 120-139.

Lall, Somik V., and Uwe Deichmann. “Density and Disasters: Economics of Urban Hazard Risk.” *World Bank Observer* 27 (July 2010): 74-105.

Lindell, Michael K. 1997. “Adoption and Implementation of Hazard Adjustments.” *International Journal of Mass Emergencies and Disasters* 15, no. 3: 327-414.

Metz, Neil E., Travis Roach, and Jordan A. Williams. 2017. “The costs of induced seismicity: A hedonic analysis.” *Economic Letters* 160: 86-90.

Naoi, Michio, Miki Seko, and Kazuto Sumita. 2009. “Earthquake risk and housing prices in Japan: Evidence from before and after massive earthquakes.” *Regional Science and Urban Economics* 39: 658-669.

Naoi, Michio, Kazuto Sumita, and Miki Seko. 2010. “Estimating Consumer Valuation of Earthquake Risk: Evidence from Japanese Housing Markets.” *International Real Estate Review* 13, no. 2: 117-133.

Pereira, Alvaro S. 2009. “The Opportunity of a Disaster: The Economic Impact of the 1755 Lisbon Earthquake.” Centre for Historical Economics and Related Research at York Discussion Paper.

Rajapaksa, Darshana, Clevo Wilson, Shunsuke Managi, Vincent Hoang, and Boon Lee. 2016. “Flood Risk Information, Actual Floods and Property Values: A Quasi-Experimental Analysis.” *Economic Record* 92, no. S1: 52-67.

Rajapaksa, Darshana, Clevo Wilson, Viet-Ngu Hoang, Boon Lee, and Shunsuke Managi. 2017a. “Who responds more to environmental amenities and dis-amenities?” *Land Use Policy* 62: 151-158.

Rajapaksa, Darshana, Min Zhu, Boon Lee, Viet-Ngu Hoang Clevo Wilson, and Shunsuke Managi. 2017b. “The impact of flood dynamics on property values” *Land Use Policy* 69: 317-325.

Rosen, Sherwin. 1974. “Hedonic Prices and Implicit Markets: Product Differentiation in Pure Competition.” *Journal of Political Economy* 82, no. 1: 34-55.

Samarasinghe, Oshadhi, and Basil Sharp. 2010. "Flood prone risk and amenity values: a spatial hedonic analysis." *The Australian Journal of Agricultural and Resource Economics* 54: 457-475.

Tang, Y, Y. Yin, K. Hill, V. Katiyar, A. Nasseri, and T. Lai. 2012. "Seismic Risk Assessment of Lisbon Metropolitan Area under a Recurrence of the 1755 Earthquake with Tsunami Inundation." 15th World Conference on Earthquake Engineering.

United Nations. *Living with Risk: A Global Review of Disaster Reduction Initiatives*. 2 vols. 2004, Geneva.

Zhang, Lei. 2016. "Flood hazards impact on neighborhood house prices: A spatial quantile regression analysis." *Regional Science and Urban Economics* 60: 12-19.

Appendix

Table A1. Descriptive Statistics

	N	*Mean*	*St. Dev.*	*Min*	*Max*
Price	32,420	243,500	148,503	25,000	2,500,000
Structural Characteristics					
Sq. Meters	32,420	98.900	45.970	15	420
New Construction	32,420	0.200	0.400	0	1
View of Tagus River	32,420	0.060	0.230	0	1
Swimming Pool	32,420	0.010	0.100	0	1
Parking Spaces	32,420	0.120	0.330	0	1
Fireplace	32,420	0.040	0.190	0	1
Double Windows	32,420	0.210	0.410	0	1
Air Conditioning	32,420	0.130	0.340	0	1
Elevator	32,420	0.230	0.420	0	1
Locational Characteristics					
Located within 3 km of the Riverfront	32,420	0.480	0.500	0	1
Located 100 m from Tagus Riverfront	32,420	0.007	0.084	0	1
Located 500 m from Tagus Riverfront	32,420	0.116	0.320	0	1
Located 500 m outside of an Area of Very High Seismic Risk	32,420	0.633	0.482	0	1
Located 500 m outside of an Area of Very High Flooding Risk	32,420	0.408	0.491	0	1
Located in Conservation Area	32,420	0.182	0.386	0	1
Neighborhood Characteristics					
% Neighborhood Property Owners	32,420	0.506	0.163	0.117	0.849
% Neighborhood Educated	32,420	0.300	0.107	0.012	0.571
% Buildings with 1 or 2 Stories	32,420	0.283	0.175	0.006	0.884
Length of Roads in 100 m	32,420	648.000	325.24	0	2071
Average Slope within 100 m	32,420	8.176	4.240	1.500	26.224
Neighborhood Crimes per Person	32,420	0.030	0.031	0.005	0.421
Neighborhood Thefts per Person	32,420	0.023	0.026	0.005	0.376
Open Spaces and Ecological Urban Hazards					
Elevation	32,420	66.900	29.710	0	145
Distance to Tagus Riverfront	32,420	2.590	1.975	0.009	7.43
No. of Urban Forests in 500 m	32,420	0.367	0.609	0	3
Average Distance (km) to Parks	32,420	4.713	0.883	3.504	7.429
Nº. of Lakes in 100 m	32,420	0.133	0.524	0	10
Average NDVI in 100 m	32,420	0.061	0.056	-0.064	0.284
Located in an Area of High or Very High Seismic Risk	32,420	0.454	0.498	0	1
Located in an Area of High or Very High Flooding Risk	32,420	0.140	0.347	0	1
Located in an Area of Very High Seismic Risk	32,420	0.196	0.397	0	1
Located in an Area of Very High Flooding Risk	32,420	0.062	0.242	0	1

Figure A1. Spatial Fixed Effects in Lisbon, Portugal

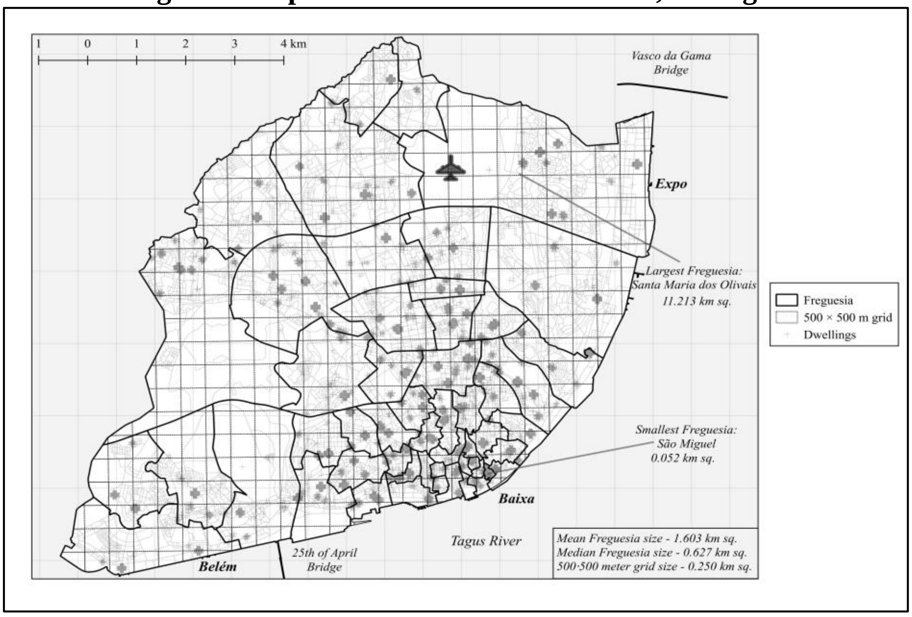


Table A2. Spatial Weight Properties

	Description	Nº. Locations	Nº. Non-zero Links	Percent Non-zero Links	Average Nº. of Links	Locations Without Links
SW1	All properties in 500 meters	32,420	32,175,894	3.06	992.47	5
SW2	Inverse distance of all properties in 500 meters	32,420	32,175,894	3.06	992.47	5
SW3	Inverse sq. distance of all properties in 500 meters	32,420	32,175,894	3.06	992.47	5
SW4	All properties in 100 meters	32,420	22,211,752	2.11	685.13	115
SW5	100 nearest neighbors	32,420	3,242,000	0.31	100.00	0
SW6	10 nearest neighbors	32,420	324,200	0.03	10.00	0

Figure A2. Geographic Regression Discontinuity: Flood Risk Zones

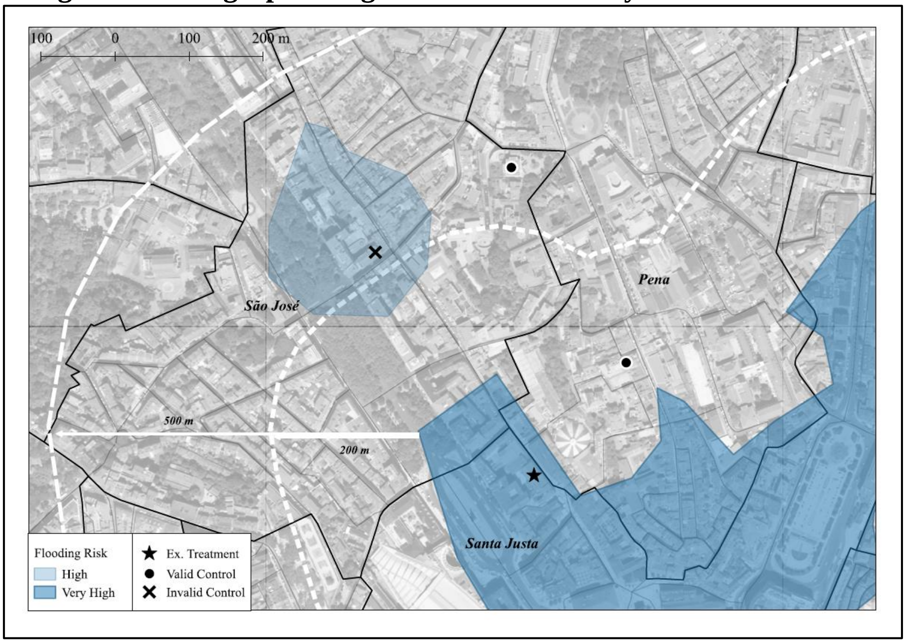
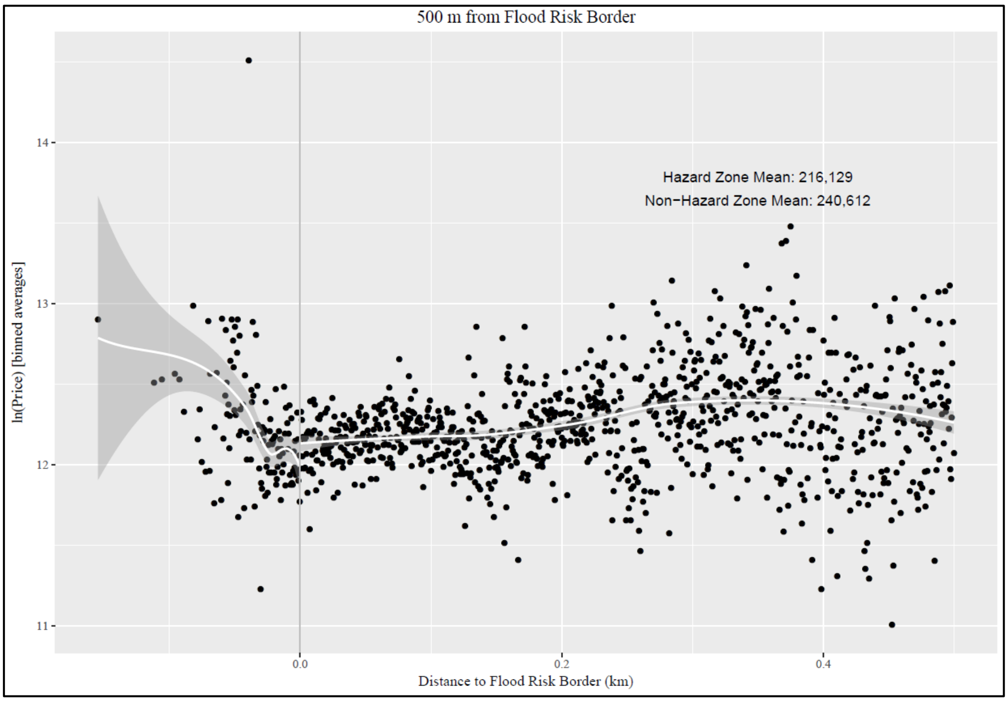


Figure A3. Price Discontinuity at Urban Hazard Boundaries

Panel A: Flood Risk Zones



Panel B: Seismic Risk Zones

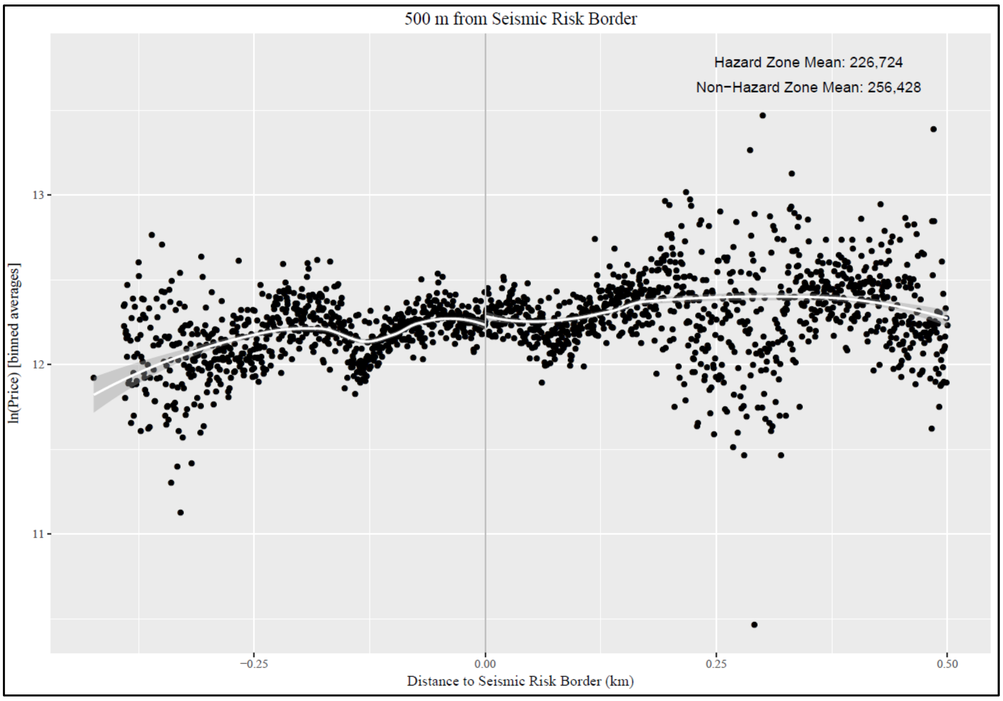


Table A3. Spatial Diagnostics

	Global Moran's I (Dep.)	Z-Value (Dep.)	Global Moran's I (Res.)	Z-Value (Res.)	LM SEM	LM SAR	Rob. LM SEM	Rob. LM SAR
Model 1: Very High Flood Risk								
SW1	0.1192***	164.90	0.0030***	5.34	15.99	1.20	14.99***	0.20
SW2	0.1292***	49.50	0.0048**	2.18	3.38*	0.83	2.57	0.02
SW3	0.0971***	244.10	0.0015***	6.04	13.41***	0.14	13.27***	0.00
SW4	0.1292***	145.10	0.0042***	6.02	22.72***	0.21	22.56***	0.05
SW5	0.1213***	162.10	0.0013***	2.85	2.85*	2.42	1.67	1.23
SW6	0.1300***	54.80	0.0033**	1.78	1.99	0.33	3.988**	2.33
Model 3: Very High Seismic Risk								
SW1	0.1192***	164.90	0.0030***	5.51	17.32	1.27	16.26	0.21
SW2	0.1292***	49.50	0.0050**	2.25	3.645*	1.00	2.684	0.04
SW3	0.0971***	244.10	0.0015***	6.25	14.78***	0.12	14.66***	0.00
SW4	0.1292***	145.10	0.0044***	6.20	24.43***	0.23	24.25***	0.06
SW5	0.1213***	162.10	0.0014***	3.02	3.451*	2.64	2.092	1.28
SW6	0.1300***	54.80	0.0035**	1.84	2.169	0.21	3.997**	2.04
Model 5: Very High Joint Hazards								
SW1	0.1192***	164.90	0.0029***	5.36	16.17	1.22	15.16	0.21
SW2	0.1292***	49.50	0.004837**	2.20	3.435*	0.91	2.56	0.03
SW3	0.0971***	244.10	0.001506***	6.16	14.16***	0.13	14.03***	0.00
SW4	0.1292***	145.10	0.004242***	6.02	22.78***	0.24	22.6***	0.07
SW5	0.1213***	162.10	0.001307***	2.90	3.039*	2.54	1.79	1.29
SW6	0.1300***	54.80	0.003315**	1.77	1.948	0.27	3.796*	2.12

Table A4. Full Estimates and GRD Robustness

	Model 1			*Model 3*			*Model 5*		
	Full Sample	*500m from VH Flood Zone*	*3km from Tagus Riverfront*	*Full Sample*	*500m from VH Seismic Zone*	*3km from Tagus Riverfront*	*Full Sample*	*500m from VH Flood Zone*	*500m from VH Seismic Zone*
Elevation	0.00130***	0.00168***	0.00111***	0.00149***	0.00042	0.00126***	0.00143***	0.00181***	0.00037
	(0.00028)	*(0.00040)*	*(0.00037)*	*(0.00027)*	*(0.00061)*	*(0.00036)*	*(0.00027)*	*(0.00040)*	*(0.00061)*
ln(Distance to Tagus River)	-0.03037*	-0.02449	-0.03913*	-0.02499	-0.04817*	-0.04155*	-0.03000*	-0.02407	-0.05193**
	(0.01769)	*(0.02191)*	*(0.02190)*	*(0.01767)*	*(0.02542)*	*(0.02251)*	*(0.01771)*	*(0.02191)*	*(0.02570)*
Elevation × ln(Distance to Tagus River)	-0.00054**	-0.00046	-0.00061	-0.00064**	0.00019	-0.00073	-0.00056**	-0.00043	0.00022
	(0.00026)	*(0.00038)*	*(0.00049)*	*(0.00025)*	*(0.00050)*	*(0.00049)*	*(0.00026)*	*(0.00038)*	*(0.00050)*
	Flood Risk			***Seismic Risk***			***Joint Hazards***		
	Very High			***Very High***			***Very High***		
Urban Geohazard Risk	-0.03513***	-0.02567**	-0.02900**	-0.01114*	-0.01323*	-0.01830**	-0.03786***	-0.02825*	-0.02897*
	(0.01128)	*(0.01270)*	*(0.01290)*	*(0.00647)*	*(0.00758)*	*(0.00912)*	*(0.01419)*	*(0.01534)*	*(0.01580)*
Lambda	0.15503***	0.30865***	0.31957***	0.16021***	0.23800***	0.32509***	0.15532***	0.31096***	0.23108***
	(0.03744)	*(0.04320)*	*(0.03810)*	*(0.01360)*	*(0.02723)*	*(0.03068)*	*(0.03940)*	*(0.04364)*	*(0.04463)*
Year F.E.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
500 m F.E.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Structural Characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Green Amenities	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	32,420	14,717	21,955	32,420	18,980	21,955	32,420	14,717	18,980

Table A5a. Seismic Risk Insurance Premiums

	Price (2018)	Area (m^2)	Dist. to Tagus (km)	Construction Year	Content Insurance	Reconstruction Value	Multi-Risk Insurance Premium			P.V. of Annual Seismic Insurance			5% Co-Payment	Hazard Impact
							Flooding	Additional Seismic	Total	3% Discount	5% Discount	7% Discount		
Very High Risk Seismic Zones (N = 6,341)														
0-10th	154,013.28	54.59	2.06	1948.9	15,000 €	43,992.30	70.58	44.70	115.28	3,842.69	2,305.61	1,646.87	2,199.62	-1,715.71
10th-20th	209,032.29	70.69	3.07	1968.5	15,000	56,790.06	75.24	37.83	113.07	3,768.95	2,261.37	1,615.26	2,839.50	-2,328.62
20th-30th	242,800.18	78.19	3.19	1969.2	15,000	62,389.08	88.21	41.56	129.77	4,325.60	2,595.36	1,853.83	3,119.45	-2,704.79
30th-40th	273,545.65	87.05	3.49	1973.5	30,000	69,587.82	119.15	46.35	165.50	5,516.77	3,310.06	2,364.33	3,479.39	-3,047.30
40th-50th	306,832.95	95.49	3.52	1980.9	30,000	75,986.70	124.99	50.62	175.61	5,853.52	3,512.11	2,508.65	3,799.34	-3,418.12
50th-60th	352,626.67	107.20	3.70	1980.0	30,000	85,585.02	134.09	57.01	191.10	6,369.97	3,821.98	2,729.99	4,279.25	-3,928.26
60th-70th	403,382.72	116.14	3.31	1985.8	30,000	92,783.76	141.54	47.14	188.68	6,289.29	3,773.58	2,695.41	4,639.19	-4,493.68
70th-80th	464,240.54	128.48	2.80	1988.2	50,000	102,382.08	199.92	52.02	251.94	8,397.84	5,038.70	3,599.07	5,119.10	-5,171.64
80th-90th	551,543.70	141.91	2.62	1991.8	50,000	113,580.12	210.92	57.70	268.62	8,954.15	5,372.49	3,837.49	5,679.01	-6,144.20
90th-100th	856,254.62	188.51	2.75	1997.6	50,000	151,173.54	247.84	76.80	324.64	10,821.46	6,492.87	4,637.77	7,558.68	-9,538.68
High (and Very High) Seismic Risk Zones (N = 14,733)														
0-10th	137,759.36	49.04	1.36	1944.0	15,000 €	39,193.14	66.35	39.82	106.17	3,539.14	2,123.48	1,516.77	1,959.66	-1,540.15 €
10th-20th	183,826.38	61.62	1.79	1955.3	15,000	49,591.32	76.09	50.39	126.48	4,215.99	2,529.59	1,806.85	2,479.57	-2,055.18
20th-30th	208,310.03	68.87	2.00	1962.9	15,000	55,190.34	81.43	56.08	137.51	4,583.63	2,750.18	1,964.41	2,759.52	-2,328.91
30th-40th	234,202.16	73.95	2.21	1960.7	30,000	59,189.64	108.09	60.14	168.23	5,607.75	3,364.65	2,403.32	2,959.48	-2,618.38
40th-50th	262,935.02	83.04	2.44	1967.6	30,000	66,388.38	115.22	67.46	182.68	6,089.24	3,653.54	2,609.67	3,319.42	-2,939.61
50th-60th	299,029.56	95.24	2.68	1973.5	30,000	75,986.70	124.57	77.21	201.78	6,726.00	4,035.60	2,882.57	3,799.34	-3,343.15
60th-70th	340,068.88	102.63	2.81	1975.2	30,000	82,385.58	130.8	83.71	214.51	7,150.40	4,290.24	3,064.46	4,119.28	-3,801.97
70th-80th	403,871.54	116.20	2.77	1983.6	30,000	92,783.76	140.94	94.28	235.22	7,840.59	4,704.35	3,360.25	4,639.19	-4,515.28
80th-90th	490,856.15	132.12	2.42	1986.4	50,000	105,581.52	196.43	107.28	303.71	10,123.71	6,074.23	4,338.73	5,279.08	-5,487.77
90th-100th	765,323.43	176.38	2.37	1992.7	50,000	140,775.36	229.42	143.04	372.46	12,415.39	7,449.24	5,320.88	7,038.77	-8,556.32

Table A5b. **Flood Risk Insurance Premiums**

	Price (2018)	Area (m²)	Dist. to Tagus (km)	Construction Year	Content Insurance	Reconstruction Value	MR Insurance Premium (Flooding)	P.V. of Annual MR Insurance			Hazard Impact
								3% Discount	5% Discount	7% Discount	
High (and Very High) Flooding Risk Zones (N = 4,547)											
0-10th	139,727.95 €	48.70	1.21	1943.3	15,000 €	38,955.82 €	66.35	2,211.67	1,327.00	947.86	-2,252.41
10th-20th	191,985.87	64.48	2.71	1965.4	15,000	51,572.43	76.92	2,564.00	1,538.40	1,098.86	-3,094.81
20th-30th	224,677.70	73.73	2.97	1964.5	15,000	58,973.27	83.96	2,798.67	1,679.20	1,199.43	-3,621.80
30th-40th	254,135.36	82.96	3.22	1969.0	30,000	66,354.56	115.22	3,840.67	2,304.40	1,646.00	-4,096.66
40th-50th	288,373.69	93.41	3.45	1976.3	30,000	74,713.21	123.01	4,100.33	2,460.20	1,757.29	-4,648.58
50th-60th	329,164.10	101.49	3.90	1984.4	30,000	81,175.44	129.24	4,308.00	2,584.80	1,846.29	-5,306.13
60th-70th	376,822.72	115.79	3.48	1977.7	30,000	92,612.11	140.94	4,698.00	2,818.80	2,013.43	-6,074.38
70th-80th	438,496.39	121.44	3.28	1990.9	50,000	97,137.37	187.74	6,258.00	3,754.80	2,682.00	-7,068.56
80th-90th	538,970.88	136.83	3.02	1985.1	50,000	109,442.85	200.53	6,684.33	4,010.60	2,864.71	-8,688.21
90th-100th	883,530.68	190.08	3.06	1992.8	50,000	152,034.24	240.03	8,001.00	4,800.60	3,429.00	-14,242.51

Table A6. **Flood Risk Insurance Premium Scenarios**

	Price (2018)	**MR Flooding**	**Hazard Impact**	**3% Discount Rate**			**5% Discount Rate**		
				Baseline	**100% Increase**	**Gradual Increase**	**Baseline**	**100% Increase**	**Gradual Increase**
High (and Very High) Flooding Risk Zones (N = 4,547)									
0-10th	139,727.95	66.35	-1,540.15	3,539.14	4,423.33	2,211.67	2,123.48	2,654.00	1,327.00
10th-20th	191,985.87	76.09	-2,055.18	4,215.99	5,128.00	3,076.80	2,529.59	3,076.80	1,846.08
20th-30th	224,677.70	81.43	-2,328.91	4,583.63	5,597.33	3,498.33	2,750.18	3,358.40	2,099.00
30th-40th	254,135.36	108.09	-2,618.38	5,607.75	7,681.33	4,800.83	3,364.65	4,608.80	2,880.50
40th-50th	288,373.69	115.22	-2,939.61	6,089.24	8,200.67	5,125.42	3,653.54	4,920.40	3,075.25
50th-60th	329,164.10	124.57	-3,343.15	6,726.00	8,616.00	5,385.00	4,035.60	5,169.60	3,231.00
60th-70th	376,822.72	130.8	-3,801.97	7,150.40	9,396.00	6,107.40	4,290.24	5,637.60	3,664.44
70th-80th	438,496.39	140.94	-4,515.28	7,840.59	12,516.00	8,135.40	4,704.35	7,509.60	4,881.24
80th-90th	538,970.88	196.43	-5,487.77	10,123.71	13,368.67	8,689.63	6,074.23	8,021.20	5,213.78
90th-100th	883,530.68	229.42	-8,556.32	12,415.39	16,002.00	12,001.50	7,449.24	9,601.20	7,200.90

Notes: Premium Values and Results Obtained via the DECO Simulator (2018)