Flood risk perception in the housing market and the impact of a major flood event

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Abstract: The impact of flood events on flood risk perception has important implications for policy. Applying a novel dataset featuring the flooding extents from a severe event in Colorado, we disentangle inundated properties from "near-misses", defined as structures not directly flooded but located in the 100-year floodplain. Using a triple-difference hedonic framework, we show that inundated properties in the floodplain underwent a decrease in price after the flood, while "near-misses" saw a relative price increase. We speculate that inundated properties are perceived as being riskier and "near-misses" relatively less risky, suggesting the possible influence of the availability heuristic or Bayesian learning.

Floods are the most common natural disaster type worldwide. Between 1995 and 2015, 2.3 billion people were affected by floods, considerably more than any other type of natural disaster event (CRED, 2015). In the United States alone, flooding causes six billion dollars in property damage in an average year (USGS, 2006). Approximately seven percent of all land in the United States is designated as having a significant level of flood risk (Holway & Burby, 1990) and development in these risky areas explains some of the high costs associated with flooding.

In this paper we consider the impact of the National Flood Insurance Program (NFIP) on flood risk perception in Boulder County, Colorado. The overall aim of the NFIP is to reduce the socio-economic impact of flooding by identifying flood hazards, encouraging sensible floodplain management and requiring flood insurance for mortgaged properties in the areas at greatest risk of flooding (FEMA, 2002). Within a difference-in-difference framework, we estimate the influence of flood hazard mapping and a flood insurance buy-requirement on property sale prices before and after a major flooding event. After including inundation of the property as a moderating variable, the results show that the extent to which flood insurance mandates are realized in the selling price of a property after a flooding event depends on whether the property was directly flooded. As economic development in high flood risk areas continues, our results raise questions in the broader discussion of how individuals view the probabilities and consequences of flooding, particularly when the risks are experienced directly.

Previous studies have largely shown that price gaps exist across flood hazard zones, suggesting that homebuyers respond to flood insurance mandates and/or risk information. In general, a property located in the riskiest floodplain has been shown to sell at a 4 to 12% discount relative to an equivalent property outside of the risky area (Harrison, 2001; Schultz & Fridgen, 2001; Meldrum, 2015). In a meta-analysis, Beltran et al. (2018) estimated a 4.6% price discount associated with 100-year floodplains in inland areas.

Broadly speaking, the price differential after a flooding event increases, signifying a change in flood risk perception from the provision of new information (Skantz & Strickland, 1987; Bin & Polasky, 2004; Carbone et al., 2006). Bin and Landry (2013) show that prices in the riskiest floodplain designation dropped 6-22%, only recovering 7-9 years after the flood, while Daniel, Florax, and Rietveld (2009a) find even longer lasting post-flood impacts on property prices. One study found that the dampening effect was also realized in areas close to, but not impacted by, the given flooding event (Hallstrom & Smith, 2006).

Moving beyond the majority of previous research, we incorporate spatially-explicit data featuring the flooding extents from a major flooding event in Boulder County, Colorado in 2013. We are able to identify structures that were directly flooded (henceforth described as inundated) and estimate their risk capitalization in combination with flood risk-zone designation and associated flood insurance mandates. By including inundation as a moderating variable, we are joining a small, yet growing body of work focused on disentangling the impact that direct flooding has on risk capitalization from a flood simply occurring in a nearby area (Atreya & Ferreira, 2015; McCoy & Zhao, 2018, Ortega & Taspinar, 2018, Beltran et al., 2019). In particular, our empirical model makes it possible to compare the risk capitalization of inundated and non-inundated properties inside the risky floodplain, as well as inundated properties outside the floodplain. Accordingly, the “pure information effect” from location in the risky floodplain can be differentiated from the “inundation effect” (Atreya & Ferreira, 2015).

The NFIP encourages efficient decision-making by identifying properties with elevated flood risk, with the aim of reducing the information asymmetry between perceived risk by individuals and FEMA’s own risk assessment. In the wake of a flood event, understanding the extent to which perceived flood risk aligns with FEMA's assessment of the risk can help policymakers to know where and how they should target their flood risk awareness campaigns to reduce and insure capital-at-risk. Motivated by the fact that over half of the properties in Boulder County designated by FEMA as being at significant risk were not directly flooded in 2013, this paper addresses the following research question: how does inundation affect the sales prices of properties inside the regulatory floodplain?

The primary feature of this study that distinguishes it from the extant literature on flood risk perceptions in the housing market is the use of detailed geospatial data of flooding extents. In combination with building footprint location, we account for heterogeneous price impacts within the floodplain due to flood-induced damages and/or differences in post-flood risk perception. This study builds on a recent study by Meldrum (2015) that did not find a statistically significant flood risk discount for single-family homes in Boulder County for the 20 years prior to the flooding event. We further explore flood-risk capitalization using more recent data that spans a major flooding event in the county and allows us to better understand the heterogeneity associated with changes in flood risk capitalization after the event.

This work most closely aligns with Atreya and Ferreira (2015) and Ortega and Taspinar (2018). These papers are among the only hedonic studies that we are aware of to explicitly estimate the impact of inundation separately from a property being located in a flood-prone area. Like this one, the two studies employ a difference-in-difference methodology. Ortega and Taspinar focus on hurricane-induced damage, using Hurricane Sandy and New York City as their case study. They show that damaged and undamaged properties located in areas with high flood risk underwent a price decrease following Hurricane Sandy, with the former undergoing a more dramatic loss in value immediately after the event. Our treatment of inundated properties in the econometric model more closely follows the approach by Atreya and Ferreira. The researchers focus on the property markets in Albany, Georgia before and after the Great Flood of 1994, showing that inundated properties in the floodplain were subject to a more dramatic post-flood price decrease than properties that were not inundated but are also located in the floodplain. Our work adds to this limited set of studies in several dimensions. The Boulder County housing stock and flood hazard is considerably different from both New York City and Albany, Georgia. Boulder County has a mix of urban, suburban and rural properties. It is also more affluent with a newer housing stock compared to the relatively stagnant housing market in Albany. Moreover, given that the Boulder County flooding event was a riverine flood, the type and extent of property damage is different to the case of Hurricane Sandy.

The empirical results that are obtained using a hedonic, triple-difference framework show that properties inside the risky floodplain in Boulder County (defined as the Special Flood Hazard Area or 100-year floodplain) sold for a 6.5% discount prior to the flood. The magnitude of the discount is generally in line with what has been found in previous studies. After the flood, areas that were "nearly missed" by the flood waters no longer sold for a significant discount. In contrast, the properties that were both inundated and located in the riskiest floodplain underwent a relative decrease in price, selling at a 19% discount.

We offer two possible explanations for the diverging price impacts within the regulatory floodplain. The first is that homebuyers were influenced by the availability heuristic, whereby individuals overestimate the probability of events that come to mind very easily (Tversky & Kahneman, 1973). For example, after the flood, homebuyers in the near-miss areas may have overestimated the probability that they would be missed by any future flooding in the county, despite the fact that they were still located inside the regulatory floodplain. Alternatively, it may be that homebuyers were following a Bayesian learning model, observing where the flooding took place and rationally updating their expectations (Viscusi, 1991; Gallagher, 2014). If the flooding extents better represent true flood risk than the flood hazard maps put forth by FEMA, then the relative price increase experienced by the near-misses may have been efficient.

In the next section we provide background information on the National Flood Insurance Program, Boulder County flood risk and the 2013 flood. Section 2 outlines the empirical strategy and fits this research into the related literature. Section 3 provides details associated with the construction of our dataset. Sections 4 and 5 present and discuss the results and section 6 concludes.

1. Background

1.1 The National Flood Insurance Program

Through the early 20th century, flood risk and recovery were managed via a combination of federal and private initiatives. The United States federal government provided funds for structural control measures (such as levees and dams) as well as disaster relief funds on a disaster-by-disaster basis, while private flood insurance providers filled the risk gaps. The private insurance market ceased to exist following the great Mississippi flood of 1927 and flood insurance was not available to homeowners for the next several decades (FEMA, 2002). Even with government incentives, the high concentration and correlation of risks associated with floods made flood insurance unattractive to private insurers (Michel-Kerjan, 2010).

The National Flood Insurance Program was crafted in the 1960's in response to the rising costs of ad-hoc post-disaster relief legislation, America's first billion-dollar hurricane, significant population growth in flood-prone areas, as well as the influential voice of prominent geographer, Gilbert White (FEMA, 2002). White helped design the NFIP and, together with the Task Force on Federal Flood Policy, emphasized in their reports that flood insurance must serve two purposes: (1) offer financial relief to those impacted by flooding events and (2) have influence on land-use and its development (or restriction thereof) (White, 1958).

The NFIP is a voluntary partnership between the federal government and local communities. By law, FEMA cannot offer flood insurance to communities that do not meet the minimum floodplain management regulations as designated by the NFIP. FEMA and the community work together to map flood hazards, partitioning the landscape into three flood risk zones: the Special Flood Hazard Area, also called the 100-year floodplain (1% or greater chance of flooding per year), as well as the 500-year floodplain (0.99-0.2% chance of flooding per year) and the floodplain of minimal flood risk. The three categories add up to 100% of habitable land. Flood maps, called Flood Insurance Rate Maps (FIRMs), identify these areas and are intended to create awareness of the hazard as well as help states and communities plan floodplain development (FEMA, 2002). Flood hazard data provided by the FIRMs is freely and publicly accessible (FEMA, 2018a).

The NFIP also provides a basis for flood insurance buy requirements and rates. With the passage of the Flood Disaster Protection Act of 1973, flood insurance coverage became mandatory for all properties with located in the Special Flood Hazard Area (FEMA, 2002) that held federally backed mortgages. For a single-family residence, the NFIP provides insurance up to a maximum limit of 250,000 dollars for building coverage and 100,000 dollars for contents coverage (FEMA, 2018b). The cost of the insurance premium increases with flood risk and property vulnerability (for example, properties with basements are more costly to insure). Table 1 presents an overview of NFIP premium costs, both yearly and the net present value of the sum of payments calculated into perpetuity. Properties built before the first FIRMs often carry subsidized rates, as indicated in the table. Nationally, one in four properties in the SFHA is eligible for a subsidized rate (GAO, 2011). In Boulder County, nearly half of SFHA properties were built before the county's first flood risk map, and therefore are potentially eligible for a subsidized rate.

1.2 Boulder County flood risk

Boulder County was among the first communities in the United States to adopt floodplain regulations, joining the NFIP at its inception (Pettem, 2006). The county's flood risk is complex, mirroring the varied landscapes in the area. Streams have their headwaters in the high reaches of the Rocky Mountains located in the western portion of the county. The streams run eastward, passing through narrow and steep canyons, alongside small mountain towns and county roads, eventually emerging from the foothills. From there they flow through large population centers until they join the larger South Platte River. The sample of property transactions that we focus on in this study represents the more populated portion of the county that lie to the east of the foothills. Figure 1 depicts the flood hazard areas in the eastern Boulder County study area in relation to its populated areas. Nearly 3% of buildings are located inside the SFHA. Structures are at risk of flash flooding, alluvial fan flooding and/or riverine flooding, depending on the surrounding topography (FEMA, 2015). Historical records show that Boulder County has seen at least three large, damaging flooding events in the last 150 years, with more regular, smaller events occurring in between (City of Boulder, 2014).

The present study uses the Boulder County FIRM to identify buildings inside the SFHA and the 500-year floodplain. The FIRM was obtained via the National Flood Hazard Layer, a geospatial dataset created by the Federal Emergency Management Agency (FEMA, 2018b). The Boulder County FIRM was last updated in 2004, nearly 10 years prior to the 2013 flooding event. For half of the municipalities in the study area, we use building footprint data available on the City of Boulder's Geospatial Open Data Site (City of Boulder, 2018). The remaining municipalities are filled in with Microsoft's Building Footprint Data, a computer-generated dataset spanning all fifty states (Microsoft, 2018). For the City of Boulder, Microsoft's machine-learning algorithm captures 90% of the buildings drawn by the county, with the remaining ten percent likely reflecting difficulties because of complex topography and/or dense urban centers.

September 2013 brought devastating and widespread flash flooding to much of Colorado's Front Range urban corridor. With a range of almost 200 miles, the scope of the flooding was unprecedented for the state. The extraordinary characteristics of the 2013 Colorado flood led the National Weather Service to state that, in some areas, the amount of rainfall was considered a 1 in 1000 year occurrence (Gochis et al., 2015). The flood resulted in a Presidential Disaster Declaration for 18 Colorado counties, of which Boulder was amongst the hardest hit. Nearly 50% of FEMA's 260 million dollars in public assistance committed to the disaster were earmarked for Boulder County (FEMA, 2015).

Flooding extent data is available on the geospatial open data sites for Boulder County and the City of Boulder and is presented in Figure 1 (Boulder County, 2014; City of Boulder, 2018). The inundated areas were drawn by the National Geospatial Agency, with supplemental information coming from Boulder County Land Use and Parks and Open Space using imagery from the Digital Globe First Look product. Multiple images, taken on different days due to cloud cover, were used to determine the high water mark.

The dataset was further refined using damage assessment data points. The county saw 4% of structures inundated by the flood, of which 70% are located inside the SFHA. It should also be noted that two-thirds of structures located inside the SFHA were not inundated.

2. Empirical Strategy

Environmental goods are not usually traded directly in markets. Real estate markets, however, provide an opportunity to observe revealed preferences for environmental characteristics (Palmquist, 1982). The most commonly used technique to study the effects of environmental traits on property prices is the hedonic property model, whereby property prices are determined by a set of structural, neighborhood and environmental characteristics (Rosen, 1974).

Applying the hedonic regression to environmental amenities and dis-amenities in the housing market began with Ridker and Henning's (1967) pioneering contribution on the effects of air pollution on property prices. A long tradition of hedonic analysis in environmental economics has followed, with recent studies evaluating the impacts of proximity to open spaces (Walls, Kousky & Chu, 2015), beach erosion (Gopalakrishnan et al., 2011), climate change forecasts (Severen et al., 2018), wildfire risk (McCoy & Walsh, 2018) and the Fukushima nuclear accident (Tanaka & Zabel, 2018).

Following the empirical strategy of previous studies, we utilize a hedonic property model to investigate the capitalization of flood risk in the Boulder County real estate market. The model features the sales price of a given property as the dependent variable, regressed on structural attributes (e.g. square footage) as well as locational and environmental amenities (e.g. distance of the property from a body of water). As shown by Atreya et al. (2013), perception of the risk of flooding can also impact property prices. Location in the Special Flood Hazard Area serves as a proxy for perceived flood risk realized through flood insurance mandates. We hypothesize that the impact of the SFHA variable depends on whether the property was sold before or after the 2013 flood. To test the hypothesis, we employ a difference-in-difference specification, designating location in the SFHA as the treatment. Year-quarter dummies τ_t control for time-specific shocks that are common to all observations. Similarly, census block group dummies (ν_i) and city dummies (μ_i) account for time-invariant spatial heterogeneity.

$$P_{i,t} = \beta_0 + \beta_1 \mathrm{S}_i + \beta_2 \mathrm{L}_i + \alpha_1 SFHA_i + \alpha_2 PostFlood_{i,t} + \alpha_3 SFHAPostFlood_{i,t} + \tau_t + \nu_i + \mu_i + u_{i,t} \quad (1)$$

Equation 1 serves as the base model, where $SFHA$ is a dummy variable equal to one if property i is located in the 100-year floodplain and zero otherwise. Similarly, $PostFlood$ is a variable equal to one if the sale occurred after the flood and zero if the sale happened before the flood. $SFHAPostFlood$ represents the post-flood sale of a property in the SFHA. In the presence of the interaction term, the coefficients α_1 and α_2 are marginal effects and must be interpreted as holding the other variable equal to zero. For example, α_1 is the impact of being located in the treatment group prior to the flood. Similarly, α_2 captures aggregate factors that caused post-flood price changes even in the absence of a treatment group.

The difference-in-difference set-up allows for the comparison of two groups; properties inside the SFHA and properties outside the SFHA, over two time periods: before and after the 2013 flood. In the simplest case, we observe that two identical properties, one treated and one not, follow a common price trend in the absence of a flooding event. If, however, we detect that the trends of the selling prices of the two properties diverge in the presence of flooding, the price wedge between the two is labeled as the impact of the flood. The difference-in-difference coefficient is α_3 on the interaction term $SFHAPostFlood$. By subtracting the average post-flood price change in the control group from the average post-flood price change in the treatment group, we are quite literally taking a difference in differences.

$$\hat{\alpha}_3 = (\bar{P}_{SFHA,PostFlood} - \bar{P}_{SFHA,PreFlood}) - (\bar{P}_{nonSFHA,PostFlood} - \bar{P}_{nonSFHA,PreFlood}) \quad (2)$$

Equation 1, the base model, does not permit model parameters to differ across inundated and non-inundation zones. By including the dummy variable $Inundated$ and its interaction $PostFloodInundated$, we constrain the model and allow intercepts to differ depending on whether a property was directly flooded as shown in Equation 3.

$$P_{i,t} = \beta_0 + \beta_1 \mathrm{S}_i + \beta_2 \mathrm{L}_i + \alpha_1 SFHA_i + \alpha_2 PostFlood_{i,t} + \alpha_3 SFHAPostFlood_{i,t} + \phi_1 Inundated_i + \phi_2 PostFloodInundated_{i,t} + \tau_t + \nu_i + \mu_i + u_{i,t} \quad (3)$$

We hypothesize that inundation of a property could have two effects. The first is that there are flood-induced changes to the structure that will be realized in the selling price of the property but are not picked up in the property-specific data provided by the county. The structural changes could be damage or damage and subsequent improvements, making the sign of the expected impact ambiguous. The second effect may be a flood-induced division within the floodplain to relatively "more risky" and relatively "less risky", assuming that changes in flood risk perception are restricted to the SFHA. For example, it may be that an inundated property located in the SFHA is perceived as a riskier investment than an identical, but non-inundated property also located in the SFHA.

Equation 3, while controlling for direct flooding, forces the average effect of the treatment, location in the SFHA, to be uniform regardless of whether a property was inundated or not. A more flexible analysis would see inundation as a moderating variable on the treatment. For this, a triple-difference specification is employed, as in Equation 4.

$$P_{i,t} = \beta_0 + \beta_1 \mathrm{S}_i + \beta_2 \mathrm{L}_i + \alpha_1 SFHA_i + \alpha_2 PostFlood_{i,t} + \alpha_3 SFHAPostFlood_{i,t} + \phi_1 Inundated_i + \phi_2 PostFloodInundated_{i,t} + \phi_3 SFHAInundated_i + \pi_1 SFHAPostFloodInundated_{i,t} + \tau_t + \mu_i + \nu_i + u_{i,t} \quad (4)$$

The marginal effects are interpreted in the same way as in the difference-in-difference set-up (Equations 1 and 2). For example, $\alpha_2$is the post-flood price effect of a property being located in neither the SFHA nor the inundation zone. Similarly, α_3 is now the additional post-flood price impact of being located in the treatment but not in the inundation zone. We refer to such areas as "near-misses", borrowing the term from Hallstrom and Smith (2006), referencing the fact that these properties, while officially located in risky areas, were not directly flooded. It follows that ϕ_2 is the additional post-flood impact of being located in an inundation zone but not in the SFHA and π_1 is the marginal post-flood impact of being both treated and located in the inundation zone. Figure 1 depicts the four mutually exclusive areas on a map of the study area.

The triple difference estimate is defined as:

$$\hat{\pi}_1 = [(\bar{P}_{SFHA,PostFlood,Inun} - \bar{P}_{SFHA,PreFlood,Inun}) - (\bar{P}_{SFHA,PostFlood,nonInun} - \bar{P}_{SFHA,PreFlood,nonInun})] - [(\bar{P}_{nonSFHA,PostFlood,Inun} - \bar{P}_{nonSFHA,PreFlood,Inun}) - (\bar{P}_{nonSFHA,PostFlood,nonInun} - \bar{P}_{nonSFHA,PreFlood,nonInun})] \quad (5)$$

The first term ($\overline{P}_{SFHA,PostFlood,Inun} - \overline{P}_{SFHA,PreFlood,Inun}$) is the average post-flood price change for properties located in both the SFHA and the inundation zone. This is the primary outcome of interest. The three terms that follow net out potentially confounding trends. The second term represents general price trends specific to the treatment area ($\overline{P}_{SFHA,PostFlood,nonInun} - \overline{P}_{SFHA,PreFlood,nonInun}$), the third term characterizes general price trends specific to the inundation zone ($\overline{P}_{nonSFHA,PostFlood,Inun} - \overline{P}_{nonSFHA,PreFlood,Inun}$) and the last term is the general temporal price trend experienced by the entire study area ($\overline{P}_{nonSFHA,PostFlood,NonInun} - \overline{P}_{nonSFHA,PreFlood,NonInun}$). Dropping the second and fourth terms is the equivalent of restricting the sample to only inundation zones and using a difference-in-difference set-up to examine the post-flood impact of location in the SFHA. Similarly, dropping the last two terms is the equivalent to subsetting the sample to only treated areas and examining the post-flood impact of location in the inundation zone. Our aim is to determine the price impact of being located in both the SFHA and the inundation zone, therefore the triple-difference framework has an advantage over sample subsetting in that it controls for systematic differences within the entire inundation zone or treated area not accounted for in the subsamples.

The focus of the present study is to identify the moderating impact that inundation has within the SFHA. In doing so, we are joining a small, yet growing, body of research. Hallstrom and Smith (2006) pioneered the literature by comparing two neighboring, coastal counties: one county that was hit by a hurricane and the adjacent county which was narrowly missed. Using a repeat-sales model, the authors detected a decrease in property sales prices in both counties. Both Atreya and Ferreira (2015) and Ortega and Taspinar (2018) use maps, as we have done, to identify inundated properties. Atreya and Ferreira, using data from an area with significant flood risk, uncovered a significant discount associated with inundated properties within and outside the SFHA immediately following the flood, but no change was detected for non-inundated properties located in flood risk areas. Ortega and Taspinar focused on the New York City housing market in the aftermath of Hurricane Sandy, showing that both damaged and undamaged properties located in areas with high flood risk underwent a price decrease following the event.

3. Data Description and Methods

Structures located in the Special Flood Hazard Area (as well as the 500-year floodplain) were identified by overlaying the FIRM for Boulder County on the building footprint dataset (FEMA, 2018a). Inundated structures were distinguished in the same way, using a map featuring the flooding extents (Boulder County 2014; City of Boulder, 2018b).

The sample of transactions that we used in the empirical analysis is limited to properties within one mile of the inundation boundary. Restricting the sample in this way is intended to promote the comparability between the treatment groups and control group. The choice is motivated by the regression discontinuity design literature, whereby samples are restricted around the targeted boundary to improve control over omitted variables that change smoothly over space (Black, 1999). By doing this, the estimated impact of the boundary on the dependent variable is subject to less potential for bias from unobserved characteristics of geographic areas that are not accounted for by the census block group dummy variables and other control variables. In particular, exposure to any potential dis-amenity effects related to the flooding (McCoy & Walsh 2018; McCoy & Zhao 2018), for example flood recovery construction that may have affected neighborhood traffic patterns, should be similar. Figure 1 in the appendix shows that our general conclusions also hold under the full sample, as well as subsamples within 0.5 miles and 1.5 miles of the inundation boundary.

In Boulder County, the regulated floodplain is clustered alongside streams. These areas may also generally be associated with positive amenities such as favorable views and walking paths. For this reason, to isolate the floodplain price impact, it is critical to accurately control for a property's location close to a stream separately from its flood risk. We tested several variables representing the distance of the property to the closest waterway. Given the complexity of the terrain, we determined the best fit is achieved using four distance bands: 0 to 600 feet, 600 to 1800 feet, 1800 to 5000 feet and 5000 to 8000 feet from the closest perennially-running stream. This is a similar strategy to that employed by Kousky (2010).

Property transaction data from the Boulder County Assessor's Office features transaction date and price, structural characteristics including the number and type of rooms, the quality of the building[1] (for which there are six level-categories), the age of the building, the number of finished square feet of the building, lot size, the presence of a finished basement and the presence of car storage[2]. The analysis was limited to single-family properties and transactions with adjusted prices less than $50,000 were removed to minimize the impact of non-arms-length transactions[3]. Observations with square footage less than 150 feet were also removed because of the high likelihood of data entry error. The structural attributes were matched to the building footprint dataset via the associated parcels. Structural quality is presented as a dummy variable equal to one if the structure is characterized as having greater than very good quality.[4]

Maps from Boulder County, the Census Bureau and the United States Geological Survey determined the distance of each parcel to lakes and reservoirs, open space, trailheads and major roads as well as each parcel's elevation and census block group (Boulder County, 2018; U.S. Census Bureau, 2018; U.S. Geological Survey, 2018). Census block group and municipality fixed effects are used to control for any additional spatial, time-invariant characteristics that may influence price[5].

By limiting the analysis to the metropolitan area of Boulder County, we further avoided difficult-to-capture unobserved amenities associated with mountainous terrain. The metropolitan area is identified in the county's wildfire risk zone map as Zone 2 (Boulder County, 2017). Eighty percent of the property transactions in the county during the study period were within the metropolitan area.

We selected the temporal window for our sample to exclude the 2008 downturn in the real estate market, beginning with observations in the third quarter of 2009. Moreover, our sample is balanced around the 2013 flooding event, with four years of data on either side. Transactions occurring in the six weeks following the flood were excluded to minimize concerns related to discrepancies between the closing date of the sale and the actual sale date of the property[6]. Year-quarter fixed effects account for time-variant unobservables common to all properties.

We estimated the models using Ordinary Least Squares (OLS). While hedonic theory does not provide much guidance in the way of functional forms, we followed the majority of previous literature by using the natural log of price as the dependent variable because, compared to more complex forms, it gives relatively unbiased estimates in the face of omitted variables and performs well at estimating marginal price effects (Cropper et al., 1988). The main results of the regressions are robust to most transformations of the explanatory variables, however taking the natural log of the distance variables, lot size and square footage as well as the quadratic of age provided the best fit.

Table 2 provides descriptions and summary statistics for each variable in our subsample. Across all observations, the mean sales price for a property in the dataset is $424,036, adjusted to 2010 dollars. Just under 50% of the transactions took place after the flood. Nearly four percent of the properties sold are located in the SFHA and three percent are located within the inundation boundary. The proportion of properties sold inside the SFHA and the inundation zone remained relatively constant after the flood. Tables 1 and 2 in the appendix provide summary statistics that are differentiated by treatment or control groups, before and after the flood.

4. Empirical Results

In this section we provide the empirical results for the econometric specifications introduced in section two, as well as evidence that assumptions for the causal interpretation of the difference-in-difference strategy are valid. The presentation of the econometric results focuses on the coefficient estimates that pertain to the flood risk variables, with the full results of the econometric models provided in the appendix.

Econometric results

Table 3 presents the coefficient estimates and total marginal effects comparing the outcomes of properties inside the SFHA and properties inside the inundation boundary to properties outside both zones.[7] Specification (1) follows from Equation (1): location inside the SFHA is the treatment and we do not account for inundation. As shown in the bottom half of Table 3, prior to the flood, the average SFHA property is associated with a 6.5% discount, which is significantly different from zero.[8] The discount corresponds to a $29,062 discount-in-dollars for the average, non-basemented property inside the SFHA. To contextualize the results, in the month prior to the flood, the average policy holder in Boulder County was insured for $230,430 in flood damage, equating to approximately $1,500-$2,500 in yearly premiums from Table 1 (Boulder County insurance data provided via a Freedom of Information Act request). The net present value of the total insurance payments is $60,000-$80,000 calculated into perpetuity assuming a discount rate of 3%. This suggests that the average Boulder County resident did indeed insure against flood risk, but the realized insurance costs were not fully capitalized into the buying price.

After the flood, there was no change in property prices inside the SFHA. The absence of a price decrease is in contrast with previous literature that found that risk updating from flooding lowers property prices within the SFHA. We speculate that the lack of decrease resulted from the fact that not all properties inside the risky floodplain were directly flooded. Atreya and Ferreira (2015) determined that in Albany, Georgia the post-flood price effect substantially differed within the SFHA, with inundated properties associated with a much larger price discount than non-inundated properties. To determine if the same phenomena is driving the post-flood average price premium within the SFHA in Boulder County, a larger and more recent case study, we include inundation in the remaining specifications.

Specification 2 in Table 3 (from Equation 3) provides estimates of the average outcome inside the SFHA while controlling for whether a building was directly flooded. Before the flood, properties that, in the future, would be inundated were not associated with a statistically significant discount. After the flood, their average price fell by 6.3%, amounting to a nearly 9% total post-flood discount. The decrease in price likely reflects updated expectations of future flooding and/or costs related to inundation such as damage. For the average property inside the SFHA, including inundation as a control diminishes the point estimate of the post-flood discount to a 3.4% discount, which is not significantly different from zero.

Specification 2, while accounting for inundation, forces the average effect inside the SFHA to be uniform regardless of whether the property was directly flooded. A more flexible analysis, using triple differences, estimates the price effect for properties inside the SFHA that were inundated separately from SFHA properties that were not inundated (near-misses), inundated properties outside the SFHA and properties subject to neither flood risk signal. Specification 3 from Equation 4 does just this. The 11% pre-flood discount for SFHA properties that in the future would be inundated was determined by summing the pre-flood coefficients on inundation, location in the SFHA and their interaction. After the flood, these properties underwent an average decrease in price, selling for a 21% discount compared to post-flood control properties. The post-flood discount was determined by summing all of the relevant flood-related coefficients provided in column 3.

The total marginal effects for near-misses and inundated properties outside the SFHA were calculated similarly. Prior to the flood, properties that would later be near-misses were subject to a 4.3% discount. Given that before the flood there was still only one risk signal – location inside the SFHA – it is not surprising that the pre-flood discounts for non-inundated and inundated SFHA properties are relatively close. After the flood, the near-miss price effect diverged from that of the inundated properties. The average near-miss property increased in price, amounting to a total 1.1% post-flood premium, not significantly different from zero. The difference in price changes between the near-misses and inundated properties inside the regulatory floodplain is statistically significant at the 10% level (p=0.059). Inundated properties outside the SFHA are not associated with a major price change after the flood. The average 500-year floodplain property underwent a relative increase in price similar in magnitude to what is experienced by the near-misses (Table 4 in the Appendix).

Sensitivity to the inundation boundary.

Figure 2 compares the triple difference results for the full sample against samples whereby properties within a 20 (40, 60, 80 and 100) foot radius inside of the inundation boundary are dropped. By incrementally removing the boundary properties, we aim to capture how flooding severity may lead to heterogenous impacts within the SFHA-inundation zone. The assumption is that the flood hazard was less severe close to the inundation boundary than it was far from the inundation boundary (and subsequently close to the sources of the flooding: streams). For inundated properties inside the regulatory floodplain, the pre-flood discount increases in absolute value as inundated properties are incrementally eliminated from the sample, suggesting the presence of pre-flood heterogenous risk perceptions within the area. Notably, however, despite changes in the pre-flood discount, the difference between the pre- and post-flood discounts also increases, lending support to the hypothesis that inundated properties closer to the source of flooding (and consequently exposed to a more severe flood hazard) underwent a more dramatic price decrease after the flood than properties farther from the source of flooding. Expanding on the flooding severity analysis by combining household-level flood damage data with property sales data is an area for future research. In doing so, researchers may be able to identify the threshold damage levels at which perceived flood risk is enhanced.

Support for difference-in-difference assumptions

The estimates obtained through difference-in-differences can only be interpreted as causal if the unobserved differences between the treatment and control groups did not change during the study period. In the present study, three statements must be true to satisfy this exchangeability assumption: (1) the timing of the Boulder County flood was exogenous, (2) if there had been no flood, property prices would have evolved in the same way for the treatment groups as the control group and (3) the composition of property types for treatment and control groups remained stable over the study period.

The first criteria is the easiest to fulfill. By its nature, the timing of a natural disaster event is unpredictable. Figure 3 gives evidence of fulfillment of the second criteria, called the parallel trends assumption. We generated the residuals of a regression of log-prices on the structural and locational controls in addition to the temporal and spatial fixed effects. Epanechikov kernel-weighted local polynomials (with a 180-day bandwidth) were fit onto the residuals and across time for all three treatment groups and the control group[9]. In all three sub-figures the pre-flood trend for the control properties is (nearly) totally enveloped in the 95% confidence interval of the flood-risk group, suggesting that there were no note-worthy differences in pre-flood trends between the treatment groups and the control group. If the timing of the flood was exogenous, then pre-flood trends should represent the post-flood counterfactual.

To get a general sense of how different the property compositions are between the pre- and post-flood periods, we borrow the housing quantity index strategy from McCoy and Walsh (2018). Table 5 reports housing quantity indices by flood risk group. The indices were estimated for each property using weights from a single pre-flood regression (using all pre-flood sales) of price on the structural and locational quantities. We then calculated the means and confidence intervals of the housing quantity indices by risk group, pre- and post-flood. The p-values for t-tests of differences in means for each risk group, comparing pre-to-post flood, generally support the conclusion that there were no significant changes in group composition.

5. Discussion

Pre-flood risk awareness

The results of the previous section show that there was a statistically significant discount on the average Boulder County SFHA property prior to the flood. Our conclusions are different from the findings of a 2002 Boulder County survey undertaken by Chivers and Flores (2002). The authors found that the majority of survey respondents were not made aware of a property's status in the SFHA until too late in the negotiations for the information to be incorporated into the bargaining process. The fact that a discount is detected in more recent years suggests that flood risk awareness prior to purchasing a property may have increased over time. This is not surprising given Boulder County's recent extensive efforts aimed at increasing flood risk awareness. In the late 2000s, some of Boulder County's communities began promoting flood risk awareness and insurance uptake as a way to improve their standing within FEMA's Community Rating System (CRS). The City of Boulder, for example, joined the CRS in 1992 as a Class 8 community. They improved to a Class 7 in 2008 and a Class 6 in 2012. In early 2013, months prior to the major flooding event, the city was awarded a Class 5 rating, decreasing the 100-year floodplain premiums by 15% compared to the 1992 level (FEMA, 2015).

Post-flood risk awareness

The majority of previous literature has estimated a decrease in average property prices inside the regulatory floodplain after a flooding event (Daniel et al., 2009b). Homebuyers are likely better able to visualize a flood event and may have a more acute sense of the costs associated with flooding than pre-flood homebuyers. Even if a homebuyer did not previously live in the flooded area, real estate agents who experienced the event themselves likely serve as a source of risk information.

This study uncovers a result that deviates from the conclusions of previous literature: the average property inside the SFHA did not experience a decrease in price after the flood. The counter-intuitive result can be explained by heterogeneous effects within the regulatory floodplain. While we do estimate a relative price decrease after the flood, it is only for SFHA properties that were directly flooded. SFHA properties outside the inundation boundaries underwent a relative increase in price, with the difference in price changes being statistically different from zero.

Prior to the flood, homebuyers were largely exposed to only one flood risk signal type: the regulatory floodplain and its associated insurance requirements. After the flood, the inundation boundaries competed with the SFHA boundaries, often conveying conflicting information about a given property's vulnerability to flooding. For inundated properties inside the SFHA, the 2013 flood was a confirmation, or even heightening, of perceived flood risk. For near-misses, where the two risk signals did not overlap, the relative increase in prices suggests the possible influence of the availability heuristic: the 2013 event provided a salient example of flood risk that was more easily recalled than the borders of the regulatory floodplain. As a result, near-miss homebuyers in Boulder County updated their flood risk perceptions biased toward the more immediate illustration of flood risk. Alternatively, it may be that homebuyers are following a Bayesian learning model, observing where the flooding took place and rationally updating their expectations (Viscusi, 1991; Gallagher, 2014). Near-miss homebuyers may have used the boundaries of the flooding extents to rationally update their flood risk expectations, concluding that their risk level is not as high as the Boulder County floodplain map suggests. Given that Boulder County's floodplain map was 10 years old at the time of the 2013 flood, and significant development (which has the potential to change flood risk hazard) had occurred in the intervening years, there is a strong possibility that at least some discrepancies existed between the county's true flood risk and the regulatory floodplain.

Evidence in support of the availability heuristic or Bayesian learning as a better descriptor of market behavior might come from temporal changes in property prices. In particular, if the relative decrease in the price of inundated properties inside the SFHA after the flood event is only temporary, this would be suggestive evidence in support of the availability heuristic, which relies on near-term recall of events. An event-study analysis of property prices (provided in the appendix) provides suggestive evidence of such a temporary decrease, however, the relatively small number of observations as well as the relatively short post-flood time horizon inhibits the precision with which we can detect statistical differences in the point estimates over time.

Whether Boulder County homebuyers are following the availability heuristic or the Bayesian learning model has implications for the county's social cost of flooding and flood risk. The National Flood Insurance Program has three main elements: hazard identification and mapping, establishing minimum floodplain management criteria for communities and making flood insurance available to give property owners financial protection (FEMA, 2003). Taken together, the components form a program that, as described in the NFIP's authorizing legislation, "promote the public interest by encouraging sound land use by minimizing exposure of property to flood losses" (42 U.S. Code § 4001). In short, the NFIP seeks to minimize the social cost of flooding by fostering internalization of flood risk. When flood risk fails to be capitalized into property prices in flood-prone areas, like in the case of the post-flood near misses, the social cost of flooding is not adequately accounted for in the decisions of would-be buyers and developers. Changes in NFIP policies, like stricter penalties for failing to notify homebuyers of their flood risk, have the potential to improve efficiency in communities subject to flooding. The change in policy, however, can only be welfare increasing if the areas designated as being vulnerable to flooding are truly at risk. For Boulder County that means that the relative increase in prices in the nearly missed areas is only problematic if the 2013 flooding extents were merely a fluke, as in the case of the availability heuristic. If the flooding extents represent true risk, then the relative price increase is rational and efficient.

Following the 2013 flood, the Colorado Water Conservation Board initiated the Colorado Hazard Mapping Program (CHAMP) to re-map the Special Flood Hazard Area of the most affected areas (FEMA, 2015). While for the majority of the county the re-mapping effort appears to be only expanding the SFHA, in some areas, particularly those with many near-miss properties, the area of the SFHA was reduced (Boulder County, 2018). This implies that the impact of the relative price increase for the near-misses is mixed: in some parts of the county the price increase is a rational response to true flood risk while in other places policies that encourage risk internalization would bring expected flooding costs closer to efficient levels. While not widely publicized, CHAMP maps first became available for public consumption in the winter of 2017 (Colorado Water Conservation Board, 2019).

6. Conclusion

This paper examines the effect of the National Flood Insurance Program in combination with an actual flooding event on sales prices in the Boulder County housing market. We estimate a 6.5% discount inside the regulatory floodplain prior to the 2013 flood. After the flood, properties that were both directly flooded and are located in the Special Flood Hazard Area were associated with a 21% discount. Properties outside the inundation boundaries but inside the SFHA underwent a relative increase in price, selling for a post-flood premium not significantly different from zero, while inundated properties outside the regulatory floodplain were associated with essentially no post-flood price change. The difference in price changes is significantly different from zero at the 10% level.

Our results are suggestive of the availability heuristic and/or a Bayesian learning model. In the former, homebuyers bias their flood risk perceptions toward an example that can easily be brought to mind: the 2013 flood. In the latter, homebuyers rationally update their risk perceptions using the 2013 flooding extents. If the flooding extents represent true differences in risk within the regulatory floodplain, then the divergence in prices is welfare increasing.

Studies like this one can help policy makers cope with changing flood risk. In the American Mountain West, heavy, prolonged rainfall events that trigger rapid snowmelt are expected to double in frequency by the end of the century due to anthropogenic warming (Musselman et al., 2018). The increase in flood hazard is accompanied by escalating exposure: in the past century, the Boulder County population has grown five times faster than that of the United States and is currently amongst the fastest growing communities with a growth rate of nearly 3% per year (U.S. Census Bureau, 2018). To keep flood risk in check, policy makers must focus on containing the county's exposure and vulnerability to flood damages. Understanding how experience with the 2013 flood influences flood risk perception can help policy makers in encouraging flood risk recognition to lower future costs of flooding. Examining the extent to which the heterogenous post-flood price effects within the regulated floodplain can be attributed to the availability heuristic versus a Bayesian learning model will be essential for maximizing the benefits of such risk awareness campaigns in the future. In addition, a better understanding of behavioral responses to updated flood-risk maps will enable planners to understand the economic tradeoffs associated with increasing the frequency of such re-mapping efforts, particularly in rapidly developing areas such as Boulder County. Conducting surveys of homebuyers may help to better elucidate the full range of behavioral responses to flooding events and how these responses may be moderated by updated flood risk maps is a fruitful area for future research.

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Table 1: Flood Insurance Premiums for Single Family Pre- and Post-FIRM SFHA Properties

Building Coverage	Contents Coverage	Pre-FIRM[b] Annual Premium[a]	Pre-FIRM[b] Premium NPV[c]	Post-FIRM[d] Annual Premium[a]	Post-FIRM[d] Premium NPV[c]
$20,000	$8,000	$297	$9900	$481	$16,033
$30,000	$12,000	$446	$14,867	$721	$24,033
$50,000	$20,000	$743	$24,766	$1202	$40,067
$75,000	$30,000	$1121	$37,367	$1488	$49,600
$100,000	$40,000	$1509	$50,300	$1550	$51,667
$125,000	$50,000	$1897	$63,233	$1612	$53,733
$150,000	$60,000	$2285	$76,167	$1674	$55,800
$200,000	$80,000	$3061	$102,033	$1798	$59,933
$250,000	$100,000	$3837	$127,900	$1922	$64,066

Notes:
[a] Rates calculated for properties without basements;
[b] Pre-FIRM rates are for valid properties built prior to the first floodplain regulations in 1969;
[c] Premium NPV calculated into perpetuity assuming constant premium rates, yearly payments and a discount rate of 3%;
[d] Post-FIRM payments calculated assuming property has one floor and that the floor is at the same elevation as the base flood elevation.

Table 2: Variables and Summary Statistics

Variable	Description	Mean	Std. Dev.	Min.	Max.
Price	Property sale price in unadjusted U.S. dollars	424,036	284,924	50,000	4,724,509
Flood					
SFHA	1 if building is in the Special Flood Hazard Area, 0 otherwise	0.04	0.19	0	1
PostFlood	1 if sale occurred after the 2013 flood, 0 otherwise	0.47	0.50	0	1
Inundated	1 if building is located inside the inundation boundary, 0 otherwise	0.03	0.17	0	1
500yrFP	1 if building is in the 500-year floodplain, 0 otherwise	0.07	0.25	0	1
Location					
Stream0to600ft	1 if building is within 600 feet of stream, 0 otherwise	0.09	0.28	0	1
Stream601to1800ft	1 if building is between 601 and 1800 feet of stream, 0 otherwise	0.24	0.43	0	1
Stream1801to5000ft	1 if building is between 1801 and 5000 feet of stream, 0 otherwise	0.20	0.40	0	1
Stream5001to8000ft	1 if building is between 5001 and 8000 feet of stream, 0 otherwise	0.14	0.35	0	1
Dist2Lake	Parcel distance to lakes and reservoirs in feet	738	477	0	2,474
Dist2OpenSpace	Parcel distance to open space areas in feet	998	855	1	3,840
Dist2Trailhead	Building distance to closest trailhead in feet	10,135	5,551	378	29,948
Dist2Road	Building distance to main road in feet	756	553	41	3,307
Elevation	Elevation of parcel centroid in feet	4,944	753	4,500	10,260
Structure					
Age	Age of building in years	37	24	1	151
Sqft	Finished square footage of the building	1,884	891	324	11,657
Lotsize	Lot size in acres	0.17	1.82	0.01	69
CarStorage	1 if property has car storage, 0 otherwise	0.93	0.25	0	1
FinishedBasement	1 if building has a finished basement, 0 otherwise	0.60	0.49	0	1
NumberBedrooms	The number of bedrooms a building has	4	1	0	12
NumberFullBaths	The number of full baths a building has	2	0.84	0	7
Number3qtrBaths	The number of three-quarter baths a building has	1	0.72	0	9
VeryGoodQuality	Building listed as very good quality or above, 0 otherwise	0.11	0.31	0	1

Notes: For the analysis, *Price*, *Dist2Stream*, *Dist2OpenSpace*, *Dist2Road*, *Sqft* and *Lotsize* were transformed with natural logs. *Age* was transformed by squaring the variable.

Table 3: Flood risk effect on property prices

	No inundation	Inundation as a control variable	Inundation as a moderating variable
	(1)	(2)	(3)
SFHA	-0.063^{***}	-0.057^{***}	-0.042^{*}
	(0.019)	(0.020)	(0.023)
Inundated		-0.024	0.020
		(0.023)	(0.027)
SFHA x Inundated			-0.083^{*}
			(0.046)
SFHA x PostFlood	-0.001	0.023	0.053^{*}
	(0.034)	(0.031)	(0.031)
Inundated x PostFlood		-0.061^{*}	-0.017
		(0.036)	(0.032)
SFHA x Inundated x PostFlood			-0.121
			(0.083)
Struc. and Locat. Characteristics	Y	Y	Y
Municipality Fixed Effects	Y	Y	Y
Census Block Group Fixed Effects	Y	Y	Y
Year-Quarter Fixed Effects	Y	Y	Y
R^2	0.775	0.776	0.776
Observations	15,056	15,056	15,056
Total Marginal Effects			
	Pre-Flood		
Average inside the SFHA	-0.063^{***}	-0.057^{***}	
	(0.019)	(0.020)	
Average inside the Inundation Boundary		-0.024	
		(0.023)	
Inundated inside the SFHA			-0.105^{***}
			(0.031)
Near-Miss			-0.042^{*}
			(0.023)
Inundated outside the SFHA			0.020
			(0.027)
	Post-Flood		
Average inside the SFHA	-0.063^{**}	-0.034	
	(0.032)	(0.028)	
Average inside the Inundation Boundary		-0.085^{***}	
		(0.033)	
Inundated inside the SFHA			-0.190^{***}
			(0.066)
Near-Miss			0.011
			(0.026)
Inundated outside the SFHA			0.003
			(0.025)

Notes: The dependent variable is the natural log of the price. Huber-White (1980) robust standard errors in parentheses. Clustering at the floodplain-by-inundation-zone-by-census-tract-by-year level. * coefficient significant at the 0.10 level; ** coefficient significant at the 0.05 level; *** coefficient significant at the 0.01 level.

Table 4: Testing for compositional differences by treatment group

Treatment Defintion	Mean Pre-Flood Quantity Index	Mean Post-Flood Quantity Index	Welch t-test p-value
$\bar{Q}_{\text{SFHA x Inundated, Pre-Flood}} - \bar{Q}_{\text{SFHA x Inundated, Post-Flood}}$	5.522 (5.439,5.606)	5.570 (5.469,5.671)	0.476
$\bar{Q}_{\text{SFHA x non-Inundated, Pre-Flood}} - \bar{Q}_{\text{SFHA x non-Inundated, Post-Flood}}$	5.311 (5.262,5.361)	5.322 (5.265,5.380)	0.781
$\bar{Q}_{\text{non-SFHA x Inundated, Pre-Flood}} - \bar{Q}_{\text{non-SFHA x Inundated, Post-Flood}}$	5.296 (5.233,5.359)	5.303 (5.230,5.378)	0.876
$\bar{Q}_{\text{Control, Pre-Flood}} - \bar{Q}_{\text{Control, Post-Flood}}$	5.353 (5.344,5.362)	5.343 (5.333,5.353)	0.143

Notes: The first two columns report the mean quantity index for each risk group, before and after the flood. 95% confidence intervals surrounding the means are given in parentheses. The last column reports the p-values from a Welch Two-Sample t-test comparing the pre- and post-flood means. The null hypothesis of the Welch Two Sample t-test is that the true difference in means is equal to zero. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. .

Figure Titles

(1) Study area flood risk hazard, exposure and risk

(2) Effect of removing observations on the inside of the inundation boundary

(3) Residuals by treatment group over time

[1] Building quality is potentially an endogenous variable for inundated properties. Tables 1 and 2 in the appendix show that there was no significant change in the ratio of properties with very good quality and above sold inside the inundation boundary and regulatory floodplain. For inundated areas outside the regulatory floodplain, the ratio increased after the flood, suggesting that post-flood changes in the risk discount associated with these properties could be viewed as an upper bound.

[2] Recent research (Bernstein et al., 2018) shows the relevance of housing tenure status associated with estimating risk discounts in property markets. While housing tenure information is not available for this case study, exploring differences in impacts, particularly when considering inundation, is an interesting area for future research.

[3] The results are robust to trimming the most expensive properties at the 1% ($1,570,780) and 5% ($867,890) cut-off levels.

[4] The results hold when including the full set of categorical quality variables.

[5] Both municipality and census block group fixed effects are included because some of the census block groups span (portions of) multiple municipalities. By including municipality fixed effects we account for time-invariant differences in municipality-level characteristics (even within the same block group) that affect housing prices. These include differences in zoning policies and services offered.

[6] The results are robust to keeping transactions six weeks after the flood in the sample.

[7] All standard errors are clustered at the floodplain-by-inundation-zone-by-census-tract-by-year level. Table 4 in the appendix shows that the results are robust to a number of clustering strategies across spatial (census block group, census tract and municipality) and temporal dimensions (year and year-quarter).

[8] Percentage change is calculated by taking the exponent of the target coefficient, subtracting one and multiplying by 100.

[9] The 180-day bandwidth was chosen based on temporal considerations associated with accurately capturing changes in housing prices. Similar results are obtained with 90-day and 270-day bandwidths.

Figure 1: Study area flood risk hazard, exposure and risk

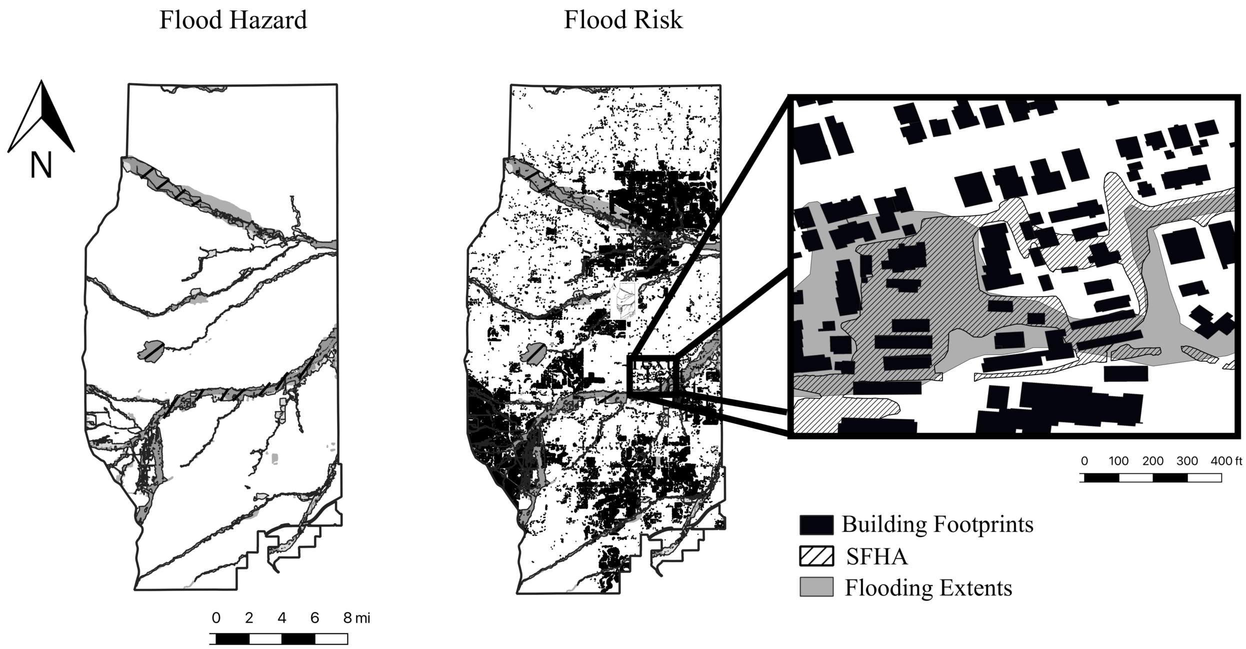


Figure 2: Effect of removing observations on the inside of the inundation boundary

Notes: This graph shows the total effects (i.e. sum of the relevant coefficients) and their 95% confidence intervals for each risk group after observations close to the inundation boundary are dropped incrementally. For example, the 20ft estimation represents all observations except those within 20ft inside of the inundation boundary. The average pre-flood effect is in black and the average post-flood effect is in grey. **Full Sample**: N=15,056; **20ft**: N=14,921; **40ft**: N=14,902; **60ft**: N=14,886; **80ft**: N=14,871; **100ft**: N=14,839

Figure 3: Residuals by treatment group over time

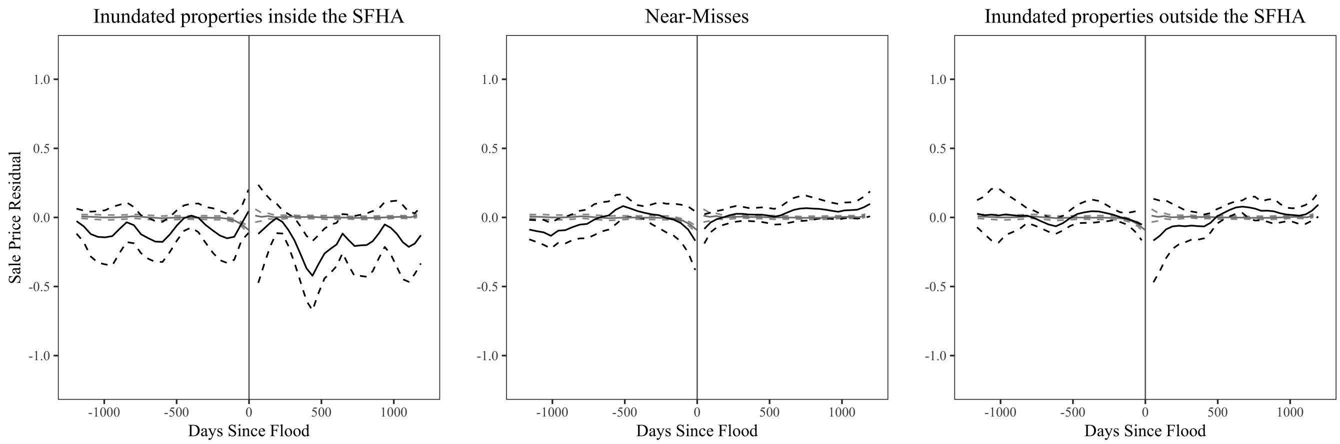
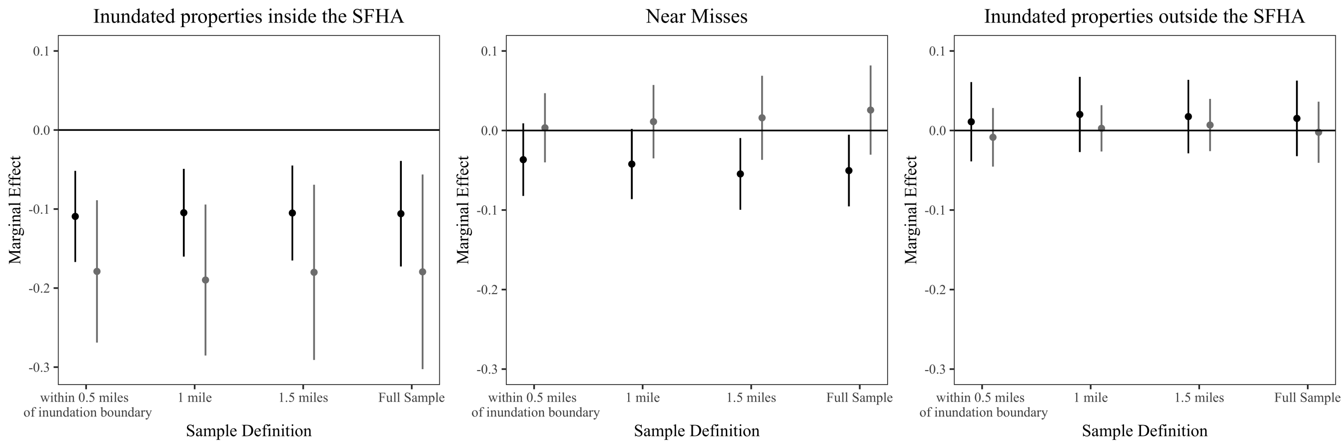
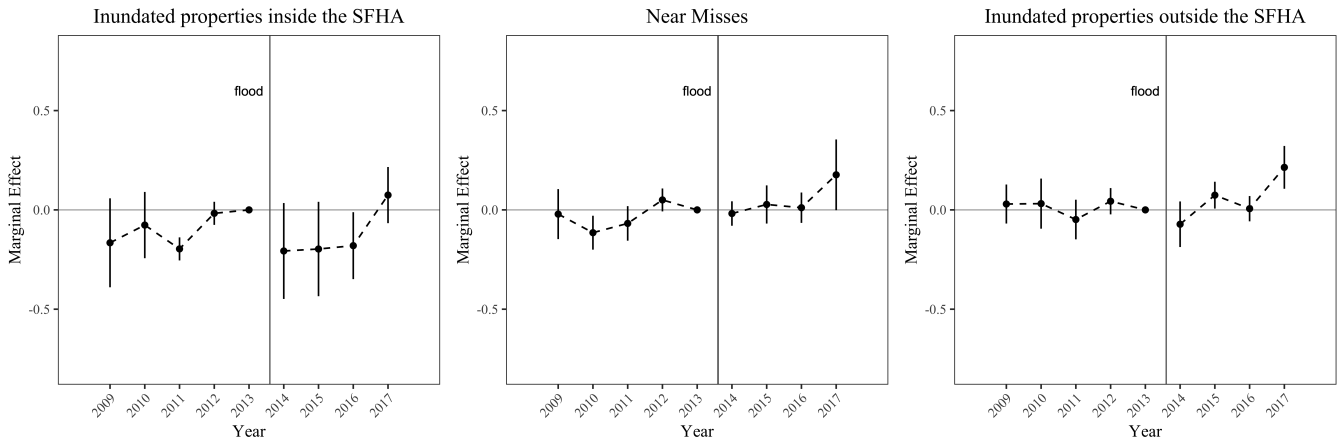


Figure 1: Effect of limiting observations around the inundation boundary



Notes: This graph shows the total effects (i.e. sum of the relevant coefficients) and their 95% confidence intervals for each risk group after observations far from the inundation boundary are dropped incrementally. The average pre-flood effect is in black and the average post-flood effect is in grey. **0.5 miles**: N=9,435; **1 mile**: N=15,056; **1.5 miles**: N=19,837; **Full Sample**: N=23,645

Figure 2: Event study



Notes: Vertical lines represent the 95% confidence interval around the coefficient estimates.[1]

[1] Others have evaluated changes in impacts in an event study framework using a parametric approach (Atreya et al., 2013). We choose to flexibly evaluate impacts by year due to the likely non-linearities associated with the flood's impact.

Table 1: Summary Statistics by Group - Inundated inside the SFHA & Near-Miss

	Inundated inside the SFHA					Near-Miss				
	Pre-Flood		Post-Flood		Welch t-test	Pre-Flood		Post-Flood		Welch t-test
Variable	Mean	Std. Dev.	Mean	Std. Dev	p-value	Mean	Std. Dev.	Mean	Std. Dev	p-value
Price	511,227	281,674	549,268	356,970	0.41	417,708	210,085	460,200	230,573	0.075
Location										
Stream0to600ft	0.30	0.46	0.38	0.49	0.29	0.24	0.43	0.24	0.43	0.96
Stream601to1800ft	0.24	0.43	0.28	0.45	0.58	0.22	0.41	0.18	0.39	0.43
Stream1801to5000ft	0.21	0.41	0.11	0.32	0.06	0.15	0.35	0.16	0.37	0.73
Stream5001to8000ft	0.05	0.23	0.06	0.23	0.96	0.08	0.27	0.10	0.30	0.45
Dist2Lake	502	368	471	299	0.51	598	423	555	405	0.34
Dist2OpenSpace	5,656	3,345	5332	3,538	0.51	5,268	3,409	4,765	3,256	0.16
Dist2Trailhead	14,194	4,665	14,119	4,647	0.91	13,930	4,462	13,740	4,671	0.70
Dist2Road	556	432	559	414	0.96	603	371	574	317	0.43
Elevation	1,686	261	1,691	284	0.89	1,629	178	1,624	176	0.82
Structure										
Age	46	24	52	26	0.09	52	28	51	25	0.62
Sqft	1,927	1,147	2,390	1,744	0.03	1,679	719	1,665	699	0.85
Lotsize	1.87	7.65	0.74	1.45	0.01	0.41	1.25	0.50	1.72	0.55
CarStorage	0.89	0.31	0.76	0.43	0.01	0.77	0.42	0.78	0.41	0.77
FinishedBasement	0.39	0.49	0.30	0.46	0.15	0.32	0.47	0.44	0.50	0.02
NumberBedrooms	3	0.87	3	1.41	0.55	3	1.13	3	0.99	0.94
NumberFullBaths	2	0.80	2	0.96	0.49	1	0.69	2	0.80	0.46
Number3qtrBaths	1	0.69	1	0.72	0.52	1	0.73	1	0.66	0.68
VeryGoodQuality	0.19	0.39	0.17	0.37	0.68	0.05	0.22	0.06	0.23	0.83
Number of Observations	N = 111		N = 90			N = 193		N = 158		

Notes: Price is adjusted to 2012 U.S. dollars. The null hypothesis of the Welch Two Sample t-test is that the true difference in means is equal to 0. ***p < 0.01, **p < 0.05, *p < 0.1.

Table 2: Summary Statistics by Group - Inundated outside the SFHA & Control

	Inundated outside the SFHA					Control				
	Pre-Flood		Post-Flood		Welch t-test	Pre-Flood		Post-Flood		Welch t-test
Variable	Mean	Std. Dev.	Mean	Std. Dev	p-value	Mean	Std. Dev.	Mean	Std. Dev	p-value
Price	350,871	203,152	379,248	267,701	0.37	420,893	289,673	425,730	282,294	0.31
Location										
Stream0to600ft	0.17	0.37	0.19	0.39	0.62	0.08	0.27	0.07	0.26	0.02
Stream601to1800ft	0.38	0.49	0.42	0.50	0.59	0.24	0.43	0.23	0.42	0.01
Stream1801to5000ft	0.17	0.38	0.11	0.31	0.16	0.20	0.40	0.21	0.41	0.05
Stream5001to8000ft	0.03	0.18	0.05	0.21	0.69	0.14	0.35	0.16	0.36	0.01
Dist2Lake	336	273	272	242	0.07	757	485	748	472	0.24
Dist2OpenSpace	3,958	3,928	3,038	3,464	0.06	3,211	2,805	3,156	2,613	0.23
Dist2Trailhead	10,320	5,475	9,270	5,120	0.14	10,091	5,552	9,765	5,433	0.00
Dist2Road	871	432	803	481	0.30	761	557	762	560	0.90
Elevation	1,606	185	1,625	257	0.52	1,647	245	1,649	262	0.64
Structure										
Age	36	16	31	15	0.04	36	23	38	23	0.01
Sqft	1,753	728	1,836	917	0.46	1,899	890	1,874	879	0.09
Lotsize	0.27	0.65	0.41	1.04	0.24	0.37	1.65	0.40	1.79	0.29
CarStorage	0.93	0.26	0.98	0.13	0.06	0.93	0.25	0.93	0.25	0.97
FinishedBasement	0.53	0.50	0.45	0.50	0.26	0.61	0.49	0.61	0.48	0.94
NumberBedrooms	3	1.07	3	0.92	0.31	4	1.00	4	0.99	0.17
NumberFullBaths	2	0.86	2	0.69	0.16	2	0.85	2	0.83	0.01
Number3qtrBaths	1	0.68	1	0.68	0.81	1	0.72	1	0.73	0.08
VeryGoodQuality	0.03	0.16	0.11	0.31	0.01	0.14	0.35	0.14	0.35	0.71
Number of Observations	*N* = 115		*N* = 110			*N* = 7,501		*N* = 6,778		

Notes: Price is adjusted to 2012 U.S. dollars. The null hypothesis of the Welch Two Sample t-test is that the true difference in means is equal to 0. ***p < 0.01, **p < 0.05, *p < 0.1.

Table 3: Full results - flood risk effect on property prices

	No inundation	Inundation as a control variable	Inundation as a moderating variable
	(1)	(2)	(3)
SFHA	-0.063^{***}	-0.057^{***}	-0.042^{*}
	(0.019)	(0.020)	(0.023)
Inundated		-0.024	0.020
		(0.023)	(0.027)
SFHA x Inundated			-0.083^{*}
			(0.046)
SFHA x PostFlood	-0.001	0.023	0.053^{*}
	(0.034)	(0.031)	(0.031)
Inundated x PostFlood		-0.061^{*}	-0.017
		(0.036)	(0.032)
SFHA x Inundated x PostFlood			-0.121
			(0.083)
PostFlood	0.365^{***}	0.365^{***}	0.364^{***}
	(0.024)	(0.024)	(0.024)
500yrFP	-0.009	-0.007	-0.007
	(0.013)	(0.014)	(0.013)
500yrFP x PostFlood	0.054^{***}	0.051^{***}	0.047^{***}
	(0.016)	(0.016)	(0.015)
Stream0to600ft	-0.009	-0.006	-0.006
	(0.016)	(0.016)	(0.016)
Stream601to1800ft	-0.023^{*}	-0.021^{*}	-0.021^{*}
	(0.012)	(0.012)	(0.012)
Stream1801to5000ft	0.006	0.006	0.007
	(0.011)	(0.011)	(0.011)
Stream5001to8000ft	-0.013	-0.013	-0.013
	(0.017)	(0.017)	(0.017)
logDist2Lake	-0.014^{**}	-0.015^{**}	-0.014^{**}
	(0.006)	(0.006)	(0.006)
logDist2OpenSpace	-0.009	-0.009	-0.009
	(0.006)	(0.006)	(0.006)
logDist2Trailhead	-0.015	-0.013	-0.014
	(0.021)	(0.021)	(0.021)
logDist2Road	0.027^{***}	0.027^{***}	0.027^{***}
	(0.005)	(0.005)	(0.005)
Elevation	0.001^{***}	0.001^{***}	0.001^{***}
	(0.000)	(0.000)	(0.000)
Age	-0.001	-0.001	-0.001
	(0.001)	(0.001)	(0.001)
squaredAge	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)
logSqft	0.386^{***}	0.387^{***}	0.387^{***}
	(0.017)	(0.016)	(0.016)
logLotsize	0.159^{***}	0.160^{***}	0.160^{***}
	(0.009)	(0.009)	(0.009)
CarStorage	0.065^{***}	0.065^{***}	0.065^{***}
	(0.014)	(0.014)	(0.014)
FinishedBasement	0.080^{***}	0.080^{***}	0.080^{***}
	(0.007)	(0.007)	(0.007)
NumberBedrooms	0.004	0.004	0.004
	(0.004)	(0.004)	(0.004)
NumberFullBaths	0.069^{***}	0.068^{***}	0.068^{***}
	(0.007)	(0.007)	(0.007)
Number3qtrBaths	0.049^{***}	0.049^{***}	0.048^{***}
	(0.005)	(0.005)	(0.005)
VeryGoodQuality	0.146^{***}	0.146^{***}	0.146^{***}
	(0.014)	(0.014)	(0.014)
Struc. and Locat. Characteristics	Y	Y	Y
Municipality Fixed Effects	Y	Y	Y
Census Block Group Fixed Effects	Y	Y	Y
Year-Quarter Fixed Effects	Y	Y	Y
R^2	0.775	0.776	0.776
Observations	15,056	15,056	15,056

Notes: The dependent variable is the natural log of the price. Huber-White (1980) robust standard errors . in parentheses. Clustering at the floodplain-by-inundation-zone-by-census-tract-by-year level. * coefficient significant at the 0.10 level; ** coefficient significant at the 0.05 level; *** coefficient significant at the 0.01 level.

Table 4: Impact of various clustering strategies on results

Cluster Spatial Dimension	Block Group	Municipality	Block Group	Tract	Municipality
Cluster Temporal Dimension	Year	Year	Year-Quarter	Year-Quarter	Year-Quarter
Number of Clusters	1,432	144	3,852	1,959	433
Average Cluster Size	11	105	4	8	35
	(1)	(2)	(3)	(4)	(5)
SFHA	-0.042^{*}	-0.042	-0.042^{*}	-0.042^{*}	-0.042^{*}
	(0.024)	(0.028)	(0.023)	(0.022)	(0.023)
Inundated	0.020	0.020	0.020	0.020	0.020
	(0.027)	(0.025)	(0.025)	(0.025)	(0.024)
SFHA x Inundated	-0.083^{*}	-0.083^{*}	-0.083^{*}	-0.083^{*}	-0.083^{*}
	(0.048)	(0.049)	(0.045)	(0.044)	(0.046)
SFHA x PostFlood	0.053^{*}	0.053	0.053^{*}	0.053^{*}	0.053^{*}
	(0.031)	(0.034)	(0.029)	(0.029)	(0.028)
Inundated x PostFlood	-0.017	-0.017	-0.017	-0.017	-0.017
	(0.032)	(0.029)	(0.030)	(0.030)	(0.028)
SFHA x Inundated x PostFlood	-0.121	-0.121	-0.121^{*}	-0.121^{*}	-0.121
	(0.082)	(0.087)	(0.072)	(0.072)	(0.074)
Struc. and Locat. Characteristics	Y	Y	Y	Y	Y
Municipality Fixed Effects	Y	Y	Y	Y	Y
Census Block Group Fixed Effects	Y	Y	Y	Y	Y
Year-Quarter Fixed Effects	Y	Y	Y	Y	Y
R^2	0.776	0.776	0.776	0.776	0.776
Observations	15,056	15,056	15,056	15,056	15,056
Total Marginal Effects					
			Pre-Flood		
Inundated inside the SFHA	-0.105^{***}	-0.105^{***}	-0.105^{***}	-0.105^{***}	-0.105^{***}
	(0.036)	(0.038)	(0.023)	(0.027)	(0.028)
Near-Miss	-0.042^{*}	-0.042	-0.042^{*}	-0.042^{*}	-0.042^{*}
	(0.024)	(0.028)	(0.023)	(0.022)	(0.023)
Inundated outside the SFHA	0.020	0.020	0.020	0.020	0.020
	(0.027)	(0.025)	(0.025)	(0.025)	(0.024)
			Post-Flood		
Inundated inside the SFHA	-0.190^{***}	-0.190^{***}	-0.190^{***}	-0.190^{***}	-0.190^{***}
	(0.067)	(0.075)	(0.048)	(0.046)	(0.050)
Near-Miss	0.011	0.007	0.007	0.007	0.007
	(0.028)	(0.034)	(0.024)	(0.024)	(0.24)
Inundated outside the SFHA	0.003	0.006	0.006	0.006	0.006
	(0.025)	(0.017)	(0.019)	(0.019)	(0.015)

Notes: For all specifications, standard errors are also clustered at the floodplain-by-inundation zone level, in addition to the spatial and temporal dimensions listed above. The dependent variable is the natural log of the price. Robust standard errors in parentheses. * coefficient significant at the 0.10 level; ** coefficient significant at the 0.05 level; *** coefficient significant at the 0.01 level. Huber-White (1980) robust standard errors.