Levees: Infrastructure and Insurance as Adaptation to Flood Risk

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Abstract

Abstract: This paper considers the interaction of two key flood policy instruments commonly used in the US, levee infrastructure and flood insurance, and measures how much flood insurance demand changes in response to levee provision. Levees are critical infrastructure that reduce expected flood damage in a protected area. Flood insurance, primarily provided through the National Flood Insurance Program, allows households to smooth consumption in the event of flood damage. When a levee is constructed, and later accredited by the Federal Emergency Management Agency (FEMA), it alters inherent flood risk, flood insurance prices, and insurance mandate requirements. Using a novel panel dataset drawing from the National Levee Database, manually collected levee accreditation documentation, and FEMA flood insurance data, we leverage variation in levee construction and accreditation timing within a DID design. Construction timing allows us to examine insurance take-up as a result of decreased flood risk, while accreditation causes changes in insurance prices and mandatory purchase requirements. Our paper has three main findings: first, we find that levee construction decreases flood insurance by 20 percent. Second, we find that levee accreditation does not further change flood insurance take-up. Third, we find that decreases in flood insurance take-up due to levee construction decreases aggregate household insurance spending by $1.9 billion, accounting for both extensive and intensive margin changes.

1 Introduction

Floods are an extremely common natural disaster in the US. Ninety-nine percent of US counties have experienced at least one flood event in the last 25 years, and damages from flooding have accounted for over $300 billion in losses since 1960 (Center for Emergency Management and Homeland Security, 2022). Given that the severity of flooding is expected to dramatically increase in the coming years due to climate change, it is imperative for policymakers to determine optimal policy provision for mitigation against flooding (IPCC). To that end, the US government has spent hundreds of millions of dollars on flood mitigation and damages, through a variety of policy instruments such as insurance, disaster aid, infrastructure, and adaptation grants (FEMA 2020). Despite these enormous outlays, very little is known of the interactions between the various policy instruments at our disposal, and the extent to which households' exposure to multiple public flood mitigation policies crowds out private investment in flood protection.

Flood policy instruments can be broadly categorized into three main groups: structural, non-structural, and risk transferring policies (Kahn and Lall, 2021; National Research Council, 2013). Structural policies, such as levees, reduce the expected damages of flooding by protecting against flood damage. Non-structural policies, such as land-use planning, may also impact the the inherent probability that flooding occurs. Lastly, risk transfer policies, such as flood insurance, affect neither damages nor probability, and instead allow households to smooth consumption across different states of the world. While non-structural and risk transfer policies may be implemented *ex-post*, this paper explores the relationship between two prominent *ex-ante* structural and risk transfer policies: levees and flood insurance. Levees are a common flood infrastructure project, often sponsored and maintained by local government agencies or large private entities. They largely consist of earthen embankments along rivers, lakes, and other flooding sources. Levees alter the fundamental flood risk of a region by reducing the damages from low-intensity, high-probability flood events, but they do not completely eliminate the flood risk of a region. An additional source of *ex-ante* flood mitigation is flood insurance, which is predominantly provided through the National Flood Insurance Program (NFIP), which is run by the Federal Emergency Management Association (FEMA). Since levees reduce expected damages, they may serve as a substitute for flood insurance (Ehrlich and Becker, 1972). However, levees also can reduce prices and relax mandatory insurance purchase requirements. These mechanisms may imply that levees complement flood insurance. Therefore, our paper empirically estimates how levees interact with the insurance system, and which of these opposing mechanisms prevails.

To understand the degree of complementarity between levees and flood insurance, we measure the impact of levee provision on households' flood insurance take-up. We combine several sources of data on levees and flood insurance policies, constructing a unique panel dataset of levee provision, including construction completion dates. Additionally, we utilize a novel data source comprised of FEMA flood map revision documents to construct an original dataset of levee accreditation timing. Accreditation dates provide the exact timing when the levee is certified by FEMA, officially changing flood insurance zones and altering insurance price and mandatory purchase requirements. To estimate the *causal* effect of levee provision on insurance take-up, we leverage variation in timing of levee construction and accreditation within a difference-in-differences design.

Our paper provides three main contributions to the literature on the economics of flood insurance. First, we provide the first empirical evidence of the causal impact of levee provision on flood insurance take-up, finding that household insurance take-up decreases by 20 percent following levee construction. Second, we compile the first known dataset of historic and effective levee accreditation dates, using National Flood Insurance Program rate maps and archived map revision documentation. Third, we provide the first empirical estimates of forgone household insurance spending after levee provision, estimating that households decrease their spending on insurance by a total of $1.9 billion following levee provision. Recent literature (Bradt and Aldy, 2023) studies the capitalization of levee construction into property values to estimate the value of levee provision to households. Our paper provides valuable additional context for this calculation by quantifying changes in household insurance spending due to levee provision.

The closest work on the complementarity of various flood policy instruments studies the correlation between flood insurance take-up and other mitigation policies (e.g., land-use planning). Zahran et al. (2009) find a significant, positive correlation, while Atreya and Kunreuther (2016) find a non-significant, negative correlation. Kousky (2011) finds a negative correlation between flood insurance take-up and proximity to a levee in St. Louis, MO, which suggests that the two policies are substitutes. Our preliminary empirical results align with those in Kousky (2011), as we find that flood insurance take-up decreases after levee provision.

Our paper also contributes to a broader literature of the mechanisms behind flood insurance demand by estimating demand responses to levee provision and distinguishing between demand changes due to levee construction and accreditation. Past work on this topic has considered the behavioral elements that help explain low take-up rate of flood insurance, relative to other types of insurance (e.g., Kunreuther, 1996). Empirical work has shown that exposure to flooding, either directly (Atreya and Kunreuther, 2016; Kousky, 2017) or through media reports (Gallagher, 2014), increases take-up, but only in the short-term. Qualitative evidence suggests that homeowners systematically misunderstand the residual risk of levees (Ludy and Kondolf, 2012). The flood insurance program is chronically under-subscribed, despite mandatory purchasing requirements and increased awareness about local flood risk. For example, Kousky et al (2021) estimates that in 2019, only 48 percent of households in 100-year floodplains held a flood insurance policy. Hence, it is imperative policymakers develop a deeper understanding of the factors driving flood insurance demand, and the extent to which access to complementary policies alter insurance take-up.

Within the broader public finance literature, our study is the first to study the crowding out of household-level risk transfer take-up by public infrastructure investments. Influential work in the crowd-out literature has focused on policy contexts in which public-sector health insurance expands and crowds out private-sector health insurance (Cutler and Gruber, 1996). In the realm of natural disaster insurance, there has been some research studying how other risk transfer policies, such as *ex post* aid provision, may reasonably crowd out household-level flood insurance take-up. Kousky et al. (2018) finds that *ex post* disaster aid reduces flood insurance coverage in subsequent years. It is also possible that other risk transfer mechanisms crowd out households' take-up of flood insurance. For example, Liao and Mulder (2021) study how home equity affects the demand for flood insurance, by leveraging cycles in the housing market as identifying variation, they find that the option of defaulting on a mortgage is a risk transfer mechanism that crowds out insurance take-up. Our findings will have implications for other policy contexts with uncertainty, including policies to mitigate damages from wildfires and other types of natural disasters.

The rest of the paper proceeds as follows: Section II describes the context and background of each of the two policies. Section III describes the data and empirical strategy. Section IV presents estimates of the effect of levee provision on flood insurance take-up. Finally Section V discusses the estimates and the overall welfare impacts of levee provision.

2 Background on Flood Risk and Mitigation

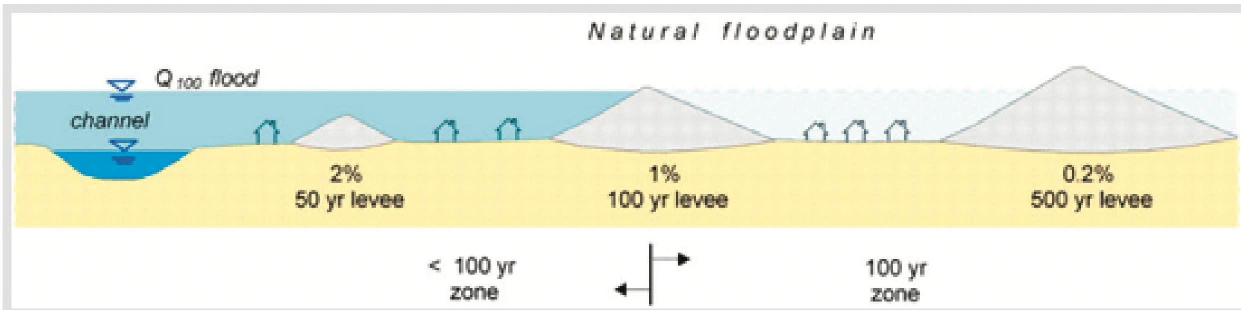
A levee is a "man-made structure, usually an earthen embankment, designed and constructed in accordance with sound engineering practices to contain, control, or divert the flow of water so as to provide protection from temporary flooding" (CFR, 44, §59.1). Levees are an ancient technology that protect subsets of floodplains, known as "leveed areas," from a certain degree of flood damage by providing physical barriers to floodwaters. Construction of a levee is a complex process, involving political capital and coordination, up-front monetary investment, and a plan to maintain the levee once construction is complete. Public or private actors fund and oversee the construction of a levee, and the ownership of the levee may be transferred during or after construction. Local funding of levees may be accomplished using debt mechanisms or tax revenue, including taxes collected through levee districts. Larger levee projects often require cost-sharing with state and federal funding sources, with costs ranging from millions to billions of dollars depending on the size and complexity of the levee (Keegan et al., 2011). The timeline of funding, designing, and constructing a levee can be protracted, taking a few years or even decades.

Although levees do not completely eliminate flood risk, engineers design levees to protect against certain degrees of flood risk. Figure 1 illustrates the varying protective capabilities of levees against a 100-year flood [1]. Levees may protect against losses for up to the degree of flood risk for which they were built, but there is still residual flood risk possible in severe circumstances. In other words, a levee does not completely erase local flood risk: leveed areas are still susceptible to a certain amount of flood damage, if there is a flood that exceeds the protective capabilities of the levee. For example, a 50-year levee is not designed to protect against a 100-year flood, as depicted in Figure 1. In the event of "overtopping," when floodwaters breach the levee, it is possible for losses to match or even exceed the counterfactual losses in the state of the world where the levee did not exist. Flood damages in leveed areas are also possible if there is some failure of the levee either due to an error in its construction, a lack of maintenance, or an unanticipated failure of one component of the levee system. Thus, levees *lower, but do not eliminate* expected flood losses for properties in leveed areas. This residual risk necessitates consideration of additional flood mitigation policies such as flood insurance (National Research Council, 2013). Within the National Levee Database (NLD), 32 percent of levees have been screened to calculate the "annual exceedance probability" (AEP), which denotes the probability-level event which will maximize the protective capacity of the levee. For example, a levee

[1] This terminology refers to a flood that has a 0.01, or one-in-hundred chance of occurring each year. This flood intensity is used as a benchmark for several flood insurance conditions. For example, accredited levees are certified to protect at most against 100-year floods.

with an AEP of 0.01 has a maximum level of protection against a 100-year flood event. Lower AEP values denote a higher degree of safety: if a levee is more protective, it will have the capacity to withstand a lower-probability, higher-intensity flood event (NLD and Wobus et al. (2019)).

Figure 1: Illustration of Levees



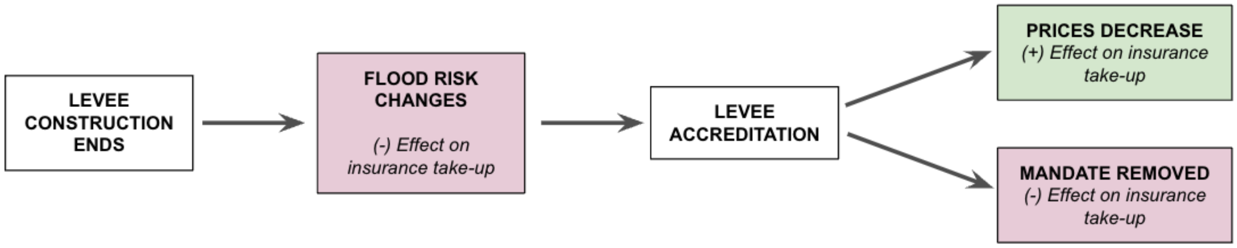
Note: This illustration is from National Research Council (2013). It shows that a 50-year levee would not protect against 100-year flood, while 100-year and 500-year levees would protect against higher-intensity, lower-probability events. The percentage listed denotes the "annual exceedance probability" (AEP) of the levee.

Flood insurance allows individuals to smooth consumption across states of the world, given that there is uncertainty of flood timing, frequency, severity, and damage. Unlike other types of insurance, the government, rather than a private market, is the primary provider of flood insurance (Kousky et al., 2018). Public flood insurance is available through the National Flood Insurance Program (NFIP), which the National Flood Insurance Act of 1968 established to protect homeowners, reduce expenditure on federal disaster aid, and share the risk more than was possible under a predominantly private insurance market (U.S.C., 42, §4001). Due to the nature of flood events, there may be a large number of claimants concurrently filing for extensive damages, known as "correlated risk". Private insurance providers would not be able to maintain profitability in this context, whereas the NFIP does not aim for profitability and theoretically faces the very large borrowing limits of the federal government. In order to ensure the viability of the program, legislation requires that NFIP imposes mandatory purchase requirements for certain properties and offers extensive subsidies. All of these features make the NFIP operate differently than private insurance providers (National Research Council, 2013).

FEMA operates the NFIP and sets insurance prices using Flood Insurance Rate Maps (FIRMs), which designate zones according to flood risk and property characteristics (e.g., structure age).[2] Floodplains with at least a 100-year flood risk are considered Special Flood Hazard Areas (SFHAs). The NFIP's mandatory

[2]Between 1968 and 1979, the Department of Housing and Urban Development (HUD) oversaw the NFIP until FEMA was established and took over operations (National Research Council, 2013). Starting in 2021, FEMA implemented Risk Rating 2.0, changing the price structure to better account for residual risk and property-specific risk factors (Horn, 2019), including proximity to levees. For the purposes of this analysis, we will not consider these substantial changes to the pricing mechanisms of NFIP.

Figure 2: Timeline of Levee Construction and Accreditation



purchase requirement decrees that all properties with federally backed mortgages in SFHAs purchase flood insurance, although enforcement varies across lenders and there is significant non-compliance (Bradt et al., 2021).

Levee provision serves as a valuable context to study homeowners' insurance take-up responses to public infrastructure investment. Notably, *construction of a levee alone does not necessarily or immediately change NFIP prices.* In order for a levee to reduce insurance prices or relax the mandatory purchasing requirement, the levee must undergo a process known as accreditation (U.S.C., 42, §4012a). However, many levees never undergo accreditation: within the NLD, only 17 percent of levees are currently actively accredited (see Table 3). This setting provides us with a unique opportunity to observe homeowners' responses to the infrastructure construction *before* their insurance prices or requirements change, providing suggestive evidence of the initial household response to flood risk changes, and how their behavior evolves following insurance market changes. Studying household insurance take-up following levee accreditation provides suggestive evidence of additional household responses to the price and mandatory purchasing requirements, which we will refer to as "insurance market changes".

3 The Process of Levee Provision

We consider levee provision as a bundled treatment, changing various factors in tandem. Figure 2 depicts the timeline of levee provision, which includes levee construction and the accreditation process. The physical construction of the levee results in a change in inherent flood risk. Shortly thereafter, certain municipalities will undergo the process of accreditation, during which rigorous engineering analyses of the levee are conducted and reviewed by FEMA. The process of accreditation is initiated by municipalities and levee owners, and requires the input of engineers to sign off that the levee meets a strict set of criteria (FEMA 2021). After the levee is deemed to be accredited by FEMA, they issue an updated map, or a "Letter of Map Revision" (LOMR) that changes the flood zone in the region affected by the levee. Once this change takes effect, flood insurance prices are lowered and mandatory purchase requirements are relaxed. Figure 3 illustrates an example of these changes. On the left is the original flood map for a portion of Fargo, North Dakota. The highlighted area of the map depicts the geographic region that is considered a high-risk flood zone. On the right, the updated map in the LOMR illustrates the region that is now considered protected by the levee (the striped area). We consider levee provision to be a bundled treatment of these three separate effects, split across the construction and accreditation processes:

1. **Flood risk**: First and foremost, the levee will protect a leveed area against a certain degree of flooding, reducing flood risk for certain types of floods. Figure 1 illustrates this point, depicting how a levee could protect against floods of a particular magnitude, but not others. *A levee will reduce overall flood risks, reducing insurance take-up*

2. **Prices**: After the levee is accredited, insurance prices will decrease, reflecting the changes in expected damages from flooding. *A levee will reduce insurance price, increasing insurance take-up*

3. **Mandate**: After the levee is accredited, insurance requirements within a leveed area will be relaxed. This will lower the costs of not being insured for homeowners, since they no longer have the threat of flouting the mandate if they decide not to purchase insurance. *A levee will reduce insurance mandate requirements, reducing insurance take-up*

Due to these three competing effects, the direction in which levee provision will affect flood insurance take-up is ambiguous. Through our analyses, we will first study the dynamics of insurance take-up across the construction date using a panel regression, which will estimate the effects of risk changes on insurance take-up rates. Next, a difference-in-differences regression using the accreditation date as an alternate definition of treatment will pick up the net effects of price and mandate changes. We further elucidate the accreditation effect with an additional specification that controls for the construction effect while estimating the accreditation effect, which will help us pick up the specific effect of the price and mandate changes.

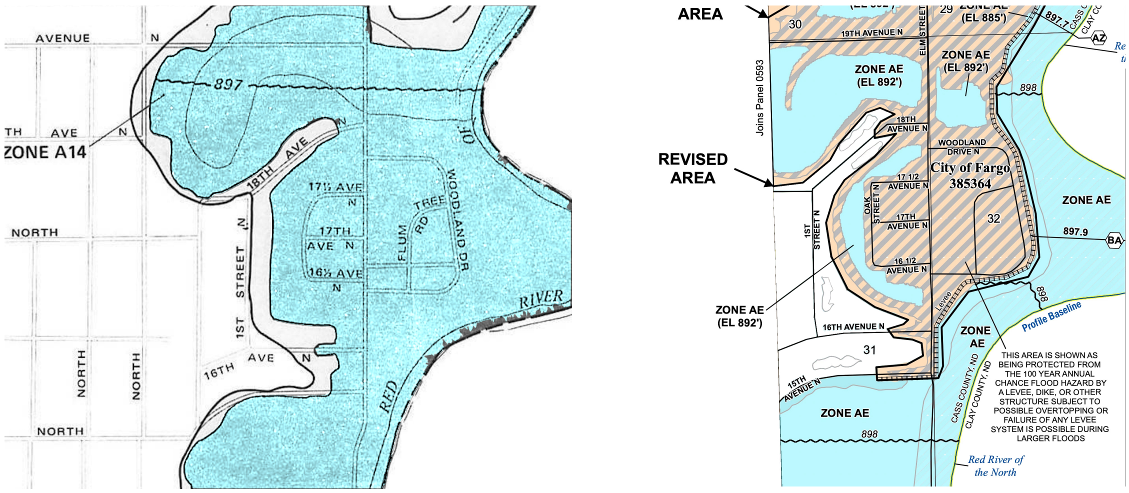
4 Data

We combine several data sources listed in Table 2 into a panel dataset that includes information about levee location, construction and accreditation dates, insurance policy counts, and housing and population characteristics. All levee information is drawn from The National Levee Database (NLD). The US Army Corps of Engineers (USACE) actively maintains and updates the NLD. (NLD; U.S. Army Corps of Engineers, 2022); [3] The NLD contains the end date of construction, current accreditation status, and information on USACE oversight. Table 3 includes data availability and covariate averages for several characteristics

[3] Our data extract was most recently updated in May 2023

Figure 3: Example Flood Map in Fargo, ND, Pre- and Post-Accreditation

(a) Pre Accreditation (b) Post Accreditation



Note: These two images depict a portion of Fargo, North Dakota before and after the levee accreditation process. On the left is the original flood map from 1978. The blue area denotes the Special Flood Hazard Area (SFHA) of the region. On the right is the updated flood map from 2015, following the accreditation of the levee (denoted by the black striped line towards the right of the frame). The gray-and-tan striped area denotes the geographic region that is now considered reduced risk (Zone X) due to the protective capabilities of the levee. This updated map was published as part of a "Letter of Map Revision" (LOMR), following the accreditation process.

included in the NLD. Additionally, the NLD contains detailed spatial data which characterize (1) the location of the levee system and (2) the boundaries of the leveed area, as determined by a number of engineering analyses, and reviewed regularly by local districts. Only 24 percent of levees in the NLD have a construction date listed. Therefore, our main construction analysis sample consists of 165 levees. Additionally, 17 percent of all levees are listed as currently being accredited, indicating that the process of accreditation is somewhat infrequent. The levees in our accreditation analysis tend to have smaller protected leveed area regions and have a lower annual exceedance probability (Table 3).

Table 1: Summary of Data Sources

	Data	*Source*	*Relevant Variables*
1	Levee characteristics	National Levee Database	Levee geography, protected leveed area geography, year constructed
2	Accreditation information	FEMA Map Service Center - Letters of Map Revision	Accreditation dates and geographic information about map revisions
3	Insurance policies ('01-'08)	Wagner (2022)	Policy counts and average premia data
4	Insurance policies ('09-'22)	FEMA Public Data Portal	Policy counts and average premia data
4	Insurance policies ('80-'07)	Gallagher (2014)	Policy counts
5	Mortgage counts	Freddie Mac; Fannie Mae	Counts of active federally backed mortgages
6	Housing and population metrics	IPUMS; FRED; SEER	Housing units, personal income, housing price indices, population

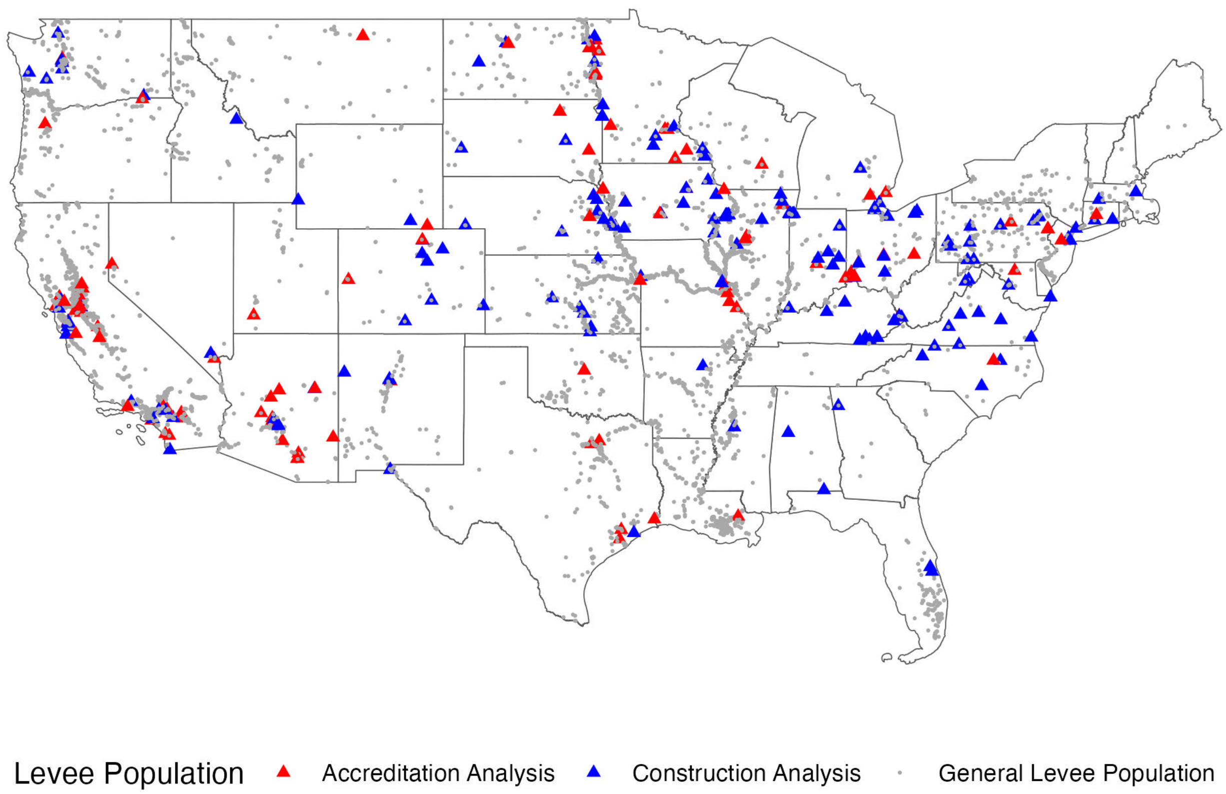
The dates of levee accreditation are not included in the National Levee Database. We used detailed documentation from the FEMA Map Service Center to identify and match areas with levees that received a "Letter of Map Revision" (LOMR) from FEMA. These documents include information about the date the revision went into effect, which we use to identify the year of accreditation. In order to ensure that the map change is specifically due to the levee, we digitally identify every LOMR that includes verbiage about levees and/or levee certification, and using a mix of manual and digital methods on the available spatial data, map each LOMR to its corresponding levee in the NLD. We were able to cross-validate this matching method using data for currently effective map revision documents, since the changes are still reflected in current flood insurance rate maps. Appendix Figure [XXX] depicts an example document, and outlines the detection and matching process we utilized to match LOMR documents with the corresponding levees.

Figure 4 displays the location of the population of levees in the continental US, demonstrating the broad geographic range of levees in the US. Our sub-sample of analysis includes 165 levees within the construction analysis, and 114 levees within the accreditation analysis. Table 3 summarizes some of the available information on levees and describes our sample of analysis. Relative to the full population of levees, our study sub-samples contain more currently accredited levees, but similar sized levee systems. The leveed areas of the sub-samples are on average smaller than those of the full population. In the sub-sample

Table 2: Matrix of Flood Insurance Policy Data Sources

Source	*Geographic Unit*	*Years*	*Available Variables*
Gallagher (2014)	Census Place	1980-2007	Policy counts
OpenFEMA	Census Tract	2009-2022	Policy counts, purchased insurance premia, purchased coverage amounts, offered insurance rates

Figure 4: National Distribution of Levee Locations



Note: The gray points indicate the locations of all 6,878 levees documented in the National Levee Database (NLD). The red triangular points represent the locations of the 165 levees utilized in the construction date analysis, and the blue triangular points represent the location of the 128 levees used in the Throughout the analyses, we only consider levees within the contiguous US. All 48 contiguous US states and the District of Columbia are represented in the NLD, and the construction and accreditation analysis subsample includes levees from 42 states.

of levees used in the accreditation date analyses, the vast majority (87.9 to 94.4 percent) of those levees are still classified as accredited on the National Levee Database. Levees can lose their accreditation status if they are not properly maintained, which is why the population of currently accredited levees does not perfectly correspond to the population of ever-accredited levees.

Table 3: Summary Statistics of Levees within Full Population and Study Sub-samples

		Census Place			*Census Tract*
	Full Population	Cons. DID	Acc. DID	Combined DID	Acc. DID
Levee Count	6878	165	99	40	59
Pct. Has System Length Data	98.65	96.97	92.93	97.5	93.22
Mean System Length (miles)	3.38	3.12	2.22	3.17	2.07
Pct. Has Leveed Area Data	100	100	100	100	100
Mean Leveed Area (sq. miles)	9.21	4.7	1.93	3.42	2.01
Pct. Has AEP Data	32.55	87.88	54.55	92.5	52.54
Mean Annual Exceedance Prob.	0.0258	0.0094	0.0024	0.0026	0.0018
Pct. Has Construction Year	24.25	100	38.38	100	35.59
Mean Construction Year	1965	1995	1997	1998	1995
Pct. Has Accreditation Year	3.01	18.79	100	100	100
Mean Accreditation Year	2009	2008	2007	2006	2015
Current Accreditation Status					
Pct. Accredited	17.24	48.48	87.88	90	94.92
Percent Not Accredited	75.62	36.36	8.08	0	1.69
Percent Other	4.57	12.73	4.04	10	3.39
Percent Unknown	2.57	2.42	0	0	0
Managed by USACE					
Percent Yes	23.07	72.73	40.4	72.5	40.68
Percent No	76.93	27.27	59.6	27.5	59.32

Note: This table provides total counts and average characteristics for the levees in the full population of levees documented in the National Levee Database (NLD), as well as several study sub-samples. The sub-samples are divided into two categories: sub-samples used in the main Census place-level specifications, and the sub-sample used in the Census tract-level specification. “Cons. DID” refers to the difference-in-differences regression analysis using construction end date as the definition of treatment (see Table 4), and “Acc. DID” refers to the analysis using accreditation date as the definition of treatment (see Table 5). “Combined DID” refers to the additional specification in Table 7. The final column refers to the levees used in the Census Tract-level analysis. Since the Census tract insurance policy data only starts at 2009, this sub-sample includes more recently accredited levees.

FEMA publishes the NFIP Policies and Claims dataset through OpenFEMA (OpenFEMA, 2022). The data contain information on the universe of flood insurance policies and claims since 2009, with earlier observations going back to 1978. From these data, we can observe details of policy premia and claim amounts. The data are at the claim and policy levels, although the only available geographic identifiers are at the Census tract and ZIP code levels. Before 2009, the policy data only include policies that were still in effect as of 2009 or later. Due to this constraint, we do not know the full volume of insurance policies prior to 2009, and thus we limit our Census tract-level analysis to 2009 to 2022. Since the average construction date of levees in the NLD is 1965, it is helpful to be able to study levee construction by considering insurance policy take-up earlier than 2009. Therefore, we supplement the OpenFEMA data with policy counts from Gallagher (2014) that includes policy counts data for NFIP at a Census place/NFIP community level, from 1980 to 2007. Since this data provides the longest possible time horizon of flood insurance policy counts, we also aggregate the Census tract data to a Census place level and append it to this dataset, forming a panel ranging from 1980 to 2022. Census tracts are the smallest possible geographic unit, so a higher percentage of the unit is within the leveed area. However, having a longer time horizon, as we do in the Census place-level data sample, allows us to study levees built in the 1980s and 1990s, significantly expanding the breadth of levees in the study sample.

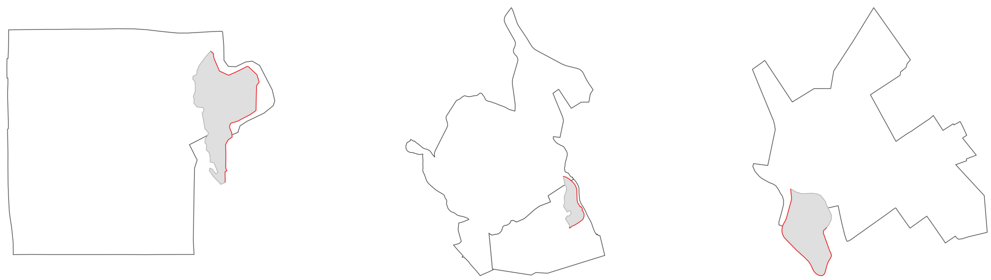
We supplement our data with a manual calculation of offered NFIP insurance rates, which is the price of \$100 of insurance coverage for different categories of properties. NFIP publishes archived versions of these rate tables from 2005 to 2020 on its website. We collect property-level characteristics from Corelogic Tax data, which compiles national tax assessment data and includes longitude and latitude, construction year, and basic housing characteristics. Using these characteristics along with NFIP effective rate maps, we match properties to an estimated coverage rate and aggregate the property-level data to a Census tract level, giving us an estimated offered rate for a given Census tract before and after the accreditation of the levee.

Additionally, we obtain demographic information from the sources listed in Table 2. We use county-level information on housing prices (Federal Reserve Economic Data, 2022), income (Federal Reserve Economic Data, 2022), and population (Surveillance, Epidemiology, and End Results Program, 2022) for summary statistics and falsification tests. We standardize our metrics for policy volume by relying on estimates of the number of housing units from IPUMS (Ruggles et al., 2022) and the Historical Housing Unit and Urbanization Database (HHUUD; Markley et al., 2022). This information is available once per decade and we linearly interpolate between decennial Census years to obtain estimates for the interim years. This allows us to construct a "policy take-up rate" which is our primary outcome of interest. We define treated geographic units as those that spatially overlap with leveed areas. Figure 5 demonstrates the procedure of defining treatment from three different levee systems on Census tracts. Since the treatment definition is broader than that of the geographic units, our estimated treatment effect will include insurance take-up behavior of both directly protected households immediately within the protected "leveed area", and households outside of the leveed area, for whom the protection benefits are uncertain.

Our main specification includes results from the Census Place population, since that constitutes the

Figure 5: Examples of Census Tract Treatment Assignment

(a) Austin, MN (b) Stroudsburg, PA (c) East Stroudsburg, PA



Note: Each spatial component, denoted by a black outline, represents a Census tract. The levee system is demarcated by the red line, and the gray area indicates the leveed area, as defined within the National Levee database. We define a geographic unit as treated if it overlaps at all with the protected leveed area of a levee system.

longest possible panel data, spanning 42 years. Within that time frame, we find that 195 Census places were treated by 165 constructed levees, and 114 Census places were treated by 99 accredited levees. However, very little additional information about the attributes of these insurance purchases is known at the Census place level. Therefore, we supplement the accreditation analysis at a Census tract level. Table 6 shows results for additional covariates at a Census tract level, which includes 148 tracts treated by 59 levee systems.

5 Empirical Design

5.1 Identification Strategy

The purpose of our empirical analysis is to identify the causal effect of levee provision on household insurance take-up. A primary threat to the naive comparison of policy take-up before and after levee provision is that levee provision may be correlated with a number of characteristics that also affect insurance take-up. For example, if we simply measured the correlation between levee provision and insurance take-up, we would likely find a positive relationship, since both levee provision and insurance take-up are positively correlated with the inherent flood risk of an area and local household income.

To avoid this threat to identification, we leverage variation in the exact timing of levee construction and levee accreditation within a DID ("difference-in-differences") regression design. The identifying variation of this empirical strategy is that the *precise timing* of levee provision is uncorrelated with characteristics that could affect insurance take-up decisions. We limit the current analysis to only ever-treated geographies, since locations with and without levees may differ substantially on a number of observable and unobservable characteristics. For example, geographic units that have levees may have greater availability of resources to fund expensive infrastructure projects, indicating different trends in population or household income than geographic units without levees.

Let i index geographic units and t index years. Our primary analyses focus on Census place as the level of geographic unit, due to the broad range of years with available insurance policy take-up information. We supplement our accreditation date analysis with Census tract-level results, since the geographic granularity of the Census tract allows for a larger range of levee accreditation events to be included. It also allows us to study a larger variety of insurance-related characteristics, such as offered insurance rates, and purchased premia, and the level of coverage purchased by households. Table 2 provides a summary of the data availability for each sample, and Table 3 documents the differences between the levees included in the Census place- and Census tract-level accreditation analyses.

The difference-in-differences methodology we use closely follows the "stacked DID" method used in Deshpande and Li (2019). This approach avoids the problematic comparison of comparing geographic units experiencing levee provision to those that have *already* experienced levee provision. First, we define a "levee cohort" of geographic units treated by a particular levee l. For each cohort l, we define a set of "not-yet-treated" control units, which consists of other geographic units that were treated four or more years after the cohort. This allows us to compare treated units to a control group that was not treated until after the observed post-trend. The treatment effect is estimated by calculating the difference in outcomes between treated and control units, before and after the treated cohort was treated, and averaging the estimated effect across all levee cohorts. We cluster our standard errors at a levee cohort level l. We perform this analysis by estimating the following event-study (staggered DID) specification, for geographic unit i, levee l and year t:

$$Y_{ilt} = \phi_i + \gamma_t + \delta_0 Treated_{il} + \sum_{\tau} \alpha D_{ilt}^{\tau} + \sum_{\tau} \left(\delta_{\tau} Treated_{il} \times D_{ilt}^{\tau}\right) \tag{1}$$

Our primary outcome of interest is the flood insurance take-up rate, Y_{it}, which we calculate by dividing the number of policies in i and year t by the estimated number of housing units in it. $Treated_{il}$ takes a value of 1 for the treated units for the particular levee cohort l, and 0 for the not-yet-treated geographic units, as of that particular levee's construction or accreditation date. Therefore, the parameter of interest δ_{τ} estimates the difference in average insurance take-up rates between already- and not-yet-treated geographic units at different event times τ. In this specification, we consider $\tau \in \{-3, 3\}$, estimating changes in policy take-up three years before and after the levee construction or accreditation event. Appendix Table[XXX] includes the event study specification when we consider $\tau \in \{-5, 5\}$. We also include the traditional two-way fixed effects estimation in Appendix Table [XXX]. The estimates are similar in sign and magnitude to our primary event study specification. This is not our preferred specification due to the negative weights issue, which arises when already-treated units are included in the comparison to the treated units (Callaway and

Sant'Anna, 2021).

To capture the static treatment effect, aggregated over event time for three post-periods used in the event study specification, we additionally estimate the following static DID regression, where the coefficient of interest, β, denotes the average change in household insurance take-up across the three years following levee provision.

$$Y_{ilt} = \phi_i + \gamma_t + \delta_0 Treated_{il} + \sum_{\tau} \alpha D_{ilt}^{\tau} + \beta Treated_{il} \times Post_{lt} \tag{2}$$

6 Results

6.1 Construction Analysis

Our primary specification estimates the effect of levee construction on flood insurance policy take-up, using the Census place-level sample. In Figure 6, we present the estimates of the δ_τ coefficients from Equation 1. We find that prior to levee construction, there is no significant difference in policy take-up trends between treated- and not-yet-treated Census places. However, following construction, treated Census places decrease their policy take-up compared to the not-yet-treated control group. We interpret this estimate as evidence that levee construction causes policy take-up to decrease by 0.5 to 1.8 percentage points. In Table 5, we also present the aggregated treatment effect β from the static stacked DID specification. We find that in aggregate, levee construction causes a decrease in insurance take-up of 1.6 percentage points. On a baseline *ex-ante* take-up rate of 8 percentage points, this corresponds to a 20 percent decrease in insurance take-up. Following from Figure 2, this decrease is suggestive evidence of household responses to the decrease in flood risk following levee construction.

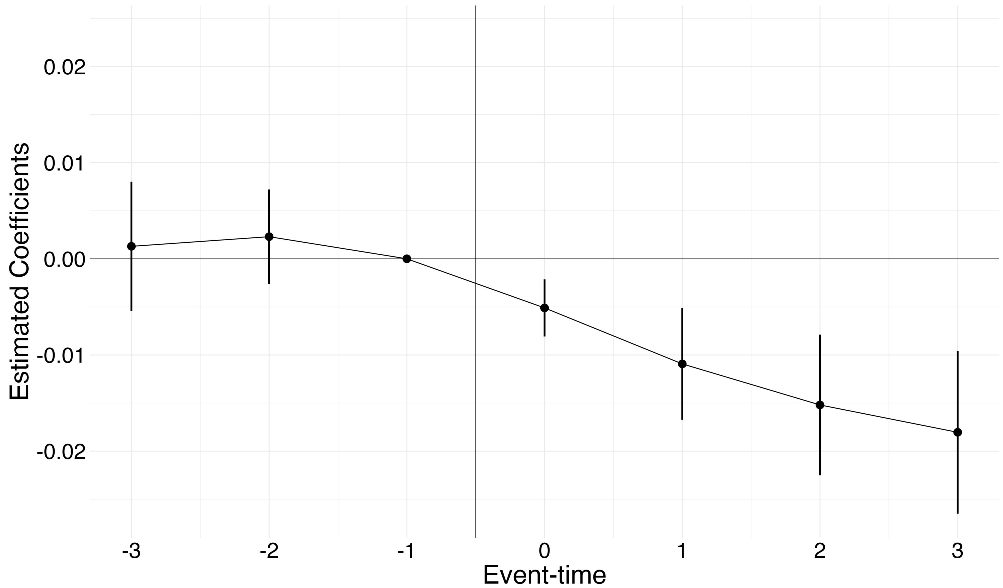
Table 4: Estimates of the Effect of Construction on Flood Insurance Take-up: Difference-in-differences

	Dependent variable:
	Policy Take-up Rate
Post Construction	-0.016^{**}
	(0.008)
Observations	8,190
Baseline Mean	0.08
Note:	*p<0.1; **p<0.05; ***p<0.01

6.2 Accreditation Analysis

We next estimate the effect of levee accreditation on our Census place population. The results from the event study specification of accreditation dates are presented in Figure 8. Here, we see a statistically significant

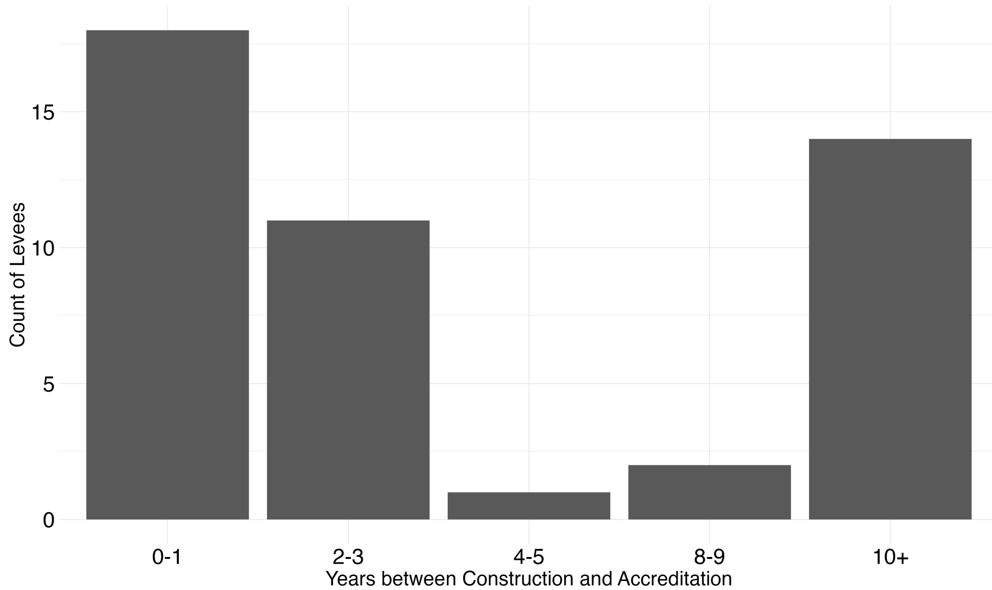
Figure 6: Estimates of the Effect of Construction on Flood Insurance Take-up: Event Study



pre-trend: even prior to accreditation, treated- and not-yet-treated Census places have differing trends in policy take-up. Following levee accreditation, treated- and not-yet-treated Census places have a difference in policy take-up ranging from 0.7 to 1.1 percentage points, which corresponds to a 3.6 to 5.4 percent decrease in flood insurance take-up. The documented pre-trend is in line with our understanding of the construction-accreditation timeline: as documented in Figure 7, more than 65 percent of levees with known construction and accreditation dates are accredited within 5 years of construction. Therefore, it is very likely that the pre-trend observed in the accreditation date event study is due to the residual decrease in insurance take-up following levee construction. Immediately following the levee accreditation, we see a change in the slope of the trend, indicating that the price and mandate changes precipitated by accreditation dampen the negative take-up trends caused by levee construction.

We conduct an auxiliary analysis of levee accreditation using our Census tract sample. This is for two reasons: first, the broader availability of premium and coverage data within the additional sample allows us to measure whether prices are indeed responding to accreditation, and how much households change their insurance premia and purchased coverage. Second, it provides a robustness check of our Census place result, especially since the levees in the Census tract sample are more recently accredited. In Table 6, we present the difference-in-difference estimates for various variables including the percent of a Census tract considered to be an accredited zone (denoted as reduced-risk Zone X on flood rate maps), and the offered insurance price (rate) per \$100 of coverage. We find that the accredited zone percentage increases significantly following accreditation, and the offered insurance rate decreases substantially. Additionally, we estimate an effect of

Figure 7: Histogram of Number of Years between Construction and Accreditation Events



a similar sign for the average purchased premium, but not statistically significant. Although we expect the average purchased premium to behave similarly to the offered rate, the offered rate is calculated to include the prices faced by *anyone* in a Census tract with a levee- not just the households who actually purchased a policy. On the other hand, the result for the average purchased premium will be subject to selection: people who buy insurance before and after the levee may substantially vary, so we cannot attribute a decrease in purchased premium solely to the lowered prices from accreditation. We also include an estimate for the effect of accreditation on coverage purchased, and find that the average coverage purchased increases. Again, this is subject to selection: households who purchase flood insurance after the levee provision may be more risk averse, or more prone to flooding, than the average household prior to levee provision, and purchase higher levels of coverage. Finally, the estimates of the effect of accreditation on policy take-up using the Census tract sample, (the δ_τ coefficients from Equation 1) are show in Figure 9. Qualitatively, the Census tract-level coefficient estimates exhibit similar trends to the Census place-level results: we see a pre-trend depicting decreasing insurance take-up rates prior to levee construction, and a deceleration of the decrease immediately following accreditation.

Table 5: Estimates of the Effect of Accreditation on Flood Insurance Take-up: Difference-in-differences

	Dependent variable:
	Policy Take-up Rate
Post Accreditation	-0.009^{*}
	(0.005)
Observations	4,788
Baseline Mean	0.045
Note:	*p<0.1; **p<0.05; ***p<0.01

Figure 8: Estimates of the Effect of Accreditation on Flood Insurance Take-up: Event Study

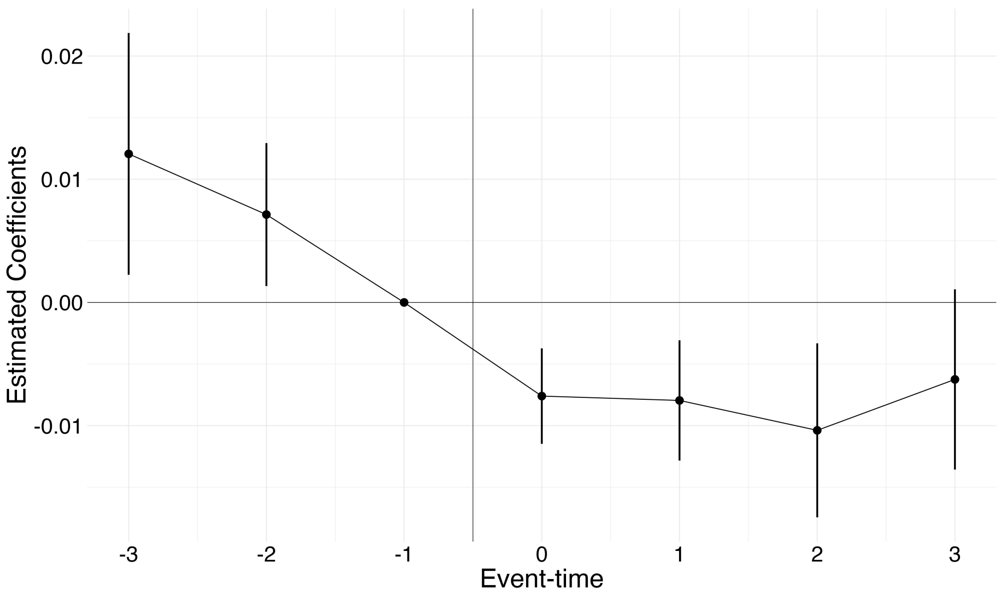
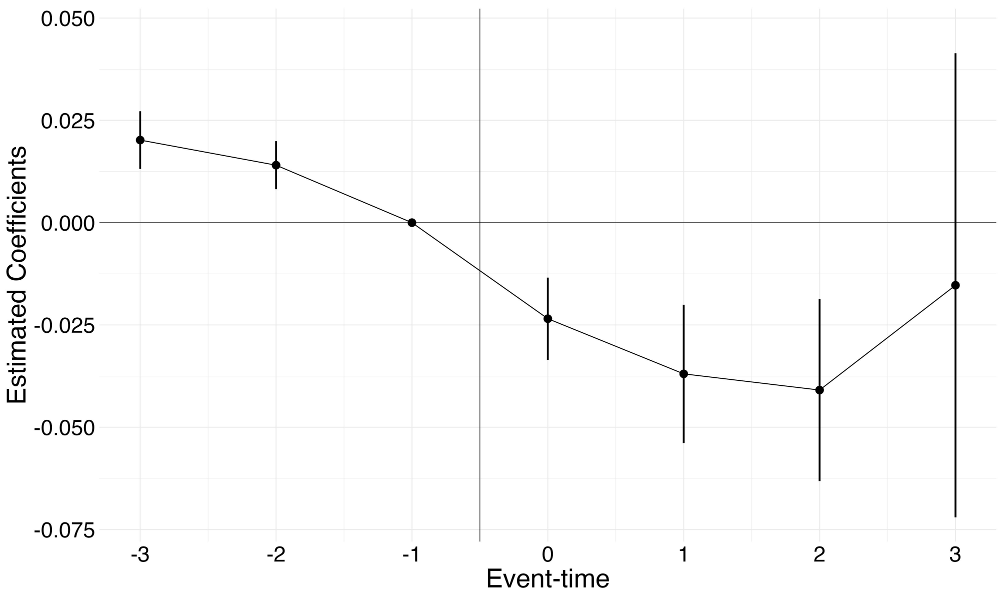


Table 6: Census Tract-level Estimates of the Effect of Accreditation on Insurance Prices and Purchase Decisions: Difference-in-differences

	Dependent variable:			
	Pct. Accred. Zone	Rate per $100 Coverage	Avg. Premium	Avg. Coverage
	(1)	(2)	(3)	(4)
Post Accreditation	0.24^{***}	-1.27^{***}	-38.15	$9{,}676.69^{**}$
	(0.06)	(0.41)	(34.27)	(4,570.19)
Baseline Mean	0.55	$1.14	$1,096	$271,118
Tract FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Note:				*p<0.1; **p<0.05; ***p<0.01

Figure 9: Census Tract-level Estimates of the Effect of Accreditation on Flood Insurance Take-up: Event Study

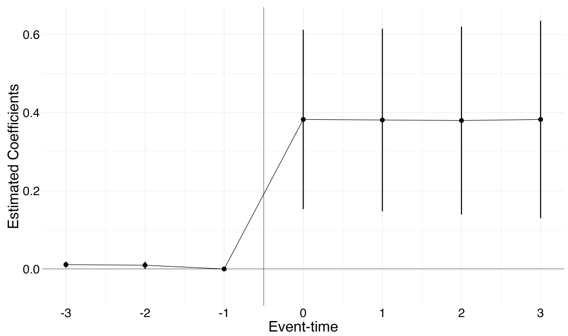


Since we have limited data on both construction and accreditation dates, the sample of levees used in accreditation analysis is different from the sample of levees in the construction analysis. Most notably, the construction date analysis includes Census places treated by levees that were never accredited. To this end, we conduct an additional analysis using the Census place data to capture the cumulative effect of both construction and accreditation within the same specification, using the limited sub-sample of levees for which we have both a construction and accreditation date. We estimate a variation of Equation 2, using the specification in Equation 3. As indicated in Table 3, this limits our sample to 40 levees and 42 Census place units. Our estimates provide a quantitative foundation to the qualitative effect of accreditation we observed in the accreditation event study specifications above, where we saw a "deceleration" in the post-construction decrease in demand following the accreditation date. We observe a large, statistically significant decrease in policy take-up following construction, and after controlling for the construction effect, the accreditation effect is small and statistically insignificant.

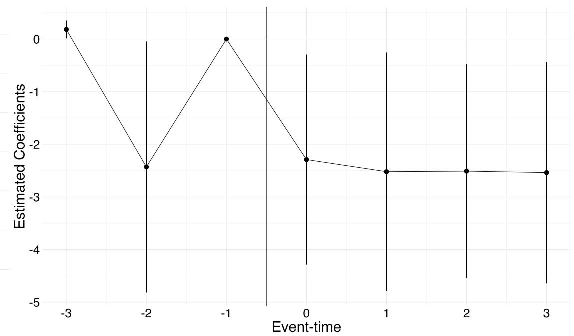
$$Y_{ilt} = \phi_i + \gamma_t + \delta_0 Treated_{il} + \sum_{\tau} \alpha D^{\tau}_{ilt} + \beta_C Treated_{il} \times PostCons_{lt} + \beta_A Treated_{il} \times PostAcc_{lt} \tag{3}$$

Figure 10: Census Tract-level Estimates of the Effect of Accreditation on Insurance Prices and Purchase Decisions: Event Study

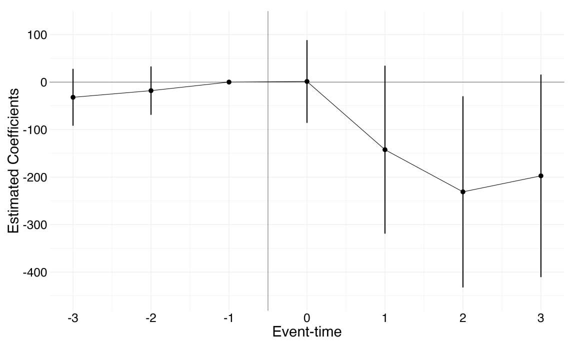
(a) Percent Accredited Zone



(b) Offered Insurance Rate per $100 of Coverage



(c) Purchased Insurance Premia (2021 $)



(d) Total Amount of Purchased Insurance Coverage

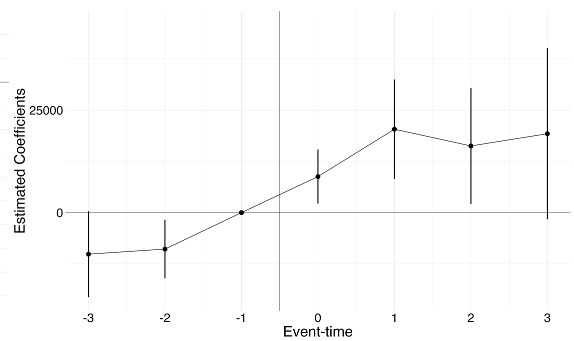


Table 7: Census Place-level Estimated Treatment Effect for Combined Specification

	Dependent variable:
	Policy Take-up Rate
Post Construction	-0.032^{*}
	(0.017)
Post Accreditation	0.017
	(0.014)
Observations	1,680
Baseline Mean	0.051
Note:	*p<0.1; **p<0.05; ***p<0.01

6.3 Falsification Tests

A concern to our causal identification strategy is that the precise timing of the levee provision may be correlated with other contemporaneously changing characteristics, such that it is unclear whether the levee or the other changing characteristics are causing the perceived change in insurance take-up. This is commonly known as a 'bundled treatment'. In order for β to causally identify the average treatment effect on the treated, we must assume that the parallel trends assumption holds. Specifically for our context, this means that in the absence of the levee's provision, affected geographic units would have had similar trends in flood insurance take-up to those units that did not yet have a levee. In other words: the exact timing of the levee provision is uncorrelated with unobserved, time-varying factors that could affect flood insurance take-up. We provide three pieces of evidence to support this claim.

First, the estimates of δ_τ from Equation 1 are presented in a coefficient plot in Figure 6. In these event study specifications, we include three time periods of "negative event time", denoting the time periods prior to the levee construction. We see in Figure 6 that these pre-periods do not exhibit any statistically significant differences in policy take-up rates, which serves as evidence that there were not pre-existing differences in already- and not-yet treated geographic units prior to levee construction. Appendix Figure [XXX] shows a similar event study plot for a specification with five, not three pre-periods. There, we see a similar lack of a differential pre-trend between already- and not-yet-treated units.

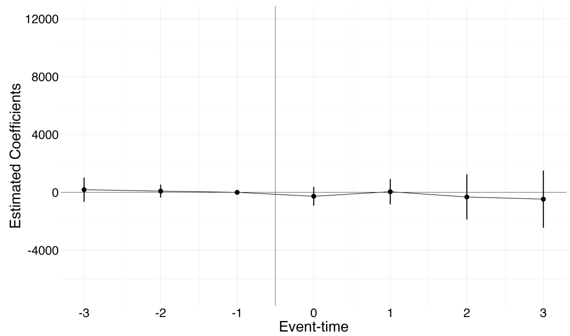
Second, in Figure 11, we present several additional estimations of Equation 1, using three different demographic characteristics: population, aggregate personal income, and the Case-Shiller housing price index. These event study estimates are a helpful diagnostic to determine whether there are any changes in trends for salient observable characteristics that are contemporaneous with levee provision. If trends in local economic conditions differentially varied between treated- and not-yet-treated geographic units, before and after levee provision, then we cannot be sure whether the observed difference in insurance policy take-up was because of the levee itself, or because the differential trends in economic conditions. We see in Figure 11 that the trends in population and personal income are stable and not significantly different before and after the levee provision, as defined by both construction and accreditation. These results indicate that economic conditions are not the drivers of the estimated changes in flood insurance take-up.

Third, we would like to consider levee construction timing to be "as if random". In order to demonstrate this, we estimate the regression in Equation 4, where $ConstructionYear_i$ denotes the year that Census place i had a levee constructed.

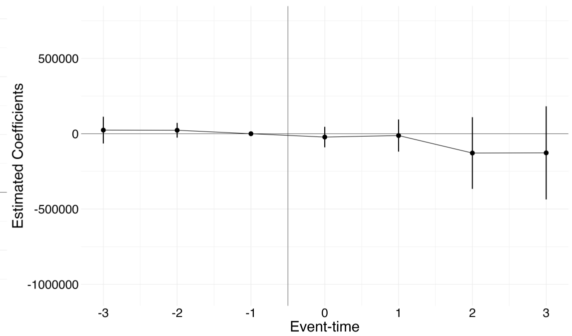
$$ConstructionYear_i = Population_i + PersonalIncome_i + HPI_i + \varepsilon_i \tag{4}$$

Figure 11: Falsification Tests: Event Study Estimation of Local Economic Conditions across Levee Provision

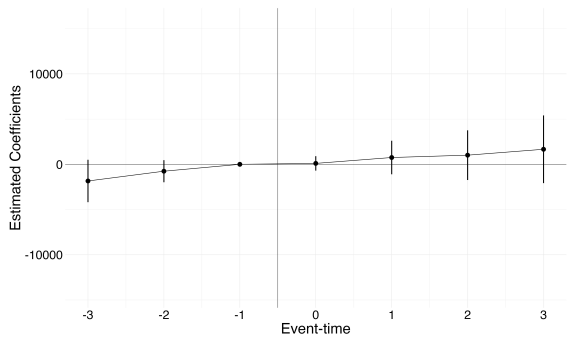
(a) Construction: Population



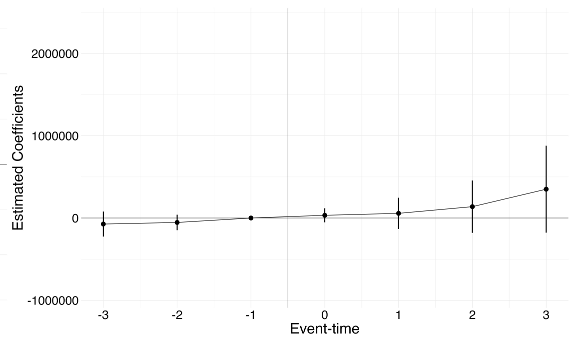
(b) Construction: Aggregate Personal Income



(c) Accreditation: Population



(d) Accreditation: Aggregate Personal Income



In this regression specification, we regress the specific timing of levee provision, both the construction and the accreditation date, as a function of observable local economic factors: population, aggregate personal income, and the Case-Shiller housing price index. The results are presented in columns (1) and (2) of Table 8. We find that these economic factors are not predictive of the specific timing of levee provision. Therefore, we are confident that the precise timing of levee provision is exogenous to trends in these observable characteristics, and we can interpret our estimated treatment effects as causal from levee provision.

7 Understanding the Welfare Impacts of Levee Provision

In this section, we discuss some approaches to calculating the benefit of levee provision, taking into consideration the estimates of policy take-up changes caused by construction and accreditation. Due to the net negative effect of levees on insurance take-up, we consider levees and insurance to be substitute goods. By providing a levee, the government endows households with a substitute for their insurance purchases: the levee serves as an implicit subsidy to households by effectively shifting the exposure to risk from the insurance-holding household to the government-provided public good. For the first approach to quantify the

Table 8: Falsification Test: Coefficient Estimates of Equation 4

	Dependent variable:		
	Construction Date	Accreditation Date	Construction-Accreditation Gap
	(1)	(2)	(3)
Total Population (1980)	0.0000	0.0001*	0.0001**
	(0.0000)	(0.0000)	(0.0001)
Total Personal Income (1980)	−0.0000	−0.0000*	−0.0000**
	(0.0000)	(0.0000)	(0.0000)
Case-Shiller HPI (1980)	−0.07	0.01	−0.24**
	(0.07)	(0.07)	(0.09)
Constant	1,998.07***	2,006.22***	13.11***
	(3.68)	(3.63)	(4.20)
Observations	122	80	26

*p<0.1; **p<0.05; ***p<0.01

value of the levee provision, we calculate the aggregate decrease in household spending on flood insurance.

$$\text{Extensive-Margin Decrease in Spending} = \text{Household Count} \times \Delta\text{Policy Take-up Rate} \times \text{Ex-Ante Premium} \tag{5}$$

$$\text{Intensive-Margin Decrease in Spending} = \text{Ex-Post Policy Holders} \times \Delta\text{Premium} \tag{6}$$

We consider the total counts of housing units in the entire Census place in our calculation of the total decrease in insurance spending, but we could also consider an alternate specification where we remove indirectly affected households that are in the same Census place as a levee, but are not immediately within the leveed area. We estimate the number of directly affected housing units by calculating the proportion of a Census place geography that overlaps with a "leveed area", and multiplying it by the total number of housing units in the Census place. The per-household extensive margin change in spending is estimated by multiplying the change in the policy take-up rate by the average *ex-ante* change in insurance premium. We can include the intensive-margin take-up savings by multiplying the *ex-post* number of insurance-purchasing households times the change in insurance premium, since continuing insurance customers will save money on lower insurance rates.

$$\text{Total Decrease in Spending} = \text{Extensive-Margin Decrease in Spending} + \text{Intensive-Margin Decrease in Spending}$$

(7)

Table 9: Statistics for Calculation of Changes in Household-level Spending due to Levee

Statistic	Estimate
Total Household Count	8,643,486
ΔPolicy Take-up	-0.20
Ex-Ante Premium	$1,098.53
Ex-Post Policy Holders	162,713
ΔPremium	-$38
Total Decrease in Insurance Spending	$1,905,208,829

From this back-of-the-envelope calculation, we estimate that levee provision causes aggregate household insurance spending to reduce by almost $2 billion. It is beyond the scope of this paper to suggest whether this decrease is efficient or exacerbates an existing market failure regarding existing low levels of household flood insurance take-up. This will depend on various assumptions about the risk aversion and preferences of households, and how these preferences change following the endowment of a large-scale protective infrastructure investment. Additionally, we plan to conduct additional research that will compile known sources of flood damages, in order to back out an estimate of dollars saved in damages as a result of the protective capabilities of the levee. Comparing this to the dollars saved on flood insurance will allow us to estimate households' net monetary benefit from the levee.

8 Conclusion

In this paper, we present a novel empirical finding concerning the relationship between levee construction and flood insurance take-up. We find a statistically and economically significant decrease in insurance take-up immediately following levee construction, and an increase following levee accreditation. Our findings suggest that, in practice, following construction levees and flood insurance are substitutes rather than complements. However, after prices and mandate requirements are changed during the accreditation process, the relationship between the policy instruments changes, and the ongoing negative effect of the levee construction is lessened. We find that this decrease in insurance take-up leads to an aggregate $1.9 billion in household savings from foregone flood insurance. From a policy-maker's perspective, this finding underscores the importance of considering the interaction of multiple policy instruments in mitigating households' exposure to flood risk.

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