# Private Benefits from Public Investment in Climate Adaptation and Resilience[*]

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## Abstract

A changing climate will cause more intense and frequent flooding across the United States, resulting in major losses of life and property. As these risks intensify, governments will consider ways to use public funds to protect communities. We estimate the magnitude and distribution of benefits from a major form of public flood risk adaptation, US Army Corps of Engineers flood control levees, to explore the efficiency and equity implications of these large-scale investments. We combine data on areas protected by Army Corps levees with 30 years nationwide residential property transactions to estimate a broad set of effects of public adaptation investments on US housing prices. We find that the expected net present value of protection benefits from Army Corps levees can exceed 2.8% of home value; however, spillover effects to surrounding, unprotected properties in the form of increased flood risk can reduce home value by as much as 1.1%. We examine the distributional incidence of the various effects of levee construction, estimate the aggregate benefits and costs of USACE levees, and explore local political economy considerations around levee siting decisions.

Keywords: Climate change adaptation, housing markets, differences-in-differences, triple differences

JEL Codes: Q54, Q58, H23, H22

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## 1 Introduction

Given the slow pace of greenhouse gas emissions mitigation, governments face a growing imperative to address the impacts of climate change. For example, a changing climate will cause more intense and frequent flooding across the United States, resulting in major loss of life and property as illustrated by recent extreme events, including Hurricane Harvey of 2017, the Mississippi River floods of 2019, and Hurricane Ida of 2021. The First Street Foundation, a non-profit flood modelling group, estimates that the share of properties in the United States at risk of regular flooding will increase by 8.2% over the next 30 years, though this figure masks significant heterogeneity as shown in Figure 1 with some areas facing substantial growth in flood risks (First Street Foundation, 2021). Public policies to manage the physical risks associated with climate change are therefore of growing importance.

Current climate adaptation policy is likely inadequate. In the face of increasing natural hazard risks, the United Nations Environment Programme estimates global adaptation spending will need to amount to \$160-340 billion annually by 2030 and \$315-565 billion annually by 2050 (United Nations Environment Programme, 2022). While recent efforts such as the Infrastructure Investment and Jobs Act of 2021, which appropriates tens of billions of dollars for climate adaptation investments in the US, make progress towards funding these needs, a wide gap still remains. As governments consider options for investing in community resiliency, the ensuing policy debate will prompt questions about the benefits and costs characterizing these alternatives: how large are the relevant benefits and costs and who receives them?

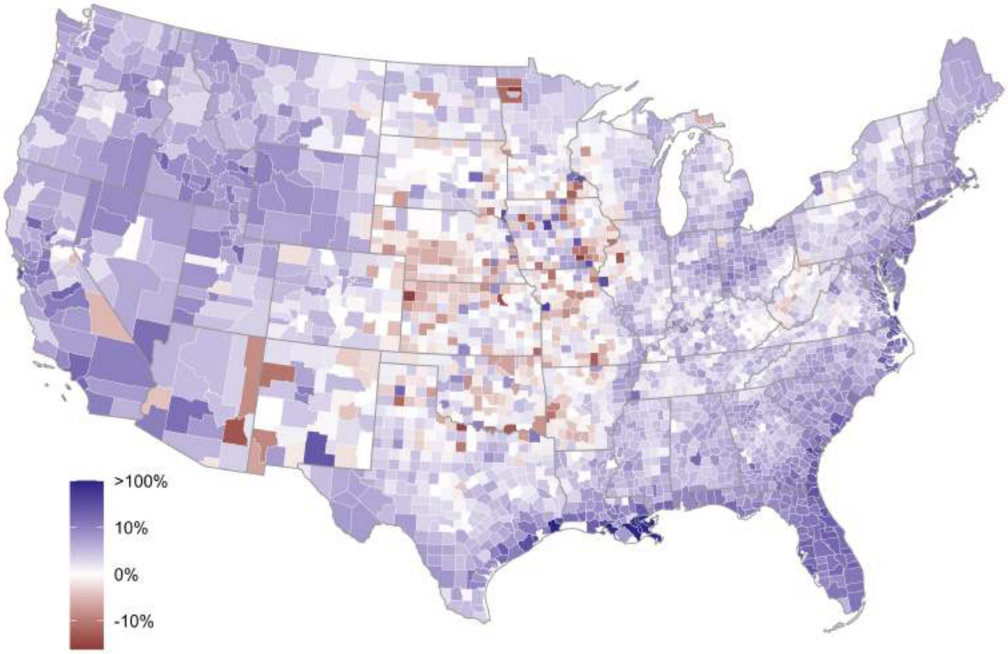
This paper examines the magnitude and incidence of benefits and costs of public climate adaptation investments. We explore how public investment in adaptation is capitalized in home prices through local property markets. We focus on what historically represents one of the largest single investments in flood risk reduction infrastructure in the US: levee projects. These are public infrastructure projects that deliver geographically specific benefits to nearby properties in the form of reduced risks of flooding. In addition to these flood protection benefits, there are a number of other hydrologically and economically relevant effects of levee construction, including potential flood risk spillovers to surrounding, unprotected areas. We provide empirical estimates of the magnitude of these housing market effects for a particularly salient subset of US levee projects, namely those constructed by the US Army Corps of Engineers (USACE), and leverage these estimates to better understand the distributional and welfare impacts of flood adaptation investments.

We combine hydrologically-precise information on the spatial extent of areas protected by USACE levees with transaction and assessor data from the near universe of residential properties in the continental US in order to estimate the geographically-differentiated impacts of levee construction. Our empirical design exploits information on the timing of USACE levee construction and rich geographic data on the proximity of residential transactions levee protected areas and nearby waterways to estimate a broad set of plausible housing market effects of levee construction. Our focus on USACE-constructed levee projects is primarily motivated by our empirical design—we are able to collect information on the date of construction for these projects—however, it also ensures that our analysis focuses on a relatively comparable set of projects. Given that the housing transaction data that we use in our analysis only goes back as far as 1990, we also restrict our analysis to levees constructed by the USACE after 1990 to ensure that we are able to compare transactions of residential properties before and after levee construction.

Employing a set of double-difference estimators to identify the various effects of levee construction, we find that the expected net present value of protection benefits from USACE levees amounts to 2.8% of a home's value on average; however, spillovers to surrounding, unprotected properties in the form of increased flood risk reduce home value by as much as 1.1%, suggesting that much of the flood risk reduction accomplished by levees is offset by increased risk elsewhere. We leverage plausibly exogenous variation in a transaction's recent exposure to flood-related storm events to find suggestive evidence that households learn about the flood risk impacts of USACE levee construction through recent experience with flooding.

Our rich, transaction-level data enable us to explore not only the capitalized effects of levee construction, but also the distribution of these effects along key sociodemographic variables. We find that flood protection benefits as a share of income are largest for lower income households: among the lowest income quintile households in our data, the total protection subsidy provided by USACE-constructed levees is around 10% of earnings. However, the same is true for flood risk spillovers: the decline in home value as a share of income is largest for the lowest income households in our sample, ranging from 4 to 5% of income among households in the lowest earnings quintile depending on homeowner race. Thus, while USACE-constructed levees appear at first to reallocate resources towards low income households, flood risk spillovers work to offset the progressivity of this transfer. Moreover, we find suggestive evidence of differential sorting around levee-driven changes in flood risk by different racial and ethnic groups: white and asian households appear more likely to move into levee protected areas and less likely to move into spillover exposed areas post levee construction. This is in contrast to black households, who appear more likely to move into spillover exposed areas after levee construction, and hispanic households, who appear less likely to move into protected areas after levee construction.

**Figure 1.** Change in Properties at Risk of Flooding, 2021-2051



This figure shows the county-level change in residential properties at risk of regular flooding from 2021 to 2051 according to the First Street Foundation National Flood Model.

We contextualize our estimates of the private housing market effects of USACE levee construction using estimates of the net effect of these projects on public expenditures. We manually collect information on construction costs for both federal and non-federal partner entities for a subset of the USACE-constructed levees in our estimation sample using a broad set of primary sources in order to better understand the upfront costs associated with these investments.[1] Given that we estimate non-trivial housing market impacts from levee construction, we also attempt to capture the various local fiscal externalities of levees and compare these impacts on local public finances with the private housing market impacts. Specifically, we leverage property-level information on local real estate tax rates to translate the impacts of levee construction on housing values into changes to local tax revenues.

We find that most projects for which we are able to collect construction costs have overall costs which exceed their benefits. Given that USACE has a policy of pursuing civil works projects with benefits that are at least as large as costs—and ideally only those projects

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[1] Construction cost information for USACE civil works projects are unavailable in a consistent, publicly-available format. We therefore collect this information for projects in our final estimation sample using federal budget requests, appropriations bills, and USACE annual reporting, where available. We are ultimately able to collect this information for over 65% of USACE-constructed levee systems in our sample. See Appendix A for additional details.

with benefit cost ratios exceeding 2.5—this suggests either that USACE systematically overestimates benefit cost ratios in their ex ante project assessments or that factors other than economic impacts drive decisions to proceed with construction. It is also worth noting that our approach to comparing the benefits and costs of USACE levee construction omits important impacts, including operations and maintenance costs, other fiscal externalities, and the indirect impacts of levees on regional economies. However, given that there are important omissions and limitations in our calculation of both benefits and costs, we argue that comparing ratios of the two is a reasonable exercise: even conditional on these limitations, our results suggest that ex post USACE does not meet its objective of pursuing levee projects with benefit cost ratios of 2.5 or greater.

This exercise of calculating the various categories of aggregate benefits and costs of USACE levee construction also illuminates important considerations around the local political economy of levee construction decisions. Given our relatively large estimates of flood risk spillovers and the non-trivial impacts of levee construction on local tax revenues, there is an important question as to the extent of impacts internalized by the local jurisdictions in which USACE levees are constructed. If local municipalities which partially fund the construction—and ultimately take over operation and maintenance—of USACE constructed levees do not experience the flood risk spillovers and the associated reduction in property tax revenues imposed by the levee, then our estimates clearly indicate that the project will appear far more appealing from their perspective. We find that 30% of USACE-constructed levee projects that we examine impose spillover effects on counties outside of the county protected by the levee, which suggests that USACE levee construction may indeed represent a classic market failure externality problem.

While our analysis focuses on a relatively narrow category of public investments and just one of myriad natural hazards affected by a changing climate, we argue that the lessons we learn from examining USACE levee projects extend to other forms of public adaptation investment. Any form of public adaptation investment which provides geographically localized benefits—and potentially external costs—is likely to raise similar questions about the distribution of impacts and the associated distortions in incentives to both individuals and policymakers. One particularly salient form of public investment in climate adaptation to which there are clear parallels with levees are sea walls, which feature prominently in discussions about adapting to climate-driven changes in storm surge flooding.[2]

These findings underscore the importance of evaluating the impact of existing institutions

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[2] In fact, sea walls appear to be one of USACE's preferred approaches to adapting to sea level rise-induced flooding in certain coastal urban centers: salient examples of locations where USACE has proposed sea wall construction include New York, New York (Barnard, 2020); Miami, Florida (Mazzei, 2021); and Galveston, Texas (Wilkinson, 2022).

when considering policies to improve resiliency to climate impacts. A large, growing literature on climate adaptation tends to focus on household-level adaptation (Barreca et al., 2016; Burke and Emerick, 2016; Kahn, 2016; Auffhammer, 2022). Recent work examines the implications of policies to mitigate and manage natural hazard risks on household adaptation, including publicly-subsidized flood insurance (Wagner, 2021) and wildfire suppression (Baylis and Boomhower, 2021). Our analysis is closely related to Baylis and Boomhower (2021)'s work exploring the equity and efficiency implications of public wildfire suppression in the US, which similarly to the various flood risk impacts of levee construction operates as a geographically-differentiated transfer to certain households. Our analysis likewise emphasizes the need to consider essential economic questions surrounding large-scale, public investments in adaptation and resilience.

Economists have studied the private benefits from similar investments in flood control infrastructure, including beach nourishment, flood walls, pump systems, and levees, finding that individuals have positive willingness-to-pay for these forms of flood protection (Fell and Kousky, 2015; Dundas, 2017; Gopalakrishnan, Landry and Smith, 2018; Walsh et al., 2019; Kelly and Molina, 2022). These results are a natural extension of a large set of results finding that flood risk is negatively capitalized in housing prices, with much of this literature focusing on the impact of flood-related disaster events (Hallstrom and Smith, 2005; Bin, Kruse and Landry, 2008; Bin and Landry, 2013; Ortega and Taṣpınar, 2018; Beltrán, Maddison and Elliott, 2019; Graff Zivin, Liao and Panassie, 2022) or exposure to future sea-level rise (Bernstein, Gustafson and Lewis, 2019; Murfin and Spiegel, 2020) on housing market outcomes.[3] While existing work is informative of the magnitude of private benefits from investments in flood risk reduction, they do not model direct spillovers in flood risk and therefore risk misinterpreting the overall impact of these investments. One noteworthy exception is Dundas and Lewis (2020), which estimates the capitalization of private coastal shoreline armoring for both adopting households and surrounding non-adopting households, with such private adaptation negatively capitalized in each spillover exposed property prices. In closely related work, Wang (2021) estimates non-zero spillover costs in county-level outcomes from levee heightening. Our results build on this literature by examining the direct spillover effects from large-scale, public adaptation projects using spatially-explicit housing market and levee data.

A growing literature examines the public finance implications of climate impacts and adaptation policy. This work emphasizes the imperative for public provision of adaptation infrastructure and other policies targeting resiliency to disaster risk, providing estimates of

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[3] For a summary of the literature examining the broader economic impacts of natural disasters, see Kousky (2014).

the costs associated with a lack of adaptation investments or a continuation of status quo policy (Barrage, 2020; Fried, 2021). Given the potential for highly localized variation in exposure to natural hazards exacerbated by climate change, this literature highlights the need to focus on policies to manage climate impacts at not only the national level, but also the sub-national level (Goldsmith-Pinkham et al., 2021; Liao and Kousky, 2022). Levees offer one such policy with localized benefits; however, the existence of spillovers highlight the need to consider plausibly strategic interactions between such investments. In this respect, our work relates to the broad literature on place-based policies that examines how strategic interactions can drive both governments' decisions to implement a policy and the policy's outcomes (Greenstone, Hornbeck and Moretti, 2010; Busso, Gregory and Kline, 2013; Mast, 2020).

The remainder of the paper proceeds as follows. Section 2 provides detailed background on public policies to address flood risk in the US. Section 3 provides a high-level description of the data that we use in our analysis (additional detail is provided in Appendix A). Section 4 outlines our empirical design and Section 5 provides our main results. We discuss our main results and provide additional context in Section 6. Section 7 concludes.

## 2 Flood Risk Policy in the United States

Public policy to address flood risk can be classified into several categories. The first are policies that address flood vulnerabilities, or the ways in which flood hazards result in adverse consequences. Examples of such policies include built flood control projects—often referred to as "grey" infrastructure—such as levees, dams, and shore-protection. Other examples include investments in natural features that provide flood management co-benefits—often referred to as "green" infrastructure—including coastal wetlands, undeveloped land in floodplains, and sand dunes. The second category are policies to reduce the consequences of a flood event, including changes to building codes, development restrictions, elevating and flood-proofing structures, or buyouts of at risk properties.

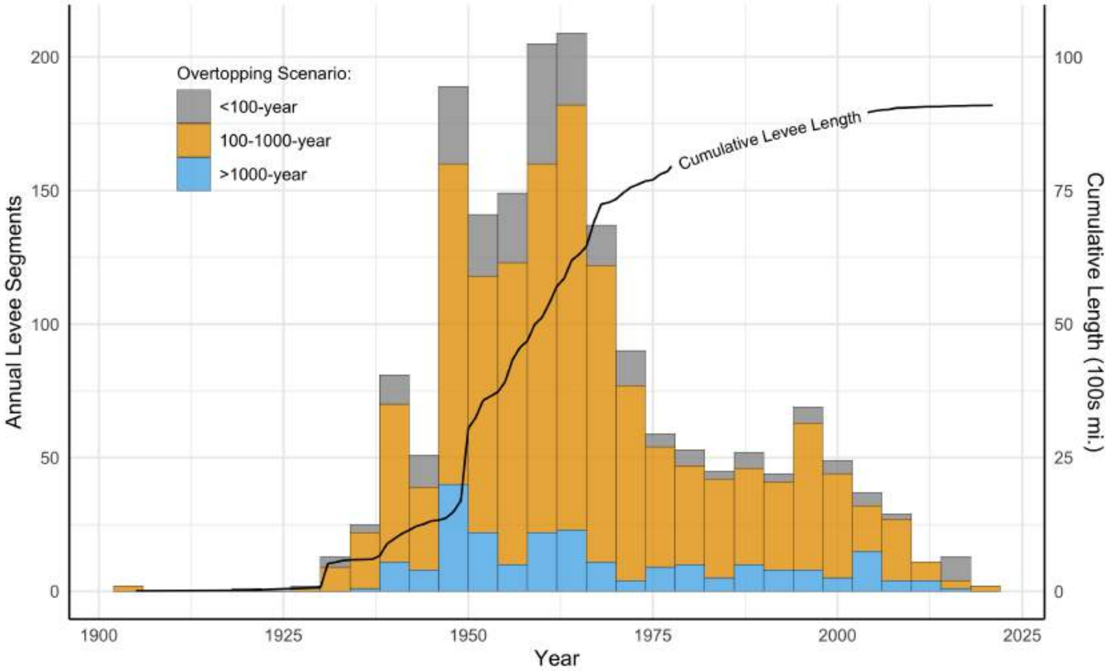
Responsibility for managing flood risk in the US is shared by federal, state, and local entities. Federal flood-related responsibilities primarily take the form of substantial programs to assist state, local, and territorial entities in controlling floodwaters and managing the consequences of flooding (Carter et al., 2019). The federal role in responding to flood-related events has grown in recent years, both through the expansion of federal flood insurance and the growth in disaster response and recovery programs(Carter et al., 2019). State and local governments exercise discretion in land use and development decisions (e.g., building codes, subdivision ordinances, and zoning) that play a major role in determining the consequences of flooding.

Historically, US flood policy focused on controlling floodwaters through public investments in large-scale engineered structures such as dams and levees. A levee is a man-made structure, usually an earthen embankment, located along a waterway that diverts water flow during flood stages. These structures are relatively inexpensive and simple to construct compared to other forms of flood control such as dams, which contributed to their relative popularity in early flood control efforts (Tobin, 1995). While early levee construction in the US was undertaken primarily at the local level for the purposes of protecting farmland, devastating floods in the early 20th century led to the passage of a series of laws authorizing federal involvement in levee building: the Flood Control Acts of 1917, 1928, and 1936 (Arnold, 1988). These Acts established the USACE as the primary federal entity responsible for the design and construction of flood control projects and set precedents around state and local involvement in levee construction and management that continue today. Taken together, the Flood Control Acts recognized flood control as a national priority and started a several decades long period of substantial growth in federal levee construction by USACE (Arnold, 1988). As shown in Figure 2, USACE levee building rose rapidly in the 1940s and 1950s, peaking in the 1960s.

USACE is a federal agency within the US Department of Defense with substantial engineering expertise and both military and civil works responsibilities. The agency's civil works activities, which include flood control, are primarily directed and overseen by Congress. Though certain USACE civil works activities are authorized and funded on a programmatic basis, USACE levee construction activities receive project-level authorization and appropriations by Congress, resulting in substantial interest by individual Members in the site selection process (Carter and Normand, 2019). Authorization of USACE civil works activities typically occurs in biennial Water Resource and Development Acts (WRDA) and appropriations for authorized activities are typically provided in annual Energy and Water Development appropriations acts (Carter and Normand, 2019).

The standard project delivery process for individual USACE-constructed levee systems has four steps: pre-construction evaluation through a formal feasibility study, design, construction, and operation and maintenance (O&M). Feasibility studies are required for any potential levee project to be eligible for construction and project-level Congressional authorization and appropriations are required to proceed with both pre-construction feasibility studies and the design and construction stages. All USACE flood and storm damage reduction projects, including levee construction, require a non-federal sponsor, such as state, tribal, territory, county, or local agencies or governments. Since WRDA 1986, nonfederal sponsors have been responsible for 50% of pre-construction feasibility study costs, up to 45%

**Figure 2.** USACE Levee Construction, 1905-2021



This figure shows the evolution of levee construction by the US Army Corps of Engineers (USACE) over the 20th and early 21st centuries. The histogram (left vertical axis) shows the annual count of levee segments constructed by the USACE and the line (right vertical axis) shows the cumulative number of levee miles constructed by the USACE. The "overtopping scenario" field refers to the level of protection that each levee segment is designed to provide, i.e., the flood level beyond which flood waters exceed the height of the levee and therefore flow over top of the levee structure.. These estimates of the level of protection are based on the return period to which the levee segment will continue to function. The "return period" can be thought of as the reciprocal of expected frequency: for example, a 100-year flood has a $1/100 = 0.01$ or 1% chance of being exceeded in any given year. Thus, a higher return period implies greater levels of protection. As shown in the figure, the vast majority of USACE-constructed levee segments are built to provide protection up to a return period between a 100- and 1000-year flood.

of design and construction costs, and all of O&M costs (Carter and Normand, 2019). Given this breakdown of O&M costs, USACE transfers ownership of the vast majority of levee systems it constructs to the non-federal, local partners involved.

At the pre-construction feasibility study stage, projects typically target a specific water resource management challenge at a regional or sub-regional level. Authorized and funded feasibility studies then identify and evaluate alternative solutions based on engineering feasibility, cost-benefit analyses, and assessments of environmental impacts. The Flood Control Act of 1936 established the precedent that USACE flood control projects should have benefits that exceed costs, though recent federal policy targets projects with ratios of benefits to costs of 2.5 or more (Carter and Nesbitt, 2016).

In parallel with the observed decrease in the rate of levee construction, US flood policy shifted away from controlling floodwaters to managing risks from flooding in the final decades of the 20th century (Tarlock, 2012). Rather than focusing exclusively on controlling flood waters through large-scale, mostly built infrastructure projects, the federal government introduced and expanded various programs during this period to manage the consequences of such events, including efforts such as floodplain easements, elevation of structures, buyouts, flood insurance, and disaster recovery funds (Carter et al., 2019). While public policies to manage the consequences of flood related risks are not our focus, they are worth noting given their interactions with levee construction. Specifically, areas protected by levees are eligible for non-trivial reductions in flood insurance premiums under the National Flood Insurance Program (NFIP), a federal program that underwrites 90-95% of residential flood insurance policies in the US (Kousky, 2018).[4] Areas protected by levees that meet minimum design criteria established by the Federal Emergency Management Agency (FEMA), which oversees the NFIP, are assigned to the X flood zone, which entitles homes in these areas to lower flood insurance premiums and removes a requirement for all homes with mortgages from federally-backed lenders to acquire flood insurance that would be present in an otherwise higher risk area (Federal Emergency Management Agency, 2021).

Our study focuses on USACE-constructed levees as a case study for understanding where and how private benefits and costs of public investments in adapting to climate related risks are distributed. Despite the slowdown in federal levee construction in recent decades, we believe that there are important lessons to be drawn from this category of investments to future policymaking given that the various categories of impacts that we explore generalize to other types of climate adaptation projects, including forms of built infrastructure which receive substantial attention such as shore hardening and sea walls. Moreover, given the substantial solvency issues surrounding public programs to manage the consequences of flooding, most notably the NFIP, it is clear that additional efforts to reduce and control risks—including through additional levee building—are necessary.[5]

## 3 Data

In this section, we summarize our primary data sources and sample restrictions. A comprehensive discussion of the data used in this analysis can be found in Appendix A. We

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[4] The NFIP was founded over 50 years ago in response to a lack of private sector flood insurance. Communities can voluntarily opt-in to the NFIP and in so doing must adopt minimum floodplain management regulations governing SFHAs. In exchange, all residents in participating communities are eligible to purchase a policy through the NFIP. Today, over 22,000 communities participate in the program and there are over 5 million policies-in-force nationwide. For a detailed overview of the NFIP, see Kousky (2018).

[5] For additional information on the fiscal solvency issues surrounding the NFIP, see Government Accountability Office (2020).

construct a dataset that combines hydrologically-accurate information on the spatial extent of areas protected by USACE levees with transaction and assessor data for a large subset of residential properties in the continental US. Our dataset also includes information on the income and race of a subset of homeowners obtained from publicly-available mortgage data in addition to information on a property's topography, proximity to surface waters, past exposure to flooding, and a set of aggregate flood insurance outcomes.

We collect data on the US housing market from Zillow's Transaction and Assessment Dataset (ZTRAX). As of April 2022, ZTRAX contains detailed information on the price, timing, location, and any associated mortgage loans for more than 400 million residential property transactions obtained from public records across 2,750 US counties. The temporal coverage of transactions contained in ZTRAX varies by state and county, going back as far as 1990 in certain geographies. In addition, ZTRAX contain tax assessor data on property characteristics—including geographic information—for approximately 150 million parcels in over 3,100 US counties. Following best practices in the literature using ZTRAX, we exclude residential parcels containing invalid or approximate geographic coordinates[6] and exclude transactions for which the price likely deviates from the property's market value (Nolte et al., 2021).[7]

We obtain novel data on over 20,000 flood adaptation projects in the continental US through an agreement with the First Street Foundation, a non-profit flood modelling group. First Street aggregates publicly-available information on the infrastructure type, geographic location, and physical characteristics of a large subset of flood adaptation projects throughout the continental US and uses the First Street Foundation National Flood Model (FSF-NFM), a granular hydrological model capturing all major forms of inundation risk, to determine the spatial extent of areas protected by each project (Bates et al., 2021).[8]

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[6] Where possible, we geocode parcels with missing, approximate, or invalid coordinates using valid street addresses and the US Census Bureau's Geocoder API. Further information about the Census Geocoder is available here: `https://geocoding.geo.census.gov/geocoder/Geocoding_Services_API.pdf` (accessed on 11/03/2022).

[7] It is important to only include arms-length transactions as our empirical approach—and hedonic pricing methods more broadly—implicitly rely on the assumption that sales prices of property transactions are indicative of the fair market value of the parcel. Examples of non-fair market value transactions include transfers between family members, foreclosures, or transactions involving public agents. Such deviations from fair market value in observed transaction prices would bias our estimates of capitalized effects of levee construction.

[8] First Street's FSF-NFM takes advantage of recent advances in remote-sensing data and computational capacity to produce granular, comprehensive measures of inundation risk across the continental US. The FSF-NFM uses a top-down flood mapping method that leverages available terrain, hydrography, hydrology, and adaptation project databases to generate fluvial, pluvial, and coastal inundation models with complete coverage of the continental US. Bates et al. (2021) provide a detailed overview of the methodology underlying FSF-NFM and additional information about the model and the First Street Foundation is available here: `https://firststreet.org/`.

We subset the flood adaptation projects in the First Street database in several ways. First we focus exclusively on USACE-constructed levees, removing all state- and locally-constructed levees and other forms of flood adaptation infrastructure. Levees—and USACE-constructed levees in particular—represent the largest single category of adaptation projects in the First Street database, covering over 9,000 federal, state, and local levee projects. We choose to focus on USACE-constructed levees given that they are relatively comparable across projects in terms of siting process, funding sources, and public engagement. Focusing on this subset of projects also mitigates sample selection concerns due to inconsistencies in data availability across other project types: First Street collects data on the universe of USACE-constructed levees from USACE's National Levee Database (NLD), whereas other project types are included only when publicly-available. Finally, we focus on USACE-constructed levees as we are able to obtain information on the timing of construction for these projects via the NLD, which is critical to our main empirical strategy discussed in detail in Section 4.[9] The second way in which we subset the First Street flood adaptation projects is that we focus on levees constructed by the USACE after 1990 due to the lack of data on housing transactions prior to this year.

We use these data on USACE-constructed levees to subset our housing market data: using valid geographic coordinates for parcel centroids, we identify those residential parcels located either inside of or within relatively close proximity to—in practice, five miles—leveed area boundaries, with distance to a leveed area boundary defined as standard Euclidean distance.[10] We assign parcels that are within five miles of multiple leveed area boundaries to their closest levee. We use transactions and other data from this subset of parcels throughout our analysis.

As noted, focusing on USACE-constructed levees enables us to merge data on the timing of construction for each levee, which we gather from the NLD. Since a USACE-constructed levee system, which is the level at which we observe each project in our First Street data, may include several levee segments with possibly differing construction dates, we obtain information on the completion date for all levee segments within USACE-constructed levees

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[9] Unfortunately, levee construction dates are not reliably recorded for all USACE-constructed levee segments in the NLD; however, they are available for around 79% of USACE-constructed segments recorded in NLD. Moreover, it is worth noting that certain large-scale, high-profile levee projects—such as the Lower Mississippi River and New Orleans levees—have been heavily modified over time, with some of these projects originally locally-constructed in the early 1900s. As a result, these salient examples of levees on which USACE has provided ongoing maintenance or to which USACE has added levee segments do not appear in our sample of USACE-constructed levee segments.

[10] Given the potential for partial overlap of parcels and leveed areas, our use of parcel centroids may introduce error in our identification of properties within and outside of leveed areas. As discussed in Section 4, we omit parcels from our estimation sample that fall within a bandwidth of either side of leveed areas to minimize the number of these potentially miscoded parcels.

in our sample from the NLD. We also obtain geographic data on the location of each levee segment in our sample to allow us to precisely assign levee construction dates to each housing parcel based on its nearest levee segment.

We access demographic information, including income, race, and ethnicity, for the subset of transactions in our sample with valid loan information using successful loan applications for home purchases made publicly-available through the Home Mortgage Disclosure Act (HMDA).[11] HMDA data provide information on the year of origination, property census tract, loan amount, application purpose, lender institution's name, and select applicant demographics and are available for the full period of transactions in our sample. We match approved HMDA loan applications to transactions based on the year of transaction, the census tract of the home, the approximate loan amount, and lender name. This procedure matches approximately 70% of the original Zillow transactions with a mortgage. Additional information on the HMDA-ZTRAX matching procedure and its performance can be found in Appendix A.

Our final dataset includes over 1.8 million transactions of 1.04 million residential parcels located within or near areas protected by 80 USACE-constructed levee systems, which include a total of 116 unique levee segments. Additional data used in our analysis include topographic information from the US Geological Survey's (USGS) 3D Elevation Program (3DEP); authoritative hydrography boundaries from the USGS's National Hydrography Dataset Plus, Version 2.1 (NHD); counts of county-level flooding events from the National Oceanic and Atmospheric Administration (NOAA); and aggregate flood insurance take-up and claims data from the National Flood Insurance Program (NFIP). We provide further information on these data sources in Appendix A in addition to detailed descriptive statistics in Appendix Table A1.

## 4 Empirical Strategy

Our goal is to recover estimates of the non-market, private costs and benefits of public investments in flood risk adaptation by measuring the capitalization of levee construction into housing prices. Houses are differentiated by proximity to a waterbody and whether or not they are protected by a levee—i.e., they fall within what we call "leveed areas." For example, houses that are located within leveed areas receive flood protection benefits, whereas houses outside leveed areas do not; houses that are located near a waterway but

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[11] The Home Mortgage Disclosure Act, enacted by Congress in 1975, requires major depository institutions to disclose loan-level information for all of their closed-end home lending activity every year. Estimates suggest that home loans reported through HMDA represent approximately 90% of all home lending nationwide in 2016.

not protected by a levee may experience adverse impacts from levee construction relative to those farther away from a waterway. We identify the different impacts of levees based on location within a leveed area and proximity to a waterway.

### 4.1 Categorizing Levee Construction Effects

We classify the main impacts of levee construction on the housing market into three categories: protection effects, spillover effects, and macro effects.

*Protection Effects.*—This category refers to the primary intended benefit of levee construction, namely the flood protection benefit that levees provide. While levees are documented to provide positive flood protection benefits in leveed areas, they do not minimize flood damages for all flood scenarios (Remo, Carlson and Pinter, 2012). Given that construction costs are convex in levee height, levees are constructed to withstand flooding events up to a maximum threshold, often referred to as overtopping scenarios.[12] The modal overtopping scenario—the flood event beyond which a levee will breach—for USACE constructed levees is a 1-in-100 year flood. Thus, while all levees are engineered to provide some degree of flood protection, there is a threshold beyond which flooding will still occur. This means that while capitalized protection benefits are likely on net positive, they should be viewed as reflecting households' expectation of avoided flood damages over the full distribution of flooding scenarios.

*Spillover Effects.*—This category refers to direct effects of levee construction experienced by homes not located inside leveed areas. Engineering and hydrology literatures have documented using theoretical modeling and observational data that levee construction exacerbates flooding outside of leveed areas (Remo, Carlson and Pinter, 2012; Remo et al., 2018). These negative flood risk spillovers occur both upstream and downstream of levees (Heine and Pinter, 2012).[13] Wang (2021) evaluates the spillover effects of levee building in response to rising flood risks and finds non-trivial downstream external costs due to upstream levee building in the Mississippi River basin. In our context, we might expect homes near waterways but not protected by a levee to therefore be exposed to greater flood risk after levee construction. As a result, these homes are likely to experience declines in prices after levee

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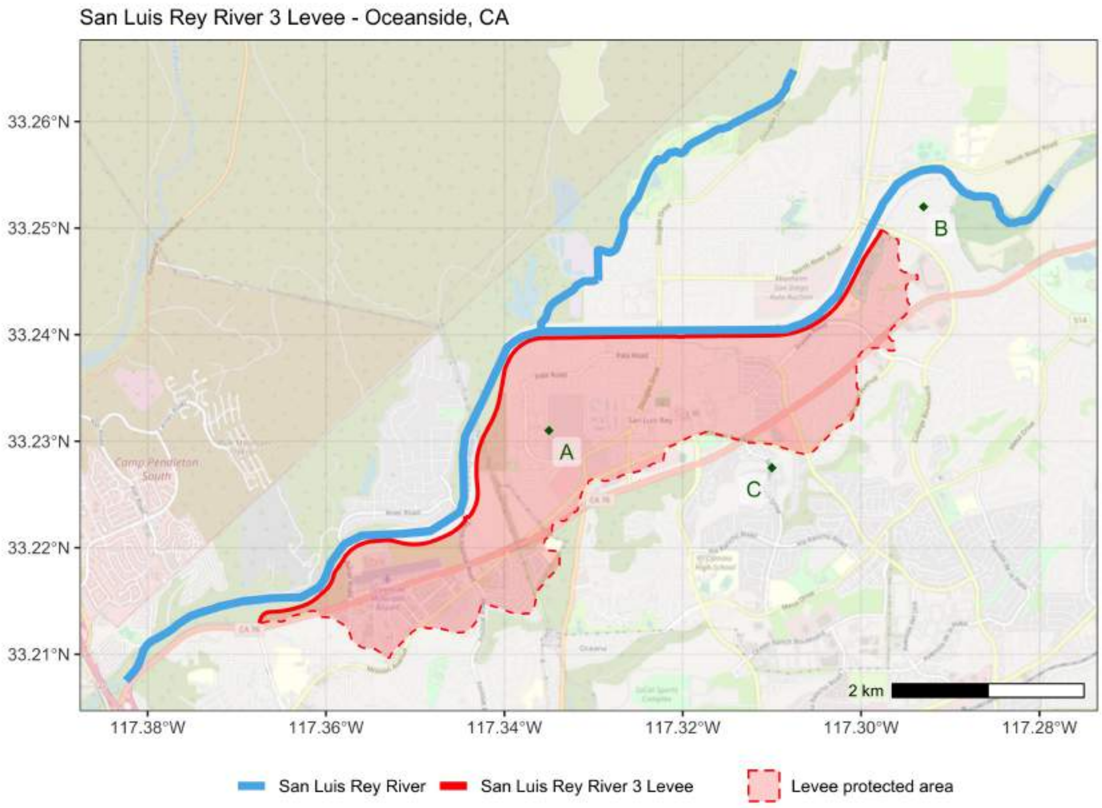
[12] USACE-constructed levees that are turned over to non-Federal, local sponsors for operation and maintenance are periodically inspected by USACE through the Inspection of Completed Works (ICW) program to ensure that the levee is being maintained to standards set out in a written agreement transferring ownership to the local entity. One such standard includes the elevation of the levee, implying that constructed levee heights are—in theory—binding.

[13] Heine and Pinter (2012) document that flood stage increases downstream are primarily due to the reduction of upstream floodplain areas open to storage of flood waters. Flood stages increase upstream due to backwater effects reducing flood water flow velocities from the levee to all points upstream Heine and Pinter (2012).

**Figure 3.** Categories of Levee Construction Effects



Five example parcels (labeled A, B, C, D, and E) demonstrating the different types of potential effects of levee construction in the context of the San Luis Rey River 3 Levee (California, US), a USACE-constructed levee completed in 2000. See Section 4.1 for a discussion of the different effects experienced by each example parcel

construction.

*Macro Effects.*—This broad category refers to effects which are not directly related to levee construction, but nonetheless coincide with the timing of construction and affect housing market outcomes in the entire region around a levee. Examples include macroeconomic factors, local labor market trends, or changes in regional or local policies. This category can also include effects from indirect economic spillovers due to levee construction—perhaps through increased investment in leveed areas—however, the empirical strategy we employ accounts for but does not identify these macro effects.

Figure 3 provides a helpful demonstration of each of the potential housing market effects of levee construction, using as an example the San Luis Rey River 3 Levee (Oceanside, California, US), a USACE-constructed levee completed in 2000. Parcel A falls within the leveed area and experiences protection effects. Parcels B is not located within the leveed area but is near the relevant surface water and as a result may experience spillover effects from levee construction.[14] All parcels experience macro effects, though this is the only effect to which parcel C is exposed.

### 4.2 Identifying Levee Construction Effects

Building on this categorization, we can use the example parcels depicted in Figure 3 to illustrate our approach to identifying the capitalized effects of levee construction. This exposition of our approach to identification is inspired by Muehlenbachs, Spiller and Timmins (2015) who employ a similar empirical strategy to identify the capitalized effects of shale gas development. Consider the price of a particular example parcel, say $P_A$, and define the operator $\Delta_t$ as the change in a given property's transaction price from before to after construction of a levee, i.e., $\Delta_t P_A = (P_{A,post} - P_{A,pre})$. Then we can decompose the change in each of the example parcel's price around levee construction as follows:

$$\begin{aligned} \Delta_t P_A &= Macro + Protect \\ \Delta_t P_B &= Macro + Spillover \\ \Delta_t P_C &= Macro \end{aligned} \tag{1}$$

where, for example, *Protect* refers to the change in observed prices attributable to protection benefits from the levee. As Equation 1 demonstrates, we can identify protection and spillover effects using difference-in-differences (DD) estimators:

$$\begin{aligned} (Protect)_{DD} &= \Delta_t P_A - \Delta_t P_C \\ (Spillover)_{DD} &= \Delta_t P_B - \Delta_t P_C \end{aligned}$$

In this framework, the first difference refers to the change in sale prices before and after levee construction for each parcel type. Identification then comes from comparing this change for homes within leveed areas (i.e., parcel A) and outside of leveed areas and near surface waters (i.e., parcel B) with the change for homes outside of leveed areas and far away from surface waters (i.e., parcel C), respectively.

It is worth noting another key benefit to this empirical strategy outlined in Equation 1. Specifically, this design addresses concerns about the endogeneity of levee site selection: given the use of ex-ante cost benefit analysis in the site evaluation process as well as the potential for political factors to enter appropriations decisions, it is likely that constructed

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[14] In practice, we define parcels as being near to waterways—and thus potentially experiencing spillover effects—based on linear distance to the nearest water feature. We test several distance definitions of proximity in addition to estimating a version of our main specification that treats water proximity as a flexible function of distance-to-water bins.

levees protect areas with a relatively high density of high value of homes. By focusing on within-parcel-type changes in sale prices around levee construction, we difference away any systematic differences between homes within and outside leveed areas and are therefore able to identify the various capitalized effects of levees outlined above.

### 4.3 Estimating Capitalized Effects

We take our identification strategy outlined in Section 4.2 to the data described in Section 3 by first defining a series of indicator variables encoding location relative to leveed areas and waterways for all homes in our final sample. Specifically, let $L_i$ equal 1 if parcel $i$ is located within a leveed area as indicated by the First Street data and 0 otherwise and $W_i$ equal 1 if parcel $i$ is located adjacent to a waterway and is outside of leveed areas and 0 otherwise.[15] We test various definitions of waterway adjacency based on distance from a parcel to the nearest water feature in different specifications.

We implement our identification strategy by defining the price of house (parcel) $i$ at time $t$ as a function of a series of interaction terms, a parcel fixed effect ($\xi_i$), a levee segment-by-year fixed effect ($\mu_{l(i)t}$), and a year-by-month fixed effect ($\delta_t$):

$$\log P_{it} = \alpha_1(T_{it} \times L_i) + \alpha_2(T_{it} \times W_i) + \xi_i + \mu_{l(i)t} + \delta_t + \varepsilon_{it} \tag{2}$$

where $T_{it} = 1$ if the transaction occurs after levee construction and 0 otherwise. As previously discussed, $T_{it}$ is assigned to transactions based on the construction date of the nearest levee segment to parcel $i$, which may result in different construction dates for transactions of parcels near the same levee system.

To account for the staggered timing of construction across levee systems—and in certain cases across levee segments within a system—and avoid the biases from standard two-way fixed effects estimators in the presence of heterogeneous treatment effects within-unit over time (de Chaisemartin and D'Haultfœuille, 2020; Goodman-Bacon, 2021), we include a levee segment-by-year fixed effect, $\mu_{l(i)t}$, which ensures that we are restricting our identifying variation to within treatment groups over time. This is particularly important in our setting given the substantial heterogeneity in treatment effect timing, which spans more than 20 years in our data. Appendix Figure C2 shows the substantial variation in treatment timing across our sample. Implementing a standard two-way fixed effects specification (i.e., omitting the levee segment-by-year fixed effect) with our highly staggered timing results in a large number of inadmissible comparisons that use early treated transactions as control

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[15] Note that the definition of $W_i$ excludes parcels protected by levees (i.e., $W_i = 1 \Leftrightarrow L_i = 0$), which allows us to use transactions of homes for which $W_i = 1$ to identify spillover effects.

units for late treated units. Such comparisons can result in later transactions near earlier constructed levee segments having negative weights when aggregating treatment effects by regression estimation (Goodman-Bacon, 2021). By identifying capitalized effects of levee construction based solely on variation between treatment and control parcels within the same levee segment, we shut down these inadmissible comparisons and avoid the issue of negative weights.[16] Note that by including this fixed effect, we cannot separately estimate a parameter on $T_{it}$ due to collinearity with $\mu_{l(i)t}$; however, this parameter is not of independent interest.

Including the parcel fixed effect, $\xi_i$, helps to not only reduce the number of parameters to estimate in our main estimating equation, but also account for a large set of unobserved, parcel-level factors which plausibly affect a home's sale price. To implement our estimating equation with a parcel fixed effect, we restrict our estimation sample to parcels for which we observe multiple transactions, which is common in the hedonics literature (Hallstrom and Smith, 2005; Graff Zivin, Liao and Panassie, 2022). While this reduces our sample size, it has the benefit of limiting the extent to which our estimates can be driven by compositional shifts in transacted homes that may occur due to levee construction by restricting the identifying variation to sales of properties that transact multiple times in our sample period.

Note that $L_i$ and $W_i$ do not enter Equation 2 on their own due to the inclusion of the parcel fixed effect, $\xi_i$. Furthermore, Equation 2 does not include the full suite of interaction terms between all three indicator variables due to the fact that interaction terms that only vary across properties are collinear with the parcel fixed effect and by definition $W_i = 1 \Leftrightarrow L_i = 0$. The terms that remain in the above estimating equation are those that are well-defined and not collinear with the fixed effects.

Our double-differencing empirical strategy controls for many unobservables that can affect the estimated capitalized effects of levee construction: the parcel fixed effect ($\xi_i$) controls for any time-invariant unobservables at the property-level; the interaction terms account for the main, spatially-explicit effects of levee construction; and levee segment-by year and month-of-sample fixed effects account for time-varying unobservables at both the local and national level. In addition to these rich controls, we restrict our sample to properties within a reasonable bandwidth of leveed areas to limit the potential for time-varying unobservables to affect our results. In our main estimates of Equation 2, we restrict our sample to properties within 5 mi of leveed area boundaries, excluding properties that are within 0.1 mi of either side of leveed area boundaries.[17] The logic behind this restriction is that it minimizes

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[16] The inclusion of this fixed effect results in an analogous estimator to the stacked regression of Cengiz et al. (2019).

[17] We test the robustness of our main estimates to alternative distance-based sample restrictions.

unobserved differences between parcels across leveed and non-leveed areas: parcels closer to the leveed area boundary are more likely to have similar neighborhood characteristics and fall within the same effective housing market as parcels within leveed areas. Moreover, we exclude parcels within 0.1 mi of leveed area boundaries to avoid biases introduced due to potential miscoding of the leveed area treatment.[18] Given that we test alternative definitions of waterbody proximity, it is unnecessary to exclude parcels within a bandwidth of any particular waterbody proximity definition.

We find suggestive evidence that restricting our estimation sample to parcels within 5 mi of leveed area boundaries, excluding parcels within 0.1 mi of either side of the boundary, successfully mitigates time-varying unobservables. We regress the log of sale price on an interaction between the leveed area indicator and indicators for the year of sale, controlling for parcel, levee segment-by-year, and month-of-sample fixed effects using data from years prior to levee construction. This regression tests for systematic variation over time across leveed and non-leveed areas within a given levee segment. We successfully reject time-varying differences prior to levee construction between transactions of parcels inside and within 5 mi of future leveed areas: an $F$-test of joint significance of the coefficients on the interaction terms fails to reject the hypothesis of joint nullity ($p$-value of 0.19), which suggest that time-varying differences between parcels within leveed areas and within 5 miles of the leveed area boundary are not a substantial concern.

The model specified in Equation 2 implicitly assumes that exposure to waterway-adjacency ($W_i$) decays with distance to the relevant feature, ultimately becoming zero at some distance. A common approach in the literature to determining exposure distance is to flexibly fit a curve between pre- and post-event prices and distance, using the crossing point of the two curves to determine exposure (Linden and Rockoff, 2008; Muehlenbachs, Spiller and Timmins, 2015). We implement this price gradient approach in Appendix Figure C3 and determine that constraining the effects of levee-adjacency and waterway-adjacency to 0.1 mile is reasonable. We also follow an alternative approach to defining these proximity-based treatment definitions by estimating the adjacency and spillover effects at 0.1 mi distance bins to empirically determine the point at which exposure to these effects ends and find qualitatively similar results.

To connect Equation 2 to the exposition of our identification strategy in Section 4.2,

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[18] Since we use parcel centroids to determine whether a given property falls within or outside of a leveed area, our leveed area treatment is likely to suffer from measurement error near leveed area boundaries. We therefore exclude parcels within a reasonable distance of either side of the boundary. The average lot size for parcels either within 5 mi of a leveed area or within leveed areas is 1.52 acres, which corresponds to a square lot size with a diagonal of 0.07 mi

consider the correspondence between the coefficients and parcels A, B, and C from Figure 3:

$$\begin{aligned}\Delta_t P_A &= \alpha_1 + \Delta_t \mu_{l(i)t} + \Delta_t \delta_t \\ \Delta_t P_B &= \alpha_2 + \Delta_t \mu_{l(i)t} + \Delta_t \delta_t \\ \Delta_t P_C &= \Delta_t \mu_{l(i)t} + \Delta_t \delta_t\end{aligned}$$

where $\Delta_t \mu_{l(i)t}$ and $\Delta_t \delta_t$ denote the change in the time-varying fixed effects for each parcel before and after levee construction.[19] This implies that the two estimators presented in Section 4.2 are as follows:

$$\begin{aligned}(Protect)_{DD} &= \Delta_t P_A - \Delta_t P_C = \alpha_1 \\ (Spillover)_{DD} &= \Delta_t P_B - \Delta_t P_C = \alpha_2\end{aligned}$$

Thus, $\alpha_1$ and $\alpha_2$ are the double-difference measures of protection and spillover effects resulting from levee construction, respectively. Two assumptions about house price counterfactuals are necessary for the estimated coefficients $(\alpha_1, \alpha_2)$ to have the causal interpretations indicated above. These assumptions are standard from the DD literature: parallel trends in outcomes (house prices) for the relevant treatment and control parcels around the time of levee construction. For example, our interpretation of $\alpha_1$ as capturing protection effects from levee construction requires that absent levee construction, the difference between parcels of type A and C in Figure 3 would remain unchanged. A second, analogous assumption about the houe price counterfactuals of parcels of type B and C is necessary to identify spillover effects. Further details on the identifying assumptions necessary for the coefficient interpretations outlined above are available in Appendix B.

### 4.4 Recovering the Distribution of Capitalized Effects

We are interested in estimating not only the magnitude of the capitalized effects of levee construction, but also the incidence of these effects along key sociodemographic variables. We use estimates of the capitalized effects of levee construction in combination with data on the income and race for a subset of buyers in our transaction sample, which we construct from publicly-available HMDA data as outlined in Section 3, to recover estimates of the distribution of these effects. In particular, we construct parcel-level demographic information at the time of levee construction using the most recent transaction to the date of construction and use these cross-sectional sub-samples to infer the distribution of capitalized costs and benefits. Since we are only able to match sociodemographic information from publicly-available

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[19] Note that the parcel fixed effects, $\xi_i$ are differenced away through the $\Delta_t$ operator.

mortgage data to a subset of observed transactions—which in practice only represents a subset of all residential parcels affected by levee construction—there are likely a non-trivial number of levee-affected households missing from this analysis. However, barring substantial heterogeneity in transaction probability or mortgage origination along the sociodemographic variables which we examine, this approach provides a reasonable approximation to the true distribution of impacts.

# 5 Results

We begin by estimating our main estimating equation and then estimate event study specifications for each of the main levee construction effects to explore dynamics over time and evaluate identifying parallel trends assumptions. Finally, we present estimates of the sociodemographic incidence of capitalized levee effects.

## 5.1 Capitalization Estimates

Table 1 reports our main estimates of Equation 2 using different definitions of the proximity-based spillover treatment definition and combinations of fixed effects. The dependent variable in each regression is the log of real sale price. All six specifications include parcel and year-by-month fixed effects and are restricted to include parcels which transaction more than once during our sample. Furthermore, each specification restricts the estimation sample to transactions of parcels that either fall within leveed areas or are within 5 mi of a leveed area boundary, excluding transactions of parcels that are within 0.1 mi of either side of a leveed area boundary. This minimizes potential measurement error in our spatial treatment definitions and ensures that we only include parcels which are appropriate controls for the parcels experiencing the various treatments as discussed in Section 4.

While our empirical design assumes that the effect of flood risk spillovers from levee construction decays over distance from an affected waterway, we do not have a strong prior as to the appropriate bandwidth to use in defining flood risk spillover exposed parcels. We plot the price gradient before and after levee construction as a function of distance from the nearest waterway in Appendix Figure C3 and find suggestive evidence that spillovers are likely outside of leveed areas between 0 and 0.3 mi of the nearest waterway. We estimate versions of our main estimating equation that define spillover exposed parcels as those properties located within 0.1, 0.2, and 0.3 mi from the nearest waterbody and report the results in columns 1-2, 3-4, and 5-6 of Table 1, respectively. For each definition of spillover exposed parcels, we report estimates with and without the levee segment-by-year fixed effect to demonstrate the importance of restricting our identifying variation to within treatment

**Table 1.** Log Sale Price on Spatial Treatment Indicators

| | $k \leq 0.1$ mi. | | $k \leq 0.2$ mi. | | $k \leq 0.3$ mi. | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Post × Intersects ($\alpha_1$) | 0.098*** | 0.029*** | 0.095*** | 0.028*** | 0.092*** | 0.027*** |
| | (0.015) | (0.009) | (0.015) | (0.009) | (0.015) | (0.009) |
| Post × $k$ mi. of Water ($\alpha_2$) | -0.062*** | -0.013* | -0.062*** | -0.011** | -0.064*** | -0.008* |
| | (0.012) | (0.007) | (0.009) | (0.005) | (0.008) | (0.005) |
| Parcel FE | Yes | Yes | Yes | Yes | Yes | Yes |
| Sale Year-Sale Month FE | Yes | Yes | Yes | Yes | Yes | Yes |
| Sale Year-Levee Segment FE | | Yes | | Yes | | Yes |
| Observations | 1,244,323 | 1,244,323 | 1,244,323 | 1,244,323 | 1,244,323 | 1,244,323 |
| $R^2$ | 0.924 | 0.948 | 0.924 | 0.948 | 0.924 | 0.948 |

The dependent variable is the log of real sale price. Data are restricted to parcels for which we observe more than one transaction during our sample period. We further restrict our data to transactions of parcels that either fall within leveed areas or are located within 5 miles of a leveed area boundary, excluding transactions of parcels that are within 0.1 mi on either side of leveed area boundaries (see Section 4 for a discussion). We report estimates of Equation 2 using different waterbody bandwidths, $k$, that define spillover exposed parcels, namely 0.1, 0.2, and 0.3 mi from the nearest waterbody. Reported coefficients ($\alpha_1, \alpha_2$) correspond directly to those in Equation 2 and correspond to the protection and spillover effects of levee construction, respectively. Standard errors, clustered at the census tract level, are reported in parentheses. Signif. Codes: ***: 0.01, **: 0.05, *: 0.1.

groups over time. Given that this fixed effect helps account for potential treatment heterogeneity over time within treated units in our setting with staggered treatment, we prefer our estimates with the levee segment-by-year fixed effect, which are reported in Columns 2, 4, and 6 of Table 1. We report standard errors clustered at the census tract level to allow for correlations in the idiosyncratic error terms for all transactions occurring in the same tract over the full sample period.

Several interesting findings emerge in Table 1. We find strong evidence of positive capitalization of protection effects from levee construction: across specifications including segment-by-year fixed effects, we estimate that the protection benefits of levee construction ($\alpha_1$) range between 2.7 and 2.9% of a homes value, with all estimates statistically significant. We also find suggestive evidence of negative spillovers to water-adjacent, unprotected homes, with $\alpha_2$ estimated to be negative across all specifications. In the three specifications that include the segment-by-year fixed effect, we estimate modest, statistically-significant negative spillovers; however, the estimates decrease in magnitude as we increase the distance-to-water bandwidth that we use to define spillover exposure. This pattern validates our assumption that spillover effects decay with distance to the nearest surface water area.

Another interesting pattern emerges in Table 1: our estimates of both the protection and spillover effects of levee construction are substantially larger in magnitude when we exclude the levee segment-by-year fixed effect. As we discuss in Section 4, there are strong conceptual justifications for preferring the specifications that include this fixed effect: they shut down inadmissible comparisons across treatment cohorts that use early treated transactions as control units for late treated transactions and can therefore result in later transactions in early treatment cohorts having negative weights when aggregating treatment effects (Goodman-Bacon, 2021). The specifications that do not include the levee segment-by-year fixed effect pool treated units across levee segments when estimating the different treatment effects, which results in a large number of plausibly problematic comparisons in our setting with highly staggered treatment time and plausibly dynamic treatment effects.

To explore why the two-way fixed effect estimates that omit the segment-by-year fixed effect produce larger-in-magnitude estimates, we examine correlations between the regression weights assigned to transactions in these specifications and transaction-specific attributes.[20] Overall, we find that the two-way fixed effect regression weights are positively correlated with purchaser income. Willingness-to-pay to avoid flood exposure may be higher for higher income households (Bakkensen and Ma, 2020), which suggests that greater weight is being placed on transactions with larger price effects from levee construction in the specifications excluding the segment-by-year fixed effect. Moreover, weights are negatively correlated with a levee segment's overtopping scenario in the case of protection treatment in these specifications, suggesting that projects providing a higher level of protection to leveed areas receive greater weight when excluding the segment-by-year fixed effect. A similar correlation emerges for elevation and spillover treatment weights.

Given the strong conceptual arguments against the specifications excluding segment-by-year fixed effect, our preferred specification includes this fixed effect. Furthermore, our

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[20] The recent literature exploring bias in two-way fixed effects estimates of staggered DD designs suggests that examining the weights placed on different observations in these estimators can help diagnose bias (de Chaisemartin and D'Haultfœuille, 2020; Goodman-Bacon, 2021; Jakiela, 2021; Baker, Larcker and Wang, 2022). We estimate treatment weights placed on each observation for each treatment by taking advantage of the Frisch-Waugh-Lovell theorem: each observation's weight for each treatment in the two-way fixed effect specification is equal to its residuals from separate regressions of the treatment status for each treatment on treatment status for the other treatment and the full set of two-way fixed effects, i.e.,

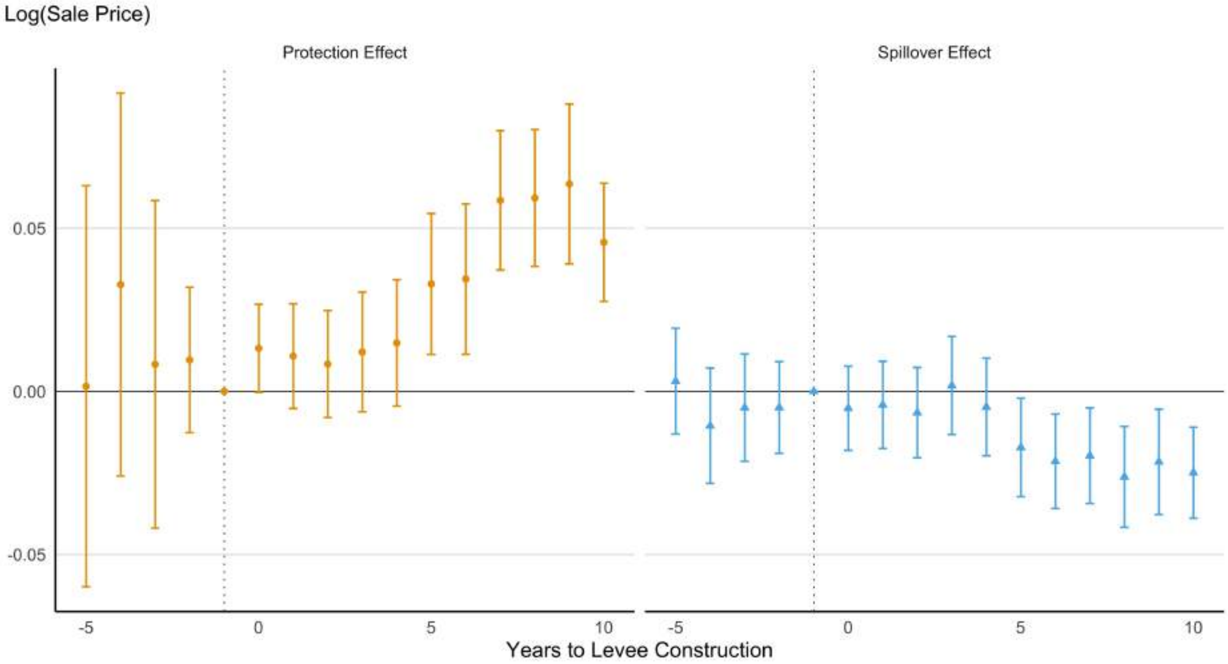
$$\hat{\epsilon}^L_{it} = (T_{it} \times L_i) - \hat{\beta}_1(T_{it} \times W_i) - \hat{\xi}_i - \hat{\delta}_t \qquad \hat{\epsilon}^W_{it} = (T_{it} \times W_i) - \hat{\beta}_1(T_{it} \times L_i) - \hat{\xi}_i - \hat{\delta}_t$$

normalized by the sum of these squared residuals, i.e.,

$$\omega^L_{it} = \frac{\hat{\epsilon}^L_{it}}{\sum_{it} \hat{\epsilon}^L_{it}} \qquad \omega^W_{it} = \frac{\hat{\epsilon}^W_{it}}{\sum_{it} \hat{\epsilon}^W_{it}}$$

Thus, each treatment effect estimate in these two-way fixed effects specifications is essentially a weighted sum of the outcome variable with the weights calculated according to the above formula. In the presence of staggered treatment timing and plausibly dynamic treatment effects, the above weights can be negative. By calculating the above weights for all observations in our two-way fixed effects specifications, we can explore any systematic trends in weights that may provide information about the likely direction of bias.

**Figure 4.** Separate Event Study Estimates of Protection and Spillover Effects



This figure shows the estimated event study coefficients for the the protection effect and spillover effects estimated from two separate regression specifications described in Equation 3. Transactions are assigned 2-year event time bins and the coefficients for the 2 years prior to construction and event-times less than -20 and greater than 26 are normalized to zero in each regression. Each regression includes parcel, year-by-month, and levee segment-by-year fixed effects and standard errors are clustered at the census tract level. The control bandwidth is set to 0.5 mi. in each regression.

preferred definition of the proximity-based spillover treatment sets the water body bandwidth at 0.2 mi given that this definition provides us with a more precise spillover effect estimate. We therefore report our preferred specification in Column 4 of Table 1 and use this as our primary result in the discussion that follows, unless noted otherwise. From this result, we conclude that on average USACE levee construction provides protection benefits to parcels within leveed areas equal to 2.8% of a homes value and leads to negative flood risk spillovers to homes within 0.2 mi of a waterway and 5 mi of a leveed area amounting to 1.1% of a homes value.

## 5.2 Event Study Estimates of Protection and Spillover Effects

As noted in Section 4.3, identification of protection and spillover effects using the relevant DD estimators relies on an assumption about parallel trends in house prices for the relevant treatment and control parcels around the time of levee construction. Thus, differential pre-trends between levee-protected and non-levee protected and waterway-adjacent and non-waterway adjacent homes are threats to our primary results regarding the protection benefits and spillover costs of levee construction. To provide suggestive evidence that differential pre-trends do not drive our results and to examine the effects of levees over time relative to construction, we implement event study specifications of the protection and spillover DD estimators.

In particular, we separately estimate the following specifications on the relevant subset of treatment and control parcels described in Section 4 to estimate event study graphs for protection and spillover effects:

$$\begin{aligned} \log P_{it} &= \sum_{\tau=-5}^{10} \alpha_1^\tau \Big( L_i \times \mathbb{1}\{t = (LeveeYear_i + \tau)\} \Big) + \xi_i + \mu_{l(i)t} + \delta_t + \varepsilon_{it} \\ \log P_{it} &= \sum_{\tau=-5}^{10} \alpha_2^\tau \Big( W_i \times \mathbb{1}\{t = (LeveeYear_i + \tau)\} \Big) + \xi_i + \mu_{l(i)t} + \delta_t + \varepsilon_{it} \end{aligned} \tag{3}$$

where $LeveeYear_i$ indicates the year parcel $i$'s nearest levee segment is constructed, $\mathbb{1}\{t = (LeveeYear_i + \tau)\}$ is an indicator variable that equals 1 if a parcel's transaction year $t$ occurs in event times $\tau$ relative to the levee construction year and zero otherwise, and the remaining variables and fixed effects are as defined in Equation 2. We set the coefficients for event time $\tau = -1$ equal to 0, which normalizes the remaining treatment effects relative to the period prior to construction for ease of interpretation.

We plot the resulting event study estimates from Equation 3, $\alpha_1^\tau$ and $\alpha_2^\tau$, in Figure 4. The figure shows suggestive evidence in favor of the identifying parallel trends assumption. Home prices for levee-protected homes relative to non-levee-protected, non-waterway adjacent homes increase slowly following levee construction: the first year for which we find a statistically-significant, positive post-construction event study estimate is event year $\tau = 5$. Similarly, home prices for non-levee-protected, waterway adjacent homes decrease slowly following levee construction. Taken together, these findings suggest that households learning about protection benefits and negative spillovers of newly constructed levees gradually over time, perhaps as a result of accumulated experience with flood related events.

### 5.3 Incidence of Protection and Spillover Effects

We use estimates of the capitalized effects of levee construction in combination with data on the income and race of a subset of buyers in our transaction sample to recover the distribution of these effects.[21] We use estimates from our preferred specification, which are reported in

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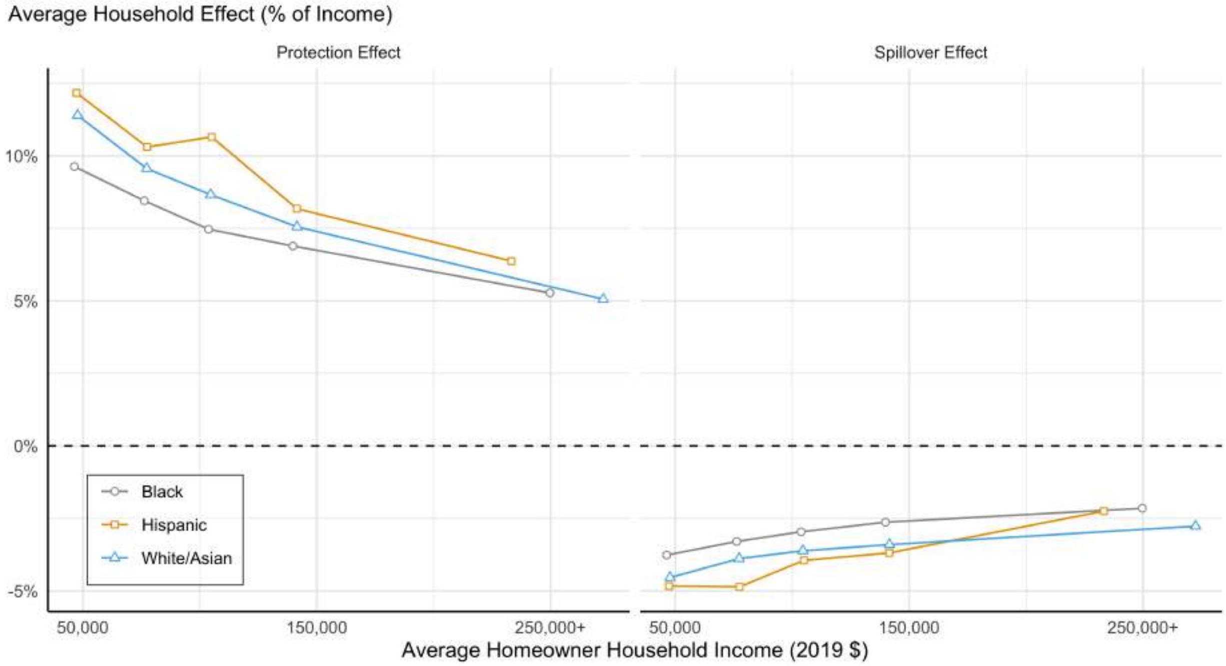
[21] Specifically, we match demographic data to our ZTRAX transaction data using publicly-available HMDA data. Additional information on the ZTRAX-HMDA matching procedure as well as comparisons of matched

**Figure 5.** Distribution of Protection and Spillover Effects



This figure shows the estimated distribution of protection and spillover effects of levee construction by race/ethnicity and income quintile. We construct parcel-level demographic information at the time of levee construction using the most recent transaction to the date of construction and use these cross-sectional sub-samples to infer the distribution of capitalized protection and spillover effects. Note that based on our preferred specification, protection effects are limited to parcels falling within leveed areas ($L_i = 1$) and spillover effects are limited to parcels adjacent to waterways ($W_i = 1$). Using the income distribution for the full matched ZTRAX-HMDA sample, we estimate average income and home values for each racial/ethnic group and each income quintile for each of these sets of treated households and then use the estimates from our preferred specification in Column 4 of Table 1.

Column 4 of Table 1 to recover estimates of the distribution of protection and spillover effects. Using the income distribution from the full matched ZTRAX-HMDA sub-sample to define income quintiles, we estimate average income and home values for all combinations of three racial/ethnic groups—white/asian, hispanic, and black homeowners—and income quintiles for the relevant set of treated households and use these values in combination with our capitalization estimates to construct distributions of protection and spillover effects. Note that we use the income and race/ethnicity of the purchaser from the most recent transaction to levee construction when calculating average transfers for each demographic group, since this represents the relevant pool of households for which levee construction operates as a lump sum transfer.[22] We report the resulting distributions of the main capitalized effects of

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and unmatched sub-samples are available in Appendix A.

[22] Households who sell an affected house prior to levee construction clearly do not receive a lump sum transfer from the public investment. Households who purchase an affected house after levee construction

levee construction as a share of average income in Figure 5.

Several striking patterns emerge in Figure 5. First, differences in incidence across racial and ethnic groups are relatively minor, particularly at the upper end of the income distribution. This suggest that conditional on income, the spatial distribution of households relative to levees is relatively consistent across white/asian, hispanic, and black homeowners. Second, we find that when normalizing by income, the flood protection provided by levee construction represents a progressive implicit subsidy to beneficiary households. Among the lowest income quintile households, the protection subsidy provided by USACE-constructed levees ranges from 9.6 to 12.2% of average income depending on the racial/ethnic group, whereas in the highest income quintile, the subsidy ranges from 5.1 to 6.3% of average income. Finally, we find that the spillover effects of levee construction represent a regressive—or at best, proportional—tax on affected households: this external cost of levee construction ranges from 3.7% to 4.8% of income in the first income quintile and from 2.1 to 2.7% in the top income quintile. Thus, ignoring the negative spillover effects of levee construction may produce misleading results: spillovers work to offset some of the progressivity of protection benefits produced by USACE-constructed levees.

While this exercise is informative about who gains—and loses—from the windfall benefit or cost of USACE levee construction, it does not give us a full picture of the distributional impacts of these investments. Evidence suggests that low income and minority residents are more likely to move into areas of high flood risk (Bakkensen and Ma, 2020), perhaps due to differences in taste (Banzhaf and Walsh, 2008), beliefs (Bakkensen and Barrage, 2021), information access (Hausman and Stolper, 2021), or housing discrimination (Christensen and Timmins, 2022). In particular, given that we estimate non-zero willingness-to-pay both for the protection benefits that levees generate and to avoid the flood risk spillovers that they cause, it is plausible that certain groups differentially sort around the changes in flood risk resulting from levees. Such "environmental gentrification" is certainly of policy relevance in evaluating the distributional impacts of public inestments climate adaptation.

To examine whether certain demographic groups differentially sort into or out of levee protected or spillover exposed areas following levee construction, we estimate versions of Equation 2 with key demographic variables as outcomes. In particular, using the matched ZTRAX-HMDA sample and the same set of sample restrictions as with our main estimates of Equation 2, we regress the log of purchaser income, an indicator for whether the purchaser is white or asian, an indicator for whether the purchaser is black, and an indicator for whether the purchaser is Hispanic on the levee protection effect treatment variable and a

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pay a premium/discount that internalizes the relevant effect of the public adaptation investment. Thus, it is the households that own affected properties at the time of construction that receive the transfer.

**Table 2.** Borrower Demographics on Spatial Treatment Indicators

| | log(Income) (1) | White/Asian (2) | Black (3) | Hispanic (4) |
|---|---|---|---|---|
| Post × Intersects | 0.001 | 0.043*** | -0.006 | -0.041** |
| | (0.013) | (0.012) | (0.004) | (0.020) |
| Post × Distance to Water Bins | | | | |
| [0.0, 0.1 mi] | -0.017 | -0.043*** | 0.019*** | -0.033** |
| | (0.011) | (0.010) | (0.005) | (0.015) |
| (0.1, 0.2 mi] | 0.0006 | -0.028*** | 0.010* | -0.010 |
| | (0.009) | (0.008) | (0.005) | (0.012) |
| (0.2, 0.3 mi] | -0.009 | -0.028*** | 0.014*** | 0.007 |
| | (0.008) | (0.008) | (0.004) | (0.012) |
| (0.3, 0.4 mi] | -0.004 | -0.013* | 0.005 | 0.0003 |
| | (0.008) | (0.007) | (0.003) | (0.012) |
| Parcel FE | Yes | Yes | Yes | Yes |
| Sale Year-Sale Month FE | Yes | Yes | Yes | Yes |
| Sale Year-Levee Segment FE | Yes | Yes | Yes | Yes |
| Dependent variable mean | 138,319 | 0.787 | 0.043 | 0.174 |
| Observations | 646,825 | 646,837 | 646,837 | 387,507 |
| $R^2$ | 0.817 | 0.668 | 0.690 | 0.816 |

The dependent variables are select household demographic variables from the ZTRAX-HMDA matched sub-sample. Given that these variables come from the subset of transactions for which we obtain a valid match with HMDA data, we refer to these dependent variables as borrower demographics (see Appendix A for further details). Data are restricted to parcels for which we observe more than one transaction during our sample period. We further restrict our data to transactions of parcels that either fall within leveed areas or are located within 5 miles of a leveed area boundary, excluding transactions of parcels that are within 0.1 mi on either side of leveed area boundaries (see Section 4 for a discussion). We report estimates of versions of Equation 2 with select purchaser/borrower demographics as the relevant outcome variable. Rather than testing different waterbody bandwidths, $k$, that define spillover exposed parcels, we estimate these spatial spillovers as flexible functions of binned values of a parcel's distance to the nearest waterbody. Post × Intersects and Post × Distance to Water Bins correspond to the protection and spillover effects of levee construction, respectively. Standard errors, clustered at the census tract level, are reported in parentheses. Signif. Codes: ***: 0.01, **: 0.05, *: 0.1.

series of variables encoding exposure to flood risk spillovers. Rather than testing different spatial definitions of spillover exposed parcels, we estimate these spatial spillovers as flexible functions of binned values of a parcel's distance to the nearest waterbody interacted with a post-levee construction indicator.

Table 2 reports the results from our examination of differential sorting patterns. Overall, we find no evidence of sorting by income; however, we do find suggestive evidence of differential sorting by race and ethnicity. In particular, we find that purchasers in levee protected areas are 4.3 percentage points more likely to be white or asian after levee construction compared to before levee construction and that white/asian households move into spillover exposed areas at lower rates after construction. On the other hand, hispanic households are

4.1 percentage points less likely to move into levee protected areas after levee construction, though they also appear less likely to move into spillover exposed areas. Black households appear more likely to move into spillover exposed areas closest to waterways after levee construction relative to before. Overall, these results are in line with past evidence on differential sorting patterns around flood risk across racial and ethnic groups (Bakkensen and Ma, 2020).

## 6 Discussion

### 6.1 Potential Mechanism: Households Learning from Floods

We estimate that USACE levee construction provides protection benefits to parcels within leveed areas equal to 2% of a home's value and leads to negative flood risk spillovers to neighboring homes amounting to 1% of a home's value. We also find suggestive evidence of a gradual capitalization of both of these effects over time: coefficients from event study specifications of both the protection and spillover effects of levee construction plotted in Figure 4 show that home prices take up to 5 years to adjust post-levee construction. This finding in particular suggests that households learn about the flood risk implications of levee construction over time, perhaps as a result of accumulated experience with flood related events. This potential mechanism is in line with existing evidence on consumer learning about flood risk in housing markets (Hallstrom and Smith, 2005; Bin and Landry, 2013; Gallagher, 2014; Bakkensen and Barrage, 2021).

We test this mechanism using county-level data on the occurrence of major flood-related storm events. Specifically, we collect information on approved Presidential Disaster Declarations (PDD) at a county-level dating back to the 1950's and use these data to construct county-year counts of the number of flood-related disaster declarations.[23] We then implement an event study framework around PDD events to estimate the causal effect of large regional floods on the price effects of levee construction. We separately estimate the following specifications using only repeat transactions that occur after levee construction in order to identify the causal effect of learning about levee's effects on flood risks through large regional

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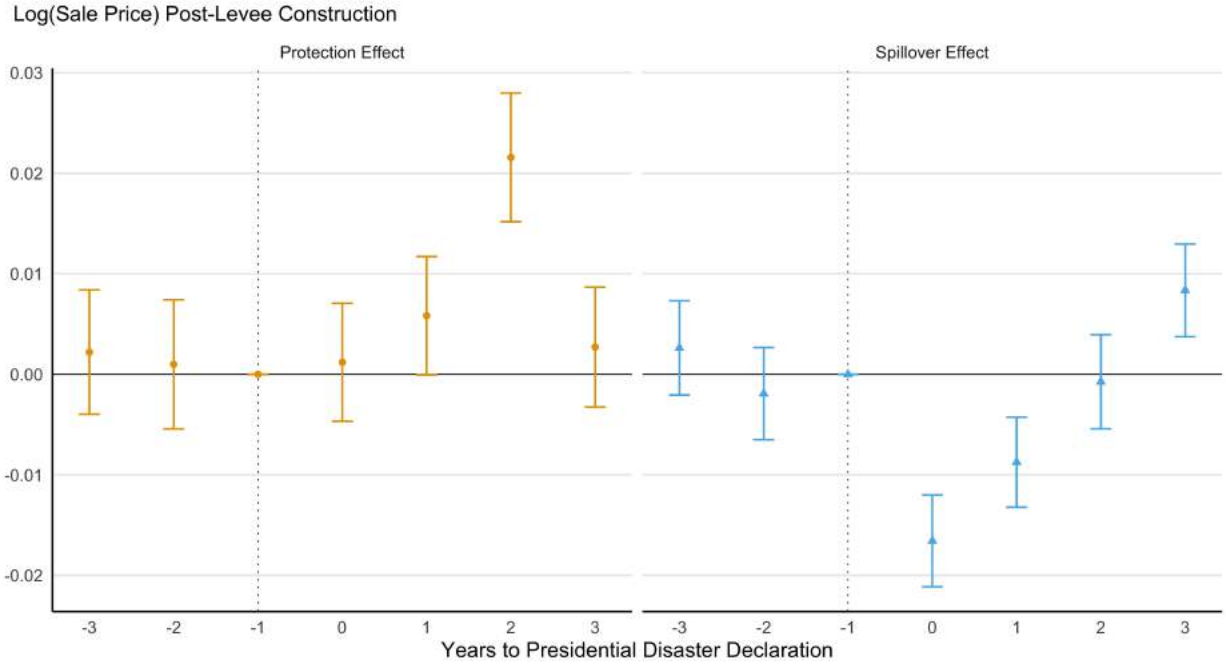
[23] The Presidential Disaster Declaration (PDD) system, established in the Disaster Relief Act of 1950, is a process by which state governor's make formal requests for federal assistance in specific counties—or in some rare cases their entire state—following major natural disasters. A PDD provides a county with access to FEMA Public Assistance and Individual Assistance programs and are therefore typically only declared for major natural disasters (Carter et al., 2019).

**Figure 6.** Household Learning from Exposure to Floods



This figure shows the effect of exposure to flood events on the capitalization of the protection and spillover effects of levee construction. The figure shows the estimated event study coefficients for the effect of experiencing a Presidential Disaster Declaration (PDD) post levee construction on the price effect of falling within a leveed area and falling within a spillover area. Data are restricted to transactions that occur after levee construction and to parcels for which we observe more than one transaction during the post-construction sample period. Data on flood-related storm events come from the FEMA's PDD database. Additional information on these data is available in Appendix A. Each regression includes parcel, year-by-month, and levee segment-by-year fixed effects and standard errors are clustered at the census tract level.

flood events:

$$\begin{aligned}\log P_{it} &= \sum_{\tau=-3}^{3} \alpha_1^{\tau}\Big(L_i \times PDD_{c(i)t}^{\tau}\Big) + \xi_i + \nu_{c(i)t} + \delta_t + \varepsilon_{it} \\ \log P_{it} &= \sum_{\tau=-3}^{3} \alpha_2^{\tau}\Big(W_i \times PDD_{c(i)t}^{\tau}\Big) + \xi_i + \nu_{c(i)t} + \delta_t + \varepsilon_{it}\end{aligned} \tag{4}$$

where $PDD_{c(i)t}^{\tau}$ is a binary variable that equals 1 if the transaction of parcel $i$ occurs in a county $c$ that experiences a federal disaster declaration $\tau$ years relative to sale year $t$ and 0 otherwise and $\nu_{c(i)t}$ is a county-by-year fixed effect. The remaining variables and fixed effects are as defined in Equation 2. We only estimate event study coefficients for the periods $\tau = -3, ..., 3$ given the potential for contamination from other PDD events within a given county outside of that window: the average transaction in our estimation sample experiences 3 years with at least 1 PDD in the 10 years leading up to the transaction.

We find suggestive evidence of a differential effect of high exposure to flood-related storm events on the capitalization of protection and spillover effects. As shown in Figure 6, there is a statistically-significant, positive, and large in magnitude difference in sale price between protected parcels that experience a PDD and those that do not in the years immediately following the event. A similar pattern emerges when examining the dynamics effects of flood exposure on spillover effects: spillover exposed parcels that experience a PDD sell at a discount relative to spillover exposed parcels that do not experience a PDD in the years immediately following the disaster. Interestingly, the differential effect of experiencing a PDD event appears stronger for spillover exposed parcels than those in levee protected areas, suggesting that the information contained in these events may come in the form of realized damage to a household's property or nearby properties.

These results suggest that households learn about the impact of USACE-levee construction on properties' flood risks based on recent experience with floods. This is in line with existing literature that finds that models of Bayesian learning about flood risks provide a reasonable fit to observed household behaviors in insurance and real estate markets (Gallagher, 2014; Bakkensen and Barrage, 2021). We provide supplemental evidence to Figure 6 in Appendix Table C1, where we report post-levee construction DD estimates of protection and spillover effects for low- and high-flood exposed transactions based on data from NOAA's Storm Events database.[24] We find that levee-protected parcels with a lagged 2-year count of flood-related storm events that exceed the 75th percentile have 3.6% higher value than low flood exposed, levee-protected parcels. We also find that waterway-adjacent, spillover-exposed parcels with a lagged 2-year count of flood-related storm events that exceed the 75th percentile have 3.4% lower value than low flood exposed, spillover-exposed parcels.

## 6.2 Aggregate Benefits and Costs

It is helpful to contextualize our main capitalization findings in the broader public finance setting of USACE levee investments, particularly in the presence of spillover effects. Given the explicit role of benefit cost ratios in the process of evaluating potential levee projects, providing estimates of the aggregate benefits and costs of the projects that we analyze using our capitalization estimates and publicly-available data is of direct policy-relevance. Constructing aggregate estimates of project benefits and costs enables us to provide a reasonable

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[24] We report the event study results for PDD in the text since these represent large, salient events which are likely to convey information to local housing markets. However, given the potential political factors that play into the declaration of federal disaster declarations, we explore whether a similar effect of exposure to flood events exists in more objective measures of flood events. Since there is a much lower threshold to NOAA reporting a flood event in the Storm Events database, we have to take a data-driven approach to defining flood exposure intensity, which may be less preferable to the PDD results.

**Table 3.** Average Benefits and Costs per Levee Mile Constructed

| | Mean | Std. Dev. | Min. | Max. | N |
|---|---|---|---|---|---|
| Protection Benefits ($Mil./mi.) | | | | | |
| ZTRAX Housing Stock Estimate | 1.066 | 2.136 | 0.007 | 10.930 | 37 |
| USACE Housing Stock Estimate | 9.608 | 14.027 | 0.000 | 71.202 | 37 |
| Costs ($Mil./mi.) | | | | | |
| Construction Costs | | | | | |
| Total | 60.781 | 157.651 | 0.189 | 852.161 | 37 |
| Federal | 49.007 | 130.027 | 0.003 | 664.098 | 29 |
| Non-Federal | 15.385 | 38.060 | 0.005 | 188.063 | 27 |
| Spillover Effects | 13.799 | 40.799 | 0.008 | 238.268 | 37 |
| Fiscal Externalities | | | | | |
| Effective Tax Rate: Leveed Area | 0.035 | 0.049 | 0.010 | 0.226 | 33 |
| Effective Tax Rate: Spillover Area | 0.032 | 0.044 | 0.006 | 0.208 | 34 |
| Protection Benefits ($Mil./mi.) | | | | | |
| ZTRAX Housing Stock Estimate | | | | | |
| 2% real interest rate | 0.943 | 1.694 | 0.000 | 6.951 | 37 |
| 3.5% real interest rate | 0.539 | 0.968 | 0.000 | 3.972 | 37 |
| USACE Housing Stock Estimate | | | | | |
| 2% real interest rate | 21.086 | 73.863 | 0.000 | 449.851 | 37 |
| 3.5% real interest rate | 12.049 | 42.207 | 0.000 | 257.058 | 37 |
| Spillover Effects ($Mil./mi.) | | | | | |
| 2% real interest rate | 34.368 | 144.968 | 0.000 | 866.797 | 37 |
| 3.5% real interest rate | 19.639 | 82.839 | 0.000 | 495.313 | 37 |

This table presents average benefits, costs, and fiscal externalities across 37 USACE-constructed levee projects. We calculate protection benefits using our preferred estimate of protection effects from Table 1 and estimates of the value of the protected housing stock for each project. We use two separate sources to construct different estimates of the protected housing stock, ZTRAX assessment data and USACE's own estimates, which are derived from the National Structures Inventory, Version 2 (2019). Fiscal externalities refer to the long-run impacts on local property tax revenues. To estimate fiscal externalities, we calculate effective property tax rates separately for the relevant treated parcels—protection and spillover exposed homes—from ZTRAX assessment data. We use two different long term interest rates to calculate the effects of annual changes in property tax revenue in perpetuity, 2% and 3.5%. All figures are in 2019 million USD per levee mile constructed.

ex-post assessment of USACE's performance relative to the benefit cost ratio policy it targets in ex ante project assessments.

We begin by constructing project-level aggregate benefits and costs by translating our capitalization estimates into their relevant aggregates. Given that our capitalization estimates are in terms of a percentage point impact on home values, this requires us to construct estimates of the total value of housing stock in each of the relevant treatment groups—protected and spillover exposed parcels—for each levee system. Unfortunately, we cannot use the transaction prices from our main estimation database for this purpose: inevitably, not all parcels within the relevant treatment areas transact during our sample period. Thus, we need to use additional data to construct measures of treated housing stock value. We do so from two different sources. First, we use the tax assessment database from ZTRAX, which in addition to geographic coordinates provides the tax valuation, estimated fair market value, and total property tax payments for over 150 million parcels across 3,100 US counties. This allows us to identify the universe of treated residential parcels for each USACE-constructed levee project.[25] We then subset these parcels to those with houses constructed prior to levee construction and use county-level annual housing price indices from the Federal Housing Finance Agency (Bogin, Doerner and Larson, 2019) to deflate current assessed fair market values to the year of levee construction, which we then convert to 2019 dollars using the consumer price index for all urban consumers.[26] The second data source that we use comes directly from USACE. Specifically, we take estimates of the total value of levee-protected property stock for each levee system directly from the NLD, which USACE sources from the National Structure Inventory, Version 2.[27] These estimates are not directly comparable to the ZTRAX-derived estimates: they include non-residential real estate values and other forms of property such as vehicles; however, they are still informative, particularly since our ZTRAX-derived estimates of protected residential property values likely produce an underestimate of the total capitalized effect of protection benefits.[28] Unfortunately, USACE does not provide a comparable measure for properties around levees from which we can derive an analogous estimate for spillover exposed property values, so we use the ZTRAX-derived estimate of spillover exposed residential property values alongside the USACE-provided estimate of protected property values. Having produced measures of the value of treated property stocks, we can then multiply these measures by our preferred estimates of the protection and spillover effects.

We explicitly model two other categories of benefits and costs beyond these capitalized effects. The first include upfront levee construction costs. Unfortunately, construction cost information is not maintained in a central, consistent, and publicly-available format for USACE civil works projects. We therefore manually scrape information on federal and non-federal partner construction costs for USACE-constructed levees in our sample from a disparate set of primary sources, including federal budget requests, appropriations bills, and USACE annual reporting. We are able to construct estimates of construction costs for a

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[25] This allows us to use the geographic boundaries of levee protected areas to identify all residential parcels falling within levee protected areas (protection effect treatment) and hydrography data from the Hational Hydrography Dataset to identify all parcels within 5 miles of leveed areas that are within 0.2 miles of a waterway (spillover effect treatment).

[26] Additional information on the FHFA county-level HPI is available here: `https://www.fhfa.gov/DataTools/Downloads/Pages/House-Price-Index-Datasets.aspx` (accessed 12/7/2022).

[27] Additional information on the National Structure Inventory, Version 2 is available here: `https://www.hec.usace.army.mil/confluence/nsi/` (accessed 12/7/2022).

[28] Furthermore, the two sources produce a similar distribution of total capitalized effects of protection benefits across projects, with a correlation coefficient of 0.7. See Appendix Figure C4.

total of 37 projects, which include 53 separate levee systems.[29]

The final category for which we account when constructing aggregate benefits and costs are local fiscal externalities. Approximately 30.2% of nationwide local general revenues came from property taxes in 2019.[30] Given the substantial changes in property values due to both protection and spillover effects of levee construction, it is important to try to capture the local tax revenue implications of levee construction. We do so using the tax assessment database from ZTRAX. Specifically, we estimate effective property tax rates accounting for exemptions and limits for each treatment group of properties by dividing the total property tax revenue by the total assessed value and averaging across all parcels in each treatment group within each levee project. This provides us with an estimated annual effective property tax rate, which we can then multiply by the relevant total capitalized effect of levee construction to get an estimate of the annual effect of each change in property value—the protection and spillover effects—on property tax revenues. We assume that these annual property tax revenue effects occur in perpetuity[31] and calculate the present discounted value of each using two separate long-term interest rates, 2% and 3.5%, the latter of which approximately corresponds to Bloomberg's index rate of return on 30-year municipal bond yields as of December 2022.[32] To be more precise, we calculate the fiscal externality of the protection benefit for a specific project, $l$, according to the following formula:

$$FE_l^{protection} = \frac{\text{Total Protection Benefits}_l \times \text{Effective Tax Rate}_l}{r}$$

where $r$ is a given long term interest rate. The fiscal externality of the spillover effect is calculated analogously. Note that our choice of interest rate, $r$, for calculating the fiscal externalities likely differs from the discount rate that households apply when valuing the flood risk impacts of levee construction, which implicitly involves assessing the present discounted value of changes in expected flood risk damages due to the levee. Regardless of the implicit discount rate that households use, the resulting changes in property values have

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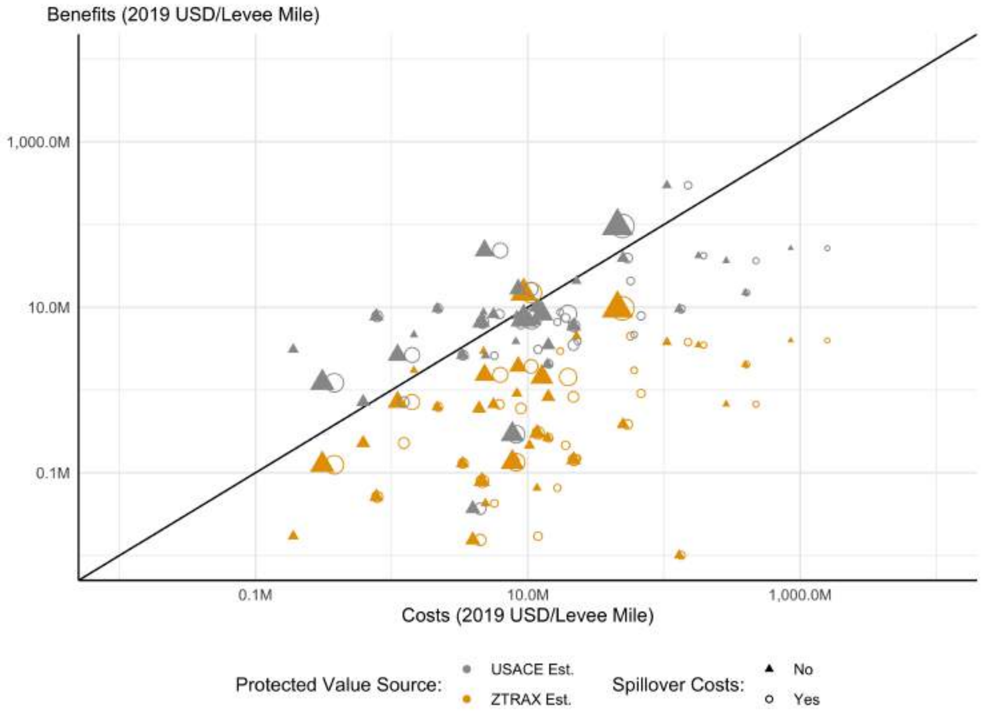
[29] A challenge in constructing these cost data is that there is no clear one-to-one mapping from levee systems as listed in the USACE NLD—and thus how they appear in our data—and projects referenced in the cost data source materials. In many cases, projects referred to in source materials refers to a collection of several NLD levee systems, which is why we have cost data for 37 projects and 53 levee systems, where a project can be a collection of multiple systems. For additional information, see Appendix A.

[30] See https://www.lincolninst.edu/sites/default/files/ptaag_full_2022.pdf for additional information (accessed 12/7/2022).

[31] Note that this assumes that local property tax rates do not change in response to levee construction, which is perhaps a flawed assumption given the need for local, non-federal partners to raise revenues for construction. Unfortunately we do not have the ability to test this assumption so we use the approach described to construct best estimates of effective property tax rates.

[32] Source: Bloomberg Finance L.P., retrieved from https://www.bloomberg.com/quote/BVMB30Y:IND on 12/7/2022.

**Figure 7.** Total Benefit and Cost Estimates per Levee Mile Constructed for Select USACE Levee Projects



This figure shows the estimated benefits and costs per levee mile constructed for the subset of 37 USACE-constructed levee projects for which we are able to collect construction cost data. The figure shows four separate sets of estimates of benefits and costs, varying the source used to construct estimates of the protected housing stock (ZTRAX-derived vs. USACE estimates) and whether or not the effects of flood risk spillovers are included. Each set of benefit and cost estimates is inclusive of fiscal externalities. We use a long term interest rate of 3.5% to calculate the effects of annual changes in property tax revenue in perpetuity, which is approximately equal to Bloomberg's index value for 30-year municipal bond yields as of December 2022. Point sizes are proportional to each project's constructed levee length. Both axes are on log-transformed scales.

annual impacts on tax revenues, the long-run impacts of which should be compared with municipalities' long-run costs of capital. This motivates our use of 2 and 3.5% interest rates in calculating fiscal externalities.

Table 3 describes the resulting estimated benefits, costs, and fiscal externalities across 37 USACE-constructed levee projects for which we are able to scrape construction cost data. Note that the fiscal externalities from protection benefits are positive while those from spillovers are negative. We normalize each category of total impacts by the levee length of each project to account for any effects of project scale on total magnitudes.

We examine the benefit cost ratios implied by these aggregate estimates. Given the role of the benefit cost ratio in policymaking and site selection, this exercise is potentially of direct policy relevance. As described in Section 2, USACE aims to select civil works projects with benefit cost ratios greater than 1—i.e., projects with benefits which exceed costs—however, recent USACE policy targets projects with ratios of 2.5 or more. Figure 7 shows four separate sets of estimates of benefits and costs per levee mile constructed for the subset of 37 USACE-constructed levee projects for which we are able to collect construction cost data. The four sets of estimates vary the source used to construct estimates of the protected housing stock, either ZTRAX- or USACE-derived estimates, and whether or not the effects of flood risk spillovers are included.

Figure 7 reveals that the majority of estimated benefit and cost combinations for the 37 projects in our data have benefit cost ratios less than 1, and therefore do not have benefits which exceed their cost. Unsurprisingly, ignoring flood risk spillovers from levee construction results in higher benefit cost ratios within each project. Using the estimate of the value of levee-protected properties from the USACE NLD to construct protection benefit estimates also produces higher benefit cost ratios. However, even when we both ignore spillovers and use the larger USACE-derived protection benefit estimate, we still find that many projects have benefit cost ratios less than 1 and all have ratios less than the goal of 2.5 or greater. While these findings may suggest that USACE systematically overestimates benefit cost ratios in their pre-construction feasibility studies of levee projects, there, they may also suggests that factors other than the economic impacts drive decisions to proceed with construction.

Moreover, there are a number of important categories of levee construction impacts which we omit from our benefit and cost estimates that may drive these results. On the cost side, we omit operations and maintenance costs, which are 100% borne by local, non-federal partners. Furthermore, there are important fiscal externalities that we ignore, such as the impact of levee construction on the federal National Flood Insurance Program (NFIP). Given that households protected by FEMA-accredited levees are no longer subject to a mandate to purchase flood insurance under the NFIP, USACE levee construction likely reduces NFIP premium revenue while also reducing claims payments for little net budgetary impact. However, the presence of flood risk spillovers perhaps increases NFIP budget outlays—reducing program solvency, a major policy concern at present—through increased claims payments. We examine these potential fiscal externalities on the NFIP in Appendix Table C2, which validates the hypothesized effects. There are also likely categories of benefits that we omit, such as the indirect local or regional economic impacts of levee construction. Indeed, our framework outline in Section 4 allows for these kinds of macro effects; however, we do not explicitly identify these impacts and therefore do not account for them in calculating benefits in costs. Finally, there may be non-trivial extensive and intensive margin effects in the real estate market as a result of levee construction for which we do not account, which would have myriad direct and indirect effects, potentially through fiscal externalities.

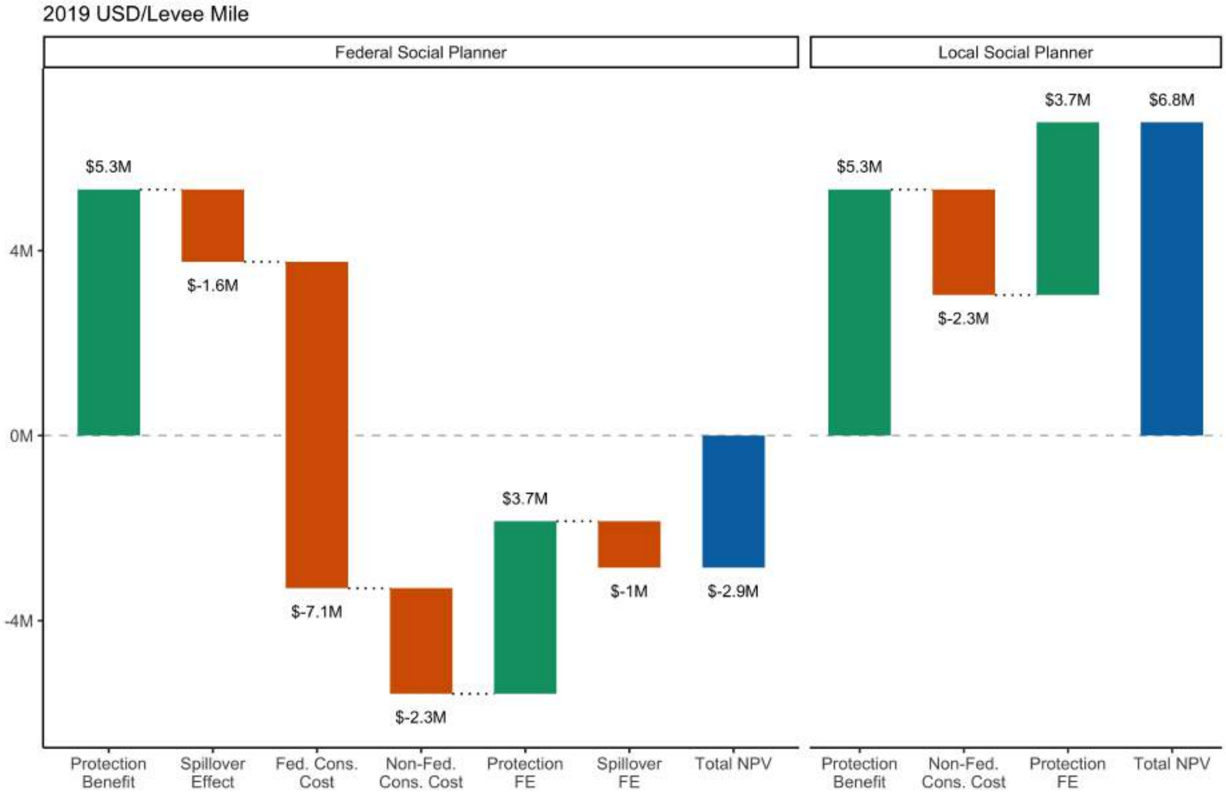
There are also important limitations to our approach to quantifying the benefits and costs for which we do account, several of which we note already. These include omitted categories of property value in both levee-protected and spillover-exposed areas, omitted heterogeneity in capitalization effects across different categories of properties, changes in local property tax rates, and noise in construction cost estimates. Furthermore, there may be important limitations in our approach to defining spillover exposure in our empirical analysis that bias our results. We nonetheless believe that our estimates provide a reasonable first order approximation of the benefits and costs of the projects for which we have cost data. Given that there are omissions and limitations in our calculations of both benefits and costs, comparing ratios of the two—a policy-relevant object—is a reasonable exercise with valid qualitative findings.

### 6.3 Local Political Economy Considerations

The fact that we find that many USACE-constructed levees have benefits that do not exceed their costs raises interesting questions around the motivations for project construction. Given the requirement for non-federal partner construction, operation, and maintenance cost share, we examine how median values of each of the aggregate cost and benefit categories that we model add up from two distinct perspectives: a federal social planner (i.e., USACE) and a local social planner (i.e., non-federal partner). The federal social planner internalizes all of the 6 categories of benefits and costs that we model, whereas the local social planner only considers the effects of levee protection and non-federal construction costs. While it is almost certainly the case that some local municipalities experience both protection benefits and spillover costs from USACE-constructed levees, the geographically-differentiated nature of the effects of levee construction raises the potential for these costs to be external from the perspective of the local municipality. Of the 80 USACE-constructed levee systems in our final estimation data, 24 impose spillover effects on counties outside of the county protected by the levee. As discussed by Wang (2021) in the case of local levee heightening, the fact that levees impose flood risk costs which are potentially external to the benefiting community results in a classic market failure externality problem.

This is clearly seen in Figure 8. If the local municipality or agency—oftentimes a county government—serving as the non-federal sponsor for a USACE levee project does not internalize the flood risk spillover effects of levee construction, perhaps because they are experienced by another locality, then the project will have a net present value of nearly $7 million per levee mile from their perspective. Since such a non-federal sponsor would only internalize the protection benefits, non-federal construction costs (and missing non-federal O&M costs), and

**Figure 8.** Net Present Value (NPV) of USACE Levees from Federal and Local Perspective



This figure decomposes the median net present value (NPV) of USACE levees for the subset of 37 USACE-constructed levee projects for which we are able to collect construction cost data from two distinct perspectives: a federal social planner (e.g., USACE) and a local social planner (e.g., non-federal project sponsor/partner). The protection benefits and protection fiscal externalities (FE) shown in the figure use estimate of the protected housing stock taken from USACE's National Levee Database (NLD). We use a long term interest rate of 3.5% to calculate the effects of annual changes in property tax revenue in perpetuity (i.e., the spillover and protection fiscal externalities), which is approximately equal to Bloomberg's index value for 30-year municipal bond yields as of December 2022.

protection fiscal externalities, the project is likely to be a clear winner from their perspective. This is in stark contrast to the social planner or federal perspective: considering the full suite of impacts that we model, the net present value of USACE levee construction amounts to −\$3 million per levee mile. Comparing median benefit and cost components from these two perspectives may help to explain, at least in part, the fact that we find USACE-constructed levee projects to have relatively low benefit cost ratios ex-post: accounting for the categories of impacts that we allow and assuming that spillovers are external, local non-federal sponsors who unambiguously gain from a levee project are likely to advocate for its construction despite these projects likely reducing aggregate welfare.

### 6.4 Implications for Policy Design

The possibility of this externality problem and the distorted incentives it presents introduces a natural policy prescription, namely a corrective Pigouvian tax. This could take the form of a policy requiring households or communities that benefit from levee protection to internalize the external spillover costs of the levee through a fee that in aggregate totals the net present value of expected damages to spillover exposed communities. Our empirical exercise provides a blueprint for how to best calculate this spatially-explicit corrective tax.

Another possible policy to address the issue of external costs in levee building from the local perspective is to enhance centralized planning in levee construction at the watershed level. Wang (2021) discusses this as a policy prescription to address spillover effects from levee heightening. In some respects, the policy architecture already exists for this approach: USACE's involvement in the pre-construction feasibility assessment phase should in theory hedge against fully ignoring external costs; however, it is unclear the extent to which external costs are taken into account in existing studies and the continued role of Congress in authorizing and funding levee construction does not eliminate incentives for prioritizing internal benefits over external costs.

Examining states represented on the Congressional committees with authorizing and appropriating jurisdiction for USACE civil works project in recent decades, we find a positive correlation between the degree of representation and amount of USACE levee construction.[33] Appendix Figure C5 shows the correlation between state-level measures of cumulative Congressional committee membership and USACE levee construction for the 103rd to 115th Congresses (1993-2018), finding a consistent, positive association. While these state-level relationships may not speak directly to the incentives Congress faces to consider external costs of levee construction, they are suggestive of Representatives prioritizing funding levee construction in their own state if not their own Congressional district.

## 7 Conclusion

Recent trends in natural disasters place the costs of a changing climate in stark relief. According to data collected by the National Centers for Environmental Information, 2022 is the

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[33] Committee membership is relevant to USACE civil works projects since committee members exercise substantial discretion in the early drafting of the relevant authorizing (WRDA) and appropriating (Energy and Water Development appropriations acts) legislation. Since flood control projects are funded at the project-level, the ability to draft this legislation offers committee members substantial input into the site selection process. The committee with authorizing and appropriating jurisdiction for USACE civil works projects in the US House of Representatives are the House Transportation and Infrastructure Committee and House Appropriations Committee, respectively. While there are corresponding committees in the US Senate, the committee membership data to which we have access do not include Senate membership.

eighth consecutive year in which the US has experienced 10 or more billion-dollar weather or climate disaster events, with total annual costs from such events averaging nearly $160 billion over the 5 years ending in 2022.[34] These trends are driven by a combination of factors, including the effects of anthropogenic climate change on the frequency and intensity of natural disasters and increasing exposure and vulnerability to these events. Current policies to control risks and manage impacts are struggling to keep pace with these trends: for example, the NFIP currently carries a debt exceeding $20 billion despite congressional approval for $16 billion in debt forgiveness after Hurricane Harvey in 2017 (Horn and Webel, 2021). Policymakers face a growing imperative to redesign and expand existing efforts to provide public goods that will enhance communities resilience and adaptability in the face of these changing risks.

Our results provide important insight into the difficulties that policymakers face in using existing institutions for climate adaptation. We find that levees provide substantial flood protection benefits; however, decisions by federal, state, and local entities about the placement of such investments generate large cost externalities by increasing flood risks elsewhere. Ignoring these external costs in analyzing this particular form of adaptation investment may produce misleading or incorrect results: for example, taking advantage of our rich, transaction-level data to explore the distribution of capitalized effects of levee construction, we find that any redistribution towards lower income households accomplished by the construction of levees is potentially offset by the regressive nature of spillover costs. Were we to assess the distributional consequences of levees on flood protection benefits alone, we would draw misleading conclusions about these projects.

Moreover, our accounting of a broad set of aggregate benefits and costs of levee construction illuminates key strategic incentives which may determine policy outcomes under current institutions. The potential for local interests in USACE levee construction to ignore external costs in the project development process results in an externality problem in the production of levee-based public flood risk adaptation. Economists have long studied similar externality problems in other settings. This insight into the local political economy of levee siting introduces a valuable set of potential policy prescriptions to the issue of climate adaptation with a long history of study and application elsewhere.

More broadly, our findings highlight the important role for economics in designing and implementing future investments in climate adaptation and resilience. The potential damages associated with poorly designed policies that do not take underlying incentives and interactions into account will only increase as climate change exacerbates underlying natu-

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[34] See: NOAA National Centers for Environmental Information (NCEI) U.S. Billion-Dollar Weather and Climate Disasters (2022). `https://www.ncei.noaa.gov/access/billions/`, DOI: 10.25921/stkw-7w73.

ral hazard risks. This should hopefully encourage economists to invest additional energy in studying how best to not only mitigate climate change, but also adapt to its many impacts.

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# A Data Appendix

## A.1 Additional Information on Data Sources

We provide additional information on each of the data sources used in our analysis below.

- *Zillow Transaction and Assessment Dataset (ZTRAX)*: provides data on transactions of residential parcels for over 2,750 counties across the US dating as far back as 1990.[35] ZTRAX consists of two main databases. The property transaction database contains over 400 million public transaction records, including information on sale price, key dates, associated loan information, source document types, and a series of Zillow-generated codes and data quality flags. The second main database, a tax assessment database, stores property-level records extracted from publicly-available property tax roll data. Given that reporting requirements are generally stricter for tax roll data than transaction data, we observe greater coverage in the assessment database: it covers approximately 150 million parcels in over 3,100 US counties. The assessment database includes key information on parcel attributes: lot size, building size, number of bedrooms, number of bathrooms, geographic coordinates, tax valuation, estimated fair market value, and more. Observations are linked across the transaction and assessment databases based on a unique parcel identifier, which allows us to assign property attributes to a transaction. We acquire ZTRAX data through a data use agreement with Zillow.[36]

- *First Street Foundation (FSF) Adaptation Database*: in an effort to capture major man-made hydrological modifications in their nationwide flood model, the FSF has collected data on the location and key physical and hydrological characteristics of over 20,000 flood adaptation projects in the continental US. FSF collect the data from state, county, and city agencies across the US and digitizes projects by drawing the area for which a structure provides flood protection and assigning a level of protection provided. The FSF adaptation database provides us with shapefiles representing the spatial extent of protected areas for each project in the database as well as key project-level information, including project type, project source, any project source identifiers,

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[35] Nolte et al. (2021) note that there are clear geographic trends in the availability of valid, fair market value transaction price information in ZTRAX: the public disclosure of sales prices is not universal across states, so such data are not universally available nationwide. In particular, Alaska, Idaho, Indiana, Kansas, Louisiana, Mississippi, Montana, New Mexico, North Dakota, South Dakota, Texas, Utah, and Wyoming do not require public disclosure of sales prices, which means that representative sales price information for these states is scarce in ZTRAX and is likely only available in select sub-geographies such as major urban centers where reporting requirements or norms are different.

[36] As of 11/20/2022, Zillow plans to end the ZTRAX program and is no longer accepting applications for access to ZTRAX.

and estimates of the level of protection provided.[37] In the case of USACE levees, a levee system appears as a single project in the FSF Adaptation Database. We acquire data from the FSF Adaptation Database through a data use agreement with FSF.[38]

- *US Army Corps of Engineers (USACE) National Levee Database (NLD)*: provides comprehensive information on the near universe of federal, state, and local levees across the US, covering over 6,900 levee systems and 24,000 miles of levees. Data contained in the NLD are provided by USACE on the universe of USACE-constructed levees and by state and local agencies/entities in the case of non-federally constructed levees. As a result, coverage is less exhaustive in the case of non-federal levees. The NLD provides detailed information on the spatial extent, overtopping scenario, construction end date, constructing agency, and operating agency at the levee segment level. A single levee system may consist of one or more levee segments. We are able to link NLD systems to projects in the FSF Adaptation Database using the unique NLD system identifier and we use NLD data on the constructing agency to subset the FSF adaptation projects to all systems with at least one USACE-constructed levee segment. The segment construction dates provide the key field that we use to determine treatment timing in our analysis. Unfortunately, levee construction dates are not reliably recorded for all USACE-constructed levee segments; however, they are available for around 79% of USACE-constructed segments recorded in NLD. Moreover, certain large-scale, high-profile levee projects—such as the Lower Mississippi River and New Orleans levees—have been heavily modified over time, with some originally locally-constructed in the early 1900s. As a result, these salient examples of levees on which USACE has provided ongoing maintenance or to which USACE has added do not appear in our sample of USACE-constructed levee segments. We use the spatial data on segment extents to calculate the distance between parcels and their nearest levee. Data from the NLD are publicly available.[39]

- Home Mortgage Disclosure Act (HMDA): HMDA, enacted by Congress in 1975, re-

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[37] These estimates of the level of protection are based on the return period to which it will continue to function. The "return period" can be thought of as the reciprocal of expected frequency: for example, a 100-year flood has a $1/100 = 0.01$ or 1% chance of being exceeded in any given year. These estimates of the level of protection are also referred to as the "overtopping scenario" in the context of levees, i.e., the flood level beyond which flood waters exceed the height of the levee and therefore flow over top of the levee structure. FSF takes the overtopping scenario values from the USACE NLD for all USACE-constructed levees.

[38] Additional information on the FSF National Flood Model (FSF-NFM) is available here: `https://firststreet.org/research-lab/published-research/flood-model-methodology_overview/` (accessed 11/20/2022).

[39] Additional information on the NLD is available here: `https://levees.sec.usace.army.mil/#/` (accessed 11/20/2022).

quires major depository institutions to disclose loan-level information for all of their closed-end home lending activity every year. Data are provided at the level of the loan application under HMDA for the entire period that we study. We harmonize loan application register and transmittal sheet data for the period 1990-2020 in order to observe the following at the loan-level: loan application purpose, loan application result, loan amount, collateralized property census tract, loan application decision date, lender institution name, applicant race, applicant income, and applicant ethnicity. Due to changes in reporting requirements over the period for which we acquire data, we are only able to access data on applicant ethnicity for a subset of later years. HMDA loan application data are publicly available.[40]

- *US Geological Survey (USGS) National Hydrography Dataset (NHD) Plus, Version 2.1*: provides spatially granular, comprehensive information on the location and physical attributes of the water drainage network of the US. Maintained by the USGS, the NHD is the most up-to-date and comprehensive hydrography dataset for the US. We use the NHD's area and waterbody features to calculate proximity between residential parcels in our data and rivers, streams, canals, lakes, ponds, estuaries, wetlands, and coastline. NHD data are publicly available.[41]

- *USGS 3D Elevation Program (3DEP)*: provides access to a national baseline of consistent high-resolution topographic elevation data derived from lidar point cloud data products. We use 3DEP-derived digital elevation models (DEM) at a 10m resolution to determine the elevation and slope at the coordinates of all parcels in our data. 3DEP data are publicly available.[42]

- *Presidential Disaster Declaration (PDD) Summaries*: provides information on all approved federal disaster declaration requests, including data on the disaster type, disaster event start and end dates, and affected counties.[43]

- *National Oceanic and Atmospheric Administration (NOAA) Storm Events Database*: provides records on storms and other significant weather events having sufficient intensity to cause injury, loss of life, significant property damage, and/or disruption to

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[40] Additional information on HMDA data is available here: `https://www.ffiec.gov/hmda/` (accessed on 11/20/2022).

[41] Additional information on the NHD is available here: `https://www.usgs.gov/national-hydrography/national-hydrography-dataset` (accessed 11/20/2022).

[42] Additional information on 3DEP is available here: `https://www.usgs.gov/3d-elevation-program` (accessed 11/20/2022).

[43] Additional information on the PDD data is available here: `https://www.fema.gov/openfema-data-page/disaster-declarations-summaries-v2` (accessed 11/20/2022).

commerce; rare weather phenomena that generate media attention; and other significant meteorological events, such as record maximum or minimum temperatures or precipitation. The database includes data for the period 1950 through 2022 and indicates all counties affected by a specific event; however, events other than tornadoes, thunderstorms, wind, and hail storms are first recorded in the dataset in January 1996. We use these data to generate measures of recent exposure to flood-related storms over various intervals—specifically, the previous 6-, 12-, 18-, and 24-months—for all transactions in our data to which we can link such storm types over the relevant interval. NOAA Storm Events Database is publicly available.[44]

- *National Flood Insurance Program (NFIP) Redacted Claims and Policies Datasets*: provide nationwide data at the policy-level for all policies issued since 2009 and all claims dating back to 1978 under the NFIP. These NFIP data include information on the term of the policy, the date of the claim, and the location of the policy/claim down to the census tract level, which we use to generate annual counts of the number of policies-in-force, number of claims, and average claim amounts conditional on making a claim at the census tract-year level for all years for which data are available. We combine our estimates of policies-in-force with estimates of the number of residential units at the census tract-year level taken from the Census Bureau's 5-year American Community Survey (ACS) to construct estimates of tract-year take up rates for 2009-2020. NFIP claims and policies data are publicly available.[45]

### A.2 ZTRAX Data Cleaning

Zillow's ZTRAX database provides unprecedented access to parcel-level information on the near universe of residential properties nationwide and associated transactions for a substantial time period. Zillow sources ZTRAX from a major third-party data provider as well as their own county-level data collection program. While Zillow makes efforts to harmonize the assessment and transaction-level data contained in ZTRAX, given the disparate underlying data sources, there are a number of additional steps that must be taken to ensure the final dataset used in our analysis contains arms-length transactions of residential parcels with valid attributes, most importantly geographic information.

It is important to only include arms-length transactions as our empirical approach—and hedonic pricing methods more broadly—implicitly rely on the assumption that sales

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[44] Additional information on the NOAA Storm Events Database is available here: `https://www.ncdc.noaa.gov/stormevents/` (accessed 11/20/2022).

[45] Additional information on the NFIP policies and claims data are available here: `https://www.fema.gov/about/openfema/data-sets` (accessed 11/20/2022).

prices of property transactions are indicative of the fair market value (FMV) of the parcel. Examples of non-FMV transactions include transfers between family members, foreclosures, or transactions involving public agents. Such deviations from FMV in observed transaction prices would bias our estimates of capitalized effects of levee construction. Moreover, it is important to only include parcels with accurate geographic information in our analysis as we use parcel coordinate information in ZTRAX to assign parcels to different spatial treatment statuses.

Fortunately, a team of researchers with substantial collective experience working with ZTRAX has collected a set of best practices for ensuring ZTRAX-derived data quality and identifying arms-length transactions (Nolte et al., 2021). In order to subset to FMV, arms-length transactions, we implement the following filters based on guidance from Nolte et al. (2021):[46]

1. We drop all transactions with listed sales prices below 1001. Ultimately we drop transactions below the 1st and the 99th percentile in our final, levee-adjacent sample described in Appendix A.5 in order to remove major outliers; however, this step removes a non-trivial number of transactions which are clearly below FMV transactions and are changing hands for nominal amounts.

2. We drop all transactions that are not recorded in ZTRAX as deed transfers, which explicitly excludes mortgage refinancing records, foreclosures, and other transactions which may appear in ZTRAX, but are identified by Zillow as explicitly not involving deed transfer.

3. We drop transactions flagged by Zillow as intra-family transfers, likely based on similarities between buyer and seller names.

4. We keep transactions with sales price sources which Nolte et al. (2021) identify with high confidence as indicative of FMV transactions. For example, Nolte et al. (2021) identify transaction prices listed in a given source document as "cash sale" as indicative of FMV with high confidence; however, a sales price listed in a given source document as derived from the transfer tax amount is indicative of FMV with either low or medium confidence.

5. We keep transactions with document type categories which Nolte et al. (2021) identify with high confidence as indicative of FMV transactions. There are 161 standardized

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[46] Additional information on the filters that Nolte et al. (2021) suggest applying to identify FMV, arms-length transactions is available in their paper and at the following website: `https://placeslab.org/ztrax/` (accessed 11/20/22).

document type categories in ZTRAX, which describe the source of the transaction information recorded in ZTRAX. Nolte et al. (2021) identify which document types in each state tend to reflect FMV transactions best and provide a complete listing of their assessment, which we use to filter out document types which they view as reflecting FMV with low confidence.

A key ZTRAX data quality issue for our analysis involves the accuracy of parcel coordinates. In addition to a non-trivial share of parcels in ZTRAX with missing point locations, some ZTRAX coordinates appear to have been derived from ZIP code area centroids instead of parcel data[47]. In addition, there are certain instances where ZTRAX coordinates fall outside of the boundaries of the county or ZIP code listed for a parcel, which are taken directly from source documentation and should therefore be viewed as authoritative.

To address these issues, we first remove all coordinate data for parcels with duplicated coordinate information, though we do not immediately drop these parcels from our sample. This addresses the concern that many coordinates are likely derived by approximate geocoding to assign ZIP code or other aggregate geographic coordinates. Next we remove all coordinate data for parcels with coordinates falling outside of their listed county boundary, but again we do not immediately drop these parcels. Finally, where possible we take street address information for all resulting parcels with missing coordinate data and use the Census Bureau's Geocoder API to assign coordinates for each of these parcels.[48]

## A.3 ZTRAX-HMDA Matching Procedure

We are interested in not only estimating the magnitude of capitalized effects of USACE levee construction, but also the distribution of these effects along key socioeconomic variables. Unfortunately, ZTRAX does not contain detailed information on purchaser demographics; however, we are able to make use of loan-specific information to link a subset of transactions in ZTRAX to information on successful loan applications for home purchases made publicly-available through the Home Mortgage Disclosure Act (HMDA).

HMDA data provide information on the year of origination, property census tract, loan amount, application purpose, lender institution's name, and select applicant demographics for all loan applications to major depository institutions. We collect loan application-level data for the years 1990 through 2020 and use available documentation to harmonize key fields across all years of data. We then subset the harmonized HMDA loan applications to those which are ultimately successful and are for the purpose of a home purchase given that

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[47] According to Nolte et al. (2021), ignoring such cases can result in geo-location errors exceeding 1km.

[48] Further information about the Census Geocoder is available here: `https://geocoding.geo.census.gov/geocoder/Geocoding_Services_API.pdf` (accessed on 11/03/2022).

the loans we observe in ZTRAX are for that purpose as well. We then follow a procedure first outlined in Bayer et al. (2016) to match the HMDA loan-level information to our ZTRAX transaction-level information. Specifically, we:

1. Define all possible matching loan application and transaction pairs from HMDA and ZTRAX as those with the same year, census tract, and loan amount (rounded to the nearest 1000).[49]

2. This results in a non-trivial number of duplicate match candidates: in a non-zero number of cases, lenders make multiple loans of the same amount in a single census tract in a given year. We keep all many-to-one and one-to-many matches in order to potentially narrow these matches down further; however, we discard all many-to-many matches as it is difficult to further refine such matches.

3. For all many-to-one and one-to-many matches, we conduct fuzzy string matching on the lender name information contained in both the HMDA and ZTRAX microdata. Specifically, we calculate the Jaro-Winkler distance between the potential HMDA-ZTRAX matched pairs, which gives us a quantified measure of the proximity of the strings in each pair. We then keep all pairs with a Jaro-Winkler distance satisfying a sufficient similarity criterion, which we validate by examining the resulting matches.

Implementing the above matching procedure on the full set of accepted loans for home purchase from 1990-2020 and the nationwide processed ZTRAX data, we are able to match 41.46% of arms-length transactions in ZTRAX to a unique loan application record in the HMDA data. This is similar to other match rates observed in the literature that employs the above approach: Bayer et al. (2016) match 55% of San Francisco Bay Area sales from 2994 to 2004; Bakkensen and Ma (2020) match 47% of residential property sales from the Miami Dade-Port St. Lucie-Fort Lauderdal CSA from 2009 to 2012; and Graff Zivin, Liao and Panassie (2022) match a little over 50% of sales across the state of Florida from 2000 to 2016. Given that we implement this procedure for the entire continental US for the period 1990-2020, it is unsurprising that we observe a slightly lower match rate. Conditioning on arms-length transactions in ZTRAX for which we observe some non-empty loan information, our match rate is 68.45%.

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[49] We match loan applications and transactions based on the year of origination as listed in the HMDA data and the year of sale as listed in the ZTRAX data. Given that HMDA data use historical census tract definitions, which can change dramatically after each decennial census, we assign each parcel in our ZTRAX data to their corresponding 1990, 2000, and 2010 census tract boundary using valid geographic coordinates and use the relevant assigned census tract to match to HMDA data depending on the year of sale/origination.

Since not all transactions in our data contain loan information and we are unable to match HMDA loan data to all those that do, it is worth evaluating how representative our HMDA-ZTRAX matches are of the broader population. Given that we are targeting the population of homeowners, we need external data on analogous demographic variables for the universe of home owning households. We do so by aggregating our income, race, and ethnicity variables for our matched ZTRAX-HMDA sample to the state-by-year level and comparing the resulting aggregates to relevant data obtained from the Census Bureau's 1-year American Community Survey (ACS) for the period for which these data are available, 2005-2019. Figure A1 shows the resulting comparison for a subset of our constructed sociodemographic variables. Compared to the median income for households with a mortgage in the ACS, median household income in our ZTRAX-HMDA matched sample is quite similar across state-years, with an overall correlation of 0.78. Our ZTRAX-HMDA matched sample also has similar shares of white and black households compared to owner-occupied households in the ACS; however, it is worth noting that our ZTRAX-HMDA matched sample seems to under-predict the share of black households in areas where the ACS estimates this figure to be relatively high.

### A.4 Constructing USACE Levee Cost Data

To better understand our estimates of the benefits and costs of USACE levee construction, we collect information on upfront construction costs for a subset of projects in our final dataset. Unfortunately, construction cost information is not maintained in a central, consistent, and publicly-available format for USACE Civil Works projects. We therefore have to manually scrape this information from a disparate set of primary sources, including federal budget requests, appropriations bills, and USACE annual reporting.

A major challenge in collecting construction cost data that applies to all primary source information that we consult is that there is no clear one-to-one mapping from levee systems as listed in the USACE NLD—and thus how they appear in our data—and projects referenced in these sources. In many cases, a project may be referred to in budgetary, appropriations, and reporting materials that refers to a collection of many NLD levee systems built over several decades. This requires us to manually map NLD levee systems to project names from various stages in the funding process, which we are only able to do with high confidence for a subset of projects.

We collect ex-post information on project costs from several sources, where possible. First, we review annual reports of the Chief of the USACE to Congress (often referred to as "Chief Reports"), which cover the period 1848-2012. These reports include detailed project-level narratives on construction, navigation, and hydropower projects undertaken by USACE

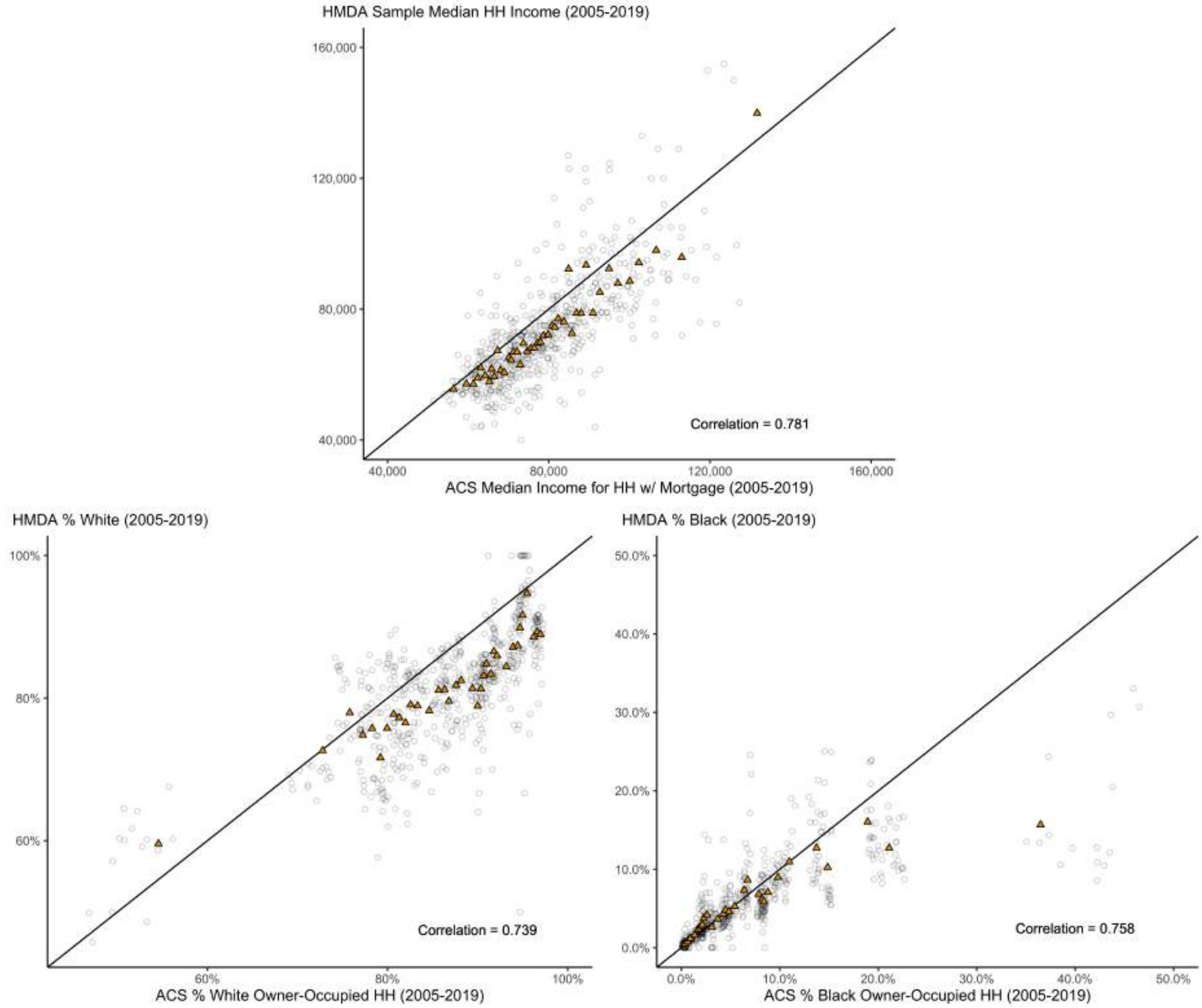

**Figure A1.** Comparing select demographic variables from the ZTRAX-HMDA matched sample with estimates from the Census Bureau's 1-year American Community Survey (ACS).

using federal funds. Over the relevant period of our analysis, these reports offer a relatively consistent format of ex-post descriptions of activities carried out in a given fiscal year by each USACE District and include tabular information on cumulative spending for a subset of Civil Works projects. Unfortunately, these Chief Reports only provide sufficient project-level information through fiscal year 2012 — USACE appears to have satisfied its annual Congressional reporting requirements in subsequent fiscal years through written committee testimony alone. Where possible, we also collect information on ex-post project construction costs from various public documents, such as press releases, published by the various USACE Districts.

Due to the incomplete coverage of the Chief Reports and the challenge presented by the lack of a one-to-one match with NLD levee systems, we also collect Civil Works project appropriations from regular and supplemental appropriations bills, which provide ex-ante measures of project costs. We also consult budget request information, which also provide ex-ante measures of project costs. These sources are subject to the same challenge of a lack of a one-to-one match with NLD levee systems and are likely only approximations to the true upfront cost of USACE levees, so we only rely on these materials where we find a high confidence match to projects in our data.

### A.5 Final Sample Construction and Summary Statistics

As described in Section 3, we use combined data on USACE-constructed levees from the FSF Adaptation Projects Database and the USACE NLD to subset our processed ZTRAX data: using valid parcel-level geogrpahic information, we identify those residential parcels located either inside of or within relatively close proximity to—in practice, five miles—leveed area boundaries, with distance to a leveed area boundary defined as standard Euclidean distance. This assumes that the housing market effects of levee construction are restricted to within five miles of a levee/leveed area boundary.

We then merge the various data sources described above to the resulting subset of residential parcels/transactions. Though HMDA-derived demographic data are only available for a subset of transactions in the resulting dataset, we keep both HMDA-matched and unmatched transactions and use both in our hedonic analyses.

In addition to filters applied to the raw ZTRAX data described above, we subset our final dataset in several ways. First, we remove price outliers by dropping transactions that are either below the 1st percentile or above the 99th percentile of real transaction price for the entire period. Finally, we remove clear outliers in terms of square footage, number of bedrooms, and number of bathrooms, which are either the result of coding errors or represent parcels which are likely uncomparable to the rest of those in our data. The final dataset is described in Table A1, which shows average values of key variables for both the unmatched and HMDA-matched sub-samples and calculates the differences in means where possible.

**Table A1.** Summary Statistics

| | Unmatched Sample | | HMDA Sample | | | |
|---|---|---|---|---|---|---|
| | Mean | Std. Dev. | Mean | Std. Dev. | Diff. | Std. Error |
| Price (1000s 2019$) | 390.465 | 286.726 | 406.597 | 262.969 | 16.133 | 0.410 |
| Bathrooms | 2.077 | 0.770 | 2.104 | 0.722 | 0.027 | 0.001 |
| Bedrooms | 3.235 | 0.837 | 3.275 | 0.807 | 0.040 | 0.001 |
| Interior Area (ft.$^2$) | 1.781 | 0.739 | 1.793 | 0.714 | 0.012 | 0.001 |
| Age (years) | 40.022 | 28.494 | 34.803 | 25.508 | -5.219 | 0.040 |
| Levee Protected | 0.121 | 0.326 | 0.132 | 0.339 | 0.012 | 0.000 |
| Dist. from Leveed Area (mi.) | -2.292 | 1.815 | -2.213 | 1.821 | 0.079 | 0.003 |
| Dist. from Levee (mi.) | 3.659 | 2.560 | 3.622 | 2.524 | -0.037 | 0.004 |
| Dist. from Water (mi.) | 0.631 | 0.480 | 0.643 | 0.484 | 0.012 | 0.001 |
| Loan Amount (1000s 2019 $) | — | — | 247.260 | 160.701 | — | — |
| Income (1000s 2019 $) | — | — | 128.298 | 732.087 | — | — |
| Black | — | — | 0.046 | 0.210 | — | — |
| White | — | — | 0.637 | 0.481 | — | — |
| Hispanic | — | — | 0.087 | 0.283 | — | — |
| Asian | — | — | 0.144 | 0.351 | — | — |
| N | 867,490 | | 944,366 | | | |

Reported standard errors are from a two-sided $t$-test of the difference in means between the unmatched and HMDA-matched sample.

# B Additional Levee Construction Effects

We explore the potential for other forms of housing market effects of levee construction alongside the protection, spillover, and macro effects outlined in Section 4.

## B.1 Categorizing Additional Levee Construction Effects

We identify two additional categories of potential levee construction effects: adjacency and salience effects.

*Adjacency Effects.*—This category refers to the full set of housing market effects associated with close proximity to a levee. This includes a potential positive amenity effect of adjacency to a levee: households may derive positive utility from residing near a waterway and it is common for levees to be built with combined recreation use in mind, for instance by building a recreation trail on top. It is also possible that there are negative disamenity—or nuisance—effects associated with proximity to a levee: given their size and the scale of construction and maintenance activities, homes near levees may experience noise and light pollution or visual disamenities associated with large built infrastructure around waterways. Given the broad set of effects captured by this category, the net capitalization effect of this category is theoretically ambiguous.

*Salience Effects.*—This category refers potential differences in the salience of flood protection effects induced by proximity to the levee itself: households may place greater weight on any flood protection effects if they regularly encounter or can see the levee near their home. This category is distinct from adjacency effects in that the latter are experienced by homes near a levee independent of whether or not they are behind the levee. These salience effects account for potential heterogeneity in households' perceptions of the flood protection benefits they receive by being behind a levee based on proximity to the levee itself. Since this category captures differential salience of protection benefits as opposed to disamenity effects associated with levee proximity—which are captured by the adjacency effects category—capitalized salience effects are likely positive.

Figure B1 amends Figure 3 to provide a demonstration of the expanded set of housing market effects of levee construction.[50] Parcels A and B both fall within the leveed area and experience *Protection Effects*. Parcel B is located near the levee itself, experiencing *Adjacency Effects* and *Salience Effects*. Parcels C and D are not located within the leveed area but are near the relevant surface water and as a result may experience *Spillover Effects* from levee construction. Given its proximity to the levee, parcel C also experiences *Adjacency Effects*. All parcels experience *Macro Effects*, though this is the only effect to which parcel

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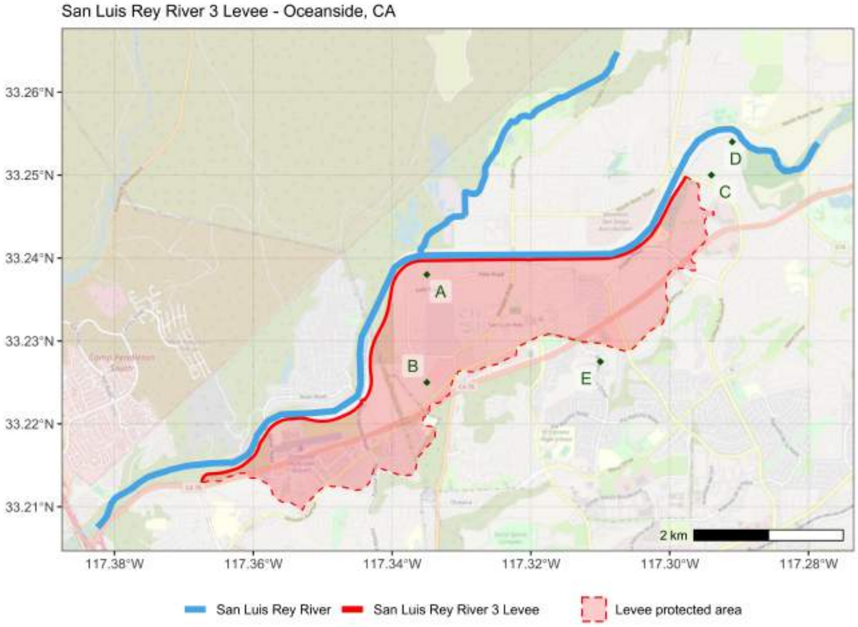
[50] Note that the labeling of different parcel types is different.

**Figure B1.** Categories of Levee Construction Effects



Five example parcels (labeled A, B, C, D, and E) demonstrating the different types of potential effects of levee construction in the context of the San Luis Rey River 3 Levee (California, US), a USACE-constructed levee completed in 2000.

E is exposed.

## B.2 Identifying Additional Levee Construction Effects

Building on this categorization, we can use the example parcels depicted in Figure B1 to illustrate our approach to identifying the capitalized effects of levee construction. This exposition of our approach to identification is inspired by Muehlenbachs, Spiller and Timmins (2015) who employ a similar empirical strategy to identify the capitalized effects of shale gas development. Consider the price of a particular example parcel, say $P_A$, and define the operator $\Delta_t$ as the change in a given property's transaction price from before to after construction of a levee, i.e., $\Delta_t P_A = (P_{A,post} - P_{A,pre})$. Then we can decompose the change in each of the example parcel's price around levee construction as follows:

$$\begin{aligned}
\Delta_t P_A &= Macro + Protect + Adjacency + Salience \\
\Delta_t P_B &= Macro + Protect \\
\Delta_t P_C &= Macro + Adjacency + Spillover \\
\Delta_t P_D &= Macro + Spillover \\
\Delta_t P_E &= Macro
\end{aligned} \tag{B1}$$

where, for example, $Protect$ refers to the change in observed prices attributable to protection benefits from the levee. As Equation B1 demonstrates, we can identify protection, spillover, and adjacency effects using difference-in-differences (DD) estimators:

$$\begin{aligned}(Protect)_{DD} &= \Delta_t P_B - \Delta_t P_E \\ (Adjacency)_{DD} &= \Delta_t P_C - \Delta_t P_D \\ (Spillover)_{DD} &= \Delta_t P_D - \Delta_t P_E\end{aligned}$$

In this framework, the first difference refers to the change in sale prices before and after levee construction for each parcel type. In the case of the protection and spillover effects, identification then comes from comparing this change for homes within leveed areas but not near the levee (i.e., parcel B) and outside of leveed areas and near surface waters (i.e., parcel D) with the change for homes outside of leveed areas and far away from surface waters (i.e., parcel E), respectively. We identify adjacency effects by comparing the pre- and post-levee construction price change for homes outside of leveed areas, adjacent to levees, and adjacent to waterways (i.e., parcel C) with that for homes outside of leveed areas and adjacent to waterways (i.e., Parcel D).

Note that to identify potential salience effects, we must difference away macro, protection, and adjacency effects from the change in sales price for homes within leveed areas and near levees. Thus, we can estimate salience effects using the following triple-difference (DDD) estimator:

$$(Salience)_{DDD} = \underbrace{(\Delta_t P_A - \Delta_t P_B)}_{=(Salience+Adjacency)_{DD}} - \underbrace{(\Delta_t P_C - \Delta_t P_D)}_{=(Adjacency)_{DD}}$$

where the first difference—depicted by $\Delta_t$—is the within home-type change in sale price around construction of a levee. The second difference compares the change in prices between homes adjacent to a levee and comparable homes not adjacent to a levee: in the case of levee-adjacent homes within leveed areas (i.e., parcel A), the relevant difference compares price changes with those for non-levee-adjacent homes within leveed areas (i.e., parcel B). In the case of levee-adjacent homes outside leveed areas (i.e., parcel C), the relevant difference compares price changes with those for non-levee-adjacent, waterway-adjacent homes outside leveed areas (i.e., parcel D). The third difference subtracts these double-differences, removing adjacency effects and leaving only salience effects. Similar to the main design used to identify protection and spillover effects in the text, this design addresses concerns about the endogeneity of levee site selection.

## B.3 Estimating Expanded Capitalized Effects

Let $L_i$ equal 1 if parcel $i$ is located within a leveed area as indicated by the First Street data and 0 otherwise; $A_i$ equal 1 if parcel $i$ is located adjacent to a levee and 0 otherwise; and $W_i$ equal 1 if parcel $i$ is located adjacent to a waterway and is outside of leveed areas and 0 otherwise.[51]

We implement our identification strategy for the expanded set of levee construction effects by defining the price of house (parcel) $i$ at time $t$ as a function of a series of interaction terms, a parcel fixed effect ($\xi_i$), a levee segment-by-year fixed effect ($\mu_{l(i)t}$), and a year-by-month fixed effect ($\delta_t$):

$$\begin{aligned}\log P_{it} = {} & \alpha_1(T_{it} \times L_i) + \alpha_2(T_{it} \times A_i) + \alpha_3(T_{it} \times W_i) \\ & + \alpha_4(T_{it} \times L_i \times A_i) + \alpha_5(T_{it} \times A_i \times W_i) \\ & + \xi_i + \mu_{l(i)t} + \delta_t + \varepsilon_{it}\end{aligned} \tag{B2}$$

where $T_{it} = 1$ if the transaction occurs after levee construction and 0 otherwise. As previously discussed, $T_{it}$ is assigned to transactions based on the construction date of the nearest levee segment to parcel $i$, which may result in different construction dates for transactions of parcels near the same levee system. Similar to our main specification in the text, we include a levee segment-by-year fixed effect to account for the staggered timing of construction across levee systems—and in certain cases across levee segments within a system—and avoid the biases from standard two-way fixed effects estimators in the presence of heterogeneous treatment effects within-unit over time (de Chaisemartin and D'Haultfœuille, 2020; Goodman-Bacon, 2021). Note that by including this fixed effect, we cannot separately estimate a parameter on $T_{it}$ due to collinearity with $\mu_{l(i)t}$; however, this parameter is not of independent interest.

Similar to our main analysis in the text, to implement our estimating equation with a parcel fixed effect, we restrict our estimation sample to parcels for which we observe multiple transactions, which is common in the hedonics literature (Hallstrom and Smith, 2005; Graff Zivin, Liao and Panassie, 2022). While this reduces our sample size, it has the benefit of limiting the extent to which our estimates can be driven by compositional shifts in transacted homes that may occur due to levee construction by restricting the identifying variation to sales of properties that transact multiple times in our sample period.[52]

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[51] Note that the definition of $W_i$ excludes parcels protected by levees (i.e., $W_i = 1 \Leftrightarrow L_i = 0$), which allows us to use transactions of homes for which $W_i = 1$ to identify spillover effects.

[52] Note that $L_i$, $A_i$, and $W_i$ do not enter Equation B2 on their own due to the inclusion of the parcel fixed effect, $\xi_i$. Furthermore, Equation B2 does not include the full suite of interaction terms between all four indicator variables due to the fact that interaction terms that only vary across properties are collinear with

The model specified in Equation B2 implicitly assumes that exposure to various treatments, specifically levee-adjacency ($L_i$) and waterway-adjacency ($W_i$) decays with distance to the relevant feature, ultimately becoming zero at some distance. A common approach in the literature to determining exposure distance is to flexibly fit a curve between pre- and post-event prices and distance, using the crossing point of the two curves to determine exposure (Linden and Rockoff, 2008; Muehlenbachs, Spiller and Timmins, 2015). We implement this price gradient approach in Appendix Figure C3 and determine that constraining the effects of levee-adjacency and waterway-adjacency to 0.1 mile is reasonable.

There are several assumptions necessary to use Equation B2 to identify the expanded set of effects outlined above

> ASSUMPTION C1: *the spillover effects of adjacency to a waterway do not vary with distance to a levee, i.e.,* $\alpha_5 = 0$*.*

Our main estimating equation therefore becomes:

$$\begin{aligned}\log P_{it} = \alpha_1(T_{it} \times L_i) + \alpha_2(T_{it} \times A_i) + \alpha_3(T_{it} \times W_i) \\ + \alpha_4(T_{it} \times L_i \times A_i) + \xi_i + \mu_{l(i)t} + \delta_t + \varepsilon_{it}\end{aligned} \tag{B3}$$

Assumption C1 rules out changes in risk or risk salience for spillover exposed parcels based on proximity to a levee. This assumption aids in identification by ensuring that we are able to fully difference out all spillover effects in our adjacency DD estimator. To see this and to connect Equation B3 to the exposition of our identification strategy in Section 4.2, consider the correspondence between the coefficients and parcels A, B, C, D, and E from Figure 3:

$$\begin{aligned}\Delta_t P_A &= \alpha_1 + \alpha_2 + \alpha_4 + \Delta_t \mu_{l(i)t} + \Delta_t \delta_t \\ \Delta_t P_B &= \alpha_1 + \Delta_t \mu_{l(i)t} + \Delta_t \delta_t \\ \Delta_t P_C &= \alpha_2 + \alpha_3 + \Delta_t \mu_{l(i)t} + \Delta_t \delta_t \\ \Delta_t P_D &= \alpha_3 + \Delta_t \mu_{l(i)t} + \Delta_t \delta_t \\ \Delta_t P_E &= \Delta_t \mu_{l(i)t} + \Delta_t \delta_t\end{aligned}$$

where $\Delta_t \mu_{l(i)t}$ and $\Delta_t \delta_t$ denote the change in the time-varying fixed effects for each parcel before and after levee construction.[53] This implies that the four estimators presented above

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the parcel fixed effect and by definition $W_i = 1 \Leftrightarrow L_i = 0$. The terms that remain in the above estimating equation are those that are well-defined and not collinear with the fixed effects.

[53] Note that the parcel fixed effects, $\xi_i$ are differenced away through the $\Delta_t$ operator.

are as follows:

$$
\begin{aligned}
&(Protect)_{DD} = \Delta_t P_B - \Delta_t P_E = \alpha_1 \\
&(Adjacency)_{DD} = \Delta_t P_C - \Delta_t P_D = \alpha_2 \\
&(Spillover)_{DD} = \Delta_t P_D - \Delta_t P_E = \alpha_3 \\
&(Salience)_{DDD} = (\Delta_t P_A - \Delta_t P_B) - (\Delta_t P_C - \Delta_t P_D) = \alpha_4
\end{aligned}
$$

Thus, $\alpha_1$, $\alpha_2$, and $\alpha_3$ are the double-difference measures of protection effects, adjacency effects, and spillover effects resulting from levee construction, respectively, and $\alpha_4$ is the estimate of the salience effect of proximity to a levee for a protected home. As the above indicates, if $\alpha_5 \neq 0$ in Equation B2, then $\Delta_t P_C - \Delta_t P_D = \alpha_2 + \alpha_5$ and we are unable to identify any adjacency effects.

Two additional assumptions about house price counterfactuals are necessary for the estimated coefficients $(\alpha_1, \alpha_2, \alpha_3)$ to have the causal interpretations indicated above. The first allows us to identify protection, adjacency, and spillover effects and is standard from the DD literature: parallel trends in outcomes (house prices) for the relevant treatment and control parcels around the time of levee construction. This is analogous to the parallel trends assumption necessary for identification in the main specification in the text.

The second assumption about house price counterfactuals builds on Olden and Møen (2022) and provides a causal interpretation for $\alpha_4$.

> ASSUMPTION C2: *the trend in the price differential between levee-adjacent and non-levee-adjacent parcels is equivalent for levee-protected parcels and non-levee-protected, waterway-adjacent parcels.*

Using the parcel categorization from Figure B1, Assumption C2 states that the price differential for parcels of type A and B must have the same trend as the price differential for parcels of type C and D. In other words, there are no factors beyond levee construction generating a difference in differential trends for levee-adjacent and non-levee adjacent homes in leveed and non-leveed areas.

### B.4 Double- and Triple-Difference Results

Table B1 reports our main results estimating Equation B3 using different proximity treatment bandwidths. Overall, the estimated protection and spillover effects are similar to those reported in Table 1 in the text. We find minimal evidence of adjacency effects. Interestingly, there do appear to be non-zero effects associated with proximity to a levee within a leveed area; however, these are estimated to be statistically significant and *negative* when

**Table B1.** Log Sale Price on Spatial Treatment Indicators

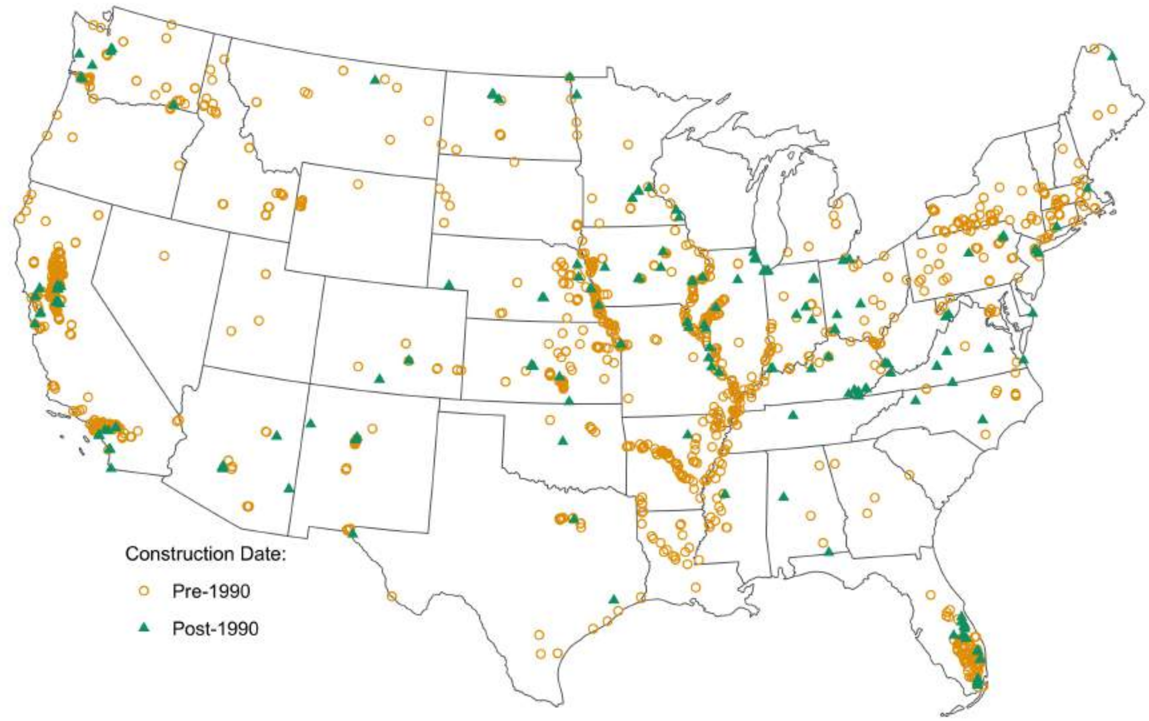
| | $k \leq 0.1$ mi. | | $k \leq 0.2$ mi. | | $k \leq 0.3$ mi. | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Post x Intersects ($\alpha_1$) | 0.098*** | 0.026*** | 0.097*** | 0.027*** | 0.095*** | 0.027*** |
| | (0.015) | (0.008) | (0.015) | (0.009) | (0.015) | (0.009) |
| Post x $k$ mi. of Levee ($\alpha_2$) | -0.0005 | -0.019 | 0.054* | 0.014 | 0.070*** | 0.018 |
| | (0.043) | (0.029) | (0.029) | (0.015) | (0.024) | (0.011) |
| Post x $k$ mi. of Water ($\alpha_3$) | -0.062*** | -0.014** | -0.063*** | -0.012*** | -0.066*** | -0.009* |
| | (0.012) | (0.007) | (0.009) | (0.005) | (0.008) | (0.005) |
| Post x Intersects x $k$ mi. of Levee ($\alpha_4$) | -0.068 | -0.021 | -0.101*** | -0.043** | -0.110*** | -0.037** |
| | (0.050) | (0.035) | (0.037) | (0.019) | (0.032) | (0.016) |
| Parcel FE | Yes | Yes | Yes | Yes | Yes | Yes |
| Sale Year-Sale Month FE | Yes | Yes | Yes | Yes | Yes | Yes |
| Sale Year-Levee Segment FE | | Yes | | Yes | | Yes |
| Observations | 1,279,984 | 1,279,984 | 1,279,984 | 1,279,984 | 1,279,984 | 1,279,984 |
| $R^2$ | 0.924 | 0.948 | 0.924 | 0.948 | 0.924 | 0.948 |

The dependent variable is the log of real sale price. Data are restricted to parcels for which we observe more than one transaction during our sample period. We further restrict our data to transactions of parcels that either fall within leveed areas or are located within 5 miles of a leveed area boundary, excluding transactions of parcels that are within 0.1 mi on either side of leveed area boundaries (see Section 4 for a discussion). We report estimates of Equation B3 using different proximity treatment bandwidths, $k$, that define spillover, adjacency, and salience exposed parcels, namely 0.1, 0.2, and 0.3 mi from the nearest waterbody or levee. Reported coefficients $(\alpha_1, \alpha_2, \alpha_3, \alpha_4)$ correspond directly to those in Equation B3 and correspond to the protection, adjacency, spillover, and salience effects of levee construction, respectively. Standard errors, clustered at the census tract level, are reported in parentheses. Signif. Codes: ***: 0.01, **: 0.05, *: 0.1.

using larger bandwidths. This may be due to a number of factors, including a differential disamenity effect relative to parcels near levees but outside of leveed areas. It may also be driven by a perception that proximity to a levee entails greater flood risk despite the protection benefits that levees provide. This may be plausible if the levee itself calls attention to the hazard from which it provides protection. Overall, the results of Table B1 validate our treatment of protection and spillover effects as the main housing market impacts of levee construction.

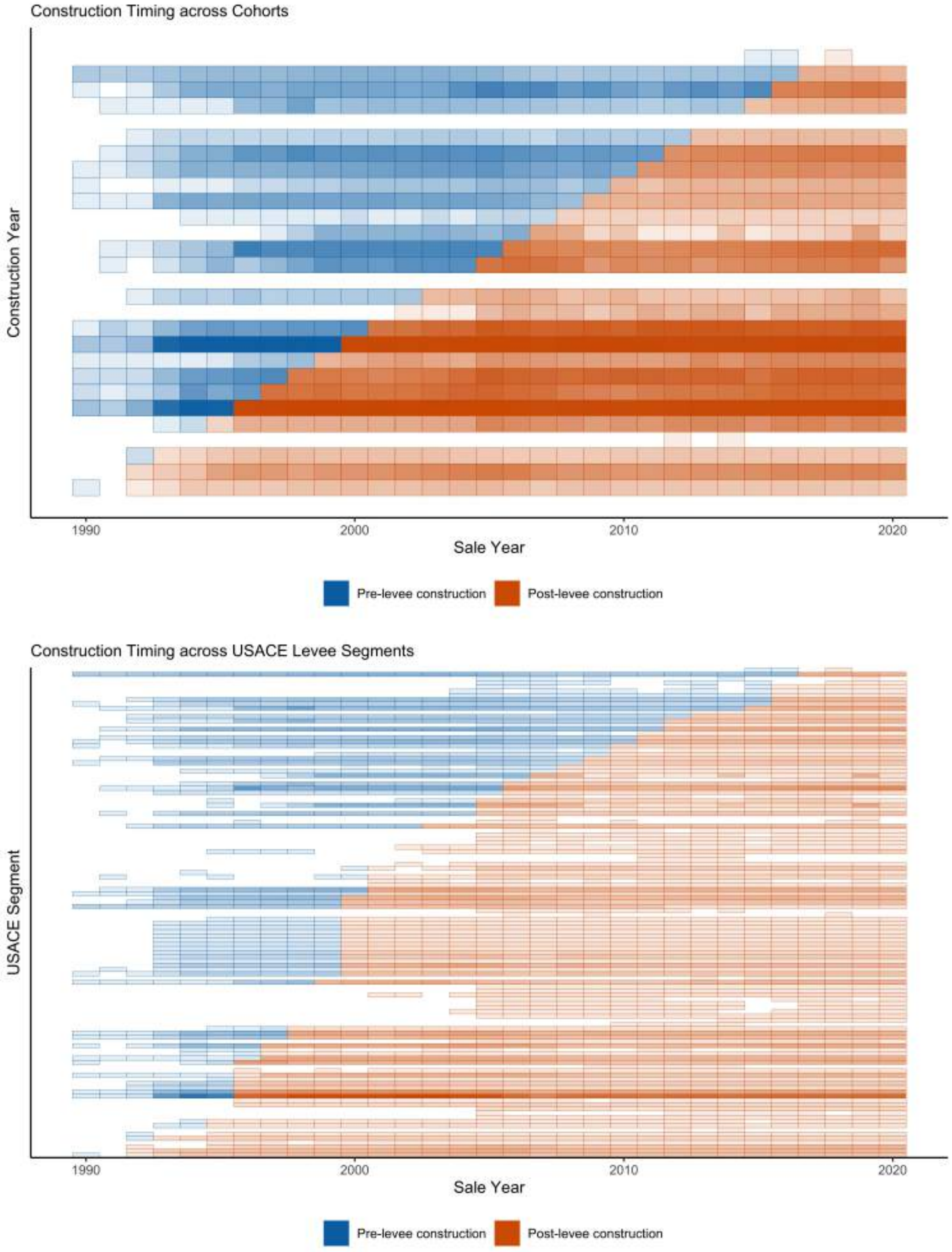
## C Supplemental Figures and Tables

**Figure C1.** Map of USACE Constructed Levee Segments



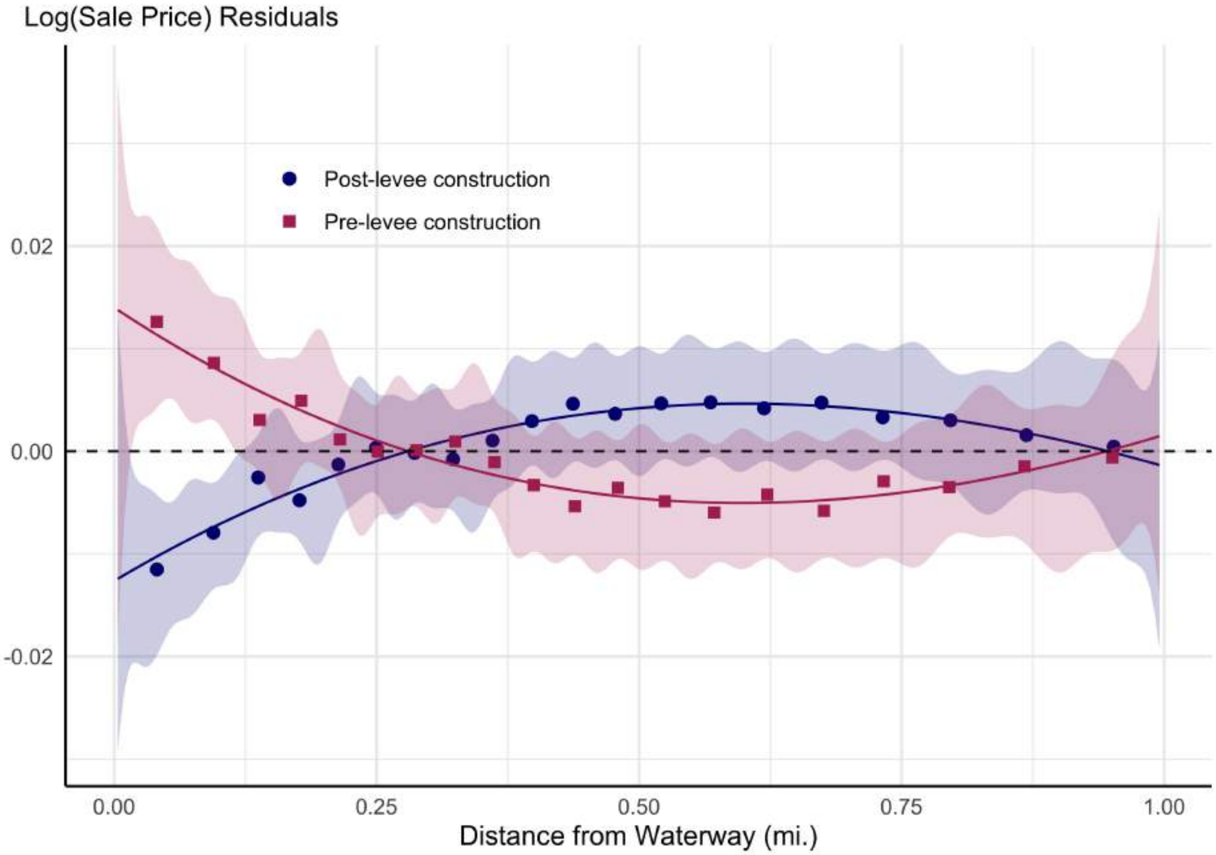
This figure shows the location of US Army Corps of Engineers (USACE) constructed levee segments built pre- and post-1990, the earliest year for which we have residential transaction data. Levee segments that are part of USACE authorized projects, but are entirely constructed by non-federal partners are omitted as are USACE constructed levee segments for which reliable construction year information are unavailable.

**Figure C2.** Treatment Timing by Construction Year Cohort and Segment



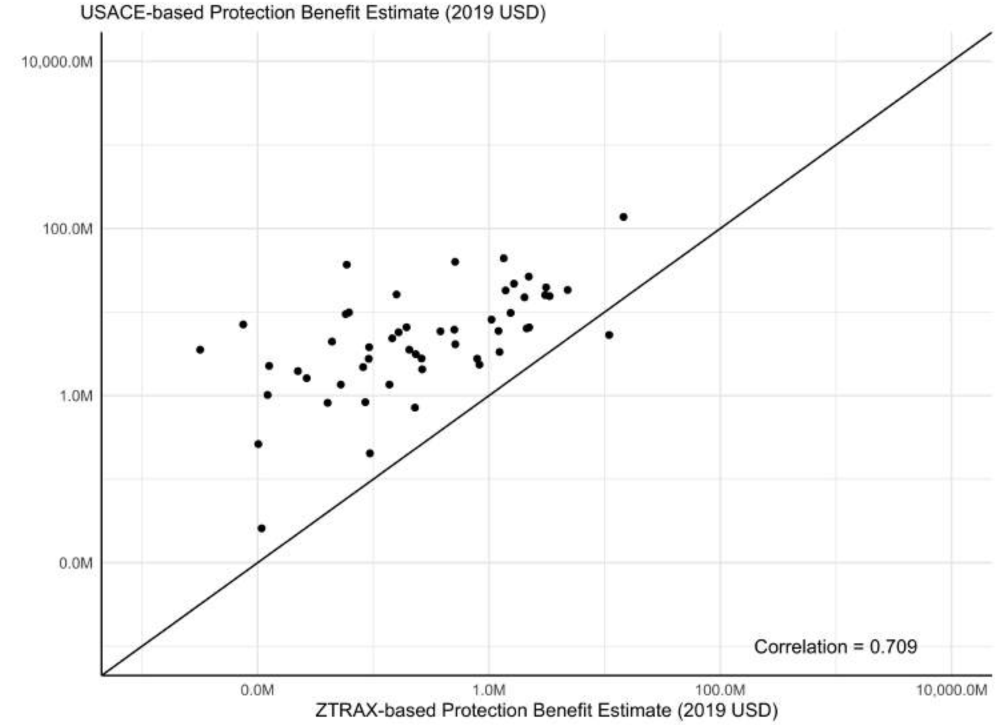
This figure plots the timing of USACE levee segment construction across levee segment construction year cohorts (upper) and across individual USACE levee segments (lower). Vertical axes are ordered in ascending order of construction year. Blue tiles represent pre-construction transaction observations, red tiles represent post-construction observations, and empty tiles represent missing transaction data. The shade of the tile indicates the number of transactions observed in a given year for each levee construction year cohort (upper) and levee segment (lower).

**Figure C3.** Price Gradient of Distance from Nearest Waterway.



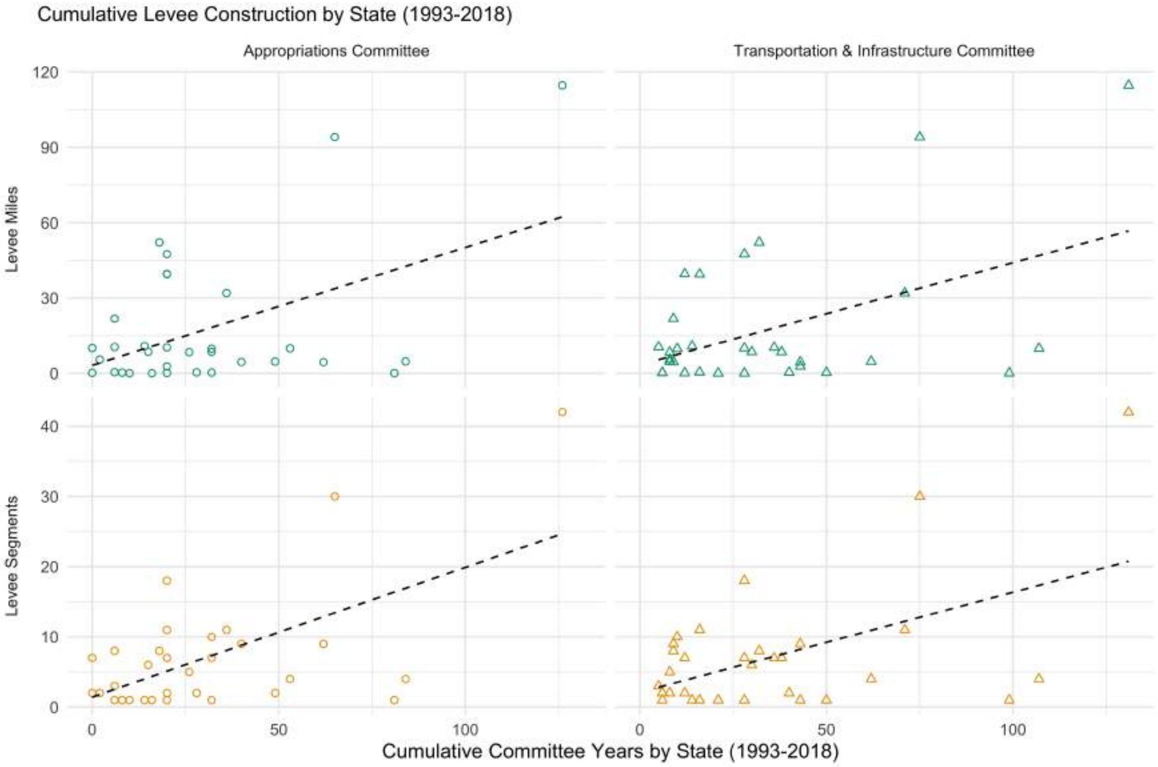
This figure fits cubic spline on the empirical relationship between the residual of house prices from a regression on parcel and time fixed effects on a parcel's distance from the nearest waterway. We use this figure to help identify the distance range over which proximity-based levee construction effects—i.e., spillover effects—are likely relevant. This approach is first used by Linden and Rockoff (2008) and is used elsewhere in the literature (Muehlenbachs, Spiller and Timmins, 2015).

**Figure C4.** Comparison of ZTRAX and USACE Derived Protection Benefit Estimates.



This figure shows the correlation between ZTRAX- and USACE-based aggregate protection benefit estimates for the 23 projects for which construction cost data are available. We apply the same protection capitalization estimate of 2% in generating each aggregate measure; however, differences between the two arise due to different approaches to constructing measures of the value of protected housing/building stock. The ZTRAX-derived measure uses assessed values from ZTRAX assessment data to construct the value of protected housing stock and the USACE-derived measure takes USACE's own estimates of the value of protected property, which are derived from the National Structures Inventory, Version 2 (2019) and include non-residential properties.

**Figure C5.** Congressional Committee Membership and USACE Levee Construction, 1993-2018



This figure shows the correlation between state-level measures of cumulative Congressional committee membership and USACE levee construction for the 103rd to 115th Congresses (1993-2018) for the relevant committees responsible for authorizing (Transportation and Infrastructure Committee) and funding (Appropriations Committee) USACE civil works projects. We generate two measures describing USACE levee construction at the state-level for this period—total levee miles constructed (top row) and total segments constructed (bottom row)—using data on the universe of USACE-constructed levee segments obtained from the National Levee Database. We generate measures of a state's cumulative years served on each committee by summing years served on the relevant committee across all US Representatives within a state from the 103rd to 115th Congresses. The dotted line shows a linear fit for each relationship.

**Table C1.** Post-levee Construction Difference-in-Differences Estimates of Protection and Spillover Effects for Low- and High-Flood Exposure Transactions

| | (1) | (2) | (3) |
|---|---|---|---|
| High Flood Exp. | -0.005* | $9.69 \times 10^{-5}$ | -0.001 |
| | (0.003) | (0.003) | (0.003) |
| High Flood Exp. × Intersects | 0.043*** | | 0.044*** |
| | (0.006) | | (0.006) |
| High Flood Exp. × Near Water | | -0.027*** | -0.026*** |
| | | (0.004) | (0.004) |
| Parcel FE | Yes | Yes | Yes |
| Sale Year-Levee Project FE | Yes | Yes | Yes |
| Sale Year-Sale Month FE | Yes | Yes | Yes |
| Observations | 745,302 | 745,067 | 858,428 |
| $R^2$ | 0.959 | 0.958 | 0.958 |

The dependent variable is the log of real sale price. Data are restricted to transactions that occur after levee construction and to parcels for which we observe more than one transaction during the post-construction sample period. We are interested in whether there are differences in capitalized protection and spillover effects for high and low-flood exposure transactions. The above interaction terms compare the effects of falling within the relevant treatment area for high flood exposed areas to that for low flood exposed areas, which are the quantities of interest. "High Flood Exp." is a binary variable that equals 1 if the transaction is defined as high flood exposure and 0 otherwise. We define a high flood exposure transaction as a transaction of a parcel falling within a county with a greater than 75th percentile value of lagged 24-month count of flood-related storm events based on data from the NOAA Storm Events Database. Additional information on these data is available in Appendix A. Standard errors, clustered at the census tract level, are reported in parentheses. Signif. Codes: ***: 0.01, **: 0.05, *: 0.1.

**Table C2.** Effects of Levee Construction on Census Tract NFIP Outcomes

| | Protection Effect | | | Spillover Effect | | |
|---|---|---|---|---|---|---|
| | Take-up<br>(1) | Pr(Claim)<br>(2) | $/Claim<br>(3) | Take-up<br>(4) | Pr(Claim)<br>(5) | $/Claim<br>(6) |
| Post × Intersects | -0.034*** | -0.107*** | -80.8 | | | |
| | (0.009) | (0.018) | (950.6) | | | |
| Post × Near Water | | | | 0.007 | 0.033*** | 2,919.7** |
| | | | | (0.007) | (0.010) | (1,205.4) |
| Sale Year FE | Yes | Yes | Yes | Yes | Yes | Yes |
| Tract FE | Yes | Yes | Yes | Yes | Yes | Yes |
| Sale Year-Levee Project FE | Yes | Yes | Yes | Yes | Yes | Yes |
| Observations | 19,284 | 33,458 | 4,019 | 19,284 | 33,458 | 4,019 |
| $R^2$ | 0.935 | 0.378 | 0.769 | 0.934 | 0.377 | 0.770 |

This table reports estimates of the effects of levee construction on a set of census tract-level National Flood Insurance Program (NFIP) outcomes, including the census tract-wide take-up rate, the probability of a census tract experiencing at least one NFIP claim, and—conditional on experiencing at least one claim—the average claim value. These results are estimated by aggregating the relevant NFIP policy and claims data to the census tract level for all census tracts that either intersect leveed areas or are within 5 miles of a leveed area boundary for a USACE-constructed levee in our sample. We then assign treatment status to each census tract based on whether they contain any parcels with the relevant treatment, either falling within a leveed area (protection effect treatment) or being not protected by a levee and adjacent to a waterway (spillover effect treatment). Note that this allows a given tract to be assigned to both, one, or neither treatment. We then estimate the following on a balanced panel at the census tract-by-year level:

$$Y_{ct} = \beta_1(T_{ct} \times L_c) + \xi_c + \mu_{l(c)t} + \delta_t + \epsilon_{ct}$$

$$Y_{ct} = \beta_2(T_{ct} \times W_c) + \xi_c + \mu_{l(c)t} + \delta_t + \epsilon_{ct}$$

where $Y_{ct}$ is one of the three NFIP outcomes; $T_{ct}$, $L_c$, and $W_c$ are as defined in Equation 2, now at the census tract, $c$, level; and $\xi_c$, $\mu_{l(c)t}$, and $\delta_t$ are tract, levee-by-year, and year fixed effects. Additional information on the NFIP data is available in Appendix A. Standard errors, clustered at the census tract level, are reported in parentheses. Signif. Codes: ***: 0.01, **: 0.05, *: 0.1.