Private Benefits from Public Investment in Climate Adaptation and Resilience*

Jacob T. Bradt and Joseph E. Aldy†

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Abstract

We estimate the welfare effects of large-scale flood protection infrastructure using a discrete-choice model of residence location. Exploiting the timing of Army Corps of Engineers levee construction, we find the average household's willingness-to-pay for flood protection is \$25,000, while the welfare loss from spillover exposure is \$42,000, with substantial heterogeneity by income and race. Accounting for both effects, the average household experiences welfare losses of \$3,500 even before construction costs. General-equilibrium effects fundamentally alter distributional impacts: while direct protection and spillover effects are progressive, equilibrium sorting and price adjustments reverse this pattern, concentrating welfare losses among lower-income households. Over half of spillover costs fall outside jurisdictions that benefit from levee protection, creating a spatial externality that helps explain why poorly performing projects persist.

Keywords: Climate adaptaion infrastructure, residential sorting, spatial spillovers, general equilibrium welfare

JEL Codes: Q54, Q58, H23, H22

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†Bradt: The University of Texas at Austin; jacob.bradt@mccombs.utexas.edu. Aldy: Harvard Kennedy School, Resources for the Future, National Bureau of Economic Research, and Center for Strategic and International Studies; joseph_aldy@hks.harvard.edu.

Given the slow pace of greenhouse gas emissions mitigation, governments, businesses, and households face a growing imperative to address the impacts of climate change. In the United States, a changing climate will cause more intense and frequent flooding, resulting in major loss of life and property as illustrated by recent extreme events, including the Mississippi River floods of 2019, Hurricane Ian of 2022, and Hurricane Helene of 2024. The share of properties in the United States at risk of regular flooding will likely increase by 8 percent over the next 30 years (First Street Foundation, 2021). These growing physical risks highlight the importance of both policy and market responses to climate change.

Current climate adaptation policy is likely inadequate. In the face of increasing natural hazard risks, the United Nations Environment Programme estimates global adaptation spending needs of nearly $400 billion annually by 2030 (United Nations Environment Programme, 2024). 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 United States, make progress towards funding these needs, a wide gap remains. As governments consider options for investing in community resiliency, the policy debate will prompt questions about who wins and loses, and by how much, under these alternatives.

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, focusing on flood control levee projects—historically one of the largest categories of investment in flood risk reduction in the United States. These infrastructure projects deliver geographically-specific flood protection benefits to nearby properties but also generate potential flood risk spillovers to surrounding, unprotected areas. We provide empirical estimates of these housing market effects for a particularly salient subset of US levee projects—those constructed by the US Army Corps of Engineers (USACE)—and leverage these estimates to understand the distributional, welfare, and political economy impacts of flood adaptation investments.

We analyze the impact of USACE levee construction on residential property values by integrating detailed hydrological data on levee-protected areas with comprehensive real estate transaction records across the continental United States. We develop a structural model of residential sorting with heterogeneous preferences to estimate household willingness-to-pay for flood protection and spillover exposure, then simulate counterfactual equilibria to evaluate welfare consequences. Our empirical design exploits variation in the timing of USACE levee construction and geographic proximity of transactions to levee-protected areas and nearby waterways. Data availability restricts our analysis to levees constructed after 1990. USACE levees provide an ideal setting for our empirical design—we can identify construction dates for these projects—and represent a policy-relevant case study: since 1992, the USACE construction account has received average annual appropriations of $2.2 billion (nominal dollars; Congressional Budget Office (2022)).

We begin with reduced-form evidence using two repeated sales approaches. The first leverages local, within-levee changes in transaction prices around levee construction, adopting a difference-in-differences strategy similar to Muehlenbachs, Spiller and Timmins (2015). To mitigate concerns over indirect effects on control parcels through equilibrium adjustments in local housing markets, our second strategy exploits variation in construction timing across levee systems, using not-yet-treated transactions as controls via the stacked regression estimator of Cengiz et al. (2019). We find that levees increase home values in protected areas by 3-4 percent while reducing values in nearby spillover-exposed areas by 1-5 percent. We also document substantial heterogeneity in post-construction sorting: White households are more likely to move into protected areas post-construction, while Black households are less likely to move into protected areas and more likely to purchase in spillover-exposed areas. Other racial groups—primarily Asian and Native American households—show reduced likelihood of purchasing in protected areas, a pattern opposite to White households.

These reduced-form findings motivate our structural analysis. Reduced-form capitalization estimates may not have a welfare interpretation when policies induce non-random sorting (Banzhaf, 2021): the hedonic price function shifts as households re-sort in response to levee construction, confounding inference about willingness-to-pay. We develop an equilibrium sorting model following Bayer and Timmins (2007) and Bayer, Ferreira and McMillan (2007), estimating household preferences via a two-stage procedure that combines maximum likelihood estimation with instrumental variables. This approach builds on a rich literature using structural discrete choice models to estimate preferences for housing and neighborhood attributes (Almagro and Domínguez-Iino, 2025; Bakkensen and Ma, 2020; Barwick et al., 2024; Bayer et al., 2016; Diamond, 2016; Ma, 2019). We find that the average household values levee protection at about $25,000 (5.8% of average home value) and disvalues spillover exposure at $42,000 (9.9% of average home value), with substantial heterogeneity across income and race. These valuations are larger in magnitude than reduced-form capitalization estimates, confirming that non-random sorting biases hedonic estimates toward zero.

Using the estimated model to simulate counterfactual equilibria without levee construction, we find that general-equilibrium effects fundamentally alter the welfare incidence of levees. While direct protection effects are progressive—providing greater benefits as a share of income to lower-income households—equilibrium sorting and housing supply responses reverse this pattern entirely. Lower-income households experience substantially larger welfare losses once general-equilibrium effects are incorporated. This reversal reflects their greater price sensitivity, which limits their ability to escape reduced housing options and spillover exposure. Welfare effects also differ sharply by race, with Black households experiencing substantially larger losses than White households across the income distribution.

We contextualize our housing market estimates by examining the net effect of levee construction on public expenditures. Though largely federally financed, USACE levees require cost-sharing from local, non-federal entities. We manually collect construction cost information for both federal and local sponsors for a subset of levees in our sample. We also translate housing value impacts into changes in local tax revenues using property-level real estate tax rates.

These benefit-cost calculations illuminate the political economy of levee investments. Even excluding construction costs, average households experience welfare losses of $3,500, as spillover effects dominate protection benefits. Large flood risk spillovers raise important questions about which impacts local decision-makers internalize. Many levees in our sample offer minimal returns to aggregate social welfare, yet local municipalities that partially fund construction experience only 38% of spillovers while capturing 97% of protection benefits. From their perspective, projects appear far more attractive than aggregate welfare would suggest. Similar incentive misalignment exists at the federal level: project-level appropriations from Congress create incentives for members to capture benefits in their districts while exporting spillovers elsewhere.[1] These patterns suggest levee construction represents a classic externality problem.

Despite our focus on USACE levees, our findings extend to other forms of public climate adaptation investment. Any public adaptation investment providing geographically localized benefits—and potentially external costs—raises similar questions about distributional impacts and distorted incentives for individuals and policymakers. Sea walls and shoreline hardening, which feature prominently in coastal adaptation discussions, represent other salient examples with similar characteristics.

These findings underscore the importance of evaluating the impact of existing institutions when considering policies to improve resiliency to climate impacts. A large, growing literature on climate adaptation tends to focus on household- or firm-level adaptation.[2] Recent work examines the implications of policies to mitigate and manage natural hazard risks on household and firm adaptation, including publicly-subsidized flood insurance (Wagner, 2022), sea walls (Hsiao, 2023), wetlands conservation (Taylor and Druckenmiller, 2022), wildfire suppression (Baylis and Boomhower, 2023), and other forms of development incentives

[1] Among the 80 USACE-constructed levee systems in our main estimation sample, 52% of flood risk spillovers fall outside the Congressional districts that experience protection benefits.

[2] Examples from this literature include: Balboni, Boehm and Waseem (2024); Barreca et al. (2016); Boustan, Kahn and Rhode (2012); Burke and Emerick (2016); Carleton et al. (2022); Dell, Jones and Olken (2012); Deschênes and Greenstone (2011); Ito and Zhang (2020); Kahn (2016)

(Druckenmiller et al., 2024). Our analysis emphasizes the need to carefully evaluate economic questions surrounding large-scale, public investments in adaptation.

Economists have studied private benefits from flood control infrastructure—including beach nourishment, flood walls, pump systems, and levees—finding positive willingness-to-pay for flood protection (Benetton et al., 2024; Dundas, 2017; Fell and Kousky, 2015; Gopalakrishnan, Landry and Smith, 2018; Kelly and Molina, 2022; Walsh et al., 2019). These results extend a large literature finding that flood risk is negatively capitalized in housing prices (Beltrán, Maddison and Elliott, 2019; Bernstein, Gustafson and Lewis, 2019; Graff Zivin, Liao and Panassie, 2022). Ouazad and Kahn (2025) simulate a dynamic spatial equilibrium model to estimate welfare effects of early US levee construction, providing important insights into adaptation policy design that account for general equilibrium effects. While existing work informs our understanding of private benefits from flood risk reduction investments, most studies do not model direct flood risk spillovers and therefore risk misinterpreting overall impacts. Noteworthy exceptions include Dundas and Lewis (2020) and Wang (2021). We build on this literature by examining direct spillover effects from large-scale public adaptation projects using spatially-explicit housing market and levee data.

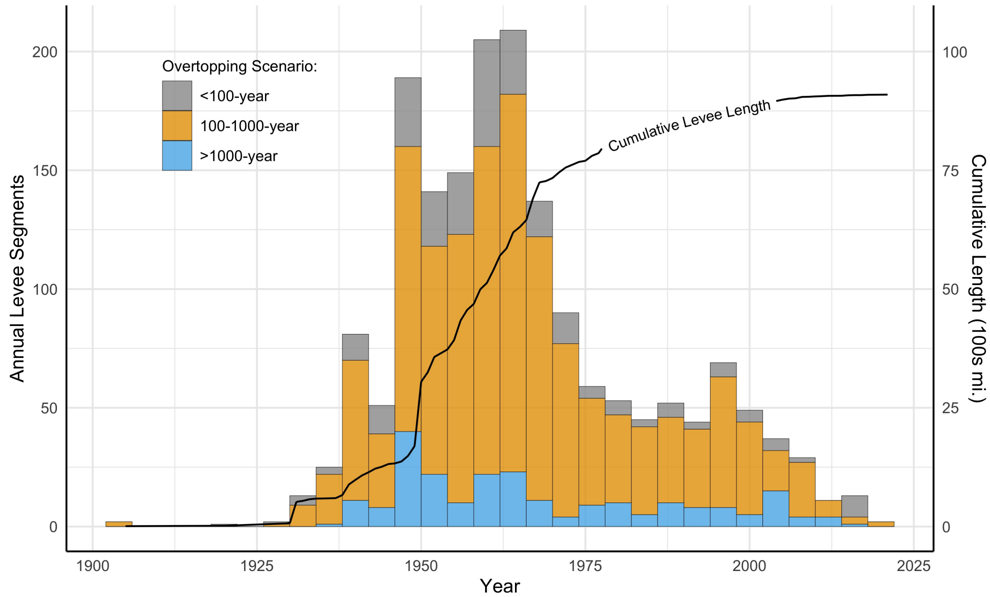
A growing literature examines public finance implications of climate impacts and adaptation policy, emphasizing the imperative for public provision of adaptation infrastructure (Balboni, 2024; Barrage, 2020; Fried, 2022). Given highly localized variation in exposure to natural hazards exacerbated by climate change, this literature highlights the importance of sub-national climate adaptation policies (Goldsmith-Pinkham et al., 2021; Liao and Kousky, 2022). Levees offer one such policy with localized benefits; however, spillovers underscore the need to consider strategic interactions between investments. Our work relates to the broader literature on place-based policies examining how strategic interactions drive governments' policy decisions and outcomes (Busso, Gregory and Kline, 2013; Mast, 2020).

The remainder of the paper proceeds as follows. Section 1 provides background on US flood policy. Section 2 describes our data. Section 3 presents reduced-form evidence on price capitalization and sorting responses. Section 4 develops our structural model, describes estimation, and presents preference estimates. Section 5 evaluates welfare effects through counterfactual simulations, examines the political economy of levee siting, and considers policy responses to spillover externalities. Section 6 concludes.

1 Flood Risk Policy in the United States

Responsibility for managing flood risk in the United States is shared by federal, state, and local entities. Historically, US flood policy focused on controlling floodwaters through public

Figure 1. USACE Levee Construction, 1905-2021.



Note: 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.

investments in large-scale engineered structures such as levees—man-made embankments that divert water flow during floods. Devastating floods in the early 20th century led to the Flood Control Acts of 1917, 1928, and 1936, which established the USACE as the primary federal entity responsible for flood control projects and set precedents around state and local involvement that continue today (Arnold, 1988). As shown in Figure 1, USACE levee construction accelerated rapidly following these Acts, ultimately peaking in the 1960s.

USACE levee construction activities receive project-level authorization and appropriations by Congress, resulting in substantial Congressional interest in site selection (Carter and Normand, 2019).[3] The standard project delivery process has four steps: pre-construction feasibility study, design, construction, and operation and maintenance (O&M). All projects require a non-federal sponsor (state, tribal, county, or local governments). Since 1986, non-federal sponsors have been responsible for 50% of feasibility study costs, up to 45% of design and construction costs, and all O&M costs (Carter and Normand, 2019). Given this breakdown, USACE transfers ownership of most levee systems to non-federal partners.

[3]USACE is a federal agency within the US Department of Defense with both military and civil works responsibilities. USACE civil works authorization typically occurs in biennial Water Resource and Development Acts (WRDA) and appropriations in annual Energy and Water Development appropriations acts (Carter and Normand, 2019).

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, and recent federal policy targets projects with ratios of benefits to costs of 2.5 or more (Carter and Nesbitt, 2016).

In parallel with the slowdown in levee construction shown in Figure 1, US flood policy shifted away from controlling floodwaters to managing the consequences of floods (Tarlock, 2012). While these policies are not our focus, they are worth noting given their interactions with levee construction. The National Flood Insurance Program (NFIP), a federal program that underwrites 90-95% of residential flood insurance policies (Kousky, 2018), allows areas protected by FEMA-accredited levees to be re-mapped out of Special Flood Hazard Areas (SFHAs), reducing premiums and eliminating mandatory flood insurance requirements for homes with federally-backed mortgages (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. In fact, the institutional features of the USACE levee production process are identical to those of several sea walls currently under consideration for construction by USACE. 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.[4]

2 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 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 United States. Our dataset also includes information

[4]For additional information on the NFIP's fiscal issues, see Government Accountability Office (2020).

on the income and race of a subset of homeowners obtained from publicly-available mortgage data as well as information on a property's proximity to surface waters.

We collect data on the US housing market from Zillow's Transaction and Assessment Dataset (ZTRAX), which contains detailed information on the price, timing, location, and mortgage loans for over 400 million residential property transactions across 2,750 US counties, with temporal coverage varying by geography back to 1990.[5] ZTRAX also contains tax assessor data on property characteristics and geographic information for over 150 million parcels in over 3,100 counties. We exclude parcels with invalid or approximate coordinates and transactions with prices deviating from market value (see Appendix A).

We obtain data on areas protected by USACE-constructed levees through an agreement with the First Street Foundation, which aggregates publicly-available information on flood adaptation projects throughout the United States. We focus on USACE-constructed levees given their comparability in siting process, funding sources, and public engagement, and because the National Levee Database (NLD) provides construction timing critical to our empirical strategies (Section 3). We subset to levees constructed after 1990 with observed transactions around the construction date, yielding a final sample of 80 projects.[6]

We obtain completion dates and geographic locations for all levee segments from the NLD, allowing precise assignment of construction dates to each parcel based on its nearest segment. We identify residential parcels located inside or within five miles of leveed area boundaries based on parcel centroids.[7] Parcels near multiple leveed areas are assigned to the closest levee, with construction dates based on the nearest segment within that system.

We access demographic information for transactions with loan data using successful home purchase applications from the Home Mortgage Disclosure Act (HMDA).[8] HMDA provides information on origination year, census tract, loan amount, lender name, and applicant demographics. We match approved applications to transactions based on year, census tract, loan amount, and lender name, matching approximately 70% of Zillow transactions with mortgage data (see 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 that we use include authoritative

[5]We deflate all ZTRAX price data to 2019 US dollars using the CPI-Urban deflator.

[6]Construction dates are available for about four-fifths of USACE-constructed segments in NLD. Large-scale projects like the Lower Mississippi River and New Orleans levees were originally locally-constructed in the early 1900s and thus do not appear in our sample.

[7]Given potential partial overlap of parcels and leveed areas, our use of centroids may introduce error in treatment assignment. We therefore omit parcels falling within a bandwidth of either side of leveed areas.

[8]The Home Mortgage Disclosure Act of 1975 requires major depository institutions to disclose loan-level information annually, covering approximately 90% of all home lending nationwide.

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, including detailed descriptive statistics in Appendix Table A2.

3 Reduced-Form Evidence on Levee Impacts

Levee construction generates spatially heterogeneous impacts on nearby properties. We present reduced-form evidence on these effects using variation in the timing and location of USACE levee construction. Our analysis serves two purposes. First, these estimates establish the magnitude of capitalized benefits and costs, documenting empirical patterns that motivate the structural analysis in Section 4. Second, evidence of differential sorting by demographic groups demonstrates that reduced-form capitalization estimates conflate preferences with equilibrium price adjustments, necessitating the empirical sorting model in Section 4.

We distinguish three types of levee impacts. *Protection effects* capture flood risk reduction benefits for homes within leveed areas. USACE levees are typically designed to withstand 1-in-100 year floods, so capitalized benefits reflect households' expectations of avoided damages across the full distribution of flooding scenarios. *Spillover effects* refer to increased flood risk for homes near levees but outside protected areas. Hydrological studies document that levee construction exacerbates flooding in adjacent unprotected areas both upstream through backwater effects and downstream through reduced floodplain storage (Heine and Pinter, 2012; Remo et al., 2018; Wang, 2021). *Macro effects* capture impacts common to all homes within the local housing market surrounding levees, such as indirect economic spillovers from infrastructure investment.

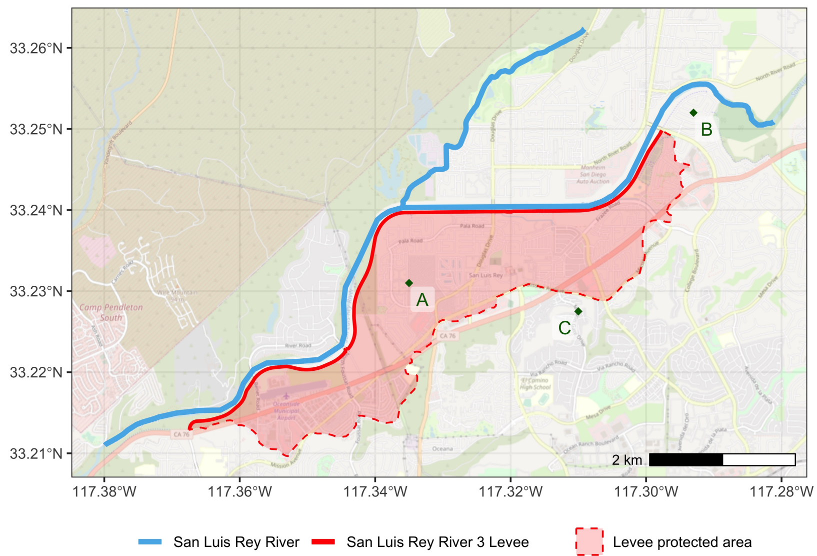
3.1 Empirical Approach

Local Variation Our first strategy to identify levee capitalization effects leverages within-levee variation in treatment status. We compare price changes for protected and spillover-exposed parcels to nearby unaffected parcels. Figure 2a illustrates this approach using the San Luis Rey River 3 Levee (Oceanside, CA), completed in 2000. Parcel A falls within the leveed area and experiences protection effects. Parcel B is adjacent to the leveed waterway but outside the protected zone, potentially experiencing adverse spillover effects. Parcel C is nearby but neither protected nor spillover-exposed, serving as our comparison group.

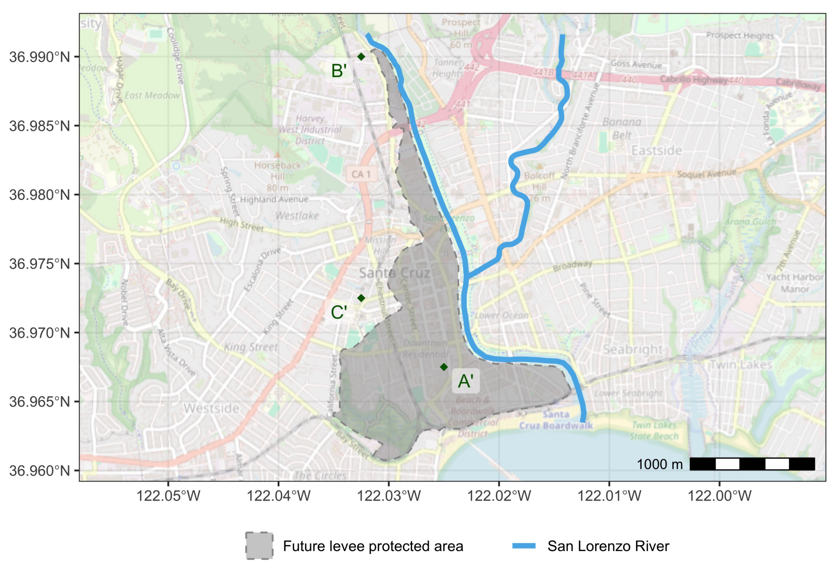
We decompose price changes around levee construction. Let P_j denote the price of parcel

Figure 2. Example Treated and Control Parcels for Estimating Levee Construction Effects

(a) Example Treated Parcels: San Luis Rey River 3 Levee (Oceanside, CA), Constructed 2000



(b) Example Control Parcels: San Lorenzo River Right Bank Levee (Santa Cruz, CA), Constructed 2004



Note: Figure 2a illustrates the spatial variation in levee impacts. Parcel A (protected) experiences flood risk reduction; parcel B (spillover-exposed) may face increased flood risk from hydraulic spillover effects; parcel C captures general macro effects. The local variation empirical design uses price changes for parcel C to identify effects on parcels A and B. Figure 2b illustrates the empirical strategy levering variation across levees, where not-yet-treated parcels A', B', C' serve as controls.

j and define Δ_t as the change in transaction price from before to after construction. In a potential outcomes framework, let $\Delta_t P_j(d)$ denote the potential price change for parcel j under treatment status $d \in \{A, B, C\}$, where A denotes protection, B denotes spillover exposure, and C denotes comparison status. The identifying assumption is parallel trends: absent their respective treatments, protected and spillover-exposed parcels would experience the same counterfactual price trend as comparison parcels. Formally:

$$\mathbb{E}[\Delta_t P_A(C)] = \mathbb{E}[\Delta_t P_B(C)] = \mathbb{E}[\Delta_t P_C(C)] \tag{1}$$

where $\Delta_t P_j(C)$ denotes the counterfactual price change if parcel j were in comparison status. Under this assumption, difference-in-differences estimators identify average treatment effects:

$$\begin{aligned}(\text{Protect})_{DD} &= \mathbb{E}[\Delta_t P_A(A)] - \mathbb{E}[\Delta_t P_C(C)] = \mathbb{E}[\Delta_t P_A(A) - \Delta_t P_A(C)] \\ (\text{Spillover})_{DD} &= \mathbb{E}[\Delta_t P_B(B)] - \mathbb{E}[\Delta_t P_C(C)] = \mathbb{E}[\Delta_t P_B(B) - \Delta_t P_B(C)]\end{aligned} \tag{2}$$

This approach requires the stable unit treatment value assumption (SUTVA): a parcel's price change depends only on its own treatment status, and our modeled effects capture all levee impacts.

Variation Across Levees The local variation design in equation (2) identifies protection and spillover effects under the assumption that any indirect or general equilibrium effects of levees are common across protected, spillover-exposed, and control parcels. Our second approach relaxes this assumption, allowing for a specific form of SUTVA violation: namely, the potential for indirect effects of levee construction on untreated parcels that differ from any equilibrium effects common to all parcels near levees. This second identification strategy exploits variation in construction timing across levee systems, using not-yet-treated parcels from later projects as controls.

Figure 2b illustrates this design: parcels A', B', and C' near the San Lorenzo River Right Bank Levee (completed 2004) serve as controls when estimating effects of the 2000 San Luis Rey River levee. Before 2004, these not-yet-treated parcels provide valid counterfactuals under a parallel trends assumption: parcels of the same type would experience similar counterfactual price trends regardless of whether they are near a treated or not-yet-treated levee. Using the same potential outcomes notation, let $\Delta_t P_j(N)$ denote the potential price change for parcel j if its levee is not yet treated. The parallel trends assumption is:

$$\begin{aligned}\mathbb{E}[\Delta_t P_A(N)] &= \mathbb{E}[\Delta_t P_{A'}(N)] \\ \mathbb{E}[\Delta_t P_B(N)] &= \mathbb{E}[\Delta_t P_{B'}(N)] \\ \mathbb{E}[\Delta_t P_C(N)] &= \mathbb{E}[\Delta_t P_{C'}(N)]\end{aligned} \tag{3}$$

This parallel trends condition—that like-for-like parcels across treated and not-yet-treated levees would have similar counterfactual trends—yields difference-in-differences estimators that identify average treatment effects plus any common macro effects:

$$\begin{aligned}(\text{Protect} + \text{Macro})_{DD} &= \mathbb{E}[\Delta_t P_A(A)] - \mathbb{E}[\Delta_t P_{A'}(N)] = \mathbb{E}[\Delta_t P_A(A) - \Delta_t P_A(N)] \\ (\text{Spillover} + \text{Macro})_{DD} &= \mathbb{E}[\Delta_t P_B(B)] - \mathbb{E}[\Delta_t P_{B'}(N)] = \mathbb{E}[\Delta_t P_B(B) - \Delta_t P_B(N)]\end{aligned} \tag{4}$$

Beyond robustness to SUTVA violations, this design allows us to directly estimate the total effect on indirectly-exposed parcels by comparing type-C parcels to their not-yet-treated counterparts:

$$(\text{Macro} + \Delta_t \xi_C)_{DD} = \mathbb{E}[\Delta_t P_C(C)] - \mathbb{E}[\Delta_t P_{C'}(N)] = \mathbb{E}[\Delta_t P_C(C) - \Delta_t P_C(N)]$$

where $\Delta_t \xi_C$ captures any unobservable changes specific to type-C parcels. Levee construction alters the supply of flood-protected and flood-exposed homes, potentially affecting prices of nearby unaffected parcels through market equilibrium adjustments.[9] Though finding significant total effects on type-C parcels could indicate economically meaningful general equilibrium spillovers, it is important to note that this is a joint test of both any common macro effects and equilibrium spillovers specific to type-C parcels.

3.2 Estimation

We implement both identification strategies using repeated sales specifications that include parcel fixed effects to control for unobservable property attributes. Our sample comprises parcels within 5 miles of leveed area boundaries, excluding those within 0.1 miles of boundaries to avoid measurement error.[10] We define $L_i = 1$ if parcel i is located within a leveed area (protected), $W_i = 1$ if parcel i is adjacent to a waterway but outside leveed areas (spillover-exposed), and $M_i = 1$ if parcel i is nearby but neither protected nor spillover-exposed.

Defining spillover exposure requires determining how far adverse effects extend from the leveed waterway. Following Linden and Rockoff (2008) and Muehlenbachs, Spiller and Timmins (2015), we implement a price gradient approach, flexibly estimating the relationship between distance to water and price changes pre- and post-construction. Appendix Figure E2 shows that spillover effects are concentrated within 0.3 miles of the leveed waterway, declining toward zero beyond this distance. We test bandwidths of 0.1, 0.2, and 0.3 miles, with 0.2 miles as our preferred specification.[11]

[9] We thank Peter Christensen and Michael Greenstone for this insight.

[10] We use parcel centroids to assign treatment status. Average lot size of 1.52 acres corresponds to a square parcel with diagonal 0.07 mi, justifying the 0.1 mi buffer.

[11] We also test the robustness of this data-driven approach to using existing floodplain boundaries to define the spillover exposure treatment. Appendix Table E1 shows that estimates of the capitalization of spillovers

We implement the local variation design using a repeated sales specification:

$$\log P_{it} = \alpha_1(T_{it} \times L_i) + \alpha_2(T_{it} \times W_i) + \xi_i + \mu_{l(i)t} + \delta_t + \varepsilon_{it} \tag{5}$$

where $\log P_{it}$ is the log real sale price of parcel i at time t, $T_{it} = 1$ if the transaction occurs after levee construction, L_i and W_i are indicators for protected and spillover-exposed parcels, ξ_i is a parcel fixed effect, $\mu_{l(i)t}$ is a levee segment-by-year fixed effect, and δ_t is a year-by-month fixed effect. The coefficients α_1 and α_2 identify the protection and spillover effects through within-parcel price changes around levee construction.

The levee segment-by-year fixed effect is critical for our setting with highly staggered treatment timing spanning over 20 years (Appendix Figure E3). This fixed effect restricts identifying variation to within-segment comparisons, avoiding biases from heterogeneous treatment effects in standard two-way fixed effects estimators (de Chaisemartin and D'Haultfœuille, 2020; Goodman-Bacon, 2021). Without this control, early treated transactions would serve as invalid controls for late treated units, potentially generating negative regression weights and biased estimates. Parcel fixed effects control for time-invariant unobservable property attributes, requiring that we restrict to repeat sales (Bishop et al., 2020). We cluster standard errors at the census tract level.

For the stacked design, we estimate protection and spillover effects separately using event-specific datasets:

$$\begin{aligned} \text{Protection:} \quad & \log P_{it} = \beta_1(T_{it} \times L_i) + \xi_{il(i)} + \mu_{l(i)t} + \varepsilon_{it} \\ \text{Spillover:} \quad & \log P_{it} = \beta_2(T_{it} \times W_i) + \xi_{il(i)} + \mu_{l(i)t} + \varepsilon_{it} \end{aligned} \tag{6}$$

where $\xi_{il(i)}$ are parcel-by-levee segment fixed effects and $\mu_{l(i)t}$ are levee segment-by-time fixed effects, both fully saturated within each event-specific dataset. We construct event-specific datasets by pairing each levee with not-yet-treated control levees constructed within 5 years.[12] The same transaction can appear in multiple datasets—as treatment in one and control in another—making the saturated fixed effects essential to avoid arbitrary weighting across datasets. We also estimate the total effect on indirectly-exposed parcels using the stacked design:

$$\log P_{it} = \beta_3(T_{it} \times M_i) + \xi_{il(i)} + \mu_{l(i)t} + \varepsilon_{it} \tag{7}$$

Note once again that this offers a joint test for the presence of common macro effects as well as equilibrium spillovers specific to indirectly-exposed parcels, potentially limiting the informational value of this specification.

are consistent across the waterbody bandwidth and floodplain-based spillover definitions.

[12]This ensures comparability given potential time-varying USACE project quality.

For the sorting analysis, we estimate a cross-sectional specification with household demographic outcomes:

$$Y_{it} = \theta_1 L_i + \theta_2 W_i + \theta_3 (T_{it} \times L_i) + \theta_4 (T_{it} \times W_i) + \xi_{bg(i)} + \mu_{l(i)t} + \delta_t + \varepsilon_{it} \tag{8}$$

where Y_{it} is a demographic characteristic from the ZTRAX-HMDA matched sample, $\xi_{bg(i)}$ is a block group fixed effect, and W_i captures spillover exposure modeled flexibly using distance-to-water bins of 0.1 mi width up to 0.4 mi. Unlike the price regressions, this specification does not restrict data to parcels for which we observe multiple transactions and therefore includes a richer set of treatment indicators and block group fixed effects rather than parcel fixed effects. This allows us to use all observations from the ZTRAX-HMDA matched sub-sample.

3.3 Results: Price Capitalization

We begin by presenting reduced-form estimates of the capitalized effects of levee construction. Table 1 reports estimates from both identification strategies. Panel A presents estimates of equation (5) using within-levee variation. Across specifications with the segment-by-year fixed effect (columns 2, 4, 6), we find economically and statistically significant protection effects of 2.7–2.9% of home values. These estimates are stable across spillover definitions, providing confidence in our identification strategy. We find negative spillover effects of −0.8% to −1.3% depending on the distance bandwidth. The magnitude of spillover effects declines as we expand the bandwidth, validating our assumption that spillover effects decay with distance from the leveed waterway. Our preferred specification (column 4) uses a 0.2 mile bandwidth. Estimates excluding the segment-by-year fixed effect (columns 1, 3, 5) are substantially larger in magnitude. This pattern is consistent with the biases documented in Goodman-Bacon (2021) arising from inadmissible comparisons in staggered adoption settings. We estimate the analogous event study version of (5) and plot the results in Appendix Figure E4: results are consistent with the parallel trends identifying assumption.[13]

Panel B presents estimates from the stacked difference-in-differences design (equations (6)–(7)). Results are qualitatively consistent with Panel A: we find positive protection effects (column 7) and negative spillover effects (columns 8–10), with spillover estimates declining as we expand the distance bandwidth. The magnitudes are larger in our stacked design, which estimates protection benefit capitalization of 4% (versus 3% in the within-levee design) and spillover cost capitalization of 5% (versus 1% in the within-levee design). These differences likely reflect control group composition differences. Column 11 reports the total effect on

[13] We also test the robustness of these capitalization results to alternative fixed effects and income-weighting (Appendix Table E2) as well as different sample restrictions (Appendix Table E3), finding consistent results across these checks.

Table 1. Capitalization of Levee Construction Effects in Home Prices

Panel A: Local Variation (Within-Levee Comparison)

Waterbody Bandwidth:	$k \leq 0.1$ mi		$k \leq 0.2$ mi		$k \leq 0.3$ mi	
	(1)	(2)	(3)	(4)	(5)	(6)
Protection Effect (α_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)
Spillover Effect (α_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

Panel B: Stacked Differences-in-Differences (Across-Levee Comparison)

		Waterbody Bandwidth: $k \leq 0.1$ mi	Waterbody Bandwidth: $k \leq 0.2$ mi	Waterbody Bandwidth: $k \leq 0.3$ mi	
	(7)	(8)	(9)	(10)	(11)
Protection Effect (β_1)	0.040				
	(0.017)				
Spillover Effect (β_2)		−0.081	−0.054	−0.044	
		(0.014)	(0.011)	(0.010)	
Macro Effect (β_3)					−0.005
					(0.008)
Parcel-by-event FE	Yes	Yes	Yes	Yes	Yes
Sale Year and Month-by-event FE	Yes	Yes	Yes	Yes	Yes
Treatment Events	107	108	108	108	105
Treated Observations	229,727	95,462	251,445	429,962	1,152,158
Observations	683,387	537,683	1,405,865	2,385,282	5,641,680
R^2	0.960	0.959	0.953	0.952	0.951

This table reports reduced-form estimates of levee construction effects on home prices using two identification strategies. Panel A presents results from equation (5), which uses within-levee variation to compare protected and spillover-exposed parcels to nearby unaffected parcels. Panel B presents results from equations (6) and (7), which use variation across levees by comparing treated parcels to not-yet-treated parcels following the stacked differences-in-differences estimator of Cengiz et al. (2019). 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, located either within leveed areas or within 5 miles of a leveed area boundary, excluding parcels within 0.1 mi on either side of leveed area boundaries. We report estimates using different waterbody bandwidths k (0.1, 0.2, and 0.3 mi from the nearest waterbody) that define spillover-exposed parcels. In Panel B, column 7 reports the protection effect, columns 8–10 report spillover effects for different bandwidths, and column 11 reports the macro effect (total effect on non-protected, non-spillover-exposed parcels). Standard errors, clustered at the census tract level, are reported in parentheses.

indirectly-exposed parcels (the "macro effect"), which is small and not statistically significant. While this suggests limited general equilibrium effects on type-C parcels within our reduced-form framework, concerns about broader equilibrium adjustments and non-random sorting motivate the structural approach we develop in Section 4.

3.4 Results: Sorting Responses

The capitalization estimates above document the magnitude of levee impacts. We now turn to the second purpose of our reduced-form analysis: establishing that levee construction induces differential sorting by demographic groups. This evidence demonstrates that reduced-form capitalization estimates conflate preference parameters with equilibrium price adjustments, motivating the need for a structural sorting model.

Table 2 examines whether the composition of households purchasing homes changes following levee construction. We estimate equation (8) with demographic outcomes from our ZTRAX-HMDA matched sample. We find minimal evidence of sorting by income (column 1) but clear evidence of differential sorting by race and ethnicity.

White households are 2.3 percentage points more likely to purchase in protected areas post-construction (column 2), though we find offsetting negative effects in the nearest spillover bins. Black households show a different pattern: they are less likely to move into protected areas and more likely to purchase in spillover-exposed areas nearest to water after construction (column 3). Other racial groups—primarily Asian and Native American households—show patterns opposite to White households, with reduced likelihood of purchasing in protected areas post-construction (column 4).

These patterns align with prior evidence on differential sorting around flood risk across racial and ethnic groups (Bakkensen and Ma, 2020) and raise environmental justice concerns. The sorting patterns may reflect differences in preferences, beliefs about flood risk, information access, or constraints from housing discrimination (Bakkensen and Barrage, 2021; Banzhaf and Walsh, 2008; Christensen and Timmins, 2022; Hausman and Stolper, 2021). Critically, the presence of differential sorting implies that reduced-form capitalization estimates do not have a welfare interpretation: as Banzhaf (2021) emphasizes, such estimates conflate shifts in the hedonic price function with movement along it. Our structural model in Section 4 addresses this challenge by allowing for heterogeneous preferences across demographic groups and recovering welfare-relevant willingness-to-pay measures.

4 Empirical Model of Residence Choice with Levee Construction

The evidence of differential sorting by race and ethnicity post-levee construction indicates that households vary in their willingness to pay for the flood risk impacts of levee construction. This raises potential concerns around how well the estimated capitalization coefficients

Table 2. Sorting Responses to Levee Construction

	log(Income) (1)	White (2)	Black (3)	Other (4)
Protection Effect (θ_3)	0.004	0.023	−0.007	−0.016
	(0.009)	(0.013)	(0.003)	(0.013)
Spillover Effects: Distance to Water Bins (θ_4)				
[0.0, 0.1 mi]	0.009	−0.024	0.006	0.018
	(0.011)	(0.006)	(0.003)	(0.006)
(0.1, 0.2 mi]	0.006	−0.015	0.004	0.011
	(0.007)	(0.005)	(0.002)	(0.005)
(0.2, 0.3 mi]	0.002	−0.011	0.002	0.009
	(0.006)	(0.004)	(0.002)	(0.004)
(0.3, 0.4 mi]	0.004	-0.010	0.002	0.008
	(0.005)	(0.004)	(0.002)	(0.004)
Block Group FE	Yes	Yes	Yes	Yes
Sale Year-Levee Segment FE	Yes	Yes	Yes	Yes
Sale Year-Sale Month FE	Yes	Yes	Yes	Yes
Dependent variable mean	11.6	0.639	0.047	0.315
Observations	912,626	912,643	912,643	912,643
R^2	0.457	0.226	0.207	0.231

This table reports results from equation (8). The dependent variables are household demographic characteristics from the ZTRAX-HMDA matched sample: log household income (column 1), and indicators for White, Black, and other racial groups (columns 2-4). The "other" race category includes all non-White and non-Black households. We 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. Spillover exposure is modeled flexibly using distance-to-water bins of 0.1 mi width up to 0.4 mi. The "intersects" indicator identifies parcels within levee-protected areas. All specifications include block group, levee segment-by-year, and year-by-month fixed effects. Standard errors, clustered at the census tract level, are reported in parentheses.

in the hedonic price regressions relate to underlying household preferences. In this section, we develop a model of residential sorting with heterogeneous preferences, using the timing of levee construction and standard tools from the empirical industrial organization literature to identify the distribution of preferences for flood protection and neighborhoods.

4.1 Model Setup

We model residence decisions as a discrete choice using a random utility framework, where preferences over housing units are a function of both observed and unobserved property attributes (Berry, Levinsohn and Pakes, 1995). We index households, which we assume are myopic, by i. Let $j = \{1, \ldots, J\} = \mathcal{J}_{mt}$ index discrete residence alternatives in market m at time t. The utility to household i of choosing alternative j in market m at time t is

$$u_{ijmt} = \underbrace{\delta_{jmt} + \mu_{ijmt}}_{\equiv v_{ijmt}} + \varepsilon_{ijmt} \tag{9}$$

where utility is the sum of a deterministic component, v_{ijmt}, and an idiosyncratic unobservable, ε_{ijmt}, which we assume is identically and independently distributed (i.i.d) across individuals and residences. The deterministic component of utility is the sum of a choice-specific mean utility (δ_{jmt}) and an individual-specific (μ_{ijmt}) component. Households choose among the set $\mathcal{J}_{mt}$, selecting the option that provides the highest utility:

$$d_{ijmt} = \begin{cases} 1 & \text{if } u_{ijmt} > u_{ikmt}, \; \forall\, k \neq j \\ 0 & \text{otherwise.} \end{cases} \tag{10}$$

Utility Parameterization Let $\mathbf{x_{jmt}}$ be a vector of l observable residence attributes and p_{jmt} be the cost of a given residence. A household-specific price parameter, α_i, is a function of household income, y_i:

$$\alpha_i = \bar{\alpha} + \frac{\alpha}{y_i}$$

where $\bar{\alpha}$ is the population average disutility of residence price.[14] We denote household preferences for observable residence attributes as $\beta_{\mathbf{i}}$. For each element l in $\beta_{\mathbf{i}}$:

$$\beta_{il} = \bar{\beta}_l + \mathbf{z_i}'\beta_{\mathbf{l}}$$

where $\bar{\beta}_l$ is the population average preference for residence attribute l and $\mathbf{z_i}$ is a vector of observable household attributes. In practice, $\mathbf{z_i}$ includes income and separate indicators for White and Black households, with the omitted "Other" category including all other racial groups, including Asian and Native American households.

Our parameterization of household preferences for residence attributes implies the mean utility for $j \in \mathcal{J}_{mt}$ takes the following form:

$$\delta_{jmt}(\theta_{\mathbf{2}}) \equiv \mathbf{x_{jmt}}'\overline{\beta} - \bar{\alpha}p_{jmt} + \bar{\xi}_m + \bar{\xi}_t + \xi_{jmt} \tag{11}$$

where $\bar{\alpha}$ is the mean disutility of price; $\bar{\xi}_m$ and $\bar{\xi}_t$ are market and time fixed effects, respectively; ξ_{jmt} is an unobserved, time-varying scalar index of residence quality; and $\theta_{\mathbf{2}}$ is a

[14] This parameterization of α_i approximates a Cobb-Douglas style indirect utility function and is adapted from Berry, Levinsohn and Pakes (1999). In practice, we center $1/y_i$ at zero so that $\bar{\alpha}$ is the population average disutility of price, for which we instrument when recovering the linear preference parameters in the second stage of estimation.

vector that collects the mean preference parameters and fixed effects to be estimated.

The individual-specific component of indirect utility for $j \in \mathcal{J}_{mt}$ is

$$\mu_{ijmt}(\theta_{\mathbf{1}}) \;\equiv\; \frac{-\alpha}{y_i} p_{jmt} \;+\; \sum_{l} x^{l}_{jmt} \cdot \mathbf{z_i}' \beta_{\mathbf{l}} \tag{12}$$

where $\theta_{\mathbf{1}}$ is a vector that collects the parameters α and $\{\beta_{\mathbf{l}}\}_l$.

Choice Probabilities We assume that the unobservable in (9), ε_{ijmt}, is i.i.d. with the type I extreme value distribution. This implies that the probability that household i selects residence j in market m at time t has the following closed-form:

$$P_{ijmt}(\theta) \;\equiv\; Pr(d_{ijmt} = 1) \;=\; \frac{\exp\Big(v_{ijmt}(\theta)\Big)}{\sum_{k \in \mathcal{J}_{mt}} \exp\Big(v_{ikmt}(\theta)\Big)} \tag{13}$$

where θ collects all target parameters, $\theta_{\mathbf{1}}$ and $\theta_{\mathbf{2}}$. Let N_{mt} be the number of households in market m at time t. The predicted share of each residence chosen is the average of (13):

$$s_{jmt}(\theta) \;=\; \frac{1}{N_{mt}} \sum_{i=1}^{N_{mt}} P_{ijmt}(\theta) \tag{14}$$

Market-Clearing and the Sorting Equilibrium The choices of individual households aggregate to total housing demand and house prices adjust to balance housing supply and demand. Let $\mathbf{g_{jmt}} \in \mathbf{x_{jmt}}$ be a vector of observable attributes defining residence j's levee protection status or spillover exposure in market m at time t. Individual choice probabilities determine aggregate housing demand:

$$D_j(\mathbf{p_{mt}}, \mathbf{g}_{mt}; \theta) \;=\; \sum_{i} P_{ijmt}(\mathbf{p_{mt}}, \mathbf{g}_{mt}; \theta) \tag{15}$$

where we make explicit the dependence of aggregate demand for residence j on the full vector of not only prices, but also levee-related flood impacts for market m at time t.

Following Barwick et al. (2024), we consider two separate scenarios for housing supply. In the first scenario, housing supply is fixed and does not adjust to changes in market prices, i.e., $S_j(\mathbf{p_{mt}}) = 1$. In the second scenario, we assume that housing supply has a constant price (semi-)elasticity and adjusts at the neighborhood level, i.e.,

$$S_j(\mathbf{p_{mt}}) = S^0_{jmt} \;\times\; \exp\Big(\gamma_{n(j)} \;\times\; (p_{jmt} \;-\; p^0_{jmt})\Big) \tag{16}$$

where $S^0_{jmt} \;=\; S_j(\mathbf{p^0_{mt}})$ is the supply of residence j at some reference price vector $\mathbf{p^0_{mt}}$ and $\gamma_{n(j)}$ is a housing supply elasticity for neighborhood $n(j)$ that is estimated in the literature. The exponential form of (16) implies that $\gamma_{n(j)} = \frac{\partial \log S_j(\mathbf{p_{mt}})}{\partial p_{jmt}}$. In practice, we use the estimated housing supply elasticity from Saiz (2010), which requires us to normalize their estimated elasticities by property-level baseline prices to ensure consistency with the exponential form of (16). While allowing for housing supply adjustments introduces a realistic response margin, it is not clear that these supply-side features are first-order in practice.[15]

The sorting equilibrium for market m at time t is defined as a vector of prices, $\mathbf{p^*_{mt}}$, such that the housing market clears for all properties j:

$$D_j(\mathbf{p^*_{mt}}, \mathbf{g}_{mt}; \theta) \;=\; S_j(\mathbf{p^*_{mt}}) \tag{17}$$

This model follows the class of residential sorting models developed by Bayer and Timmins (2007) and Bayer, Ferreira and McMillan (2007) and implemented across a number of empirical contexts. Equilibrium existence follows from the assumed structure of the error term in (9) and Brouwer's fixed point theorem. The fixed point of the system of equations (13) and (17) defines equilibrium housing prices.[16]

4.2 Estimating Housing Demand

Estimation follows a two-step procedure similar to that of Bayer and Timmins (2007) and Bayer, Ferreira and McMillan (2007). In the first stage, the nonlinear parameters $\theta_\mathbf{1}$ and mean utilities δ_{jmt} are estimated via maximum likelihood with a nested contraction mapping. In the second step, linear parameters $\theta_\mathbf{2}$ are estimated via linear IV/GMM. In practice, each levee project in our main estimation sample serves as a separate housing market. We restrict our estimation of the model to only those residential parcels in protected areas and within 5 miles of a protected area boundary which transact between 5 years prior to and 10 years after construction of a levee. We define a discrete time period as a calendar year.

[15]We find limited reduced form evidence for supply responses on the extensive margin: using a panel of all parcels in our sample with valid construction date information from ZTRAX, we estimate the effect of levee construction on the probability a parcel experiences new home construction, finding minimal effects in both protected and spillover areas (Appendix Table E4). We also find limited evidence for supply responses on the intensive margin: we find minimal impact of protection on renovation rates and a modest negative impact of spillover exposure on renovation decisions (Appendix Table E5).

[16]Equilibrium uniqueness is not guaranteed, though as Bayer, Ferreira and McMillan (2007) discuss, the parameterization of utility based on exogenous observable attributes with strong explanatory power can be sufficient for uniqueness. Following Barwick et al. (2024), we solve the model with many starting values to ensure uniqueness in practice.

Defining Households' Choice Set Our equilibrium sorting model requires us to specify households' choice sets. While households could in theory select from all residences on the market at a given point in time, the size of such a choice set presents a challenge for estimation. We follow a choice-based sampling approach to reduce the dimension of households' choice set: we assume that households select their residence from a discrete set of alternatives that includes their chosen residence and a 1% random sample of residences that transact in the same quarter in which they purchase their chosen residence.[17]

First Stage: Recovering Preference Heterogeneity and Mean Utilities In the first stage, we use the individual choice probabilities (13) to recover mean utilities, δ_{jmt}, and the parameters governing preference heterogeneity, θ_1. We do so by maximizing the following log-likelihood:

$$\ell(\delta_{jmt}, \theta_1) = \sum_t \sum_m \sum_j \sum_i d_{ijmt} \times \log\Big(P_{ijmt}(\delta_{jmt}, \theta_1)\Big) \tag{18}$$

Given the dimensionality of the mean preference terms, δ_{jmt}, we follow Berry (1994) and use a contraction mapping to recover mean utility estimates for each guess of the parameters θ_1.[18] We nest this fixed point routine inside our likelihood estimation of the preference heterogeneity parameters, θ_1, which greatly reduces the dimensionality of this first stage.

Second Stage: Decomposing Mean Utilities Having recovered estimates of mean utilities and preference heterogeneity parameters, $\{\hat{\delta}_{jmt}\}_j$ and $\hat{\theta}_\mathbf{1}$, in the first stage, the second stage recovers the linear parameters, $\theta_\mathbf{2}$, by estimating (11) via instrumental variables regression, treating the unobservable ξ_{jmt} as the regression residual. The resulting parameter estimates, $\hat{\theta}_\mathbf{1}$ and $\hat{\theta}_\mathbf{2}$ enable estimation of willingness-to-pay (WTP) for levee protection and flood risk spillover exposure for different demographic groups. Our use of instrumental variables in this second stage is motivated by relatively standard price endogeneity concerns, on which we elaborate in the subsection that follows.

[17] Guevara and Ben-Akiva (2013) show that choice-based sampling yields consistent estimates in logit models. Others adopt a similar approach in the context of empirical sorting models (Barwick et al., 2024; Bayer, Keohane and Timmins, 2009).

[18] We do so by normalizing the mean utility of one alternative in each market m and period t to zero and then iterating over the following contraction mapping until convergence, where for each iteration d and a given guess of $\tilde{\theta}_1$, the next iterate is given by

$$\delta_{jmt}^{(d+1)} = \delta_{jmt}^{(d)} + \log(s_{jmt}) - \log\Big(s_{jmt}(\delta_{jmt}^{(l)}, \tilde{\theta}_1)\Big)$$

where s_{jmt} and $s_{jmt}(\delta_{jmt}^{(d)}, \tilde{\theta}_1)$ are the observed and model-implied market shares for each residence type.

4.3 Identification

Identification of the preference parameters, $\hat{\theta}$, requires addressing two endogeneity concerns. First, the spatial distribution of levee impacts may correlate with residence quality: high quality residences may be more likely to receive protection while low quality residences face spillovers, biasing preference estimates. We leverage the timing of levee construction combined with rich property attributes—including distance to water—and fixed effects to identify household preferences for levee protection and spillovers.

For unbiased estimates, the change in preferences for a residence around levee construction must depend only on that residence's treatment status as encoded by $\mathbf{g'_{jmt}} = \begin{bmatrix} L_{jmt} & W_{jmt} \end{bmatrix}$, where L_{jmt} and W_{jmt} indicate post-construction levee protection and spillover treatment. That is:

$$\mathbb{E}[L_{jmt}\xi_{jmt} \mid \mathbf{x_{jmt}}, \bar{\xi}_m, \bar{\xi}_t] = 0 \qquad \mathbb{E}[W_{jmt}\xi_{jmt} \mid \mathbf{x_{jmt}}, \bar{\xi}_m, \bar{\xi}_t] = 0$$

This orthogonality condition requires that treatment status is uncorrelated with unobserved quality conditional on observables and fixed effects.

Our sorting model addresses potential endogeneity by solving for time-varying mean preferences, δ_{jmt}, that rationalize observed sorting patterns in space and time. Conditional on observed equilibrium housing costs, rich residence attributes, and fixed effects, variation in mean preferences around levee construction reflects only treatment status differences up to an idiosyncratic unobservable, ξ_{jmt}. The inclusion of residence attributes ($\mathbf{x_{jmt}}$) and fixed effects—in practice, granular time-invariant spatial fixed effects ($\bar{\xi}_m$) and time-period fixed effects ($\bar{\xi}_t$)—accounts for systematic differences in the quality of residences or areas that experience different treatments from levee construction.

This identification argument relies on a parallel trends assumption analogous to that in Section 3. Specifically, absent levee construction, the unobservable quality difference ξ_{jmt} between treated and untreated properties must remain constant over time. This allows for persistent unobserved differences in quality across treatment groups, but rules out differential trends in unobservables that coincide with treatment timing. The plausibly exogenous timing of levee construction—conditional on observables and fixed effects—then identifies household preferences for levee protection and spillover exposure.

The second endogeneity concern is standard in demand estimation: residence price p_{jmt} likely correlates with unobserved quality ξ_{jmt}. We address this with two instrument sets. The first follows Waldfogel (2003) and Berry and Haile (2016): prices depend partly on other consumers' preferences. Heterogeneous preferences imply differential exposure to aggregate demographic changes—residence types popular with growing demographic groups face greater demand and smaller residual supply than those popular with shrinking groups.

We implement this via a Bartik (1991) shift-share instrument: we discretize consumers by income and race, characterize base period demand for residence types using observed choices (all years up to five years before levee construction), then apply nationwide demographic growth rates using microdata from the US Census Bureau's Current Population Survey (CPS) for 1990-2020. The instrument is

$$z_{jmt} = \sum_{\iota} \gamma_t^{\iota} d_{jm}^{\iota}$$

where γ_t^{ι} is the aggregate growth rate for consumer type ι from the CPS and d_{jm}^{ι} is base period demand for residence type j by type ι in market m from ZTRAX-HMDA data.

The second instrument set uses exogenous attributes of distant neighborhoods following Bayer, Ferreira and McMillan (2007). Following Berry, Levinsohn and Pakes (1995), distant neighborhood attributes affect residence j's price through substitution patterns but do not directly enter utility for j. We use average attributes of properties beyond four miles, including undeveloped area and single-family share. Appendix B provides additional detail on instrument construction.

4.4 Estimation Results

We estimate the housing demand model with two specifications of preference heterogeneity and report results from the first stage in Table 3. In column 1, we interact the treatment indicators with race and only allow income-based heterogeneity in the disutility of residence price and the utility of residence size. In column (2), we add interactions between the natural logarithm of income and the treatment indicators.

As expected, high income households tend to be less price-sensitive as indicated by the negative parameter estimate on the price-income interaction across both specifications in Table 3. High income households also have stronger preferences for larger homes relative to the average household in the sample. White households have a preference for levee protection as indicated by the positive parameter estimate on the Post $\times$ Protected treatment interaction for that group. Though we estimate a positive preference for spillover-exposed parcels for White households, these parameters are not statistically-distinguishable from the average household's spillover preferences. Interestingly, Black households appear to have a strong distaste for not only spillover exposure, but also levee protection relative to the average household in the sample. While adding interactions between income and the treatment indicators in column 2 leads to an increase in the log-likelihood, this is quite modest. Moreover, the estimated parameters on the post-treatment interaction terms are not sta-

Table 3. Housing Demand: First Stage Nonlinear Parameters from MLE

	Race Treatment Interactions (1)		+ Income Treatment Interactions (2)	
Income Interactions:				
Price / Income	−1.935 (0.024)		−1.925 (0.022)	
log(Home Size) × log(Income)	0.615 (0.044)		0.612 (0.042)	
Spillover × log(Income)			0.217 (0.052)	
Protected × log(Income)			−0.066 (0.055)	
Post × Spillover × log(Income)			−0.103 (0.064)	
Post × Protected × log(Income)			−0.107 (0.057)	
Race Interactions:	× White	× Black	× White	× Black
Spillover	0.012 (0.041)	0.407 (0.072)	−0.002 (0.033)	0.411 (0.063)
Protected	−0.604 (0.031)	−0.033 (0.111)	−0.596 (0.031)	−0.026 (0.102)
Post × Spillover	0.055 (0.046)	−0.150 (0.074)	0.065 (0.037)	−0.152 (0.069)
Post × Protected	0.105 (0.034)	−0.301 (0.124)	0.108 (0.034)	−0.302 (0.116)
Choices	336,448		336,448	
Log-likelihood	−807,680		−807,595	

This table reports first stage MLE estimates of the nonlinear parameters in housing demand using the matched HMDA-ZTRAX data. We restrict data to transactions of parcels in protected areas and within 5 miles of protected area boundaries which transact between 5 years prior to and 10 years after construction of a levee. All household attributes (the inverse of income and race indicators) are re-centered to be mean zero, so the estimated nonlinear parameters correspond to the change in value relative to the average household. Bayesian Bootstrap standard errors are reported in parentheses (Rubin, 1981). Bootstrap weights for each choice occasion are drawn according to a Dirichlet distribution with $\alpha = 1$ across 100 bootstrap samples.

tistically distinguishable from the average household's preferences. We nonetheless use the richer specification in column 2 in the results that follow.

Table 4 reports the coefficient estimates on the population-average utility in (11) for the specification in column 2 of Table 3. Columns 1-3 use OLS while columns 3-6 use instrumental variables (IV). All regressions include year and month fixed effects to capture time-varying and seasonal changes in aggregate housing market conditions and amenities. Columns 2-6 also include property-level controls and columns 3-6 include census block group fixed effects to capture unobserved time-invariant neighborhood amenities.

The price parameter, which shifts the average disutility of price across households, is negative and statistically-significant across all specifications. Consistent with much of the literature on demand estimation, the IV estimates of the mean price parameter are larger in magnitude. Column 4 uses the Waldfogel (2003) shift-share instrument, column 5 adds the square of the number of transactions within 4 miles of a property in a 6-month window, and column 6 includes additional Bayer, Ferreira and McMillan (2007) instruments. The first-stage F-statistics for the IV regressions range from 25.2 to 75.3, which is suggestive of strong instruments. We use column 6 as our preferred specification given that it makes use

Table 4. Housing Demand: Second Stage Linear Parameters

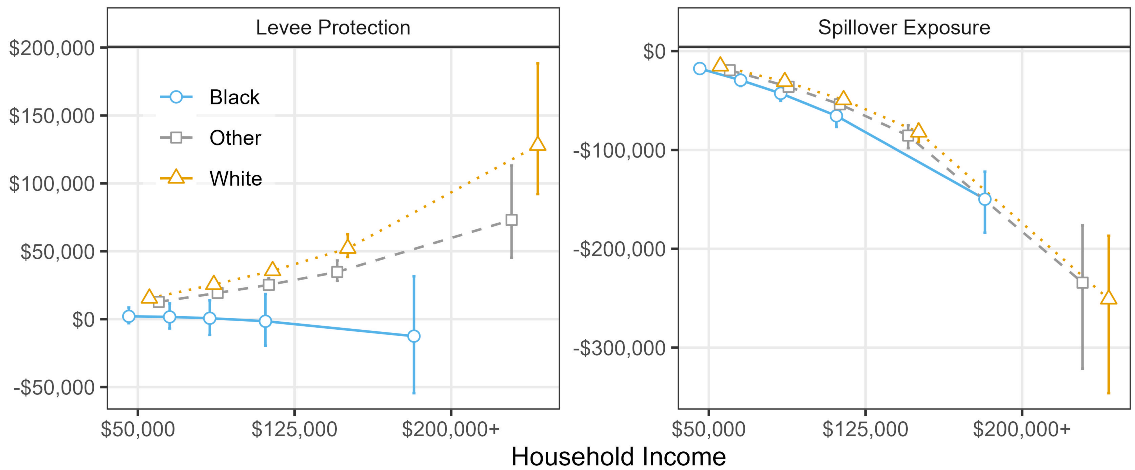
	OLS			IV		
	(1)	(2)	(3)	(4)	(5)	(6)
Price ($100,000s)	−0.473	−0.527	−0.465	−0.811	−1.33	−1.35
	(0.011)	(0.011)	(0.011)	(0.087)	(0.153)	(0.145)
Post	0.648	0.636	0.708	0.678	0.632	0.630
	(0.040)	(0.041)	(0.041)	(0.050)	(0.064)	(0.065)
Protected	−0.251	−0.273	−0.191	−0.348	−0.584	−0.596
	(0.078)	(0.075)	(0.147)	(0.137)	(0.142)	(0.141)
Spillover	0.207	0.213	0.243	0.317	0.426	0.432
	(0.032)	(0.032)	(0.034)	(0.045)	(0.064)	(0.063)
Post x Protected	0.205	0.215	0.188	0.245	0.330	0.335
	(0.061)	(0.061)	(0.062)	(0.068)	(0.074)	(0.074)
Post x Spillover	−0.274	−0.290	−0.344	−0.432	−0.564	−0.571
	(0.038)	(0.038)	(0.041)	(0.056)	(0.080)	(0.078)
Year, Month FE	Yes	Yes	Yes	Yes	Yes	Yes
Tract FE	Yes	Yes				
Property Controls		Yes	Yes	Yes	Yes	Yes
Block Group FE			Yes	Yes	Yes	Yes
First Stage Kleinberg-Paap F				75.3	33.2	25.2
Median Housing Price Demand Elasticity	−0.42	−0.62	−0.40	−1.65	−3.60	−3.70

The number of observations is 336,448. The dependent variable is the mean utility recovered using parameter estimates in column 2 of Table 3. We restrict data to transactions of parcels in protected areas and within 5 miles of protected area boundaries which transact between 5 years prior to and 10 years after construction of a levee. Property controls include the natural logarithm of residence size, residence age, and number of bedrooms. Column 4 uses the Waldfogel (2003) shift-share instrument, column 5 adds the square of the number of transactions within 4 miles of a property in a 6-month window, and column 6 adds the Bayer, Ferreira and McMillan (2007) instruments. Standard errors, clustered at the block group level, are reported in parentheses.

of multiple sources of identifying variation.

We find that the average household values levee protection at $25,000 and spillover exposure at −$42,000. These correspond to 5.8% and −9.9% of the average residence sale price or 19.4% and −33.1% of the average annual income in the sample, respectively. These averages mask substantial heterogeneity: using parameters from column 2 in Table 3 and column 6 in Table 4, we estimate average willingness-to-pay for levee protection and spillover exposure across different racial groups and income quintiles and plot the results in Figure 3. This exercise offers several takeaways: first, the magnitude of valuations of levee protection and spillover exposure are both increasing in income. Second, while there are meaningful differences in valuations across racial groups in their valuation of levee protection—Black households appear to place little value on levee protection across the income distribution—there is general agreement across demographic groups in distaste for spillover exposure, which

Figure 3. Estimated Value of Levee Protection and Spillover Exposure



Note: This figure shows estimates of average willingness-to-pay of different demographic groups for levee protection and spillover exposure. Average values are based on parameter estimates from column 2 of Table 3 and column 6 of Table 4. Average willingness-to-pay is calculated for each income quintile in the estimation sample, separately by race, using average income values for income quintile and demographic group. The "other" race category includes all non-White and non-Black households. Bars represent 95% confidence intervals from bootstrapped standard errors. Monetary values are in 2019 USD.

is larger in magnitude than the valuation of levee protection at each income quintile.[19]

4.5 Discussion

This equilibrium sorting model offers several advantages over our capitalization estimates. First, at the expense of structural assumptions on the form of preferences in household residence location decisions, the sorting model enables us to recover estimates of willingness-to-pay, which we can use to capture the welfare impacts of levee construction. While Kuminoff and Pope (2014) and Banzhaf (2021) identify conditions under which capitalization estimates have a welfare interpretation, it is unlikely that this is true in the context of levee construction. Levees are large-scale investments which provide a rich set of non-marginal changes in flood risk and other residential amenities—it is likely that such investments alter the sorting equilibrium in local housing markets, thereby complicating any welfare-relevant interpretation of our capitalization estimates. By modeling the sorting process, we are able to estimate household preferences up to a set of identifying assumptions discussed above.

[19] Protection willingness-to-pay may partly reflect NFIP interactions: FEMA-accredited levees enable re-mapping out of Special Flood Hazard Areas, removing mandatory flood insurance requirements and lowering premiums. Though we find larger capitalized benefits for accredited levees (Appendix Table E6), this may reflect other quality differences. The present discounted value of NFIP insurance costs (Appendix Figure E5) is lower than average WTP as a share of home value, suggesting NFIP interactions contribute to but do not fully explain protection valuations.

Comparing the model estimates with our capitalization estimates of levee construction validates the need for an equilibrium sorting model to recover preferences. The average estimates of willingness-to-pay for levee protection and spillover exposure as a share of residence price are both larger in magnitude than the capitalized estimates in Table 1. This is in line with Banzhaf (2021), which suggests that capitalization estimates will be biased away from the true welfare effects of construction if the hedonic gradient shifts over time through non-random sorting. It therefore appears as though our capitalization estimates in Section 3 conflate shifts in the price function and movement along the price gradient after levee construction.

Second, our equilibrium sorting model allows us to explicitly account for heterogeneity in household preferences for the effects of levee construction. As our reduced form evidence of heterogeneous sorting post-levee construction suggest, this is likely an important feature of housing market equilibrium for which our model accounts. Moreover, our sorting model enables us to extend the welfare interpretation of our model to account for the disparate preferences for and exposure to the various impacts of levee construction, a potentially important part of the story of *who* gains or loses as a result of these investments.

While the results from the heterogeneous sorting model offer a clear improvement over our reduced form capitalization approach, the model is not without its own limitations. Our setup makes several simplifying assumptions, primarily for tractability given the scale of our setting, including the assumption of myopic consumers and the assumption of closed housing markets with no outside options. Though we may miss important transition dynamics and potential in- and out-migration resulting from levee construction, we nonetheless believe that our setup captures those equilibrium adjustment margins which are of first-order importance to understanding the magnitude and incidence of private impacts from levee construction.

5 Welfare Effects of Levee Construction

To better understand the magnitude and incidence of the effects of levee construction, we use our model estimates to compare equilibrium outcomes with and without the levees in our sample. We begin with a brief summary of our counterfactual solution method in Section 5.1 before turning to our results on the household-level welfare impacts of levee construction in Section 5.2. We close with discussions of the local political economy of levee construction and potential mitigation of levee spillover costs in Sections 5.3 and 5.4.

5.1 Characterizing Counterfactual Equilibrium

We define a counterfactual equilibrium as a vector of housing prices, $\mathbf{p}^*_{mt}$, that satisfies the market-clearing conditions in (13) and (17). To construct the no-levee counterfactual, we remove levee treatments from (11) and (12) and iteratively solve the market-clearing conditions until convergence to the fixed point $\mathbf{p}^*_{mt}$. We then compare equilibrium sorting patterns, transaction prices, and welfare outcomes between the levee and no-levee equilibria. Additional details on the counterfactual simulation algorithm are provided in Appendix C.

We incorporate equilibrium effects of price changes on local property tax revenues using assessment data from ZTRAX. For each levee project, we estimate effective property tax rates by dividing total revenue by total assessed value and averaging across parcels within treatment groups. We multiply this annual tax rate by equilibrium price changes, $\mathbf{\Delta p}^*_{mt}$, to obtain implied annual revenue changes, then compute their present discounted value using a discount rate of 3.5% to reflect municipalities' long-run cost of capital.[20]

Welfare Channels Throughout our discussion of the welfare changes of levee construction, we focus on the underlying channels through which welfare adjusts for specific households, following a similar approach to Barwick et al. (2024) to decompose welfare. Let households' ex ante welfare be

$$CS_{ijmt} \;=\; \mathbb{E}_{\varepsilon_{ijmt}}\Big[\max_{j\in\mathcal{J}_{mt}} u_i(\mathbf{p_{mt}},\mathbf{g_{mt}})\Big]$$

where $\mathbf{g_{mt}} \;=\; \{\mathbf{L_{mt}},\mathbf{W_{mt}}\}$ is a vector of observable attributes defining residences levee protection status, $\mathbf{L_{mt}}$, and spillover exposure, $\mathbf{W_{mt}}$, in market m at time t. Since $\mathbf{g_{mt}}$ involves discrete changes, we are interested in the finite difference in ex ante welfare from the levee construction to no-levee construction counterfactual. Define

$$\Delta CS(\mathbf{p},\mathbf{L},\mathbf{W}) \;=\; CS(\mathbf{p},\mathbf{L},\mathbf{W}) \;-\; CS(\mathbf{p^0},\mathbf{L_0},\mathbf{W_0})$$

[20] The 3.5% rate approximately corresponds to Bloomberg's index yield on 30-year municipal bonds as of December 2022 (Bloomberg Finance L.P., retrieved from https://www.bloomberg.com/quote/BVMB30Y:IND on 12/7/2022).

where $\mathbf{p^0}$, $\mathbf{L_0}$, and $\mathbf{W_0}$ denote the baseline price and treatment status with levee construction. This total finite difference of household welfare with respect to levee construction $\mathbf{g_{mt}}$ is

$$\Delta CS \;=\; \underbrace{\underbrace{\Delta CS(\mathbf{p^0}, \mathbf{0}, \mathbf{W_0})}_{\substack{\text{(1) Direct Protection}\\ \text{Effect}}} + \underbrace{\Delta CS(\mathbf{p^0}, \mathbf{L_0}, \mathbf{0})}_{\substack{\text{(2) Direct Spillover}\\ \text{Effect}}}}_{\text{(1) + (2) Direct Policy Effect}}$$
$$+ \underbrace{\Delta CS(\mathbf{p_D^{CF}}, \mathbf{0}, \mathbf{0}) \;-\; \Delta CS(\mathbf{p^0}, \mathbf{0}, \mathbf{0})}_{\text{(3) Sorting Effect}} + \underbrace{\Delta CS(\mathbf{p^{CF}}, \mathbf{0}, \mathbf{0}) \;-\; \Delta CS(\mathbf{p_D^{CF}}, \mathbf{0}, \mathbf{0})}_{\text{(4) Supply Adjustment Effect}} \tag{19}$$

where $\mathbf{p_D^{CF}}$ denotes equilibrium prices in the no-levee counterfactual with housing supply fixed at baseline levels (i.e., with market clearing condition $D(\mathbf{p_D^{CF}}, \mathbf{0}, \mathbf{0}) = 1$), and $\mathbf{p^{CF}}$ denotes equilibrium prices in the no-levee counterfactual with housing supply allowed to adjust (i.e., with $D(\mathbf{p^{CF}}, \mathbf{0}, \mathbf{0}) = S$).

The first two channels of welfare change—the direct protection effect and the direct spillover effect—represent the partial-equilibrium effects of levee investment. Each is defined as the change in household welfare from eliminating one effect of levee construction while holding housing prices and the other effect of construction fixed. The sorting channel allows households to relocate in response to changes in the impact of levees, therefore allowing sale prices to adjust, but holds fixed housing supply at levels observed in the levee construction equilibrium. Finally, the supply adjustment effect allows neighborhood-level housing supply to adjust in response to price changes in the no-levee counterfactual.

5.2 Household Surplus from Levees

Panel A of Table 5 shows residence location choices under the observed equilibrium with levee construction and the no-levee counterfactual.[21] Allowing for household sorting (column 3) and supply adjustments (column 4), we find that in the absence of levee construction, below-median income households would sort into currently protected and unaffected areas and away from spillover-exposed areas. The opposite pattern emerges for above-median income households, who would sort away from currently protected and unaffected areas and toward spillover-exposed areas in the no-levee counterfactual.

This pattern is further illustrated in Figure 4, which examines changes in equilibrium sorting induced by levee construction across income quintiles and racial groups, accounting for the full general-equilibrium effects of levee investments. Using the no-levee equilibrium

[21] Table 5 presents welfare changes from the perspective of levee construction effects—comparing the observed equilibrium with levees to the counterfactual without levees. This framing clarifies that the counterfactual represents a world in which these levees were never built, not a policy of removing existing levees.

Table 5. Simulated Effects of Levee Construction with Different Response Margins

	Baseline w/ Levees (1)		Remove Levees: No Sorting Δ's from (1) (2)		+ Sorting Δ's from (1) (3)		+ Supply Adj. Δ's from (1) (4)	
Income relative to median:	Low	High	Low	High	Low	High	Low	High
Panel A. Residence Location Choice (percentage points)								
Protected Areas	19.21	18.77			0.70	−0.80	0.75	−0.81
Spillover Areas	11.54	11.60			−2.1	1.07	−2.10	1.04
Other	69.25	69.63			1.35	−0.25	1.35	−0.23
Panel B. Welfare Change per Household (thousand $)								
Consumer Surplus			−0.59	9.16	3.51	3.85	3.65	3.44
Fiscal Externality					0.53	0.53	0.55	0.55
Forgone Cons. Cost			24.85	24.85	24.85	24.85	24.85	24.85
Net Welfare			24.27	34.01	27.84	28.17	27.96	27.74

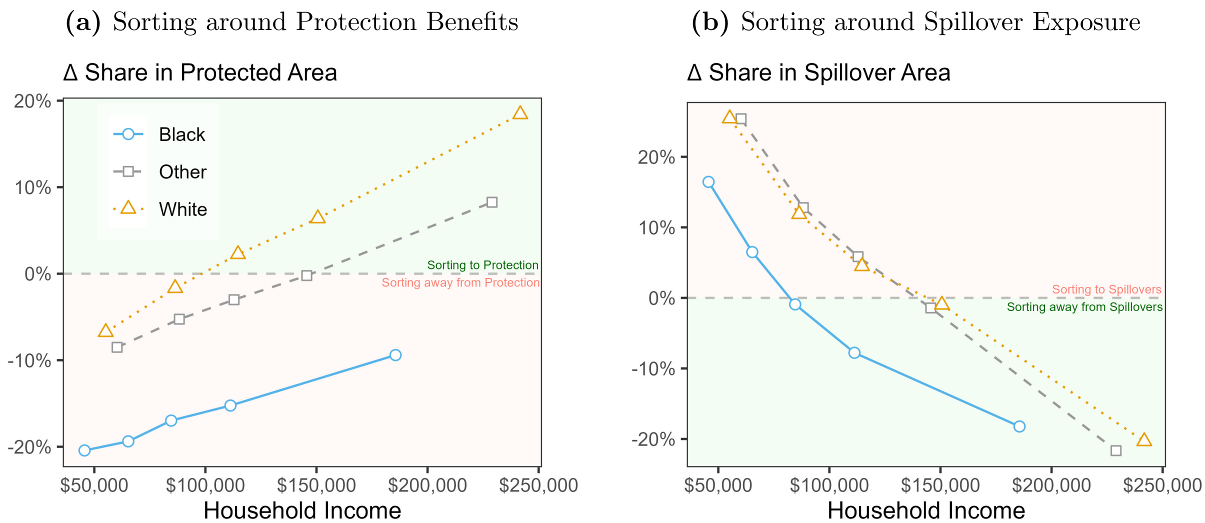
This table compares equilibrium outcomes under levee construction (observed) to a counterfactual equilibrium in which levees were never constructed. Panel A shows the share of households residing in protected, spillover-exposed, and unaffected areas under each scenario, along with the percentage point change in these shares. Panel B reports per-household changes in consumer surplus, fiscal externalities (present discounted value of property tax revenue changes), median construction costs, and net welfare. Results are shown separately for below- and above-median income households. Fiscal externalities are calculated using effective property tax rates from ZTRAX assessment data for protected and spillover-exposed parcels. Construction cost data are compiled for 41 USACE levee projects. Monetary values are in 2019 USD.

reported in column (4) of Table 5 as the reference point, Figure 4 shows that higher-income households tend to sort toward levee-protected areas and away from spillover exposure when levees are introduced into a local housing market. White households experience greater exposure to levee protection benefits across the income distribution, while Black households sort away from protected areas at all income levels. Spillover exposure varies little across income quintiles for White households and households in the Other racial group; by contrast, Black households exhibit consistently lower spillover exposure across the income distribution.

Panel B of Table 5 reports the per-household components of welfare change from levee construction, including changes in consumer surplus. In partial equilibrium, below-median income households appear to benefit from levee construction (losing $590 in the no-levee counterfactual), while above-median–income households appear worse off (gaining $9,160 in the absence of levees). Once we account for equilibrium sorting and housing supply adjustments (column 4), this pattern reverses: both below- and above-median–income households experience welfare losses from levee construction, with average surplus decreases of $3,650 and $3,440, respectively (or equivalently, gains in the no-levee counterfactual).

We further examine the ex post distributional impacts of levee construction in Figure

Figure 4. Effect of Levee Construction on Household Sorting



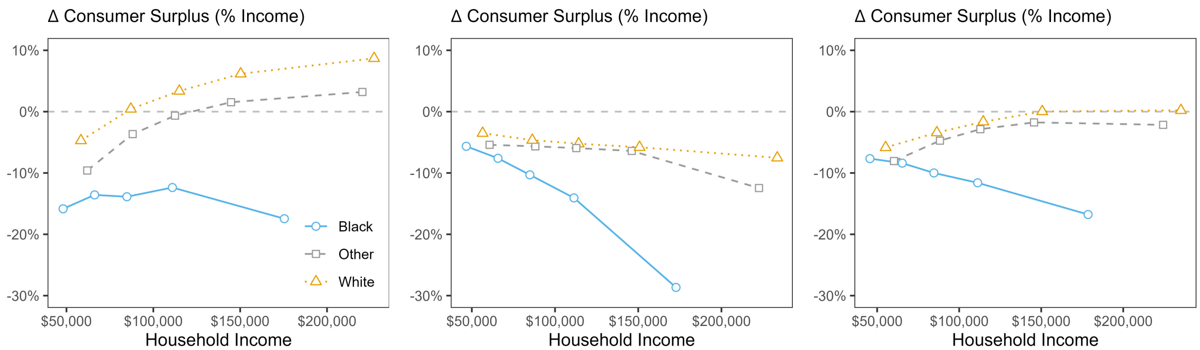
Note: This figure shows changes in equilibrium sorting patterns induced by levee construction for different demographic groups. Values are the percentage point difference in the share of each demographic group residing in (a) protected areas and (b) spillover exposed areas, comparing the observed equilibrium with levees to a counterfactual equilibrium in which levees were never constructed. Sorting patterns are shown for each income quintile in the estimation sample, separately by race. The "other" race category includes all non-White and non-Black households. The counterfactual equilibrium accounts for both sorting and changes in housing supply.

5, which reports average household surplus changes as a share of income across income quintiles and racial groups, shown separately for households that sort into levee protection, spillover exposure, and the full population. Allowing for the full equilibrium effects of levee investments, several patterns emerge. Flood protection operates as a regressive implicit subsidy among beneficiary households: as shown in Figure 5a, levee-protected households in the lowest income quintile experience surplus losses ranging from 4% of annual income for White households to 15% for Black households, while high-income households that sort into levee protection are among the few groups that benefit. Incidence also differs sharply by race within income groups: White and Other households in the highest income quintile gain 3–8% of annual income, whereas Black households in the same quintile experience losses equivalent to 17% of annual income. Although spillover costs are progressive—losses as a share of income are concentrated among higher-income households (Figure 5b)—they are insufficient to offset the regressivity of protection benefits, leaving overall welfare losses concentrated among lower-income households (Figure 5c). Average welfare effects range from 5-8% of annual household income among the lowest income quintile to between a 16% loss for Black households and a 0.2% gain for White households in the highest income quintile.

Although Figure 5a shows that lower-income households who sort into levee-protected

Figure 5. Average Household Surplus of Levee Construction with Sorting

(a) Protected Households **(b)** Spillover Exposed Households **(c)** All Households

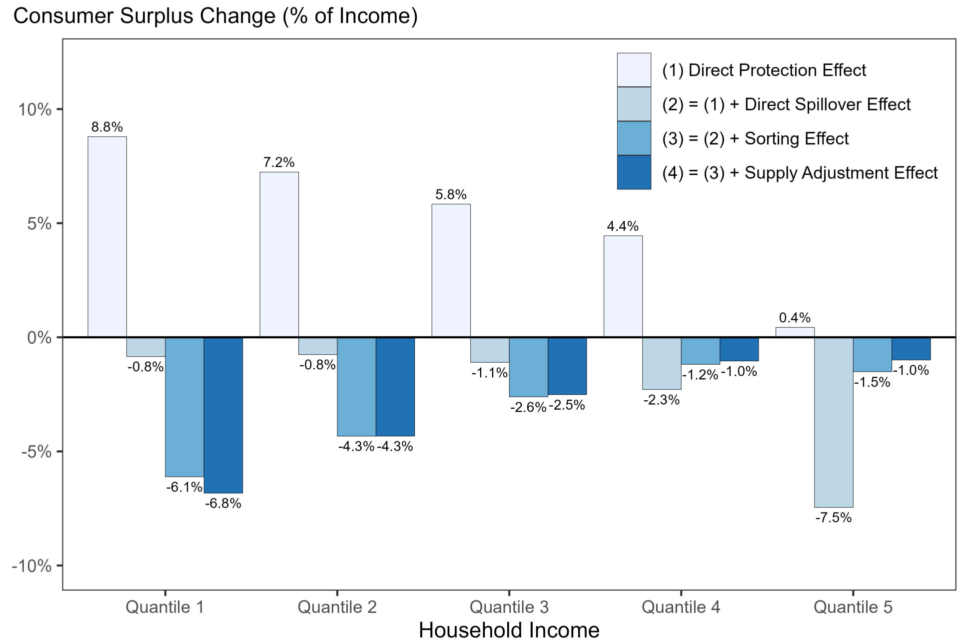


Note: This figure shows welfare effects of levee construction for different demographic groups. Values represent the average change in household-level surplus from levee construction, comparing the observed equilibrium with levees to a counterfactual equilibrium in which levees were never constructed. Panel (a) shows average household-level surplus changes for households that reside in protected areas under the observed equilibrium with levee construction, panel (b) shows average household-level surplus changes for households that reside in spillover areas under the observed equilibrium with levee construction, and panel (c) shows average household-level surplus changes for all households. Surplus changes are shown for each income quintile in the estimation sample, separately by race. The "other" race category includes all non-White and non-Black households. The counterfactual equilibrium accounts for both sorting and changes in housing supply.

areas are worse off under levee construction than in the no-levee counterfactual, this result reflects a central feature of our sorting model rather than a paradox. Sorting into the investment area is voluntary, but it does not guarantee that households are better off relative to a no-investment equilibrium. Low-income households—who are the most price sensitive in our estimates—can experience welfare losses when price capitalization and reduced outside options more than offset the amenity value of protection, even as they optimally choose among the constrained set of post-investment alternatives.

Turning to the channels underlying household surplus changes from levee construction, Figure 6 presents the welfare decomposition in (19) by income quintile. The direct protection effect is progressive as a share of income, declining from 8.8% for households in the lowest income quintile to 0.4% for those in the highest. This direct protection effect is likely the category closest to what the USACE estimates in its economic impact assessments of proposed levee projects. Adding direct spillover effects preserves this progressivity: although all households are worse off relative to the no-levee counterfactual, welfare losses as a share of income remain concentrated among higher-income households. Allowing housing prices to adjust and households to re-sort, however, reverses the incidence. Higher-income households are able to offset welfare losses through sorting, while price capitalization of levee investments—combined with aversion to relatively low-priced, spillover-exposed housing—

Figure 6. Channels of Household Surplus Changes from Levee Construction



Note: This figure reports average per-household changes in surplus from levee construction under alternative assumptions about adjustment margins. Surplus is measured as the difference between the observed equilibrium with levees and a counterfactual equilibrium in which levees were never constructed. The Direct Protection Effect captures surplus changes for households located in levee-protected areas after construction, holding prices, residential sorting, and housing supply fixed. The Direct Spillover Effect additionally includes surplus changes for households exposed to spillover effects, still holding equilibrium outcomes fixed. The Sorting Effect allows prices and residential choices to adjust when comparing the with-levee and no-levee equilibria and reports average surplus changes across all households. The Supply Adjustment Effect further allows housing supply to adjust in the no-levee counterfactual.

imposes disproportionately large losses on lower-income households. These effects are further amplified by housing supply responses: under the full general-equilibrium adjustment to levee construction, households in the lowest income quintile experience average surplus losses of 6.7% of income, compared with losses of roughly 1% for households in the highest quintile.

5.3 The Local Political Economy of Levees

The large welfare losses experienced by affected households raise questions about forces motivating policymakers' support for levee construction. Panel B of Table 5 shows that local fiscal externalities—operating through price capitalization effects on property tax revenues—reinforce rather than offset household welfare losses. Municipalities experience modest revenue declines following levee construction, as losses from spillover-exposed properties exceed gains from protected areas. The key local public finance question, however, addresses the geography of protected areas and spillovers across multiple political jurisdictions affected by a given levee.

Levee construction in our sample also entails substantial fiscal outlays by the federal government and the non-federal partner (typically a local municipality). We compile federal and non-federal construction cost data for USACE-built levees from primary sources including federal budget requests, appropriations bills, and USACE annual reports. This yields cost estimates for 41 projects encompassing 53 levee systems.[22] We summarize these construction costs on a per–protected-household and per–levee-mile basis in Table A1: the median total construction cost per protected household is $24,850. As we show in Table 5, this large cost yields average household surplus losses from levee construction of $3,650 and $3,440 for below and above median income households, respectively.

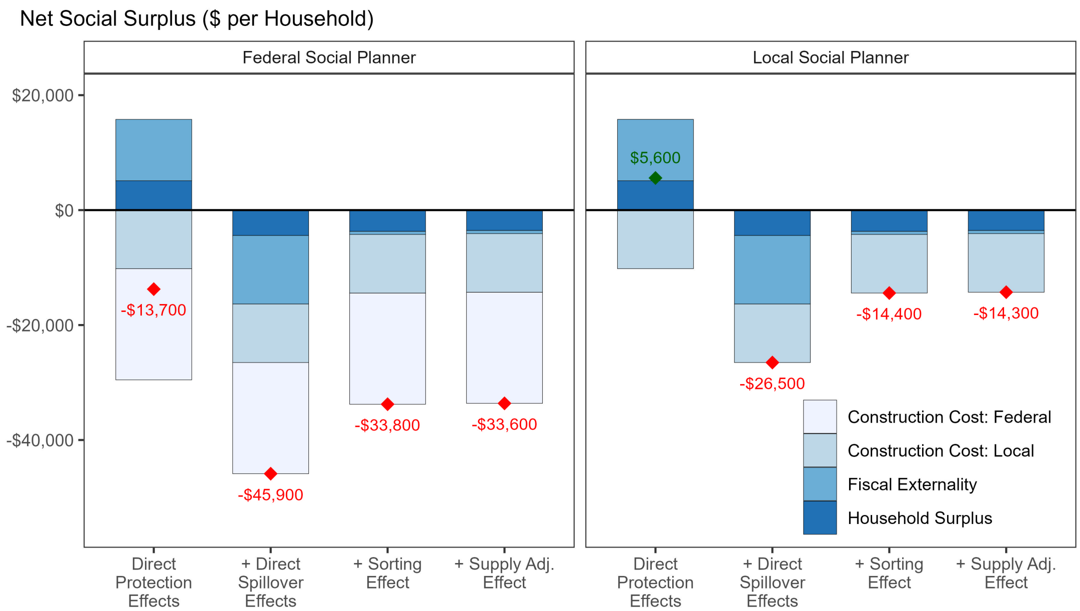
One explanation for continued support of these poorly performing investments lies in the role of local jurisdictions in the levee production process. We evaluate per-household changes in net social surplus from two perspectives: a federal social planner, e.g., USACE, and a local social planner, e.g., the non-federal project sponsor. The federal planner internalizes all modeled costs—federal construction expenditures, spillover effects, and general-equilibrium adjustments—whereas the local planner abstracts from federal construction costs. Figure 7 shows the results. From the federal perspective, levees generate net losses per protected household under all assumptions. From the local perspective, however, levees appear beneficial when spillover costs and general-equilibrium effects are ignored. Under this myopic local assessment, levee investment generates an estimated $5,600 in net surplus per protected household, compared with a loss of $13,700 from the federal perspective. Once all adjustment margins are internalized, both planners perceive losses, but the local planner's loss ($14,300 per household) remains substantially smaller than the federal planner's $33,600 loss.

While some local municipalities experience both protection benefits and spillover costs, the geographically-differentiated nature of levee impacts raises potential for these costs to be external from the perspective of the local political jurisdiction that serves as the non-federal project sponsor. Of the 80 levee systems in our sample, 24 impose spillover effects on counties outside the protected county hosting the levee project. Among the 35 systems listing a city or town as local sponsor, only 38% of spillover-exposed parcels fall within that jurisdiction compared with 97% of protected parcels—a classic externality problem.

These local externalities manifest through Congressional representation on the committees responsible for authorizing and appropriating funds for USACE levee projects. Among the 80 systems in our sample, 52% of spillover-exposed parcels fall outside the Congressional districts that host levee projects and receive protection benefits. Examining historical representation on Congressional committees with jurisdiction for USACE civil works projects,

[22] Project-level sources often aggregate multiple NLD levee systems; see Appendix A for details.

Figure 7. Net Social Surplus per Household for Different Social Planners



Note: This figure reports median per-household changes in net social surplus from levee construction under alternative assumptions about adjustment margins and for different perspectives: a federal social planner (e.g., USACE) and a local social planner (e.g., a non-federal project sponsor/partner). Surplus is measured as the difference between the observed equilibrium with levees and a counterfactual equilibrium in which levees were never constructed. Construction cost estimates are based on observed federal and non-federal shares (see Table A1), not statutory cost-share mandates. The Direct Protection Effects capture surplus and fiscal externality changes for households located in levee-protected areas after construction, holding unprotected prices, residential sorting, and housing supply fixed. The Direct Spillover Effects additionally include surplus and fiscal externality changes for households exposed to spillover effects, still holding equilibrium outcomes fixed. The Sorting Effects allow prices and residential choices to adjust when comparing the with-levee and no-levee equilibria and reports surplus changes and fiscal externality changes across all households. The Supply Adjustment Effect further allows housing supply to adjust in the no-levee counterfactual. We implicitly assume a marginal cost of public funds of zero. Surplus components are averages with the exception of per household construction costs, for which we use median values to account for the skewed distribution across levee systems. Monetary values are in 2019 USD.

we find positive correlations between committee membership and levee construction.[23] Appendix Figure E6 shows consistent positive associations between state-level cumulative committee membership and USACE levee construction for 1993-2018. We also find negative relationships between House Appropriations Committee membership and spillover-exposed parcels in a district. As reported in Appendix Table E7, one additional year of district representation on House Appropriations is associated with a 4 percentage-point reduction in the share of a levee's spillover-exposed parcels falling within that district.[24] This represents a

[23]The relevant House committees are Appropriations and Transportation and Infrastructure. We obtain committee membership data for the 103rd to 115th Congresses (1993-2018) from Grossmann, Lucas and Yoel (2024) and map historical representation using district boundaries from Lewis et al. (2013).

[24]We focus on the House Appropriations Committee given that its Members exercise discretion in selecting

7% reduction in the average district's spillover exposure, suggesting Representatives exercise discretion to capture levee benefits while minimizing spillovers in their own districts.

We note that there are a number of important categories of levee construction impacts which we omit in Figure 7. On the cost side, we omit operations and maintenance costs, which are 100% borne by the local, non-federal partners, as well as other fiscal externalities, such as the impact of levee construction on the federal NFIP.[25] There are also categories of plausible benefits that we omit, such as protection of commercial and industrial properties and the indirect economic impacts of levee construction.

5.4 Policies to Address Levee Spillovers

The spillover externality problem suggests a corrective Pigouvian tax requiring households or communities benefiting from levee protection to internalize external spillover costs through a fee totaling the net present value of expected damages to spillover-exposed communities. Our empirical exercise provides a blueprint for calculating this spatially-explicit corrective tax; however, Pareto-improving transfers may not be possible: levees in our sample generate \$1.26 billion in total consumer surplus gains but \$2.09 billion in total losses.[26]

Another possible policy is to enhance centralized planning at the watershed level. Wang (2021) discusses this as a prescription to address spillover effects from levee heightening. The policy architecture already exists: USACE's involvement in ex-ante feasibility assessment should hedge against fully ignoring external costs. However, the extent to which spillover costs are considered ex-ante is unclear, and Congress's continued role in authorizing and funding levee construction does not eliminate incentives to prioritize internal benefits over external costs. Since USACE civil works projects require project-level authorization and appropriations from Congress, committee members exercise substantial discretion in drafting legislation and therefore have input into site selection. This introduces potential for committee members to exercise substantial discretion in drafting legislation that selects sites for levee construction funding.

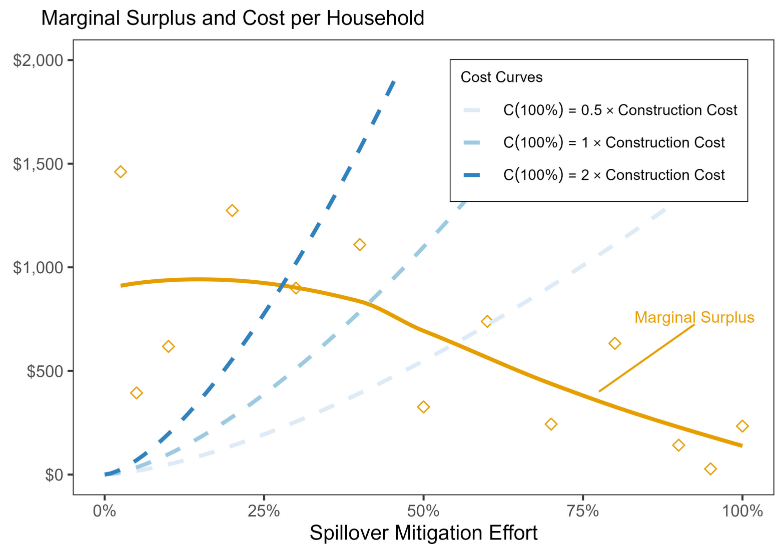
A final possible policy is to finance direct spillover mitigation. We evaluate spillover mitigation through counterfactual equilibria in which spillover exposure is defined over pro-

sites for appropriated funding. While authorization is necessary for construction, it is not sufficient given that authorized levees require appropriations. Moreover, the Transportation and Infrastructure Committee largely follows USACE recommendations.

[25]USACE levee construction likely reduces NFIP premium revenue while also reducing claims payments for an ambiguous net budgetary impact. However, the presence of flood risk spillovers perhaps increases NFIP budget outlays through increased claims payments. We examine these potential fiscal externalities on the NFIP in Appendix Table E8, which validates the hypothesized effects.

[26]These totals sum across all households in our estimation sample and differ from per-household averages discussed elsewhere.

Figure 8. Marginal Surplus and Costs from Spillover Mitigation



Note: This figure plots marginal household surplus from spillover mitigation (solid) and assumed marginal cost curves (dashed). Mitigation effort is measured as the fraction of baseline spillover exposure eliminated. Marginal surplus is computed from differences in equilibrium welfare across adjacent mitigation levels, where welfare is obtained by re-solving the full residential equilibrium and aggregating expected consumer surplus across households and is inclusive of fiscal externalities; points denote discrete estimates and the solid line is a smoothed interpolation. Cost curves are convex, with an assumed functional form of $C(E) = c_0 E^{2.5}$ where E is the spillover mitigation effort and c_0 is calibrated so that total cost at full mitigation equals 0.5, 1, or 2 times the median total levee construction cost per household. We then re-scale marginal cost to reflect the x-axis percentage point scale. Monetary values are in 2019 USD.

gressively narrower spatial bandwidths around affected waterbodies, simulating interventions that reduce flood risk for properties at varying distances from waterbodies. Narrower bandwidths correspond to higher mitigation effort, with the limiting case eliminating spillover exposure entirely. For each bandwidth, we resolve the residential equilibrium with re-sorting and price adjustment and compute expected consumer surplus, then calculate marginal surplus from differences in equilibrium welfare across adjacent bandwidth reductions. Appendix D provides technical details on the implementation of this exercise.

Figure 8 shows the results. Marginal surplus—inclusive of fiscal externalities—from mitigation is positive but declining as bandwidths contract, implying diminishing returns as mitigation extends beyond the most exposed locations. Interpreted as reduced-form representations of feasible policies (channel modifications, drainage improvements, or vegetated buffers), comparisons with convex cost schedules calibrated to construction cost benchmarks imply an interior optimum level under moderate cost assumptions. Though Pareto-improving transfers may be infeasible, some welfare gains are possible through spillover mitigation.

6 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, the United States experienced 102 separate natural disasters with individual costs exceeding \$1 billion over the 5-year period ending in 2023.[27] 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: 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 to these risks.

Our analysis provides important insights into the private welfare consequences of large-scale public investments in climate adaptation infrastructure. Our structural model of residential sorting with heterogeneous preferences exploits USACE levee construction timing to identify household valuations. Households value levee protection substantially but dislike spillover exposure even more, with considerable heterogeneity by income and race. These valuations differ markedly from reduced-form capitalization estimates, which conflate price gradient shifts with movement along the price gradient, biasing welfare inference when sorting responds to policy changes.

Counterfactual equilibria reveal that welfare incidence differs sharply from partial equilibrium predictions. Direct protection effects are progressive, but equilibrium sorting and housing supply responses reverse this: lower-income households experience substantially larger welfare losses once general-equilibrium effects are incorporated. This reversal reflects price capitalization and greater price sensitivity among lower-income households, limiting their ability to avoid spillover exposure. Though spillover costs alone are progressive, they cannot offset the regressivity from sorting and price adjustments. Welfare effects also vary sharply by race, with Black households experiencing substantially larger losses than White households across the income distribution.

Our results highlight the political economy enabling poorly performing adaptive investments. From a myopic local perspective ignoring federal costs, spillovers, and general-equilibrium effects, levees appear welfare-enhancing; from the federal perspective internalizing all modeled costs, the same projects generate substantial net losses. This divergence

[27] See: NOAA National Centers for Environmental Information (NCEI) U.S. Billion-Dollar Weather and Climate Disasters (2023). https://www.ncei.noaa.gov/access/billions/, DOI: 10.25921/stkw-7w73.

is reinforced by geographically differentiated spillover costs: over half of spillover-exposed parcels in our sample fall outside the Congressional districts receiving protection benefits. We find evidence that Representatives exercise discretion to capture levee benefits while minimizing spillovers in their districts, creating a classic externality problem.

We evaluate direct spillover mitigation as a policy response to these externalities. Our counterfactual analysis finds positive but declining marginal surplus from mitigation, with diminishing returns beyond the most exposed locations. Under plausible cost assumptions, interior optimal mitigation levels could generate welfare improvements relative to the status quo with levees even when Pareto-improving transfers are infeasible.

More broadly, our findings demonstrate how existing institutions for climate adaptation can generate perverse distributional outcomes and misallocate resources through inadequate consideration of external costs and general-equilibrium effects. As policymakers confront growing imperatives to expand investments in climate resilience, careful attention to these economic forces will be essential for designing policies that enhance welfare while avoiding unintended distributional consequences.

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Online Appendix for "Private Benefits from Public Investment in Climate Adaptation and Resilience"

Jacob T. Bradt and Joseph E. Aldy

The following appendices are **for online publication only**:

—Appendix Section A: Data Appendix
—Appendix Section B: Price Instruments
—Appendix Section C: Counterfactual Solution Method
—Appendix Section D: Spillover Mitigation Counterfactuals
—Appendix Section E: Supplemental Figures and Tables

A Data Appendix

A.1 Data Sources

- *Zillow Transaction and Assessment Dataset (ZTRAX)*: Provides transaction data for over 2,750 counties since 1990.[1] ZTRAX comprises two databases: (1) property transactions (400+ million records with sale price, dates, loan information, document types, and quality flags) and (2) tax assessments (150 million parcels across 3,100+ counties with lot size, building size, bedrooms, bathrooms, coordinates, and valuations). Parcels link across databases via unique identifiers. We obtain ZTRAX through a data use agreement with Zillow.[2]

- *First Street Foundation (FSF) Adaptation Database*: Contains location and characteristics of 20,000+ flood adaptation projects across the continental US, collected from state, county, and city agencies. Provides shapefiles of protected areas plus project type, source identifiers, and protection levels.[3] USACE levee systems appear as individual projects. We obtain data through a data use agreement with FSF.[4]

[1] Nolte et al. (2021) note geographic variation in data availability: 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, limiting coverage to select urban areas.

[2] As of 11/20/2022, Zillow plans to end the ZTRAX program.

[3] Protection levels are based on return period (e.g., 100-year flood has 1% annual exceedance probability). For levees, this is the "overtopping scenario"—the flood level exceeding levee height. FSF obtains these from USACE NLD for USACE-constructed levees.

[4] Additional information: https://firststreet.org/research-lab/published-research/flood-model-methodology_overview/ (accessed 11/20/2022).

- *US Army Corps of Engineers (USACE) National Levee Database (NLD)*: Covers 6,900+ levee systems and 24,000 miles of levees. USACE provides data on federal levees; state and local agencies provide non-federal levee data (less complete coverage). Contains spatial extent, overtopping scenario, construction dates, and constructing/operating agencies at the segment level. We link NLD to FSF using unique system identifiers and subset to USACE-constructed segments. Construction dates (available for 79% of segments) determine treatment timing. Note: heavily-modified projects like Lower Mississippi River and New Orleans levees are excluded from our sample. Spatial data enable distance calculations. Publicly available.[5]

- Home Mortgage Disclosure Act (HMDA): Enacted 1975, requires major depository institutions to disclose closed-end home lending activity annually. We harmonize 1990-2020 data to observe loan-level purpose, result, amount, census tract, decision date, lender name, applicant race, income, and ethnicity (ethnicity available for subset of years due to reporting changes). Publicly available.[6]

- *US Geological Survey (USGS) National Hydrography Dataset (NHD) Plus, Version 2.1*: Comprehensive, spatially granular data on US water drainage network. We use area and waterbody features to calculate parcel proximity to rivers, streams, canals, lakes, ponds, estuaries, wetlands, and coastline. Publicly available.[7]

- *USGS 3D Elevation Program (3DEP)*: National baseline of high-resolution topographic elevation data from lidar. We use 10m resolution digital elevation models to determine parcel elevation and slope. Publicly available.[8]

- *Presidential Disaster Declaration (PDD) Summaries*: Information on approved federal disaster declarations including type, start/end dates, and affected counties. Publicly available.[9]

- *National Oceanic and Atmospheric Administration (NOAA) Storm Events Database*: Records storms and significant weather events (1950-2022) causing injury, loss of life, property damage, or commerce disruption. Indicates counties affected by each event.

[5] `https://levees.sec.usace.army.mil/#/` (accessed 11/20/2022).

[6] `https://www.ffiec.gov/hmda/` (accessed 11/20/2022).

[7] `https://www.usgs.gov/national-hydrography/national-hydrography-dataset` (accessed 11/20/2022).

[8] `https://www.usgs.gov/3d-elevation-program` (accessed 11/20/2022).

[9] `https://www.fema.gov/openfema-data-page/disaster-declarations-summaries-v2` (accessed 11/20/2022).

We construct measures of recent flood-related storm exposure[10] over 6-, 12-, 18-, and 24-month intervals. Publicly available.[11]

- *National Flood Insurance Program (NFIP) Redacted Claims and Policies Datasets*: Policy-level data for policies since 2009 and claims since 1978. Includes policy term, claim date, and census tract location. We generate tract-year counts of policies-in-force, claims, and average claim amounts. Combined with ACS residential unit estimates, we construct tract-year take-up rates for 2009-2020. Publicly available.[12]

A.2 ZTRAX Data Cleaning

ZTRAX provides near-universal parcel-level residential property data nationwide. To ensure our analysis uses arms-length transactions with valid attributes (especially coordinates), we implement filtering procedures following Nolte et al. (2021)'s best practices.[13] Arms-length transactions are essential because hedonic methods assume sales prices reflect fair market value (FMV); non-FMV transactions (family transfers, foreclosures, public agent sales) would bias estimates. Accurate coordinates are critical for spatial treatment assignment. We apply the following filters to identify FMV arms-length transactions:

1. Drop transactions with sales prices below $1,001 (clearly below FMV). We later drop transactions below the 1st and above the 99th percentile in our final sample (Appendix A.5) to remove outliers.

2. Keep only deed transfers, excluding refinancings, foreclosures, and other non-deed-transfer transactions.

3. Drop Zillow-flagged intra-family transfers.

4. Keep transactions with sales price sources that Nolte et al. (2021) identify as high-confidence FMV indicators.

5. Keep transactions with document type categories (among 161 standardized types) that Nolte et al. (2021) identify as high-confidence FMV indicators for each state.

Coordinate accuracy is critical. Some parcels have missing locations; others use ZIP code centroids (errors can exceed 1km[14]) or fall outside listed county boundaries. We address this

[10] Includes coastal floods, flash floods, floods, heavy rain, hurricanes, tropical storms, etc.
[11] `https://www.ncdc.noaa.gov/stormevents/` (accessed 11/20/2022).
[12] `https://www.fema.gov/about/openfema/data-sets` (accessed 11/20/2022).
[13] `https://placeslab.org/ztrax/` (accessed 11/20/22).
[14] Nolte et al. (2021).

by: (1) removing duplicated coordinates (likely from approximate geocoding); (2) removing coordinates falling outside listed county boundaries; (3) using Census Geocoder API[15] to assign coordinates from street addresses where possible.

A.3 ZTRAX-HMDA Matching Procedure

To analyze distributional effects across socioeconomic groups, we link ZTRAX transactions to HMDA loan applications, which contain borrower demographics. We harmonize 1990-2020 HMDA data and subset to successful home purchase loans, then match to ZTRAX using:

1. Match on year, census tract, and loan amount (rounded to nearest $1,000).[16]

2. Keep many-to-one and one-to-many matches for further refinement; discard many-to-many matches.

3. Apply fuzzy string matching (Jaro-Winkler distance) on lender names for remaining non-unique matches. Remove matches failing similarity criteria.

We match 41.46% of ZTRAX arms-length transactions to unique HMDA records, similar to other studies: Bayer et al. (2016) (55%, San Francisco Bay Area 1994-2004), Bakkensen and Ma (2020) (47%, Miami area 2009-2012), Graff Zivin, Liao and Panassie (2022) (50%, Florida 2000-2016). Our slightly lower rate reflects nationwide coverage over 1990-2020. Conditioning on ZTRAX transactions with loan information yields a 68.45% match rate.

To assess representativeness, we compare state-year aggregates of our matched sample to Census ACS data (2005-2019) in Figure A1. Median income correlates 0.78 with ACS mortgage holder income. White and Black household shares are similar to ACS owner-occupied households, though we slightly under-predict Black household shares in high-Black-share areas.

A.4 Constructing USACE Levee Cost Data

We manually collect upfront construction costs for a subset of projects from federal budget requests, appropriations bills, and USACE annual reports. No central, consistent public database exists for USACE Civil Works project costs.

[15] https://geocoding.geo.census.gov/geocoder/Geocoding_Services_API.pdf (accessed 11/03/2022).

[16] We use historical census tract boundaries (1990, 2000, 2010) since HMDA definitions change after each decennial census.

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).

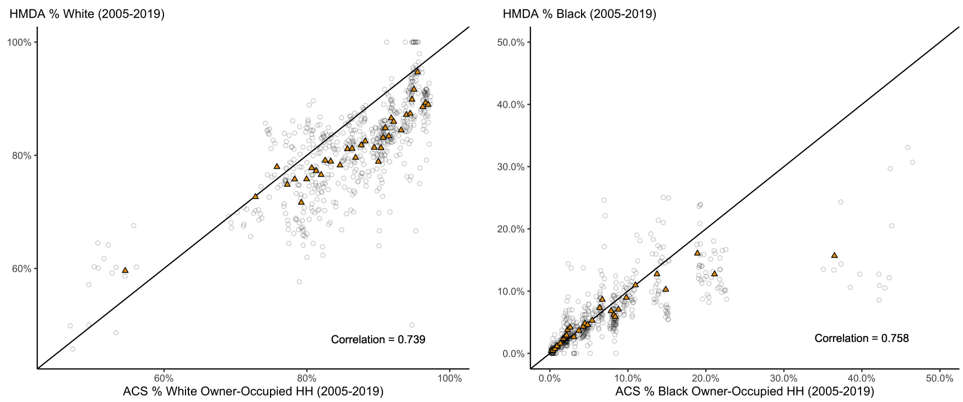


Table A1. Estimated Levee Construction Costs

	Cost per Household (thousand $)				Cost per Levee Mile (million $)			
	N	Mean	SD	Median	N	Mean	SD	Median
Federal Cost	18	815.97	1911.97	19.34	29	40.43	119.17	5.60
Non-federal Cost	17	362.20	684.77	10.19	27	12.13	33.81	1.87
Total Cost	23	913.66	2285.11	24.85	41	60.45	168.34	5.48

The table shows estimates of USACE levee construction costs per protected household and per levee mile. We collect ex-post information on project costs from annual reports of the Chief of the USACE to Congress for 1848-2012 as well as ex-ante project cost information on Civil Works project appropriations from regular and supplemental appropriations bills. We are able to construct estimates of construction costs for a total of 41 USACE Civil Works projects, which include 53 separate levee systems. To calculate costs per protected household, we use the ZTRAX Assessor data to construct estimates of the number of properties protected by each levee project for which we are able to collect cost data.

A major challenge is that NLD levee systems (our data unit) do not map one-to-one to projects in budget/appropriations sources. Projects often aggregate multiple NLD systems built over decades. We manually map systems to project names where we can establish high-confidence matches.

We collect ex-post costs primarily from USACE Chief Reports to Congress (1848-2012), which provide project-level narratives and cumulative spending for Civil Works projects. Coverage ends at FY2012 when USACE shifted to written testimony. We supplement with USACE District press releases where available. We also collect ex-ante costs from appropriations bills and budget requests, using only high-confidence matches to NLD systems.

Table A1 shows cost estimates per household and per levee mile. We distinguish federal and non-federal costs where source documents allow (available for smaller subset). The household cost sample is smaller than the levee mile sample because some projects protect few or no residential parcels.

Table A2. 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.

A.5 Final Sample Construction and Summary Statistics

We identify parcels inside or within five miles of USACE leveed area boundaries using ZTRAX coordinates (Euclidean distance; negative values indicate interior). This assumes housing market effects are limited to five miles.

Beyond filters described above, we drop price outliers (below 1st or above 99th percentile) and clear outliers in square footage, bedrooms, and bathrooms (coding errors or incomparable parcels). Table A2 summarizes the final dataset for unmatched and HMDA-matched subsamples.

A.6 Structural Model Estimation Data Construction

Our structural housing demand model requires discrete choice data with choice sets and demographics for BLP-style estimation. We process HMDA-matched data as follows:

Sample and Market Definition Starting from the levee-adjacent HMDA-matched sample (Section A.5), we restrict to USACE levees completed 1990-2020 with pre- and post-construction transactions. We define 127 spatial markets at the levee project level, grouping projects sharing county boundaries for sufficient market size.

Choice Set Construction For tractability, we draw 1% random samples of alternative residences within each market-year-quarter cell per observed purchase. Each transaction becomes a choice occasion with its purchased residence plus sampled alternatives. We iteratively remove alternatives appearing in < 4 choice sets and choice sets with < 4 alternatives until thresholds are met, balancing substitution patterns against computational feasibility.

Treatment Variables We construct property-time indicators for levee protection and spillover exposure (within 0.2 miles of leveed area boundaries, following reduced-form analysis).

Demographic Variables HMDA provides income and race (white, black, other). We center demographics within markets to focus on relative preferences.[17] Demographics interact with housing/neighborhood attributes and treatment indicators, enabling heterogeneous preference estimation across groups.

The final dataset contains 336,448 choice occasions and 5 million property-time observations (15 alternatives per choice set). Variables include prices, property attributes (square footage, bedrooms, bathrooms, lot size, age), geographic attributes (distance to water, elevation, flood risk), and levee treatments.

B Price Instruments

As we discuss in Section 4, recovering valid estimates of the preference parameters, θ, requires addressing a relatively standard price endogeneity issue. In particular, we are concerned that the cost of a particular residence, p_{jmt}, is likely correlated with unobserved residence quality ξ_{jmt}. We address this issue following standard two types of instruments from the literature on empirical demand estimation.

"Shift-share" Instrument The first set of instruments follows the logic of Waldfogel (2003) and Berry and Haile (2016), which argue that the prices a consumer faces are in part a function of the preferences of other consumers in the market. In our context, heterogeneity in preferences for different residences across household race and income implies differential exposure of residences to aggregate demographic changes. In particular, residence types which are popular with growing demographic groups will face greater demand—and hence, smaller residual supply assuming relatively inelastic supply—than those which are popular with shrinking demographic groups.

[17]For income: we center inverse income around sample mean for price coefficient, log income around sample mean for other attributes.

The identifying logic of this first instrument is similar to that of Bartik (1991) "shift-share" instruments. We operationalize this logic in our context by first discretizing consumers in our data into nine types based on in-sample observed household income terciles and the three racial groups: White, Black, and Other. We then characterize relative demand for residence types across these discrete consumers in a base period using observed residence choices. To do so, we take all transactions which occur at least 5 years prior to levee construction for each levee project in our estimation data and estimate the agent type-specific purchase probability for each property using a probit model. Let y^{ι}_{jmt} be an indicator that equals 1 if an agent of type ι purchases property j in market m at time t. Then we model the probability of agent type ι purchasing property j in market m at time t as:

$$\Pr(y^{\iota}_{jmt} = 1|\mathbf{x_{jm}}) \;=\; \Phi\Big(f(\mathbf{x_{jm}};\Gamma)\Big) \tag{B1}$$

where $\Phi(\cdot)$ is the cumulative distribution function of the standard normal distribution and $f(\cdot)$ is some flexible function of a vector of property-specific attributes, $\mathbf{x_{jmt}}$, with parameters, Γ. In practice, we include in $f(\cdot)$ polynomials of property age, the natural logarithm of square footage, and a series of fixed effects encoding distance to waterbody bins, the number of bedrooms, and county. Estimating (B1) generates a set of nine agent-type-specific purchase probabilities for all properties in our estimation data based on baseline agent preference. We then use these choice probabilities as the "shares" in our shift-share instrument.

To construct the shifts, we take microdata from the US Census Bureau's Current Population Survey for the years 1990 to 2020 and discretize all heads of household using the same discrete definitions as we used to discretize agents in our estimation data. We then construct—using the appropriate sampling weights—nationwide growth rates for each of the nine discrete agent types for the period 1990 to 2020. These are plotted in Figure B1.

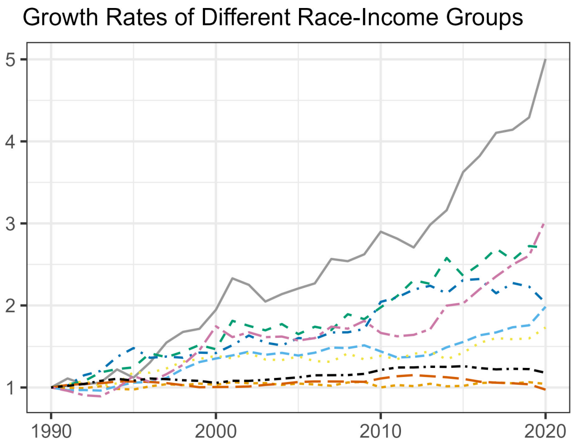
We then construct the scalar shift-share instrument as

$$z_{jmt} \;=\; \sum_{\iota=1}^{9} \gamma^{\iota}_t d^{\iota}_{jm} \tag{B2}$$

where γ^{ι}_t is the nationwide, aggregate growth rate at time t for households of type ι and $d^{\iota}_{jm} = Pr^{\iota}_{jm}$ is the baseline share predicted according to (B1).

Bayer, Ferreira and McMillan (2007) Instruments The second set of price instruments follow recent work in the literature estimating empirical models of residential sorting. In particular, this approach follows seminal work by Bayer and Timmins (2007) and Bayer, Ferreira and McMillan (2007) where exogenous attributes of distant neighborhoods serve as

Figure B1. Changes in Household Types Used to Construct "Shift-share" Instrument



Note: This figure plots growth rates in the nine discrete household types used to construct the "shift-share" (Bartik, 1991) price instrument. The types include all unique combinations of the estimation sample income terciles (with cutoffs held fixed) and racial groups (White, Black, and Other). Growth rates are calculated using microdata from the US Census Bureau's Current Population Survey for 1990-2020, setting 1990 populations equal to 1.

instruments for residence price. The logic of this instrument follows Berry, Levinsohn and Pakes (1995): though exogenous attributes of distant neighborhoods will affect the cost of selecting a given residence j through substitution patterns, these exogenous attributes do not otherwise enter directly into the utility of selecting that residence j.

In practice, we construct these instruments by calculating the average attributes of transacted properties greater than four miles from each focal property, including the average undeveloped area and share of single family residences in those areas. Table B1 reports results from the price regressions used in the second stage of estimation for different combinations of these two types of instruments.

C Counterfactual Solution Method

This appendix provides technical details on the algorithm used to solve for counterfactual equilibria in our residential sorting model. We describe the market-clearing conditions, the iterative solution procedure, and our approach to welfare measurement.

C.1 Equilibrium Characterization

A counterfactual equilibrium consists of a vector of housing prices $\mathbf{p}^*_{mt}$ such that the market-clearing condition in equation (17) holds for all residential properties $j \in \mathcal{J}_{mt}$. Recall from

Table B1. Price Instruments First Stage

	(1)	(2)	(3)
Instrument 1	8.8×10^{-5} (1.01×10^{-5})	8.76×10^{-5} (1.02×10^{-5})	8.77×10^{-5} (1.02×10^{-5})
Instrument 2		-2.6×10^{-7} (4.41×10^{-8})	-2.55×10^{-7} (4.4×10^{-8})
Instrument 3			-0.246 (0.089)
Post	-0.091 (0.036)	-0.084 (0.036)	-0.084 (0.036)
Protected	-0.464 (0.127)	-0.483 (0.126)	-0.493 (0.124)
Spillover	0.213 (0.039)	0.214 (0.039)	0.212 (0.039)
Post x Protected	0.167 (0.030)	0.215 (0.030)	0.218 (0.030)
Post x Spillover	-0.257 (0.046)	-0.259 (0.047)	-0.257 (0.046)
R^2	0.88	0.88	0.88
Wald (1st stage)	75.3	33.2	25.2

The number of observations is 336,448. The dependent variable is the property-specific sale price (thousands of 2019 USD). All specifications include additional property controls and block group, year, and month fixed effects. We restrict data to transactions of parcels in protected areas and within 5 miles of protected area boundaries which transact between 5 years prior to and 10 years after construction of a levee. Property controls include the natural logarithm of residence size, residence age, and number of bedrooms. Column 1 uses the Waldfogel (2003) shift-share instrument, column 2 adds the square of the number of transactions within 4 miles of a property in a 6-month window, and column 3 adds the Bayer, Ferreira and McMillan (2007) instruments. Standard errors, clustered at the block group level, are reported in parentheses.

Section 4 that the market-clearing condition requires aggregate demand to equal supply:

$$D_j(\mathbf{p}^*_{mt}, \mathbf{g}_{mt}; \theta) \;=\; S_j(\mathbf{p}^*_{mt}) \tag{C1}$$

where aggregate housing demand is the sum of individual choice probabilities:

$$D_j(\mathbf{p_{mt}}, \mathbf{g}_{mt}; \theta) \;=\; \sum_i P_{ijmt}(\mathbf{p_{mt}}, \mathbf{g}_{mt}; \theta) \tag{C2}$$

and $\mathbf{g}_{mt} = \{\mathbf{L}_{mt}, \mathbf{W}_{mt}\}$ encodes the levee protection and spillover exposure status of all residences in market m at time t.

We consider two supply specifications. In the baseline case, supply is perfectly inelastic at observed levels: $S_j(\mathbf{p}_{mt}) = 1$. This corresponds to the short-run equilibrium in which the housing stock is fixed. In the alternative specification, supply responds to price changes at the neighborhood level according to equation (16):

$$S_j(\mathbf{p}_{mt}) = S^0_{jmt} \times \exp\Big(\gamma_{n(j)} \times (p_{jmt} - p^0_{jmt})\Big) \tag{C3}$$

where $\gamma_{n(j)}$ is the housing supply elasticity for neighborhood $n(j)$ containing residence j. We calibrate $\gamma_{n(j)}$ using estimates from Saiz (2010), normalizing their estimated elasticities by baseline prices to ensure consistency with the semi-elasticity form in (C3).

C.2 Iterative Solution Algorithm

We solve for equilibrium prices using an iterative *tâtonnement* process. The algorithm begins with initial prices set to observed values, $\mathbf{p}_{mt}^{0}$, and iteratively adjusts prices in the direction that reduces excess demand until the market-clearing conditions converge.

At each iteration τ, the algorithm performs the following steps:

Step 1: Compute Choice Probabilities Given current prices $\mathbf{p}_{mt}^{\tau}$ and the counterfactual specification of levee treatments $\mathbf{g}_{mt}$, compute the deterministic utility component for each household-residence pair:

$$v_{ijmt}^{\tau} = \delta_{jmt}(\mathbf{p}_{mt}^{\tau}, \mathbf{g}_{mt}; \hat{\theta}_{\mathbf{2}}) + \mu_{ijmt}(\mathbf{p}_{mt}^{\tau}, \mathbf{g}_{mt}; \hat{\theta}_{\mathbf{1}}) \tag{C4}$$

where $\hat{\theta}_{\mathbf{1}}$ and $\hat{\theta}_{\mathbf{2}}$ are the estimated preference parameters from Section 4. The choice probability for household i selecting residence j is then:

$$P_{ijmt}^{\tau} = \frac{\exp(v_{ijmt}^{\tau})}{\sum_{k \in \mathcal{J}_i} \exp(v_{ikmt}^{\tau})} \tag{C5}$$

where $\mathcal{J}_i$ is household i's choice set. To ensure numerical stability in computing these probabilities, we use the standard "max-trick" for evaluating the log-sum-exp:

$$\log\left(\sum_{k \in \mathcal{J}_i} \exp(v_{ikmt}^{\tau})\right) = m_i^{\tau} + \log\left(\sum_{k \in \mathcal{J}_i} \exp(v_{ikmt}^{\tau} - m_i^{\tau})\right) \tag{C6}$$

where $m_i^{\tau} = \max_{k \in \mathcal{J}_i} v_{ikmt}^{\tau}$. This transformation prevents overflow.

Step 2: Aggregate Demand Compute aggregate demand for each residence by summing choice probabilities across households:

$$D_j^{\tau} = \sum_{i: j \in \mathcal{J}_i} P_{ijmt}^{\tau} \tag{C7}$$

Step 3: Price Updates Update prices based on the gap between demand and supply. For the inelastic supply case:

$$p_j^{\tau+1} = p_j^{\tau} + \lambda_{\tau} \cdot \log\left(\frac{D_j^{\tau}}{S_j}\right) \tag{C8}$$

where λ_τ is a step size parameter. For the elastic supply case, we adjust for the supply response:

$$p_j^{\tau+1} = p_j^\tau + \frac{\lambda_\tau}{\gamma_{n(j)}} \cdot \log\left(\frac{D_j^\tau}{S_j(p_j^\tau)}\right) \tag{C9}$$

where $\gamma_{n(j)}$ is the neighborhood-level supply elasticity. The division by $\gamma_{n(j)}$ accounts for the endogenous supply response: in neighborhoods with more elastic supply, prices adjust less in response to excess demand.

Step 4: Price Normalization To pin down the absolute price level—which is not separately identified in the discrete choice framework—we normalize prices at each iteration to maintain the mean price at its initial level:

$$\bar{p}^{\tau+1} = \frac{1}{|\mathcal{J}_{mt}|} \sum_{j \in \mathcal{J}_{mt}} p_j^{\tau+1} \tag{C10}$$

$$p_j^{\tau+1} \leftarrow p_j^{\tau+1} + \left(\bar{p}^0 - \bar{p}^{\tau+1}\right) \quad \forall j \tag{C11}$$

This normalization ensures that only relative prices adjust while the overall price level remains anchored.

Step 5: Convergence Check The algorithm terminates when the maximum absolute price change across all residences falls below a tolerance threshold:

$$\max_{j \in \mathcal{J}_{mt}} |p_j^{\tau+1} - p_j^\tau| < \varepsilon \tag{C12}$$

In practice, we use $\varepsilon = 10^{-4}$.

Step 6: Update Step Size To ensure convergence, we use a decreasing step size:

$$\lambda_{\tau+1} = \rho \cdot \lambda_\tau \tag{C13}$$

where $\rho \in (0.95, 0.98)$ is a damping factor. In practice, we set $\lambda_0 \in [0.4, 1.0]$ depending on the counterfactual scenario.

This iterative procedure is guaranteed to converge to a fixed point for sufficiently small step sizes under standard regularity conditions (Berry, Levinsohn and Pakes, 1995). The algorithm typically converges in 100–300 iterations across our counterfactual scenarios.

C.3 Welfare Calculation

We measure changes in household welfare using the money-metric consumer surplus implied by the logit structure. For household i in market m at time t, the expected maximum utility (inclusive value) is:

$$W_{imt}(\mathbf{p}_{mt}, \mathbf{g}_{mt}; \theta) = \log\left(\sum_{j \in \mathcal{J}_i} \exp(v_{ijmt}(\mathbf{p}_{mt}, \mathbf{g}_{mt}; \theta))\right) \tag{C14}$$

The compensating variation for household i from moving from a baseline equilibrium with prices $\mathbf{p}_{mt}^{\text{base}}$ and levee treatments $\mathbf{g}_{mt}^{\text{base}}$ to a counterfactual equilibrium with prices $\mathbf{p}_{mt}^{\text{cf}}$ and treatments $\mathbf{g}_{mt}^{\text{cf}}$ is:

$$CV_{imt} = -\frac{1}{\alpha_i}\left[W_{imt}(\mathbf{p}_{mt}^{\text{cf}}, \mathbf{g}_{mt}^{\text{cf}}; \hat{\theta}) - W_{imt}(\mathbf{p}_{mt}^{\text{base}}, \mathbf{g}_{mt}^{\text{base}}; \hat{\theta})\right] \tag{C15}$$

where $\alpha_i = \bar{\alpha} + \alpha/y_i$ is household i's marginal utility of income (with $-\alpha_i$ being the coefficient on price in the utility function). The negative sign ensures that CV_{imt} is positive when welfare increases. This compensating variation represents the dollar amount that would leave household i indifferent between the baseline and counterfactual equilibria.

C.4 Counterfactual Scenarios

We primarily analyze a no-levee counterfactual where we remove levee impacts from the utility specifications in equations (11) and (12). We also analyze a series of counterfactuals in which we keep the levee but remove the spillover costs of levee at specified waterbody bandwidth intervals, starting with those spillover locations furthest from the waterbody. For each counterfactual, we compute equilibria under three market structures that correspond to the welfare decomposition in 19:

- **Partial equilibrium (no sorting):** Prices are held fixed at baseline levels ($\mathbf{p}_{mt} = \mathbf{p}_{mt}^0$), so households do not re-optimize their location choices. This isolates the direct utility effect of the policy change.

- **General equilibrium with inelastic supply:** Prices adjust to satisfy the market-clearing condition (C1) with fixed housing stock ($S_j = 1$). This captures household sorting responses and their effect on equilibrium prices and welfare.

- **General equilibrium with elastic supply:** Both prices and quantities adjust endogenously according to equation (C3). This represents the longer-run equilibrium incorporating supply responses.

The comparison across these scenarios enables us to decompose the total welfare effect of levee construction into the direct policy effect, the sorting effect operating through price capitalization, and the supply adjustment effect as described in Section 5.1.

C.5 Fiscal Externalities

For each counterfactual equilibrium, we calculate the implied changes in local property tax revenues. Using property tax assessment data from ZTRAX, we estimate an effective property tax rate τ_c for each treatment category $c \in \{\text{Protected}, \text{Spillover}, \text{Unaffected}\}$ by dividing total annual tax revenue by total assessed value and averaging across parcels within the category. The annual change in tax revenue for category c under a counterfactual is:

$$\Delta\text{Revenue}_c = \tau_c \times \sum_{j \in c} \left(p_j^{\text{cf}} D_j^{\text{cf}} - p_j^{\text{base}} D_j^{\text{base}} \right) \tag{C16}$$

where D_j^{cf} is the equilibrium demand for residence j under the counterfactual. We assume these revenue changes persist in perpetuity and compute their present discounted value using discount rates of $r = 2\%$ and $r = 3.5\%$:

$$\text{PDV}(\Delta\text{Revenue}_c) = \frac{\Delta\text{Revenue}_c}{r} \tag{C17}$$

D Spillover Mitigation Counterfactuals

This appendix provides technical details on the spillover mitigation counterfactual exercise discussed in Section 5.4 and illustrated in Figure 8. We describe how we operationalize varying levels of mitigation effort, the welfare calculation procedure, and the construction of marginal surplus estimates.

Defining Mitigation Effort In our baseline model, spillover exposure is determined by proximity to affected waterbodies. Specifically, a residence is classified as spillover-exposed if it falls within a spatial bandwidth k of the nearest waterbody downstream from a levee. In our main analysis (Section 3), we set $k = 0.2$ miles based on reduced-form estimates of the spatial decay of spillover effects.

Spillover mitigation can be interpreted as interventions that reduce flood risk for properties near affected waterbodies—such as channel modifications, improved drainage systems, or vegetated buffers—without altering the footprint of levee-protected areas. We operationalize mitigation effort by progressively narrowing the spatial bandwidth defining spillover exposure. Specifically, we define a sequence of bandwidths:

$$\mathcal{K} = \{k_0, k_1, k_2, \ldots, k_M\} \tag{D1}$$

where $k_0 = 0.2$ miles represents the baseline (no mitigation) and $k_M = 0$ represents complete mitigation.

Under mitigation level k_m, the spillover treatment indicator for residence j becomes:

$$W_{jmt}(k_m) = \begin{cases} 1 & \text{if } \mathrm{dist}(j, \text{waterbody}) \leq k_m \text{ and levee upstream} \\ 0 & \text{otherwise} \end{cases} \tag{D2}$$

where $\mathrm{dist}(j, \text{waterbody})$ is the Euclidean distance from residence j to the nearest waterbody. Narrower bandwidths correspond to higher mitigation effort: fewer residences are subject to spillover disutility, effectively simulating the removal of flood risk for properties beyond distance k_m from the waterbody.

Welfare Calculation and Marginal Surplus For each bandwidth $k_m \in \mathcal{K}$, we solve for a counterfactual equilibrium using the iterative algorithm described in Appendix C. The key modification is that we update the spillover treatment vector $\mathbf{W}_{mt}(k_m)$ according to the narrower bandwidth while holding the levee protection vector $\mathbf{L}_{mt}$ fixed at baseline levels.

For each mitigation level k_m, we compute total expected consumer surplus across all households using the inclusive value from the logit model:

$$CS(k_m) = -\frac{1}{\bar{\alpha}} \sum_{i \in \mathcal{I}} \log \left(\sum_{j \in \mathcal{J}_i} \exp(v_{ijmt}(\mathbf{p}^*_{mt}(k_m), \mathbf{L}_{mt}, \mathbf{W}_{mt}(k_m); \theta)) \right) \tag{D3}$$

where $\bar{\alpha}$ is the mean marginal utility of income and $\mathcal{I}$ is the set of all households in the estimation sample.

We also incorporate fiscal externalities operating through property tax revenues. For each mitigation level, we calculate the present discounted value of tax revenue changes using the methodology described in Appendix C. Total surplus inclusive of fiscal externalities is:

$$TS(k_m) = CS(k_m) + \mathrm{PDV}(\Delta\mathrm{Revenue}(k_m)) \tag{D4}$$

Marginal surplus from mitigation is computed as the discrete difference in total surplus between adjacent bandwidth levels:

$$MS(k_m) = \frac{TS(k_{m+1}) - TS(k_m)}{(k_m - k_{m+1}) \times N_{\text{hh}}} \tag{D5}$$

where N_{hh} is the total number of households and the denominator normalizes by the change in bandwidth and household count to express marginal surplus in dollars per household per 0.01-mile reduction in the spillover bandwidth. This yields the marginal welfare gain from eliminating spillover exposure for properties between distances k_{m+1} and k_m from waterbodies.

Figure 8 plots $MS(k_m)$ against the cumulative fraction of baseline spillover exposure eliminated, defined as:

$$E(k_m) = \frac{\sum_j \mathbb{1}[W_{jmt}(k_0) = 1] - \sum_j \mathbb{1}[W_{jmt}(k_m) = 1]}{\sum_j \mathbb{1}[W_{jmt}(k_0) = 1]} \tag{D6}$$

where $\mathbb{1}[\cdot]$ is the indicator function. The value $E(k_m) = 0$ corresponds to no mitigation ($k_m = k_0 = 0.2$ miles) and $E(k_m) = 1$ corresponds to complete mitigation ($k_m = 0$). The declining marginal surplus as $E(k_m)$ increases reflects diminishing returns: mitigating spillover exposure closest to waterbodies (where flood risk is highest) generates larger welfare gains than mitigation further from waterbodies.

Assumed Cost Schedules The dashed curves in Figure 8 represent assumed marginal cost schedules for spillover mitigation. We model costs as convex in mitigation effort:

$$C(E) = c_0 \times E^{2.5} \tag{D7}$$

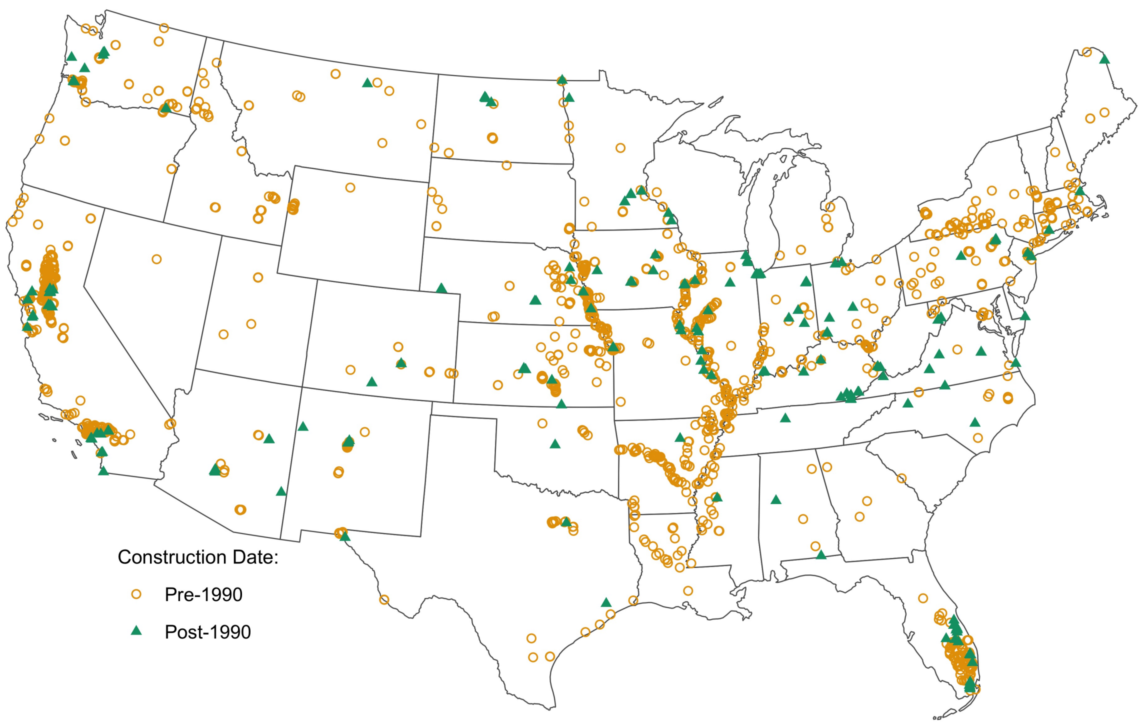
where $E \in [0, 1]$ is the fraction of baseline spillover exposure eliminated and c_0 is a scaling parameter. Marginal cost is:

$$MC(E) = 2.5 \times c_0 \times E^{1.5} \tag{D8}$$

We calibrate c_0 so that total cost at full mitigation equals a multiple of the median levee construction cost per household from Table A1. Specifically, we consider three scenarios where total mitigation cost equals 0.5, 1.0, and 2.0 times the median construction cost of \$24,850 per household. The convex functional form reflects the intuition that mitigating flood risk furthest from waterbodies (where baseline risk is lower) is more costly per unit of risk reduction than mitigating risk closest to waterbodies.

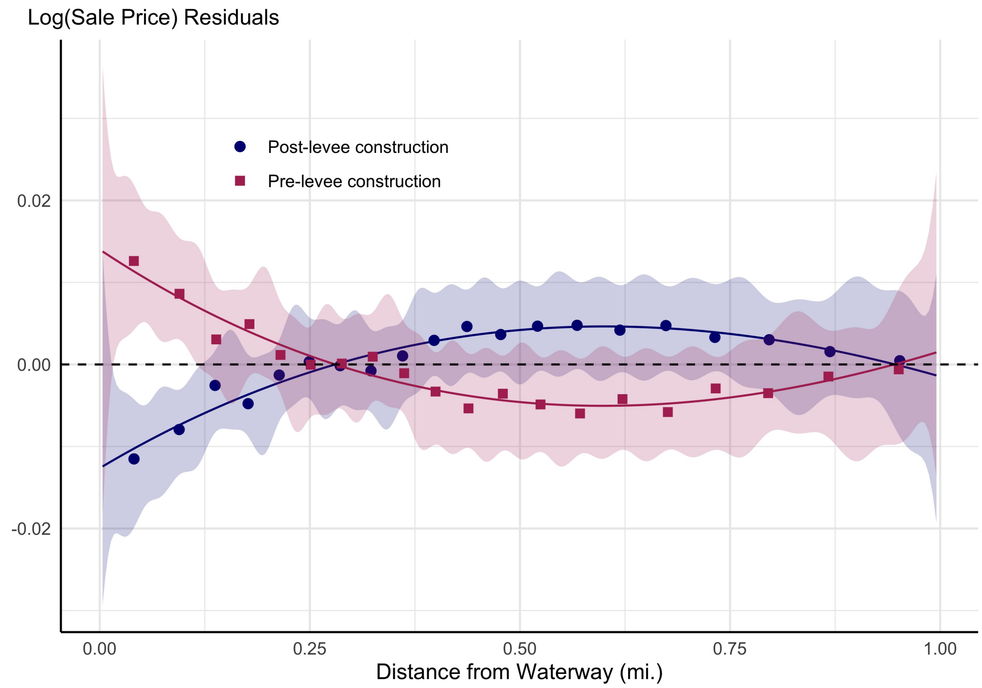
E Supplemental Figures and Tables

Figure E1. Map of USACE Constructed Levee Segments.



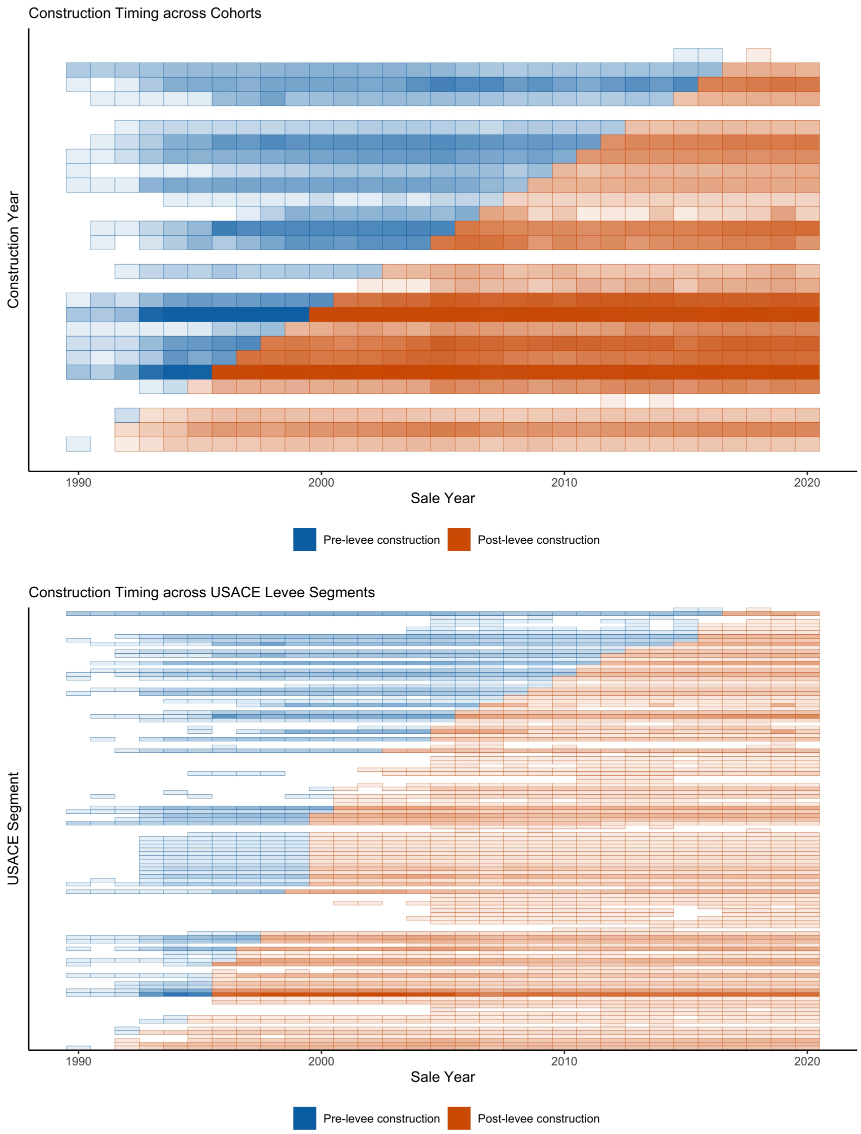
Note: This figure shows the location of US Army Corps of Engineers (USACE) constructed levee segments built pre- and post-1990, the earliest year for which we have residential transaction data. Levee segments that are part of USACE authorized projects, but are entirely constructed by non-federal partners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

Figure E2. Price Gradient of Distance from Nearest Waterway.



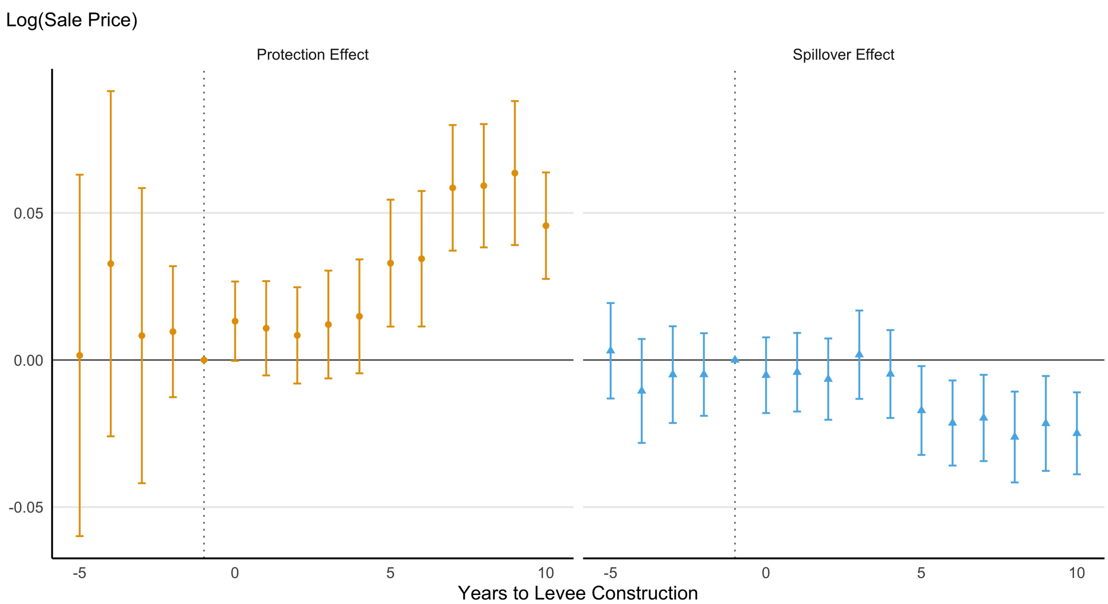
Note: This figure fits cubic spline on the empirical relationship between the residual of house prices from a regression on parcel and time fixed effects on a parcel's distance from the nearest waterway. We use this figure to help identify the distance range over which proximity-based levee construction 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 E3. Treatment Timing by Construction Year Cohort and Segment.



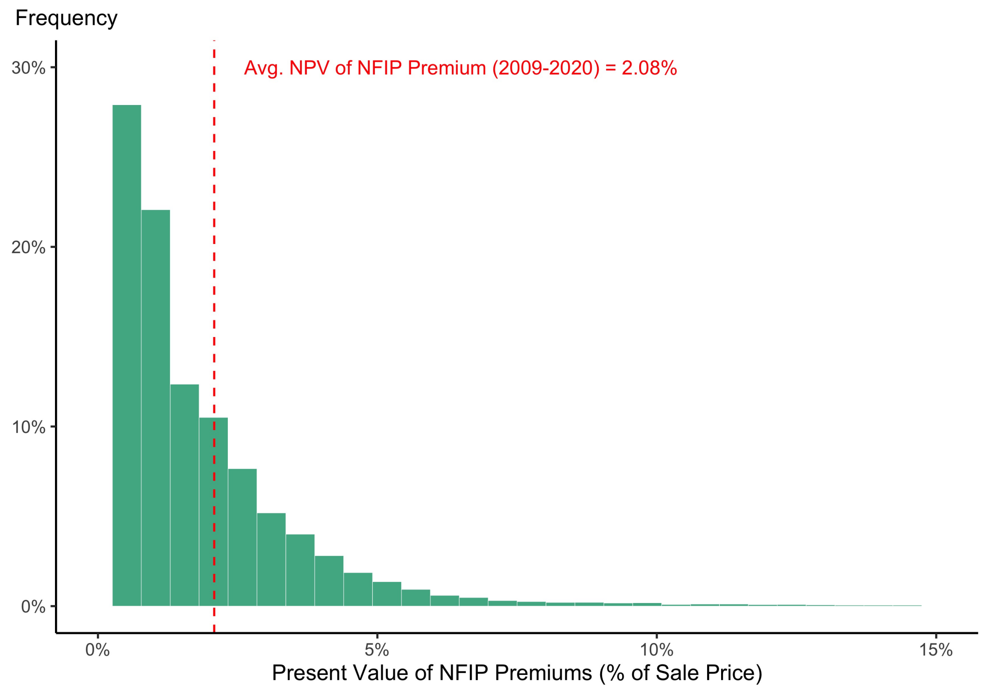
Note: This figure plots the timing of USACE levee segment construction across levee segment construction year cohorts (upper) and across individual USACE levee segments (lower). Vertical axes are ordered in ascending order of construction year. Blue tiles represent pre-construction transaction observations, 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 E4. Event Study Estimates of Protection and Spillover Effects



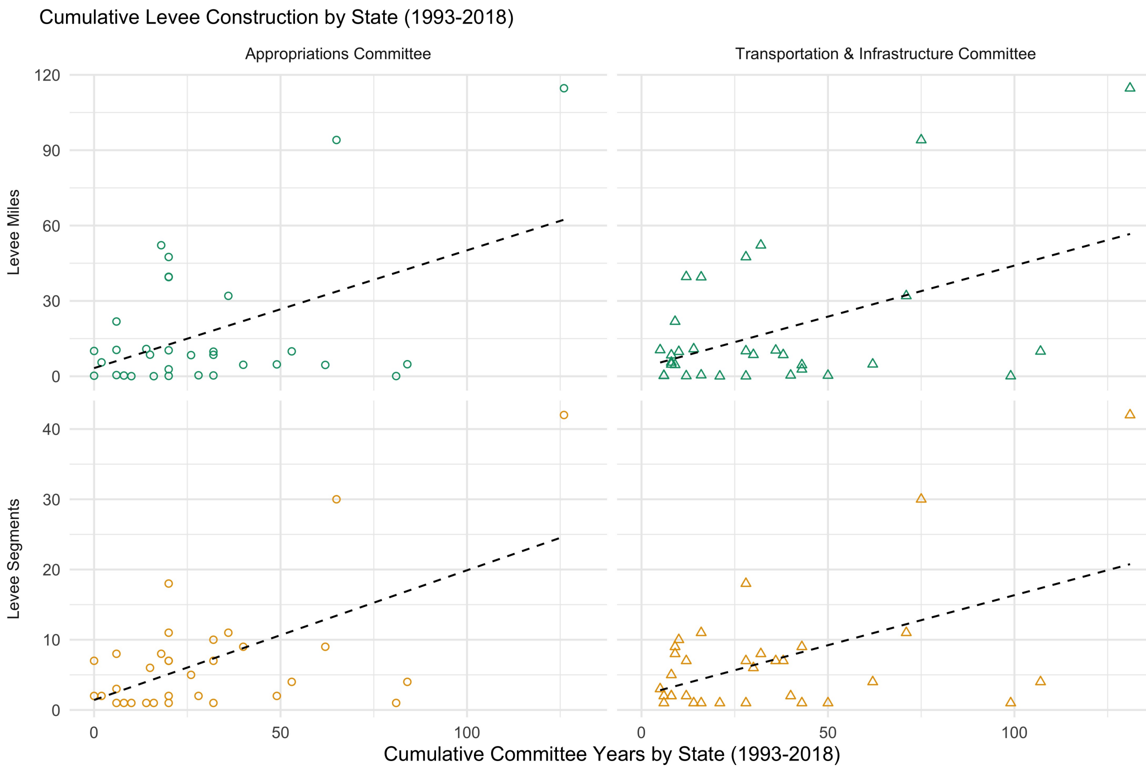
Note: This figure shows the estimated event study coefficients for protection and spillover effects. We estimate equation (5) replacing the post-treatment indicator T_{it} with event-time indicators for years relative to levee construction. Transactions are assigned to 1-year event time bins and coefficients for the year prior to construction ($\tau = -1$) are normalized to zero. Each regression includes parcel, year-by-month, and levee segment-by-year fixed effects. Standard errors are clustered at the census tract level.

Figure E5. Present discounted value of maximum coverage NFIP premiums for levee protected homes.



Note: This figure plots the distribution of National Flood Insurance Program (NFIP) premiums as a share of a home's sale price for all transactions of levee protected homes in our estimation sample between 2009 and 2020. This exercise assumes that levee protected homes pay area average SFHA coverage costs. For each levee protected home sale in this period, we assume that the household takes up the maximum allowable coverage of flood insurance under the NFIP and discount the stream of annual insurance premiums in perpetuity using a 4.09% annual discount rate, which corresponds to the average interest rate on a 30-year fixed rate mortgage for 2009-2020 according to Freddie Mac (retrieved from https://www.freddiemac.com/pmms/pmms_archives on 10/11/2024). We use policy-level observations of NFIP premiums for 2009-2020 to estimate the average premium per dollar of coverage for each census tract-year of this period and assume all protected households take-up insurance under the NFIP in perpetuity at a coverage level equal to the lower of the value of their home or the $250,000 building (plus $100,000 contents) NFIP coverage limit. This figure explores the potential for re-mapping out of Special Flood Hazard Areas (SFHAs) following levee construction to drive our main protection benefit estimates. Re-mapping out of SFHAs entails lower NFIP premiums and a removal of the mandatory flood insurance purchase requirement for homes with mortgages from federally-backed lenders. For this re-mapping to drive our results, the difference in the present discounted value of insurance premiums before and after levee construction would have to equal our estimate of the protection benefit. While on average the present discounted value of premiums as a share of home value is similar in magnitude to our main estimates, the assumptions of full take-up and complete coverage are strong and often not observed in practice.

Figure E6. Congressional Committee Membership and USACE Levee Construction, 1993-2018.



Note: 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 E1. Robustness of Spillover Exposure Definition

Spillover Exposure Defined by:	Proximity to Water			Floodplain
	(1)	(2)	(3)	(4)
Post × Intersects	0.029	0.028	0.027	0.028
	(0.009)	(0.009)	(0.009)	(0.009)
Post x k mi. of Water	−0.013	−0.011	−0.008	
	(0.007)	(0.005)	(0.005)	
Post × Floodplain				−0.013
				(0.009)
$k \leq$	0.1 mi.	0.2 mi.	0.3 mi.	—
Parcel FE	Yes	Yes	Yes	Yes
Sale Year-Levee Segment FE	Yes	Yes	Yes	Yes
Sale Year-Sale Month FE	Yes	Yes	Yes	Yes
Observations	1,244,323	1,244,323	1,244,323	1,244,308
R^2	0.948	0.948	0.948	0.948

The dependent variable is the log of real sale price. The table compares our main estimates of the spillover effects of levee construction with those using an alternative definition of spillover exposure based on whether a house fall outside of a levee protected area, but inside a FEMA-defined floodplain. The "Floodplain" variable is an indicator of whether a parcel falls within a FEMA-mapped 100-year floodplain and is outside of a levee protected area. 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 3 for a discussion). Standard errors, clustered at the census tract level, are reported in parentheses.

Table E2. Robustness of Log Sale Price on Spatial Treatment Indicators to Income-Weighting and Alternative Fixed Effects

Panel A: Income-weighted Results

	$k \leq 0.1$ mi.		$k \leq 0.2$ mi.		$k \leq 0.3$ mi.	
	(1)	(2)	(3)	(4)	(5)	(6)
Post x Intersects	0.029	0.039	0.028	0.038	0.027	0.038
	(0.009)	(0.007)	(0.009)	(0.007)	(0.009)	(0.007)
Post x k mi. of Water	−0.013	−0.016	−0.011	−0.011	−0.008	−0.009
	(0.007)	(0.007)	(0.005)	(0.005)	(0.005)	(0.004)
Parcel FE	Yes	Yes	Yes	Yes	Yes	Yes
Sale Year-Levee Segment FE	Yes	Yes	Yes	Yes	Yes	Yes
Sale Year-Sale Month	Yes	Yes	Yes	Yes	Yes	Yes
Weights	None	Income	None	Income	None	Income
Observations	1,244,323	646,825	1,244,323	646,825	1,244,323	646,825
R^2	0.948	0.987	0.948	0.987	0.948	0.987

Panel B: System-by-Year Fixed Effect

	$k \leq 0.1$ mi.		$k \leq 0.2$ mi.		$k \leq 0.3$ mi.	
	(1)	(2)	(3)	(4)	(5)	(6)
Post x Intersects	0.054	0.029	0.053	0.028	0.053	0.027
	(0.011)	(0.009)	(0.011)	(0.009)	(0.011)	(0.009)
Post x k mi. of Water	−0.012	−0.013	−0.009	−0.011	−0.006	−0.008
	(0.007)	(0.007)	(0.005)	(0.005)	(0.005)	(0.005)
Parcel FE	Yes	Yes	Yes	Yes	Yes	Yes
Sale Year-Sale Month	Yes	Yes	Yes	Yes	Yes	Yes
Sale Year-Levee System FE	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	0.948	0.948	0.948	0.948	0.948	0.948

Two sets of robustness checks of the primary capitalization results reported in Table 1. Panel A compares the set of preferred estimates with analogous estimates using weighted least squares, with transaction weights determined by purchaser income. The differing sample sizes are driven by the fact that the weighted results rely on the matched ZTRAX-HMDA subsample. Panel B compares the set of preferred estimates with analogous estimates replacing the preferred levee segment-by-year fixed effect with a levee system-by-year fixed effect. Note that levee systems often include multiple levee segments, each of which can be constructed in different years. Each panel reports the main estimates from Table 1 in the odd numbered columns. Standard errors, clustered at the census tract level, are reported in parentheses.

Table E3. Robustness of Log Sale Price on Spatial Treatment Indicators to Different Sample Restrictions

	(1)	(2)	(3)	(4)	(5)
Post x Intersects	0.028	0.023	0.033	0.022	0.024
	(0.009)	(0.008)	(0.011)	(0.010)	(0.010)
Post x 0.2 mi. of Water	−0.011	−0.012	−0.012	−0.003	0.0009
	(0.005)	(0.005)	(0.005)	(0.007)	(0.010)
Parcel FE	Yes	Yes	Yes	Yes	Yes
Sale Year-Levee Segment FE	Yes	Yes	Yes	Yes	Yes
Sale Year-Sale Month	Yes	Yes	Yes	Yes	Yes
Donut BW (mi)	0.1	0.0	0.2	0.1	0.1
Control/Spillover BW (mi)	5.0	5.0	5.0	2.0	1.0
Observations	1,244,323	1,279,984	1,208,892	521,695	310,298
R^2	0.948	0.948	0.948	0.950	0.950

Robustness check of the primary capitalization results reported in Table 1 to alternative sample restrictions. Column 1 reports the preferred specification from the text. Columns 2 through 5 separately vary the size of the two spatial bandwidths used to restrict the main estimation sample. In particular, columns 2 and 3 test alternative definitions of the "donut design" sample restriction, which drops transactions of parcels within a specified distance on either side of levee protected area boundaries. Columns 4 and 5 test alternative restrictions of the pool of potential control and spillover-exposed parcels based as falling within a certain distance outside of leveed area boundaries. Standard errors, clustered at the census tract level, are reported in parentheses.

Table E4. New Construction Probability on Spatial Treatment Indicators

	Pr(New Construction)		
	(1)	(2)	(3)
Post x Intersects	0.002	0.002	0.002
	(0.002)	(0.002)	(0.002)
Post x k mi. of Water	6.17×10^{-5}	5.75×10^{-5}	0.0001
	(0.002)	(0.001)	(0.0010)
Parcel FE	Yes	Yes	Yes
Year-Levee System FE	Yes	Yes	Yes
$k \leq$	0.1 mi.	0.2 mi.	0.3 mi.
Dependent variable mean	0.010	0.010	0.010
Observations	60,812,356	60,812,356	60,812,356
R^2	0.053	0.053	0.053

The dependent variable is an indicator variable of whether a parcel experiences new construction of a primary structure in a given year. Data include a panel of all parcels in the ZTRAX tax assessment database that either fall within leveed areas or are located within 5 miles of a leveed area boundary and for which we observe data on renovations. To ease the computational burden, we subset the parcel-year panel data to observations 5 years pre- and 5 years post-levee construction. Cluster robust standard errors are reported in parentheses.

Table E5. Renovation Probability on Spatial Treatment Indicators

	Pr(Remodel)		
	(1)	(2)	(3)
Post x Intersects	−0.002	−0.002	−0.002
	(0.002)	(0.002)	(0.002)
Post x k mi. of Water	−0.0008	−0.001	−0.001
	(0.0003)	(0.0005)	(0.0006)
Parcel FE	Yes	Yes	Yes
Year-Levee System FE	Yes	Yes	Yes
$k \leq$	0.1 mi.	0.2 mi.	0.3 mi.
Dependent variable mean	0.005	0.005	0.005
Observations	44,387,585	44,387,585	44,387,585
R^2	0.093	0.093	0.093

The dependent variable is an indicator variable of whether a parcel experiences a renovation or remodel in a given year. Data include a panel of all parcels in the ZTRAX tax assessment database that either fall within leveed areas or are located within 5 miles of a leveed area boundary and for which we observe data on renovations. To ease the computational burden, we subset the parcel-year panel data to observations 5 years pre- and 5 years post-levee construction. Cluster robust standard errors are reported in parentheses.

Table E6. Differential Capitalization of Protection Benefits for FEMA-accredited Levees

	$k \leq 0.1$ mi. (1)	$k \leq 0.2$ mi. (2)	$k \leq 0.3$ mi. (3)
Post $\times$ k mi. of Water	-0.013	-0.012	-0.009
	(0.007)	(0.005)	(0.005)
Post $\times$ Intersects	-0.005	-0.007	-0.008
	(0.019)	(0.019)	(0.019)
Post $\times$ Intersects $\times$ FEMA-accredited	0.052	0.053	0.053
	(0.021)	(0.021)	(0.021)
Parcel FE	Yes	Yes	Yes
Sale Year-Levee Segment FE	Yes	Yes	Yes
Sale Year-Sale Month FE	Yes	Yes	Yes
Observations	1,244,323	1,244,323	1,244,323
R^2	0.948	0.948	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 3 for a discussion). We report estimates of Equation 5 that include an additional interaction with a FEMA accreditation indicator and using different waterbody bandwidths, k, that define spillover exposed parcels, namely 0.1, 0.2, and 0.3 mi from the nearest waterbody. The FEMA-accredited term is a binary indicator of whether a levee segment meets certain safety and protection benefit requirements established by FEMA. Parcels protected by FEMA-accredited levees are eligible for re-mapping out of FEMA's Special Flood Hazard Areas (SFHAs), which entails lower National Flood Insurance Program (NFIP) premiums and a removal of the mandatory flood insurance purchase requirement for homes with mortgages from federally-backed lenders. Standard errors, clustered at the census tract level, are reported in parentheses.

Table E7. Share of Spillover-exposed Parcels Falling within a Congressional District (CD) as a Function of Cumulative House Appropriations Committee Membership

	% Spillovers within CD (1)
Appropriations Committee Membership: CD	-0.037
	(0.007)
Appropriations Committee Membership: State Delegation	-0.017
	(0.001)
asinh(Protected Parcels in CD)	0.041
	(0.003)
Dependent Variable Mean	0.549
Mean Appropriations Committee Membership: CD	0.965
Mean Appropriations Committee Membership: State Delegation	6.66
Congress FE	Yes
Observations	713
R^2	0.238

The dependent variable is a measure of spillover internalization for all Congressional districts (CDs) whose boundaries intersect a treatment area for the 80 levee systems in our final estimation sample. The measure is defined as the share of spillover-exposed parcels for a given levee system that fall within a given Congressional district boundary. Observations are at the Congressional district-levee system-Congress-level. To account for variation in Congressional district boundaries over time, we use historical data on district boundaries from the 103rd to 115th Congresses (1993-2018) from Lewis et al. (2013). We combine these district boundary data with data on Representative-level committee membership for the 103rd to 115th Congresses from Grossmann, Lucas and Yoel (2024), which allows us to create measures of cumulative representation on the House Appropriations Committee at the Congressional district and state level. We control for the number of protected parcels falling within a district and include Congress fixed effects. We restrict data to those Congresses for which we have boundary and membership data prior to the Congress in which levee construction was completed. Standard errors are reported in parentheses.

Table E8. Effects of Levee Construction on Census Tract NFIP Outcomes

	$k \leq 0.1$ mi.			$k \leq 0.2$ mi.			$k \leq 0.3$ mi.		
	Take-up	\$/Claim	Avg. Premium	Take-up	\$/Claim	Avg. Premium	Take-up	\$/Claim	Avg. Premium
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Post × Intersects	−0.03	−518.3	75.0	−0.03	−269.9	77.8	−0.03	−283.2	78.4
	(0.009)	(4,120.9)	(65.2)	(0.009)	(3,680.2)	(65.7)	(0.009)	(3,675.6)	(65.8)
Post x k mi. of Water	0.006	6,581.3	18.4	0.001	5,478.6	24.3	0.005	5,414.9	26.2
	(0.007)	(3,315.2)	(17.4)	(0.008)	(3,181.0)	(17.7)	(0.009)	(3,216.0)	(17.6)
Sale Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Tract FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Levee Project FE-Sale Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	19,284	1,374	17,210	19,284	1,374	17,210	19,284	1,374	17,210
R^2	0.9	0.9	0.8	0.9	0.9	0.8	0.9	0.9	0.8

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 average claim value conditional on experiencing at least one claim, and the average NFIP premium amount. 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. Note that we restrict our analysis to the period 2009-2020 due to data NFIP data limitations. 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. In cases where tracts intersect multiple levees with different construction dates, we assign treatment at the tract-level using the earliest date of possible treatment. We then estimate the following on a balanced panel at the census tract-by-year level:

$$Y_{ct} = \beta_1(T_{ct} \times L_c) + \beta_2(T_{ct} \times W_c) + \xi_c + \mu_{l(c)t} + \delta_t + \epsilon_{ct}$$

where Y_{ct} is one of the three NFIP outcomes; T_{ct}, L_c, and W_c are as defined in Equation 5, now at the census tract, c, level; and ξ_c, $\mu_{l(c)t}$, and δ_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.

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