CESifo WORKING PAPERS

10243
2023

January 2023

Efficient Adaptation to Flood Risk

Winston P. Hovekamp, Katherine R. H. Wagner

CESifo

Impressum:

CESifo Working Papers
ISSN 2364-1428 (electronic version)
Publisher and distributor: Munich Society for the Promotion of Economic Research - CESifo GmbH
The international platform of Ludwigs-Maximilians University's Center for Economic Studies and the ifo Institute
Poschingerstr. 5, 81679 Munich, Germany
Telephone +49 (0)89 2180-2740, Telefax +49 (0)89 2180-17845, email office@cesifo.de
Editor: Clemens Fuest
https://www.cesifo.org/en/wp

CESifo *Working Paper No. 10243*

Efficient Adaptation to Flood Risk

Abstract

This paper studies whether private adaptation to flood risk is economically efficient. We estimate the return to elevating houses, one of the most significant private defensive investments against flooding, using two decades of microdata on the universe of houses and flood damages in high-risk flood zones in the Atlantic and Gulf Coast United States. We find that undertaking adaptation is socially optimal in the highest risk areas over a house's lifetime, but that individual homeowners may under-invest in flood protection because the benefits do not accrue over their average tenure. We identify conditions under which adaptation yields the highest returns.

JEL-Codes: H540, Q540, Q580.

Winston P. Hovekamp
Yale University / New Haven / CT / USA
winston.hovekamp@yale.edu

Katherine R. H. Wagner
University of Berkeley / CA / USA
katherine.wagner@berkeley.edu

January 12, 2023
We thank Jason Abaluck, Patrick Baylis, Matthew Gibson, Matthew Kotchen, Kendra Marcoux, and Cormac O'Dea for helpful comments and the Cowles Foundation for funding.

Today, there are over 15 million houses and businesses with a combined valuation of over $5 trillion in high-risk flood zones in the United States (Wing et al., 2018). The floods that put these houses at risk are the costliest natural disasters in the U.S., and their costs are rising: two-thirds of this century's hurricane damage has occurred in the last two decades. The pace of destruction is accelerating due to increasingly severe storms, but also increasing population and development in harm's way. The federal government's current approach to reducing the vulnerability of coastal properties has been to "armor the coast" by elevating houses, building sea walls, widening beaches, and funding other forms of expensive in-place adaptation to flood risk (Gaul, 2019).

In this paper, we ask whether it is economically efficient to invest in adaptation of these properties in high-risk flood zones. We estimate the return to adaptation policy that requires houses built in high-risk flood zones to comply with minimum elevation standards for their foundations. The U.S. Federal Emergency Management Agency (FEMA) mandates that all new structures in high-risk flood-zones comply with these construction codes as a condition of accessing publicly provided flood insurance. The agency also provides up to $30,000 in subsidies to flooded houses to defray the costs of rebuilding in compliance with these standards, and currently proposed legislation would raise the available subsidy to $100,000 (Rice, 2022). Despite the emphasis that policymakers place on this type of adaptation in reducing future flood costs, there is limited evidence on whether the reductions in flood damages exceed the substantial costs of retrofitting houses, or exceed even the more modest cost of elevating houses during construction. We study this question using two decades of microdata on the universe of flood insurance policies in the Atlantic and Gulf Coast U.S., where 83% of national flood insurance contracts are written (NRC, 2015).

Our research design uses fixed effects panel regressions to compare flood insurance claims for similar houses built in the same zip code, flood zone, and decade that experience floods of the same severity, some of which are required to be elevated and some of which are not. We exploit the staggered roll-out of construction codes between 1968 and today that mandate minimum elevation standards for new construction in high-risk flood zones.

Our estimates suggest that adaptation plays an important role in reducing damages from floods, especially in areas with little other development. Minimum elevation requirements reduce flood insurance claims by about 30% on average. In the riskiest areas, this expected reduction in damages over a house's lifetime is sufficiently high to justify the upfront investment costs of complying with FEMA's elevation mandate for newly constructed homes. However, the expected reduction in damages over the average duration of homeownership does not exceed the additional construction costs. As a result, homeowners seem likely to under-invest in adaptation, because the expected benefits from elevation are also not capitalized into houses' resale value (Ostriker and Russo, 2022). Since the cost of retrofitting existing homes is generally substantially higher than the cost of elevating a home during the course of construction, such *ex post* elevation doesn't look efficient even for most homeowners at the highest risk for hurricanes and floods.

This paper contributes to two main literatures. The first is a literature on the effects of construction codes on natural disaster damages. Our contribution is to quantify the wedge between public and private benefits of adaptation that arises due to differences in planning horizons. This wedge leads to divergent adaptation investment decisions between households and a social planner. These results complement other research on the social cost-effectiveness of wildfire resilience codes (Baylis and Boomhower, 2022), the welfare effects of flood zone regulation policies (Mulder, 2022; Ostriker and Russo, 2022), and the average flood damage reduction from minimum elevation requirements (Wagner, 2022). Related papers study the effects of building codes on energy use (Jacobsen and Kotchen, 2013). This paper also extends an engineering literature modeling the benefits of construction codes using simulations (NIBS, 2018).

The second related literature studies the benefits of adaptation to climate change more generally. A large literature quantifies the benefits of adapting to rising temperatures (Barreca et al., 2016), water scarcity (Burlig et al., 2021), sea level rise (Balboni, 2021), and other climate change effects. We extend this literature by providing new estimates of the extent to which the benefits of adapting to flood risk vary with features of the natural and built environment over a broad geography. We turn now to discuss our empirical setting, data and research design, and policy implications of our results.

1 Background on Flood Insurance and Adaptation

The NFIP is the primary provider of flood insurance in the United States. The program's dual objectives are to provide access to flood insurance for at-risk properties and to regulate development in the riskiest areas. The program, which is managed by FEMA, currently underwrites over \$1.3 trillion of flood insurance coverage on over 5 million insurance contracts. Despite annual premium revenue in excess of \$4.6 billion, cumulative claims have left the NFIP with a \$20 billion debt to the U.S. Treasury (Horn and Webel, 2022).

In exchange for access to insurance provided by the NFIP, participating communities are required to adopt minimum elevation standards for the foundations of houses built or substantially improved in high-risk flood zones (Gaul, 2019).[1] The NFIP rolled out these requirements as they gradually mapped communities between the program's start in 1968 and today. Houses built in high-risk flood zones before communities were mapped are not required to comply with any height requirement, but failure to enact them for new construction can result in the suspension of flood insurance in the community (Horn and Webel, 2022).[2] These minimum standards are based on the height of the flood that has a 1% chance of occurring in a community in any given year.

Elevating a house after it has been built is much more expensive than making the same investment when the house is initially constructed. Retrofitting an existing house can cost substantially more than the conservative estimate of $40,000 that we use to assess the efficiency of this adaptation policy, while the engineering literature generally agrees that initially elevating a house costs a few thousand dollars (Durante, 2022; Hurley, 2017). FEMA provides adaptation subsidies of up to $30,000 to defray some of these elevation costs if flood damages exceed 50% of a house's pre-flood market value, but in practice very few homeowners elevate their houses *ex post*, even after repeated flood exposure.

2 Data

This section discusses the data on flood insurance contracts, housing, and natural and built flood defenses. Additional details are in Appendix A.

Flood insurance and flood risk—We obtained contract-level administrative data on flood insurance policies and claims through Freedom of Information Act (FOIA) requests from

---

[1] NFIP communities are roughly equivalent to American metropolitan statistical areas.

[2] Existing construction is also grandfathered into flood insurance premiums that are subsidized relative to actuarially fair levels. See Wagner (2022) for additional details on flood insurance premium structure.

FEMA. The data comprise the universe of flood insurance contracts in-force from 2001 to 2017, for the 20 Atlantic and Gulf Coast U.S. states shown in Appendix Figure A.1. Key to our analysis is that we also observe whether a house is required to be comply with minimum elevation requirements based on its date of construction. Other important variables are floodwater depth, flood zone, and claim and damage amounts, which are generally equivalent. We deflate all monetary variables to 2017 dollars using the consumer price index for housing.

We restrict the full data set to policies and claims written for single-family primary residences in high-risk flood zones. We do so because these houses have variation in elevation requirements that low-risk houses and other types of dwellings do not. Other data cleaning details are described in Appendix A and closely follow Wagner (2022).

Land Use—Data on wetlands extent and impervious surfaces are from Taylor and Druckenmiller (2022). The data include the share of each zip code that is covered by wetlands and the share that is developed, which allows us to analyze how average flood risk varies with these geographic characteristics. These data are based on the National Land Cover Database, a gridded remote sensing land cover product that covers the entire country.

3 Econometric Model

Our goal is to estimate the extent to which the requirement to elevate houses affects flood damages. We estimate the following regression equation:

$$y_{it} = \beta 1[adapted_i] + \theta 1[adapted_i] \times 1[t \geq 2013] + \lambda_{zt} + \nu_{zdf} + \tau_{fdt} + \epsilon_{it} \tag{1}$$

In this equation, y_{it} is a cost outcome (i.e., payout per \$1000 coverage or an indicator for making a claim) for house i in year t. The variable $1[adapted_i]$ takes the value 1 if a house is required to be elevated. The variable $1[t \geq 2013]$ takes the value 1 if an observation is from after 2012; when interacted with the adaptation indicator, it controls for the fact that flood insurance premiums changed for adapted houses after 2012.[3] Zip code × year fixed effects λ_{zt} control for differences in how badly each zip code is flooded in each year. Decade built × flood severity time trends τ_{fdt} control for differential appreciation and, by extension, payouts for houses that are and are not flooded. Zip code × decade built × flood severity fixed effects ν_{zdf} control for determinants of the flood insurance rate schedule (i.e., house vintage and local flood zone). Finally, ϵ_{it} is the error term. We cluster standard errors at the NFIP community level throughout.

The main parameter of interest is β, which measures the effect of the adaptation policy on flood damages, conditional on the variables in the model; if the adaptation policy reduces damages to the average home, β will be negative. The inclusion of the fixed effects means that the identifying variation comes from comparing claims for houses that are built in the same decade and zip code and which experience floods of the same severity, but face different elevation requirements. Controlling for flood severity is important because flood damages are highly variable across years; in some years, no flood occurs, and so the difference in costs between adapted and non-adapted houses is mechanically equal to zero, while in some catastrophic loss years adaptation matters a lot, as we will show. This high cost variability is a distinguishing feature of natural disaster insurance markets.[4]

We are also interested in how the effect of adaptation varies depending on the severity of the flood event and on features of the natural and built environment where the house

---

[3] Wagner (2022) finds no evidence that premiums affect costs in this market.

[4] Appendix A discusses the construction of our flood severity measures in greater detail.

is located. To this end, we separately estimate equation (1) for zip codes that experience no floods, minor "nuisance" floods, and FEMA-designated catastrophes. We also allow the effect of adaptation to differ depending on the extent to which the zip code is characterized by wetlands or development:

$$y_{it} = \beta_0 1[adapted_i] + \beta_1 1[adapted_i] \times 1[envr_z] + \theta 1[adapted_i] \times 1[t \geq 2013] + \lambda_{zt} + \nu_{zdf} + \tau_{fdt} + \epsilon_{it}$$

In this equation, $1[envr_z]$ is an indicator variable equal to 1 if the share of the zip code covered by infrastructure or dwellings is above the median. We also separately consider the effects of above median wetlands coverage in a parallel way. The parameter β_1 measures the differential effect of these environmental features on flood insurance claims. In Appendix Table A.1, we also explore a continuous measure of development and wetlands coverage.

4 Results

First, we find that adaptation reduces damages: houses that are required to be elevated have 30% lower damages than non-elevated houses (Table 1). These savings are comparable to the 40% reduction in the probability of house destruction from wildfire resulting from fire-specific building codes, but about one-third of the magnitude of the damage reduction provided by one hectare of wetlands, which protect many houses (Baylis and Boomhower, 2022; Taylor and Druckenmiller, 2022).[5] This percentage reduction from the elevation standards is similar in both nuisance floods and catastrophes, though the dollar value of the reduction in damages is higher in the more costly catastrophes (Table 2).[6] In Appendix Table A.2, we also show the reduction in damages from the adaptation policy varies even within the set of catastrophic

---

[5] Ostriker and Russo (2022) find that total flood damages fall by a further 15% due to the reallocation of construction outside the floodplain.

[6] When no flood occurs, the effect of adaptation is mechanically equal to zero (Table 2, Cols 1 and 2).

floods; adaptation policy reduced claims amounts by roughly three times as much during Hurricane Katrina as during Hurricane Sandy, for example. Overall, the return to elevating houses varies substantially depending on a property's flood risk.

This heterogeneity in returns to private adaptation investment also depends on the presence of other adaptive investments or structures. In Table 2, we show that the benefits of adaptation are lower in highly developed areas; the positive coefficient on the interaction between adapted houses and the high developed indicator suggests that the reduction in damages from adaptation is smaller in more developed areas. Highly urbanized areas are more likely to have undertaken additional defensive investments against flooding (e.g., building sea walls) to protect the greater number of people who live there. Conversely, the negative coefficient on the indicator for high wetland coverage pushes in the direction of increasing the difference between adapted and non-adapted houses. One implication is that there is scope to target FEMA's adaptation subsidies to areas that are less protected.

Despite the benefits from adaptation policy, our results suggest that homeowners may under-invest in private defenses against floods. Table 3 shows that the costs of elevating a house, both at the time of construction or afterward, exceed the benefits over the average period of homeownership (i.e., 16 years). However, for the riskiest areas, the benefits of elevating houses at the time of construction exceeds the cost by a factor of 2 over the lifetime of the house.[7] For areas at risk of catastrophic flooding, upfront investment in adaptation is efficient, but the benefits are not recouped by homeowners because their investment is not capitalized into house prices (Ostriker and Russo, 2022). Elevating houses *ex post* is

---

[7] Expected damage savings from Col 2 are approximately \$9,000 over 80 years assuming a 4% discount rate, while the *ex ante* elevation cost is a one-time upfront investment of \$5,000. These estimates are a lower bound on the value of adaptation if homeowners are risk-averse, rather than risk neutral.

significantly more costly and may only be efficient for a small share of the highest-risk houses. The slow turnover of the housing stock may therefore limit the rate at which in-place adaptation can cost-effectively reduce flood damages.

5 Discussion and Conclusion

We identify a wedge between the social and private returns to adaptation policy: if the additional cost of elevating a house in a high-risk flood zone isn't capitalized into its resale price, homeowners may under-invest in adaptation because the social cost savings that accrue over the house's lifetime exceed the expected private cost savings over the homeowner's tenure. The wedge between the perceived private benefits and the social value of adaptation is exacerbated by any undervaluation of flood protection while living on the coast, and the full benefits of adaptation also aren't internalized by homeowners purchasing better-than-actuarially fair, public flood insurance (Bakkensen and Barrage, 2021; Wagner, 2022). These results suggest that FEMA's current mandate for new construction to meet minimum elevation standards encourages efficient outcomes in areas at high risk of catastrophic flooding.

We note in conclusion that our estimates of the benefits of adaptation policy are based on historical flood insurance data. Given the current increasing trend in flood costs, coastal homeowners may come to further appreciate the additional protection afford by mandatory adaptation requirements in the future. Indeed, the high costs of retrofitting existing construction suggest that elevation mandates should consider how flood risk will change over the lifetime of regulated structures. In the long run, however, the costs of "armoring the coasts" by investing in increasingly extensive in-place adaptation may exceed the cost of relocating people and property further out of harm's way.

References

Bakkensen, L. and Barrage, L. (2021). Flood risk belief heterogeneity and coastal home price dynamics: Going under water? Working paper.

Balboni, C. (2021). In harm's way? infrastructure investments and the persistence of coastal cities. Working Paper.

Barreca, A., Clay, K., Deschenes, O., Greenstone, M., and Shapiro, J. S. (2016). Adapting to climate change: The remarkable decline in the us temperature-mortality relationship over the twentieth century. *Journal of Political Economy*, 1(124):105–159.

Baylis, P. W. and Boomhower, J. (2022). Mandated vs. voluntary adaptation to natural disasters: The case of u.s. wildfires. NBER Working Paper 29621.

Burlig, F., Preonas, L., and Woerman, M. (2021). Energy, groundwater, and crop choice. Working Paper.

Durante, N. (2022). What is the cost to raise a house above the flood zone? Technical report, Upgraded Home.

FEMA (2011). Answers to questions about the nfip: Report fema f-084. Technical report, Federal Emergency Management Agency.

Gaul, G. M. (2019). *The Geography of Risk: Epic Storms, Rising Seas, and the Cost of America's Coasts*. Sarah Crichton Books.

Horn, D. P. and Webel, B. (2022). Private flood insurance and the national flood insurance program. Technical report, Congressional Research Service, R44593.

Hurley, A. (2017). The house of the future is elevated. Technical report, CityLab Design.

Jacobsen, G. D. and Kotchen, M. J. (2013). Are building codes effective at saving energy? evidence from residential billing data in florida. *Review of Economics and Statistics*, 95(1):34–49.

Mulder, P. (2022). Mismeasuring risk: The welfare effects of flood risk information. Working Paper.

NIBS (2018). National hazard mitigation: 2018 interim report. Technical report, National Institute of Building Sciences.

NRC (2014). *Reducing Coastal Risk on the East and Gulf Coasts*. Washington, DC: The National Academies Press.

NRC (2015). Affordability of national flood insurance program premiums, report 1. Technical report, National Research Council.

Ostriker, A. and Russo, A. (2022). The effects of floodplain regulation on housing markets. Working paper.

Rice, T. (2022). Rice introduces bipartisan bill to increase funding for flood victims. Technical report, 7th District of South Carolina.

Taylor, C. A. and Druckenmiller, H. (2022). Wetlands, flooding, and the clean water act. *American Economic Review*, 112(4):1334–1363.

Wagner, K. R. H. (2022). Adaptation and adverse selection in markets for natural disaster insurance. *American Economic Journal: Economic Policy*, 14(3):380–421.

Wing, O. E. J., Bates, P. D., Smith, A. M., Sampson, C. C., Johnson, K. A., Fargione, J., and Morefield, P. (2018). Estimates of present and future flood risk in the conterminous united states. *Environmental Research Letters*, (13):1–7.

Figures and Tables

Table 1: Effects of Adaptation Policy on Flood Damages

	Average Cost (1)	Any Claim (2)
Adapted	-2.211***	-0.004***
	(0.470)	(0.001)
Dep. Var. Mean	8.196	0.023
N	11,983,183	
Zip code × Year FE	✓	✓
Decade Built × Flood Severity Controls	✓	✓

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Notes: Outcome variables are average flood insurance cost (payouts per $1000 coverage) and an indicator variable equal to one if a claim is made. Adapted houses are built after communities are mapped and are required to be elevated. The dependent variable mean is for non-adapted houses. Decade built × flood severity controls are zip code × decade built × flood severity fixed effects and decade built × flood severity time trends. Flood severity is defined using flood water depth and flood event type (see text). Standard errors clustered by community are in parentheses.

Table 2: Heterogeneous Effects of Adaptation Policy on Flood Damages

	No Flood		Flood		Catastrophe	
	Average Cost (1)	Any Claim (2)	Average Cost (3)	Any Claim (4)	Average Cost (5)	Any Claim (6)
Panel A: Average Effect						
Adapted	0.000	0.000	-0.276***	-0.002***	-10.038***	-0.017***
	(0.000)	(0.000)	(0.070)	(0.001)	(1.686)	(0.002)
Panel B: Wetlands Heterogeneity						
Adapted	0.000	0.000	-0.253***	-0.0013***	-8.291***	-0.013***
	(0.000)	(0.000)	(0.076)	(0.0003)	(2.104)	(0.003)
Adapted × 1[High Wetlands]	0.000	0.000	-0.052	-0.0006	-3.650	-0.008
	(0.000)	(0.000)	(0.075)	(0.0004)	(2.322)	(0.004)
Panel C: Developed Heterogeneity						
Adapted	0.000	0.000	-0.505***	-0.003***	-13.088***	-0.023***
	(0.000)	(0.000)	(0.118)	(0.001)	(2.258)	(0.002)
Adapted × 1[High Development]	0.000	0.000	0.374***	0.002***	5.093**	0.010**
	(0.000)	(0.000)	(0.112)	(0.001)	(2.388)	(0.004)
Dep. Var. Mean	0.000	0.000	0.952	0.006	38.512	0.103
N	5,793,255		3,808,697		2,381,231	
Zip code × Year FE	✓	✓	✓	✓	✓	✓
Decade Built × Flood Severity Controls	✓	✓	✓	✓	✓	✓

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Notes: Outcome variables are average flood insurance cost (payouts per $1000 coverage) and an indicator variable equal to one if a claim is made. Adapted houses are built after communities are mapped and are required to be elevated. 1[High Wetlands] is an indicator variable equal to 1 if a zipcode has above median wetland coverage, while 1[High Development] is an indicator variable equal to 1 if a zipcode has above median development. The dependent variable mean is for non-adapted houses. Decade built × flood severity controls are zip code × decade built × flood severity fixed effects and decade built × flood severity time trends. Flood severity is defined using flood water depth and flood event type (see text). Standard errors clustered by community are in parentheses.

Table 3: Benefits and Costs of House Elevation Over Average Homeownership Period

	Estimated Damage Savings		Ex Ante Elevation Cost		Ex Post Elevation Cost	
	% of Total Damages (1)	Dollars (2)	% of Total Damages (3)	Dollars (4)	% of Total Damages (5)	Dollars (6)
Average	0.36	529.54	3.41	5,000.00	27.29	40,000.00
No Flood	-	0.000	-	5,000.00	-	40,000.00
Flood	0.48	60.40	35.98	5,000.0	287.83	40,000.00
Catastrophe	0.35	2,407.00	0.72	5,000	6	40,000.00

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Notes: Homeowners' average tenure is 16 years. Estimated damage savings are over the period 2001-2017 and are based on the estimates in Tables 1 and 2. Ex ante elevation refers to elevating houses when they are first constructed. Ex post elevation refers to elevating houses after they are constructed. All dollar values are in 2017 USD.

Appendix – For Online Publication

A Data

Flood Insurance Policies and Claims—The administrative records on flood insurance policies and claims are identical to the data used by Wagner (2022). We outline the restrictions imposed both here and in this other paper to arrive at the final analysis sample.

The full data set includes the universe of flood insurance policies and claims written by the NFIP between 2001 and 2017 for 20 Atlantic and Gulf Coast U.S. states. These microdata are from FEMA's BureauNet database, which the NFIP itself uses to track its internal operations. The 20 states are Alabama, Connecticut, Delaware, Florida, Georgia, Louisiana, Maine, Maryland, Massachusetts, Mississippi, New Hampshire, New Jersey, New York, North Carolina, Pennsylvania, Rhode Island, South Carolina, Texas, Vermont, and Virginia. These states together account for approximate 85% of total flood insurance policies written in the U.S. (NRC, 2015).

The main analysis focuses on approximately 12 million observations on single-family primary residences located in high-risk flood zones. Following the NFIP rating system, we consider a house to be high-risk if it is located any of A, numbered A, V, or numbered V flood zones, and low-risk otherwise. Low-risk houses are not required to be elevated and so the effect of elevation can't be assessed for this group. Damages for multi-family homes, mobile dwellings, and condominiums also are unlikely to be a comparable control group for elevated single-family residences. These other structure types also face different building code requirements, insurance prices, and take-up incentives than single family primary residences.

Evaluating the importance of house elevation necessitates matching house characteristics available in the contracts data set (e.g., differences in building codes) with the claims and damages associated with them. We therefore use information available from both data sets to match policies to claims in a manner that respects the prices and elevation differences between houses. Specifically, we match claims to policies based on policy written date, house construction year, flood zone, and zip code. These variables almost perfectly uniquely identify claims and policies and the match rate is 99%. In addition to the variables used for merging policies and claims, the data also include information on coverage, premia, and damages. Other relevant variables are premium paid, coverage purchased for building and contents, minimum elevation required, amount claimed, the NFIP community identification number, the flood identification number assigned by FEMA, and the depth of water that flooded the house.

We impose several additional restrictions on the single-family primary residence sample to arrive at the data set used in the analysis. We exclude 1% of policies that are missing flood zone or construction data since these variables are needed to identify whether houses are required to be elevated or not. We also exclude 4% of policies with coverage that is negative, equal to 0, or exceeds the maximum amount available for purchase. In addition, we exclude policies with premia smaller than the 1st and larger than 99th percentile of the distribution of values because these are clearly miscoded relative to the NFIP rate schedule, where policies are not written including e.g., total premia in excess of $60,000 per year or $16,000 per $1,000 of coverage or less than less than $0.10 per $1,000 of insurance are not written. We impose similar restrictions on the claims data, dropping the 7% of claims reporting damages or payouts that are zero or negative, or with realized payouts that exceed purchased coverage.[8]

Zip codes are a key variable on which we merge claims to policies and insurance data to features of the natural and built environment. The data for the years 2010-2017 are missing between 5 and 10% of zip codes, which were erroneously deleted when the data were anonymized. As in Wagner (2022), we recover these zip codes by building a concordance from zip code to "flood map panel identifier", which is the unit of analysis of FEMA hydrological studies and is typically fully contained within a zip code. We recover approximately 75% of missing zip codes by identifying others with the same flood map panel identifier and assigning them to the same zip code.

Flood Severity—One of the heterogeneity analyses we are interested in is the extent to which the benefits of adaptation vary with flood severity. This information is not available in the raw insurance data, and so we construct it using information on flood type and floodwater depth from the claims data.

Each claim is associated with a "flood event number" assigned by FEMA that identifies whether it was incurred during a uniquely identified presidentially declared disaster event (PDD) or during a "nuisance" flood. FEMA assigns innocuous nuisance floods an identifying number of zero, while catastrophic flooding receives a unique identifier corresponding to the disaster (e.g., Hurricane Katrina). We identify the maximum of the flood event numbers in each zip code × year to determine whether or not a catastrophic flood struck the zip code. We assign zip codes without any claims to a third, "not flooded" category.

Each claim also includes information on the depth of the water that flooded the house during the flood event. We average flood depth in each zip code-year and bin the depths into quintiles, which results in four bins since approximately 40% of zip codes are not flooded in a given year. Before doing so, we first assign water depths of 0.0001 to claims with recorded depth of zero because depths are rounded to the nearest foot and then assign depths of zero to policies without claims, to distinguish small floods from no floods. We treat the 2% of observations with negative water depths as missing and impute the depth implied by claims made by the same type of house (i.e., elevated or not) in the same flood zone in the same flood event. We follow the same imputation procedure for the 7% of claims with recorded water depths exceeding 25 feet.

We use these measures of flood severity based on event type and floodwater depth to define six monotonically increasing water depth categories. The first comprises zip codes that are not flooded (i.e., quintiles one and two). The second comprises nuisance floods in the third quintile of flood depth. The remaining four categories split the fourth and fifth quintiles of flood depths into nuisance floods and catastrophes, respectively. Wagner (2022) discusses analysis that ascertains the validity of these flood severity measures.

Land Use—The aggregation of the land use data is discussed in Taylor and Druckenmiller (2022). The data are derived from the National Land Cover Database, which provides remotely-sensed information on the spatial extent of different types of land cover for the United States at 30-m resolution. The database identifies 21 different classes of land use,

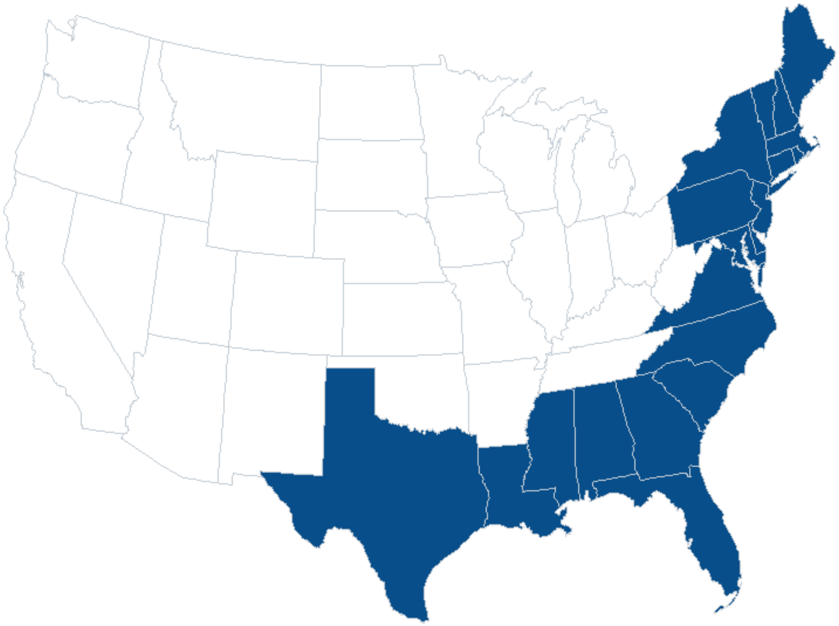
---

[8] Zero entries for damages or payouts indicate either that no payout was made or that the claim is still outstanding.

including wetlands (categories 91 and 92). The data are aggregated to the zip code level by intersecting the spatial data with zip code maps. We merge the zip code aggregates for developed share and wetlands share in 2001 (our first year of data) with the flood insurance data set.

B Figures and Tables

Figure A.1: States in Analysis



Notes: The 20 states included in the analysis are Alabama, Connecticut, Delaware, Florida, Georgia, Louisiana, Maine, Maryland, Massachusetts, Mississippi, New Hampshire, New Jersey, New York, North Carolina, Pennsylvania, Rhode Island, South Carolina, Texas, Vermont, and Virginia. These 20 states account for 83% of flood insurance policies written nationwide (NRC, 2015).

Table A.1: Heterogeneous Effects of Adaptation Policy on Flood Damages

	No Flood		Flood		Catastrophe	
	Average Cost (1)	Any Claim (2)	Average Cost (3)	Any Claim (4)	Average Cost (5)	Any Claim (6)
Panel A: Average Effect						
Adapted	0.000	0.000	-0.276***	-0.002***	-10.038***	-0.017***
	(0.000)	(0.000)	(0.070)	(0.001)	(1.686)	(0.002)
Panel B: Wetlands Heterogeneity						
Adapted	0.000	0.000	-0.250***	-0.001***	-8.662***	-0.014***
	(0.000)	(0.000)	(0.082)	(0.001)	(2.189)	(0.003)
Adapted × Wetland Fraction	0.000	0.000	-0.193	-0.003**	-4.169	-0.012
	(0.000)	(0.000)	(0.316)	(0.001)	(6.171)	(0.010)
Panel C: Developed Heterogeneity						
Adapted	0.000	0.000	-0.639***	-0.003***	-13.187***	-0.025***
	(0.000)	(0.000)	(0.139)	(0.001)	(2.497)	(0.004)
Adapted × Developed Fraction	0.000	0.000	0.770	0.003***	8.366*	0.019**
	(0.000)	(0.000)	(0.180)	(0.001)	(5.038)	(0.007)
Dep. Var. Mean	0.000	0.000	0.952	0.006	38.512	0.103
N	5,793,255		3,808,697		2,381,231	
Zip code × Year FE	✓	✓	✓	✓	✓	✓
Decade Built × Flood Severity Controls	✓	✓	✓	✓	✓	✓

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Notes: Outcome variables are average flood insurance cost (payouts per $1000 coverage) and an indicator variable equal to one if a claim is made. Adapted houses are built after communities are mapped and are required to be elevated. Wetlands fraction is the share of the zipcode covered by wetlands and developed fraction is the share of the zipcode devoted to urban infrastructure or dwellings. The dependent variable mean is for non-adapted houses. Decade built × flood severity controls are zip code × decade built × flood severity fixed effects and decade built × flood severity time trends. Flood severity is defined using flood water depth and flood event type (see text). Standard errors clustered by community are in parentheses.

Table A.2: Effects of Adaptation Policy on Flood Damages for Specific Disasters

	Hurricane Katrina		Hurricane Sandy		Hurricane Harvey	
	Average Cost (1)	Any Claim (2)	Average Cost (3)	Any Claim (4)	Average Cost (5)	Any Claim (6)
Adapted	-14.042***	-0.029***	-4.040***	-0.006***	-7.334***	-0.010***
	(3.361)	(0.009)	(0.680)	(0.001)	(1.131)	(0.002)
Dep. Var. Mean	38.870	0.069	12.293	0.041	23.278	0.059
N	103,194		451,844		709,683	
Zip code × Decade Built FE	✓	✓	✓	✓	✓	✓

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Notes: Outcome variables are average flood insurance cost (payouts per \$1000 coverage) and an indicator variable equal to one if a claim is made. Adapted houses are built after communities are mapped and are required to be elevated. The dependent variable mean is for non-adapted houses. Standard errors clustered by community are in parentheses.