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LETTER

Housing market dynamics of the post-Sandy Hudson estuary, Long Island Sound, and New Jersey coastline are explained by NFIP participation

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Abstract

How flooding affects home values can determine the path of economic recovery for communities and have lasting impacts on national and global financial systems. Yet, our understanding of how flood insurance, community risk perception, and past flooding events shape future housing prices (HPs) remains limited. To explore this, we used a socio-environmental (SE) model and studied the temporal impacts of flooding on mean housing values across 496 coastal census tracts of New York, Connecticut, and New Jersey, US, from 1970 to 2021. The modeling exercise demonstrated that the initial economic impact of Hurricane Sandy was largely absorbed by the National Flood Insurance Program (NFIP); however, the region then exhibited a long-term decline in home values, which was well described by an interrupted time series model. We found significant correlations between SE model parameters describing HP change and those describing tract-scale behaviors and perceptions, suggesting that the salience of past flooding events and NFIP participation may be important regional drivers of HPs. Tracts with greater post-flood change in active insurance policies exhibited larger decreases in mean home values than those with more stable NFIP participation. An improved understanding of relationships between HPs, flood insurance, and community perceptions could support more equitable distributions of resources and improved policy interventions to reduce flooding risk.

1. Introduction

Homeownership lies at the core of the American dream. The ability to purchase a home, and the expectation that the value of that home will grow over time, underpins the economic security and social mobility of millions of people. Homeownership is connected to ideas of citizenship and belonging (McCabe 2016, Taylor 2019). For decades, social policy has targeted the expansion of homeownership through both direct and indirect measures, making it the cornerstone of social provision in the US (Conley and Gifford 2006, Martin 2008, Quinn 2019, Kohl 2020). Homeownership is consequential not only for individual fates, but also for collective prosperity. States and municipalities often rely heavily on value-assessed property taxes in order to fund public goods like schools, libraries, fire departments, hospitals, and so forth (Martin 2019).

Climate change threatens all of this for flood exposed communities. Flooding has long been the costliest natural disaster in the US (Smith 2020). Now, across the country, both the magnitude (Hodgkins *et al* 2019) and seasonality of flooding hazards (Basu *et al* 2023) are changing. Communities with exposure to flood hazards that are increasing (e.g., low elevation areas within proximity of rising sea levels) are anticipated to experience decreases in the value of flood exposed properties, which could end catastrophically if a seller is unable to find willing buyers or to sell at a loss (Siders *et al* 2019). In 2016, Freddie Mac issued a ponderous report entitled 'Life's a Beach,' (Freddie Mac 2016) which warned that rising sea levels and expanding flood plains '*appear likely to destroy billions of dollars in property and to displace millions of people. The economic losses and social disruption may happen gradually, but they are likely to be greater in total than those experienced in the housing crisis and Great Recession.*' As the 2007–8 housing crisis laid plain, the losses may not be contained: what happens to home values can have dramatic effects on the national and global financial system (Thomson *et al* 2023). In a context where homeownership constitutes an economic, political, and cultural pillar of society, it is therefore crucial to examine how hazards interact with coastal housing markets, which are in turn shaped by risk perceptions and community responses (Keenan *et al* 2018, Keys and Mulder 2020).

There is evidence that home values are impacted by both past exposures to flooding as well as perceptions of future risk (Bin *et al* 2008, de Koning *et al* 2019). Flooding often results in an initial decrease in property values which recover across years to decades as the memories of floods held by residents fade (Atreya *et al* 2013, Bin and Landry 2013, Beltrán *et al* 2019, Chandra-Putra and Andrews 2020). Perceptions of future flood risk and access to flood insurance can have varied impacts on the value of housing markets. For example, the publication of floodplain maps which delineate risk zones, determine insurance rates, and set limitations on development, can have negative effects on property values (Elliott 2019). Increasing National Flood Insurance Program (NFIP) premiums have been negatively correlated with home values, possibly due to perceptions of increased risk (de Koning *et al* 2019, Colby and Zipp 2021). Another study suggested that positive correlations between home values and the number of active insurance policies was due to the option for homeowners to default on a mortgage (Liao and Mulder 2021). Home value therefore serves as a cap on total flood losses, possibly discouraging the purchase of insurance policies for low value properties.

Across the northeastern US, there is evidence that recent changes in coastal housing prices (HPs) have been driven more by perceptions of risk rather than actual hazard regimes (Bakkensen and Barrage 2022). Hurricane Sandy caused the highest storm surge within the period of record for several coastal tidal gauging stations (NOAA 2022b); however, sedimentary records suggest that Sandy should not be discounted as an outlier as five surges of similar magnitude have impacted the region within the past 600 years (Donnelly *et al* 2001, Brandon *et al* 2014). In the immediate aftermath of Hurricane Sandy, the prices of impacted properties initially decreased, possibly reflecting an updated objective understanding of coastal flood risk, but then showed evidence of price recovery (Ortega and Taşpınar 2018, Cohen *et al* 2021, Chun *et al* 2022, Pradhan *et al* 2023). Similarity in the post-Sandy price discounting of both flooded and non-impacted properties further suggests that perceptions of risk have shaped home value recovery (Ortega and Taşpınar 2018, Fang *et al* 2023). A successful recovery and future flood mitigation must adopt an approach that seeks to understand why home values and objective estimates of flood risk are decoupled across the region.

Conceptual and numerical socio-environmental (SE) models have helped to map relationships between flooding hazards, community perceptions of flooding, community actions taken in response to flooding (e.g., levee construction, insurance uptake), and economic losses (e.g., damage to structures and property) (Yu *et al* 2017, Taberna *et al* 2020, Bertassello *et al* 2021). However, numerical implementations of these models possibly remain overly simplistic (Baldassarre *et al* 2015, Barendrecht *et al* 2019). New approaches are required that explicitly consider the dominant causal processes defining flooding risk to support equitable flood hazard mitigation (Ranasinghe 2020, Keenan and Maxwell 2022), with particular attention to the economization of flood risk. Critically, there have been few attempts to develop SE models to capture the effects of flooding events on future HPs in years immediately following flooding events, which then support estimates of future loss and risk perception conditioned on altered mean home values.

Our study focuses on coastal communities in New Jersey, New York, and Connecticut, US that were impacted by Hurricane Sandy to understand if HP changes observed across the region could be attributed to community-scale perceptions of risk. We first estimated community perceptions of flooding with a SE model applied to 496 census tracts. Calibration of an SE model to SE datasets allows for estimation of community flood perceptions (Barendrecht *et al* 2019, Knighton *et al* 2021). The SE modeling was validated with publicly available socioeconomic datasets of population density (US census), flood insurance claims and policies (US NFIP), and HP estimates (National Historical Geographic Information System and Zillow). Next, we evaluated four competing model representations of the relationship between flooding loss, community perception, and mean house value. We then used the most representative model to test if model parameters controlling HP responses to flooding hazards were correlated with parameters controlling changes in community flood perceptions.

2. Methodology

2.1. Study region

This study centered on 496 coastal census tracts across New York, New Jersey, and Connecticut (figure 1). The average number of housing units per census tract was relatively stable with a mean of 1890 units in the year 2000 reaching a peak of 2031 units in 2010 and

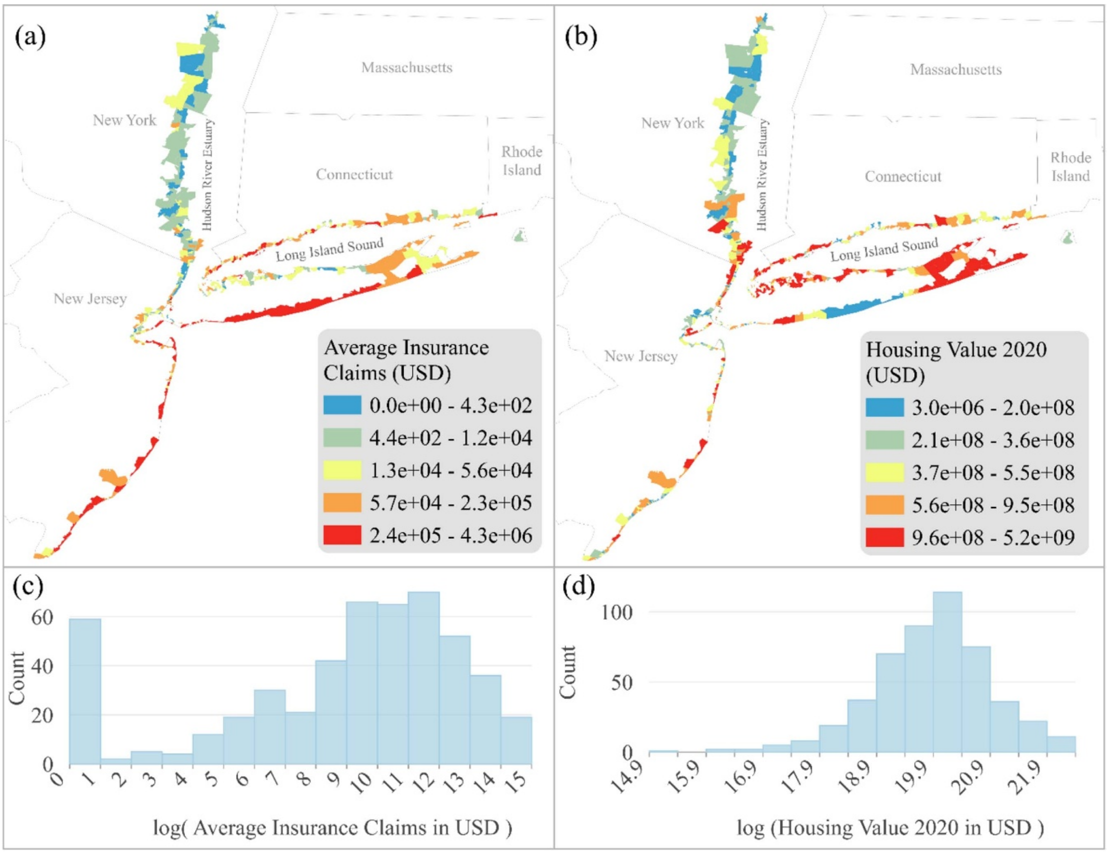

Figure 1. Study region showing the spatial distributions of (a) mean annual average insurance claim within each tract and (b) the 2020 total value of homes within each tract. Panels (c) and (d) show histograms of these variables.

then dropping to 1970 in 2020 (Steven *et al* 2022, U.S. Census Bureau 2022a). Median HPs increased from \$274 500 in 2000 to \$504 100 in 2010 and \$581 700 in 2020 (Steven *et al* 2022, U.S. Census Bureau 2022b).

This region has a documented history of flooding from storm surge, riverine, and pluvial flooding (Depietri *et al* 2018). The spring season is characterized by moderately intense precipitation on snow, potentially inducing riverine or pluvial flooding. Late summer and fall are characterized by heavy tropical storms that bring both intense precipitation and wind-driven storm surge. Nor'easter cyclones are most common during the winter season and can cause elevated storm surge and intense precipitation. The average annual maximum daily precipitation was 7.4 $\mathrm{cm}^1\ \mathrm{day}^{-1}$ with nine precipitation events exceeding 10 $\mathrm{cm}^1\ \mathrm{day}^{-1}$ from 1970–2021 (NOAA 2022a). Mean high tide at the battery, NY is 0.76 m MSL. From 1970 to 2021, the region experienced an average annual maximum storm surge of 1.57 m MSL, with three events exceeding 2 m MSL (figure S1) (1992, 2011, 2012) (NOAA 2022b).

From 1979 to 2021, the average annual number of flood insurance claims submitted through NFIP in this region was 3,476 $\mathrm{claims}^1\mathrm{year}^{-1}$ with an average annual claim total of \$112 million. Historical NFIP flood losses were highest with 75 247 claims in 2012, due to rainfall and storm surge from Hurricane Sandy (peak water elevation of 3.5 m MSL at Battery, NY). Reported NFIP claims in this year were approximately \$4.86 billion. Following Hurricane Sandy the rate of new NFIP flood insurance policies decreased from a maximum of 182 530 insurance policies held in 2013–144 954 in 2021 (US FEMA 2022).

2.2. SE modeling of community flood dynamics

We studied relationships between HP dynamics and community awareness of flooding with a SE model (Baldassarre *et al* 2015, Barendrecht *et al* 2019). This model simulates annual economic losses (L), population density (D), community flood awareness (A), and flood preparedness (P) based on a time series of peak annual flood hazards (figure 2). Flood hazards (i.e., high surge elevations, extreme rainfall, (W)) above some threshold (T) result in a simulated loss (L), based on current housing density (D) and a parameter controlling the hazard to loss ratio (β_R). Losses greater than 0 cause A (and preparedness, P) to increase and D to decrease. In the absence of floods, A and P gradually decay and D increases. This model structure has been shown to accurately simulate human-flood dynamics across a variety of case studies (Barendrecht *et al* 2019, Knighton *et al* 2021). Datasets used in model development are presented in section S1.

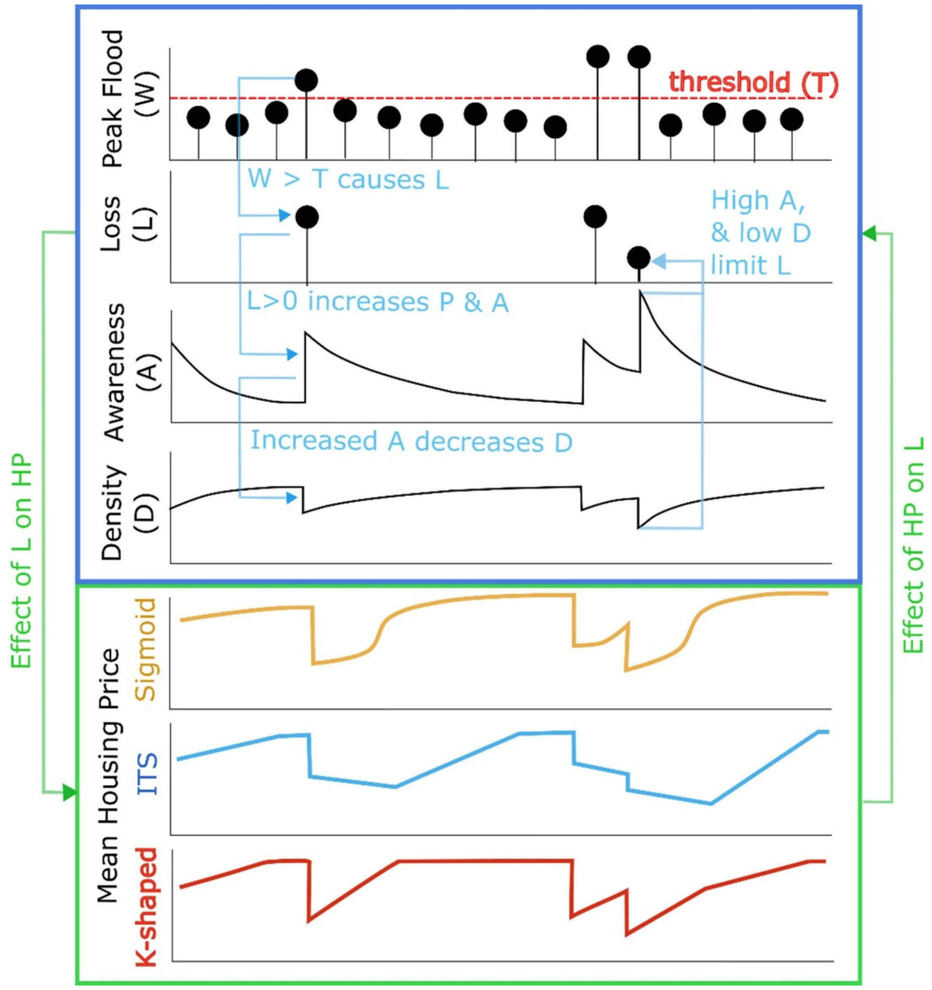

Figure 2. Schematic representation of the original SE model (blue box) and new time-varied HP models (green box) showing the three competing HP models evaluated (sigmoid model, interrupted time series (ITS), and the K-shaped recovery model). Light blue arrows graphically demonstrate how flooding hazards impact simulated perceptions of flooding and housing density. Green arrows depict new relationships between the original model and simulated time-varying HPs.

For application to the study region, we modified this model to separate the effects of surge- and rainfall-driven flooding events, which yielded a significant improvement in simulations across the study region (figure S3). A full description of this modification is presented in section S2. We hereafter refer to the SE model with this modification as the base model. The SE model was also adapted to include three separate approaches to simulating temporal changes in HPs due to flooding impacts: a sigmoid recovery (Pryce *et al* 2011), an interrupted time series (ITS) recovery, and a K-shaped recovery (Beltrán *et al* 2019) (figure 2). A full description of time varying HP models is presented in section S3. We calibrated the SE model for each census tract individually with data spanning 1970–2021. The difference between normalized total annual NFIP claims and simulated L were summarized with the Kling-Gupta Efficiency (KGE_L) (equation 1), where r is the linear correlation coefficient between simulated and observed values, σ_{sim} is the standard deviation of simulated values, σ_{obs} the standard deviation of observed values, μ_{sim} the average of simulated values, and μ_{obs} the average of observed values

$$\text{KGE} = 1 - \sqrt{(r-1)^2 + \left(\frac{\sigma_{\text{sim}}}{\sigma_{\text{obs}}} - 1\right)^2 + \left(\frac{\mu_{\text{sim}}}{\mu_{\text{obs}}} - 1\right)^2}. \quad (1)$$

KGE_A was computed between annual simulated awareness (A) and the normalized value of active NFIP policies. KGE_D was computed between simulated population density (D) and normalized observed population density. KGE_{HP} was computed between simulated HPs and normalized observed HPs. All metrics were first compared to the KGE mean observational benchmark, above which models have predictive skill (Knoben *et al* 2019). We then evaluated the relative performance of each HP model through Mann Whitney U-tests comparing all KGE scores across all census tracts. This calibration approach was used to determine which HP model was most appropriate and to estimate relationships between HP dynamics and community perceptions of flooding.

2.3. Relationship between SE model HP and behavior parameters

Integration of housing models into an SE model supports an exploration of relationships between housing market values, external flooding hazards, and perceptions of future risk. Through model calibration, we estimated parameters related to community-scale flood behaviors. Anxiousness (a_A) and forgetfulness (μ_A) control how population density changes immediately following a flood-related loss and through periods of no loss, respectively. The decay of precautionary measures (μ_P) controls how floods impact simulated awareness (A) and preparedness (P) (figure 2) which in turn impacts the loss from future surges. We also estimated parameters related to HP change. Parameters $b2$ and $b3$ which control initial drop in HPs due to flooding and the rate of HP recovery, respectively. We examined relationships between these calibrated model parameters to those parameters describing temporal changes in the housing market using Spearman's ranked correlation.

3. Results

3.1. Simulation of regional HP responses to flooding

Calibration of the models to observed NFIP claims, policies, population density, and mean HPs demonstrated that the ITS model provided the most accurate representation of flooding dynamics across the study region (see section S3 for further details). Each model was capable of adequately simulating the period of rising HPs from 1970 through 2011, with some disagreement on the impact of minor flooding events (figures 3(a)–(d)). Each model simulated different HP responses to flood events in 2011 (tropical storm Lee) and 2012 (hurricane Sandy). The Sigmoid and K-shaped models each imposed immediate drops in HPs and monotonic recoveries starting in 2013 (figures 3(b) and (d)). As this pattern was not evident in the observed data, the calibration algorithm minimized model residuals by estimating parameters for each model that predicted small losses and limited recovery (figures 3(b) and (d)). Calibration of the ITS model similarly reproduced the case of a limited initial impact on HPs followed by a period in which HPs steadily declined (figure 3(c)).

3.2. Relationships between housing values and community perceptions of flooding

We compared correlations between SE model parameters describing community perceptions and responses to floods, and parameters describing changes in housing values (figure 4). The analysis was performed with calibrated ITS model parameter values across the 496 census tracts within the study region (figure S6 and S7). Across all tracts, the $b2$ parameter describing the initial drop in HPs immediately following a flood loss was significantly positively correlated with anxiousness (a_A), effectiveness of preparedness (a_R), forgetfulness (μ_A), and decay of precautionary measures (μ_P) (figure 4(a)). The $b3$ parameter describing the gradual decrease in HPs after flooding was significantly positively correlated with a_A, μ_A, and μ_P (figure 4(a)). State-level variations in the relationships between model parameters describing flood risk perceptions and HP dynamics are evident. The regional patterns are driven largely by NY (figure 4(c)). In NJ and CT, there are similar significant positive correlations between a_A and $b2$ (figures 4(b) and (d)). In CT, μ_P and $b3$ are significantly positively correlated (figure 4(d)).

4. Discussion

4.1. Post-sandy HP dynamics

Understanding HP dynamics is critical for regional flood mitigation planning. From 1970 to 2012, the study region experienced a steady increase in HPs, which were potentially temporarily slowed by several minor flood events occurring in the 1980s and 1990s (figures 3(a) and (c)). In the absence of substantial flooding losses between 1970 and 2012, regional awareness of flooding risk may have gradually decreased (Meyer *et al* 2014), resulting in an inaccurate discounting of the negative impacts of flood risk on property values (Lamond and Proverbs 2006).

After Hurricane Sandy in 2012, HPs continued to rise, but more gradually than in the preceding 30 years (figure S2) (U.S. Census Bureau 2022b), which has been proposed as evidence of the limited effect of flooding on coastal property values (Murfin and Spiegel 2020). Our findings generally support the idea that the region exhibited a lower immediate impact of flooding on housing values; however, we observed a clear drop in relative HPs (figures 3 and S2). This result is similar to a study in Brisbane which found increasing home values after a flood, but also a sustained differential between the prices of flood-impacted and non-impacted properties (Eves and Wilkinson 2014). The observed trend of home values after Hurricane Sandy is counter to the frequent observation of immediate decreases in home values followed by relatively quick recoveries in other case studies (Atreya and Ferreira 2015, Beltrán *et al* 2019, Chandra-Putra and Andrews 2020). The slow decline in HPs after Hurricane Sandy relative to the national mean HP may be related to the capacity for NFIP to limit the exposure of residents to economic losses related to flooding. Surveys conducted 5 years after Hurricane Sandy indicated that coastal residents in the region slightly underestimated flooding risks and that coastal prices exceeded expected prices by

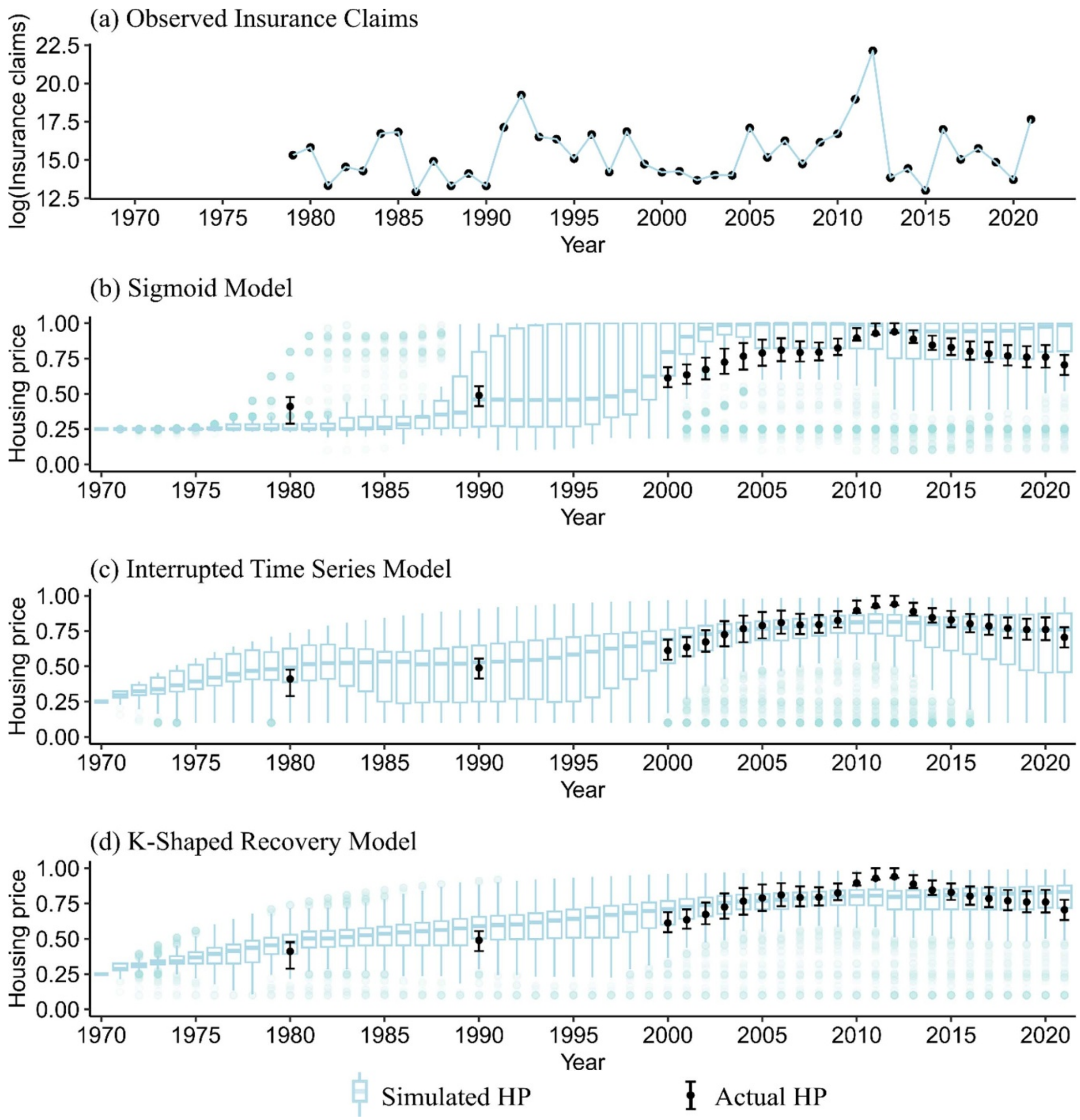

Figure 3. Annual time series of (a) NFIP reported flooding insurance claims and distributions of actual and simulated mean HPs across all census tracts for the (b) sigmoid recovery model, (c) ITS model, and (d) the K-shaped recovery model. Box plots show the median and interquartile range of simulated values. Error bars on observed data correspond to the 25th and 75th percentiles.

6%–13% (Bakkensen and Barrage 2022), suggesting that HPs have not been corrected to the true flood risk profile as the memory of Hurricane Sandy fades.

The coastal communities of the study region remain highly vulnerable to flooding under climate change (Kirshen *et al* 2008, Sweet *et al* 2022). Future regional precipitation will likely be characterized by more intense rainfall interspersed with extended droughts (Hayhoe *et al* 2008, Xue and Ullrich 2022). Predictions of coastal storm surge are less certain with some forecasts suggesting increased (Michaelis *et al* 2017) or stable (Lin *et al* 2019) wave and surge inundation regimes. In aggregate, the region is likely to experience more frequent flooding and economic loss. The SE model developed in this research suggests that the immediate negative consequences of an isolated intense flooding event may continue to be absorbed by NFIP; however, predicted changes to the flooding regime may result in a sustained decreases in property values.

4.2. Relationships between housing values and community perceptions of flooding

Flood risk is the aggregation of compound flooding events (Ghanbari *et al* 2021), variations in community exposure and resilience (Knighton *et al* 2021, Tate *et al* 2021, Wing *et al* 2022), perceptions of flooding (Merz *et al* 2015), and governance (Tullos 2018, Snel *et al* 2020). Risk perception itself is intricate, with the characteristics that shape it being both unclear and specific to research problem and applied methods (Lechowska 2018). These complexities necessitate that we study SE systems with tools that consider how these processes interact.

Significant positive correlations between the SE model parameter describing changes community risk

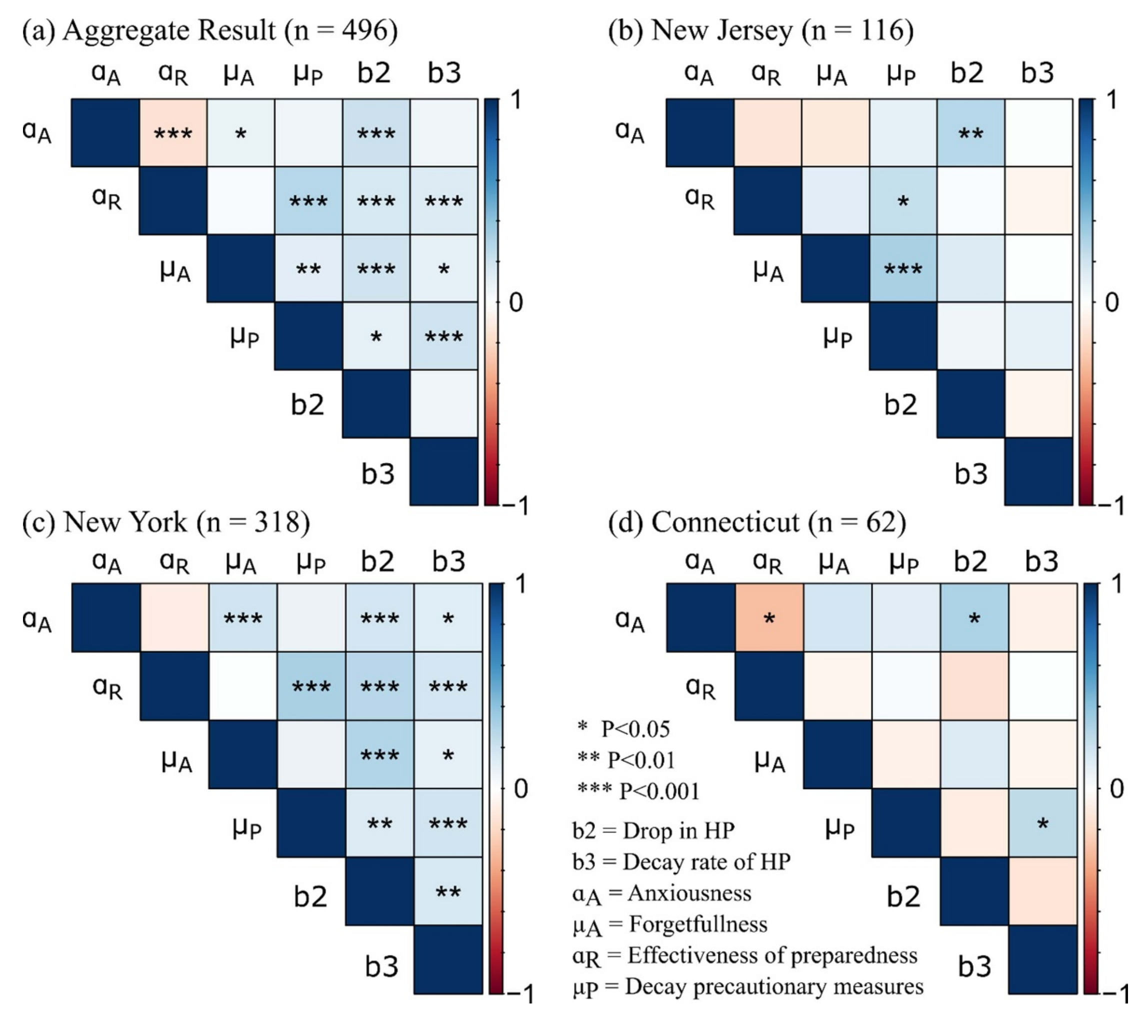

Figure 4. Correlation plot of calibrated SE model parameters across (a) all census tracts in the study region, (b) New Jersey census tracts, (c) New York census tracts, and (d) Connecticut census tracts.

awareness in response to flooding losses (a_A) and the initial drop in HPs post-flood ($b2$) suggested that census tracts in which individuals were most flood-aware (and increased NFIP policy uptake) experienced the largest immediate changes in HP. Similarly, positive correlations between $b2$, $b3$, forgetfulness (μ_A) and the decay of precautionary measures (μ_P) possibly suggested that awareness of flooding reflected by NFIP participation is correlated with the memory of past floods that is encoded in housing market values. Both μ_A and μ_P are related to the lapse rate of NFIP policies in the years after floods. Where these parameters indicated a greater lapse in NFIP policies, HPs were more likely to decrease than those with less variability in the number of active policies. Together, these correlations possibly suggest that increases in the participation in NFIP across the study region was driving short-term perceptions of increased risk which then steadily drove down housing values over the next decade (Colby and Zipp 2021). Positive correlations between effectiveness of preparation (a_R) and HP changes (b2) further reinforced that housing values in the region were driven more by perceptions and NFIP participation than actual changes to flood hazards. Variations in correlations across the states may be due to differences in social vulnerability, which in turn drives variations in NFIP participation (Dixon *et al* 2017). Alternately, the variations may be related to the number of tracts (n) considered from each state, where more tracts in NY could support more robust statistical inferences (figure 4).

While NFIP appears to have shielded the housing market from a substantial immediate economic loss (figure 3) it possibly had the unintended consequence of conditioning housing values on perceived risks (figure 4). There is empirical evidence that regional perceptions of risk across the study region are decoupled from actual risk (Bakkensen and Barrage 2022). Though they are often treated as objective information about the world, property values are unavoidably and fundamentally subjective determinations. They can reflect all manner of human biases–from cognitive heuristics that shape natural hazard risk perception (Kahneman *et al* 1982, Slovic 1987, Kunreuther *et al* 2001), to prejudices that associate the presence of racial/ethnic minorities with 'riskiness,' as the history of redlining has shown (Rothstein

2017). As Freddie Mac noted in its 2016 report, it is therefore hard to predict, in the context of climate change, the time path of house prices (Freddie Mac 2016). Perhaps house prices will decline gradually as the expected life of the property becomes shorter as we observed post-Sandy (figure 3). Or perhaps they will reach a tipping point and plummet when a cautious mortgage lender or insurer refuses to underwrite a property, or when homeowners begin to sell defensively.

4.3. Incorporating time-varying housing values into an SE flood model

The development of an SE model to predict time-varying HPs as a function of both external floods and community perceptions could substantially contribute to our understanding of socio-economic disparities in flood risk related to home value (Siders *et al* 2019) and the capacity for communities to recover (Ranasinghe 2020). The ITS model which best reproduced the combined NFIP and housing market system throughout the study period (figure 3(c) and S4) has the flexibility to simulate a sudden drop in HPs, but also a lagged decrease in value (figures 2 and 3). In contrast, the Sigmoid (Pryce *et al* 2011) and K-shaped (Beltrán *et al* 2019) models each imposed an initial sudden drop in value followed by a monotonically increasing recovery (figures 2, 3(b) and 4(d)). The housing value dynamics described by the Sigmoid and K-shaped models may prove to be more appropriate in other settings where housing markets have incurred sudden losses and then steadily recovered (Pryce *et al* 2011, Atreya *et al* 2013, Beltrán *et al* 2019, Chandra-Putra and Andrews 2020). The sigmoid and K-shaped recovery models may be most appropriate for systems not modulated by insurance, or for modeling systemic losses incurred across both the housing and insurance markets (Thomson *et al* 2023).

Studies have demonstrated that complex feedbacks can emerge between flood insurance uptake and home values (Petrolia *et al* 2013, Gallagher 2014, de Koning *et al* 2019, Indaco *et al* 2019). We therefore anticipated that simulating time-varying house prices would improve the representation of NFIP losses and policy uptake in subsequent years over that provided by the base model. Simulating flood impacts on HPs significantly improved the simulations of both HPs (KGE_{HP}) and community awareness (KGE_{A}) (figure S5), supporting this concept. This result was also in agreement with observations of flood-induced insurance uptake (Gallagher 2014). We observed trade-offs between KGE_{HP} and loss (KGE_{L}) (figure S8), indicating the models evaluated did not support simultaneously reproducing all aspects of the housing and NFIP system (figure S4). This may be caused by imperfect forcing data (i.e., overly generalized surge elevations), imperfect census and NFIP data (i.e., missing or incomplete records), or possibly an overly-simplistic model formulation. Alternatively, this result may be due to the lack of large flooding events in sequence within the historical record and not necessarily a deficiency of the model or input data.

5. Conclusions

We developed a SE model to assess the impact of floods on future HPs, which then feedbacks to the estimate of future flood loss. The model incorporates both precipitation and storm surge flood hazard and includes four HP response scenarios: (1) a model assuming no impact, and models assuming initial losses followed by (2) a sigmoid recovery, (3) an ITS recovery, and (4) a K-shaped recovery. The ITS recovery model best captured flooding dynamics in the study region. We found that the immediate impact of 2012 Hurricane Sandy on the housing market was largely absorbed by the NFIP; however, the region experienced a sustained decline in housing values afterwards. We also observed significant correlations between model parameters representing changes in housing values post-floods and those describing community behavior and perceptions. Census tracts with greater change in insurance uptake following floods witnessed larger decreases in mean home values compared to those with more stable NFIP participation. These findings suggest that the memory of past flooding and participation in NFIP may be important regional drivers of future HPs.

Data availability statement

No new data were created or analysed in this study.

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