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ORIGINAL ARTICLE

Benefits of and strategies to update premium rates in the US National Flood Insurance Program under climate change

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Abstract

The United States' National Flood Insurance Program (NFIP) has accumulated over $20 billion in debt to the US Treasury since 2005, partly due to discounted premiums on homes in flood-prone areas. To address this issue, FEMA introduced Risk Rating 2.0 in October 2021, which is able to assess and charge more accurate and equitable rates to homeowners. However, rates must be continually updated to account for increasing flood damage caused by sea level rise and more intense hurricanes due to climate change. This study proposes a strategy to adopt updated premium rates that account for climate change effects and address affordability and risk mitigation issues with a means-tested voucher program. The strategy is tested in a coastal community, Ortley Beach, NJ, by projecting its future flood risk under sea level rise and storm intensification. Compared with using static rates for all the properties in Ortley Beach, the proposed strategy is shown to reduce the NFIP's potential losses to the community from 2020 to 2050 by half (from $4.6 million to $2.3 million), improve the community's flood resistance, and address affordability concerns. Sensitivity analysis of varying incomes, loan interest rates, and conditions for a voucher indicates that the strategy is feasible and effective under a wide range of scenarios. Thus, the proposed strategy can be applied to various communities along the US coastline as an effective way of updating risk-based premiums while addressing affordability and resilience concerns.

KEYWORDS
affordability, climate change, NFIP flood insurance

1 | INTRODUCTION

Floods are the costliest natural disaster (Chignell et al., 2015; Klemas, 2015) and a leading cause of natural disaster fatalities worldwide (Paterson et al., 2018). In the United States, floods are the costliest natural hazard events in terms of lives and property losses (Cigler, 2017). Coastal flooding is of particular concern, as 40% of the US population live in coastal counties with the number growing every year (NOAA, 2015). To illustrate, from 1980 to 2018, the population of hurricane-prone counties in Florida increased by 163%, from 3.7 million people to 9.8 million, compared to a 61% increase in the population of the United States (Kunreuther, 2020). Furthermore, coastal flooding is likely to increase due to sea level rise (SLR) and more intense hurricanes caused by climate change (Garner et al., 2017; IPCC, 2014; Lin et al., 2012; Marsooli et al., 2019; Talke et al., 2014).

Under climate change and rapid coastal development, coastal flood damage and economic losses are expected to increase (Aerts et al., 2014; IPCC, 2014). Studies have suggested that the compound effects of SLR and storm surge from more intense hurricanes will result in more frequent coastal flooding and greater property damage (Emanuel, 2005; Kirshen et al., 2008; Lin & Shullman, 2017). As a result, today's 100-year coastal floods are predicted to become under-20-year events by 2100 (Lin et al., 2016; Marsooli et al., 2019). Aggregate losses to coastal properties in the United States from flood hazards are estimated to be approximately $1 trillion at the end of this century (Neumann et al., 2015). In the face of escalating flood hazards, it is critical to adopt a sustainable and robust insurance scheme that encourages cost-effective mitigation measures to ensure the welfare of millions of coastal residents.

The United States' National Flood Insurance Program (NFIP), launched in 1968, was designed to provide affordable insurance to homeowners residing in hazard-prone areas and enforce more effective floodplain management policies (Michel-Kerjan, 2010). The Federal Emergency Management Agency (FEMA) currently operates the program and issues flood insurance rate maps (FIRMs) that depict flood zones and base flood elevation (BFE)[1] for coastal communities. Although flooding and hurricanes have caused nearly $200 billion in damage in the United States over the last decade (see http://www.ncdc.noaa.gov), the national penetration rate for flood insurance in high-risk zones remains surprisingly low. Fewer than half of the homes in these areas are insured against damage from floods despite mandates to purchase coverage and premium discounts on properties in high-hazard areas (Kunreuther, 2018).

A discounted insurance premium signals to individuals that they do not have a serious flood risk and fails to provide incentives for them to invest in cost-effective mitigation measures (Atreya et al., 2015; Kousky, 2010; Kousky & Kunreuther, 2014). Although several types of discounted premiums are gradually being phased out after the passage of the Homeowner Flood Insurance Affordability Act (HFIAA) of 2014, many properties have had their premiums grandfathered by the NFIP in response to affordability and equity concerns from the public. Grandfathering allows property owners to retain their premiums when their flood zones or BFE in an updated FIRM would imply higher costs of insurance. Thus, if BFE increases over time due to climate change, grandfathering allows homeowners to pay their current lower premiums (Kousky et al., 2021). It is estimated that grandfathered properties account for about 9% of NFIP policies and form a major category of discounted premiums (Horn, 2019).

Discounted and grandfathered premiums have caused FEMA to suffer greater losses in recent decades. To address the NFIP's solvency issues and assess and charge more equitable rates to homeowners, FEMA recently launched Risk Rating 2.0, which is a new rating methodology that incorporates more factors into consideration when calculating a home's premium. Under Risk Rating 2.0, discounted premium and grandfathering will be eliminated and rates should reflect the most update-to-date flood risk. As of today, Risk Rating 2.0 has been fully rolled out in two phases. Phase I began in October 2021, with all new policies subject to the new rating methodology; Phase II began in April 2022 and requires all remaining policies renewing on or after this date be subject to the new rates. After Phase II, it is estimated that 77% homeowners will see an immediate rate increase, and some may even see continued increases every year until their rates reflect the true flood risk, as rate increases may be no more than 18% annually (FEMA, 2021).

To address the affordability issue with a risk-based premium, Kousky & Kunreuther (2014) proposed a means-tested voucher program coupled with low-interest loans to incentivize the investment in cost-effective loss reduction measures. Under this proposal, homeowners can obtain a low-interest home improvement loan to mitigate risk and receive a voucher subsidy covering the annual payment of the loan and premium if the costs exceed a specified criterion (e.g., 2% of their annual income). Their case study of homes in Ocean County, NJ, revealed that the requirement to invest in elevating homes as a condition for obtaining a means-tested voucher would significantly reduce future flood-related losses as well as the cost of the voucher program itself.

Elevating one's property is found to be highly effective in reducing flood losses (Zhao et al., 2016). Although often expensive, elevating one's property is one of the few measures recognized by FEMA for reducing flood insurance premiums. If the NFIP updates premium rates on a regular basis to reflect the increasing impact of climate change, it would create economic incentives for homeowners to elevate their homes in exchange for reduced insurance premiums. FEMA recommends that properties in the 100-year flood zones be elevated to at least one foot above the BFE. However, Xian et al. (2017) found that this general recommendation may not be cost-effective. They propose that elevating houses to their optimal elevation level (OEL) minimizes the combined cost of elevation and cumulative insurance premiums over the lifespan of the house. They also found that, when coupled with a means-tested voucher program, the OEL strategy could minimize total costs for both homeowners and the NFIP compared to FEMA's one-foot freeboard recommendation. Recent studies have applied and further extended the concept of OEL. For example, Adhikari et al. (2021) found significant benefit of elevating houses to their optimal levels within a community through 2100 when considering the effects of SLR. Zarekarizi et al. (2020) recommended incorporating uncertainties and multiple objectives when examining the impacts of elevating houses. For example, the height of one's house may have an impact on other loss reduction measures undertaken by the homeowner in addition to purchasing insurance.

In this study, we propose a strategy of adopting updated premium rates that account for climate change effects while addressing affordability and risk mitigation issues with a means-tested voucher program (henceforth referred to as the dynamic + voucher + OEL strategy) and test its economic feasibility. Specifically, we compare the cost to the NFIP of the voucher + OEL strategy when adopting the updated premium policy and that of maintaining static rates.[2] To do so,

[1] The base flood elevation corresponds to the 100-year flood level or the flood level of 1% annual exceedance, meaning that the probability of the maximum flood height in a year exceeding this level is 1%. The 100-year flood zones include A zones (e.g., AE zone, AO zone, etc) and V zones (e.g., VE zone and V1-V30 zones).

[2] FEMA or another federal government agency would pay the voucher cost. To highlight the savings by imposing means-tested vouchers based on updating premium rates and elevating to the OEL, we are assuming the NFIP would pay these costs.

we project the future BFE by projecting SLR and storm surge due to climate change and assume that premium rates will be updated to reflect these effects so that a true risk-based premium can be adopted. Premiums are calculated based on the rating methodology prior to Risk Rating 2.0 for illustrative purposes.

In addition to the potential loss reduction for the NFIP, we also investigate other advantages of the proposed strategy by demonstrating how it improves community flood resistance and addresses affordability for low- and mid-income families. We apply the analysis to a coastal community, Ortley Beach, NJ. To determine whether this strategy can be generalized to other coastal communities, we conduct sensitivity analyses for a range of parameters and scenarios.

The paper is organized as follows: Section 2 introduces methods to project future BFE, determine OEL, and calculate voucher costs. Section 3 illustrates the analysis of the dynamic + voucher + OEL strategy for three sample houses in Ortley Beach and then for the entire community to identify its major benefits to the NFIP and homeowners. Section 4 presents our conclusions and suggests future research directions.

2 | METHODOLOGY

2.1 | Base flood elevation projection

BFE is an important concept in the NFIP as the risk-based insurance premium applied to a property largely depends on its elevation relative to BFE. Although more house-specific characteristics are introduced in Risk Rating 2.0, BFE remains one of the prominent factors in rate setting. Rates are usually set much higher for properties below the BFE than for those at or above it. In this study, we project the future BFE for the study area based on the dataset and methodology of Marsooli et al. (2019). In Marsooli et al. (2019), a large number of synthetic hurricanes were generated for the US East and Gulf Coasts under historical and future projected climate conditions (based on six climate models) using a statistical/deterministic hurricane model (Emanuel et al., 2008). The storm tides from these synthetic hurricanes were simulated using the advanced circulation model (ADCIRC) (Luettich et al., 1992; Westerink et al., 1994), and the probabilistic distributions of the storm tide at the beginning and end of the 21st century were obtained for each coastal county. Here we apply linear interpolation to determine the storm tide distribution for each decade from 2020 to 2050 for the study area. We then combine the estimated storm tide distribution with a probabilistic SLR projection (Kopp et al., 2014) for the study area through convolution (as in Marsooli et al., 2019) to develop the probability distribution of the flood height for each decade.

We identify the flood level associated with a 1% probability of annual exceedance based on the obtained flood height distribution for Ortley Beach for each decade. Then we estimate this "100-year" flood level for each year between the decades by linear interpolation. To make our analysis consistent with FEMA's approach, we assume the BFE in the latest 2015 FIRM to be the baseline for 2020 and add the changes of our projected 100-year flood level to the baseline to obtain the BFE projection for each year during the 30-year study period (2020-2050). We use this specific projection in our insurance policy analysis, assuming that future flood maps would be updated annually to reflect the effects of SLR and storm climatology change.

2.2 | Determination of OEL

With the projection of the future BFE, annual risk-based insurance premiums for individual houses can be readily calculated based on the FEMA flood insurance manual (FEMA, 2019) and specific characteristics of the house such as the flood zone in which it is located, the lowest floor level relative to its BFE, and presence or absence of a basement. We then calculate the annual premium for the house when elevated to different levels and the associated elevation cost to determine its OEL. Following Xian et al. (2017), the OEL of a house (h^*) is obtained through cost-benefit analysis (CBA) and is defined as the level that minimizes the sum of the upfront elevation cost and the present value of insurance premiums over a given time period. It is calculated as follows:

$$h^* = \text{argmin}_h \left(C(h) + \sum_{t=1}^{T} \frac{1}{(1+r)^t} E(h_0 + h, t) \right) \quad (1)$$

where h_0 is the original height of the house, h is the elevation height for the house, $C(h)$ is the upfront cost to elevate the house by h, T is the total time span in years, and r is the annual discount rate for calculating the present value (e.g., 3%). $E(h_0 + h, t)$ is the risk-based insurance premium with elevation $h_0 + h$ in year t; it is a function of t because the BFE will change over time due to future SLR and storm change. $E(h_0 + h, t)$ is also considered as the FEMA-estimated annual expected loss of the house plus loading cost to reflect marketing and administrative expenses. The upfront elevation cost $C(h)$ for the house can be estimated from FEMA's "*Homeowners' Guide to Retrofitting*" based on house square footage, type of foundation, and elevation height (FEMA, 2014).

The cost reduction to homeowners by elevating to OEL compared to another elevation height (h_1) can be calculated as:

$$S(h_1, h^*) = \left(C(h_1) - C(h^*) + \sum_{t=1}^{T} \frac{1}{(1+r)^t} \left(E(h_0 + h_1, t) - E(h_0 + h^*, t)\right) \right) \quad (2)$$

where $S(h_1, h^*)$ is the total cost that could be saved by homeowners over time period T, if the house is at OEL (h^*) compared to an elevation of h_1. For the case when $h_1 = 0$, $C(h_1)$ is also equal to zero, and then $S(h_1, h^*)$ represents the total cost reduction to homeowners by elevating the house to OEL from its current level.

2.3 | Calculation of means-tested voucher cost

Under risk-based premiums, it will be optimal for homeowners to elevate to OEL if they want to minimize their total cost. To address the affordability issue, a means-tested voucher and loan program is offered to low- and mid-income families. Homeowners may finance their upfront elevation cost with low-interest loans over a specified time period. In addition, a voucher is provided on an annual basis to cover the insurance and loan payments that exceed the owner's ability to make payments. In our analysis, all homeowners are required to elevate their homes to OEL to be eligible for vouchers provided by FEMA (or another federal agency). For any individual house elevated to OEL, its annual voucher cost $V(h^*, t)$ during year t is calculated as:

$$V(h^*, t) = \begin{cases} \max\left(0, \dfrac{C(h^*)}{\sum_{j=1}^{s} \dfrac{1}{(1+l)^j}} + E(h_o + h^*, t) - k \cdot m\right) & t \leq s \\ \max\left(0, E(h_o + h^*, t) - k \cdot m\right) & t > s \end{cases} \tag{3}$$

where $C(h^*)$ is the upfront elevation cost or total loan amount that is paid off in annual equal installments, s is the length of the loan, l is the loan interest rate (e.g., 3%), k is the affordable percent of income (e.g., 2%), and m is annual household income. Equation (3) indicates that when the annual loan payment plus annual risk-based insurance premium exceeds k percent of the family's annual income, a voucher is provided to cover the difference.

Although individuals' income data is not publicly available, a previous survey (Xian et al., 2017) collected income information from 24 households in the community of Ortley Beach. Using these data, we undertake a linear regression that correlates household income with the type of house (primary or secondary), property value, and total square footage to obtain a preliminary income distribution. To improve reliability, we assume the annual household income follows a log-normal distribution, which is often applied to model income (Clementi & Gallegati, 2005), and determine its parameters based on the 2017 census data for the community (US Census Bureau, 2017). We then find the percentile of each household's income from the preliminary income distribution and map it to the corresponding percentile of the log-normal distribution. The income value from the log-normal distribution at the same percentile is utilized as the estimated household income for our analysis.

2.4 | Comparison with static premium rates

To assess the feasibility and benefits of the dynamic + voucher + OEL strategy, we compare it with the scenario where premium rates are kept unchanged in three different ways: (a) the loss reduction to the NFIP, (b) the flood resistance of the community, and (c) the affordability to homeowners. Because static rates will not reflect the up-to-date flood risk under climate change, the NFIP may not be able to collect sufficient premium amounts to cover the actual flood damage. This shortfall can accumulate rapidly, causing the program to suffer substantial losses. On the other hand, the dynamic + voucher + OEL strategy will induce a voucher cost to the NFIP, so we compare this additional expenditure with the potential premium loss due to static rates to quantify the benefit (or loss) to the NFIP. In our study, we determine the flood resilience of the community using the house elevations in the community. The more elevated the houses above the BFE, the lower the flood risk for the community. It is important that the proposed strategy encourages homeowners to undertake cost-effective mitigation measures against the flood hazard. To investigate the effects of the dynamic + voucher + OEL strategy on affordability to homeowners, we estimate the overall costs to households from different income groups, compared with their overall costs when premiums are static.

3 | CASE STUDY AT ORTLEY BEACH, NJ

In this section, benefits of the dynamic + voucher + OEL strategy are determined using a case study of Ortley Beach, NJ, a coastal community that was heavily damaged by flooding from Superstorm Sandy in 2012 (Hatzikyriakou et al., 2015; Hatzikyriakou & Lin, 2018). All 323 houses within the 100-year flood inundation area (310 in the AE zone and 13 in the high-risk VE zone) before Sandy are included in this study. The house information data were collected from an onsite survey after Sandy and have been analyzed in several published works (Hatzikyriakou et al., 2015; Xian et al., 2015).

We first illustrate the benefits of the proposed strategy with three sample houses and then extend the analysis to the entire community. We assume a study period of 30 years, from 2020 to 2050, to test the strategy's feasibility. We assume an annual discount rate of 3%, which is widely used in practice for housing and flood insurance calculations (e.g., Neumann et al., 2015; Adhikari et al., 2021). We also assume an annual loan interest rate of 3% and affordable percent of income of 2% (i.e., a voucher will be provided to homeowners if the annual insurance premium and mitigation loan cost exceeds 2% of annual income); the sensitivity of the results to these policy parameters will be investigated in Section 3.3.

Our analysis involves the following three scenarios: (1) homeowners continue to pay the 2020 insurance rate and their houses are not elevated; (2) homeowners pay the annually updated rates without a voucher subsidy, and their houses are

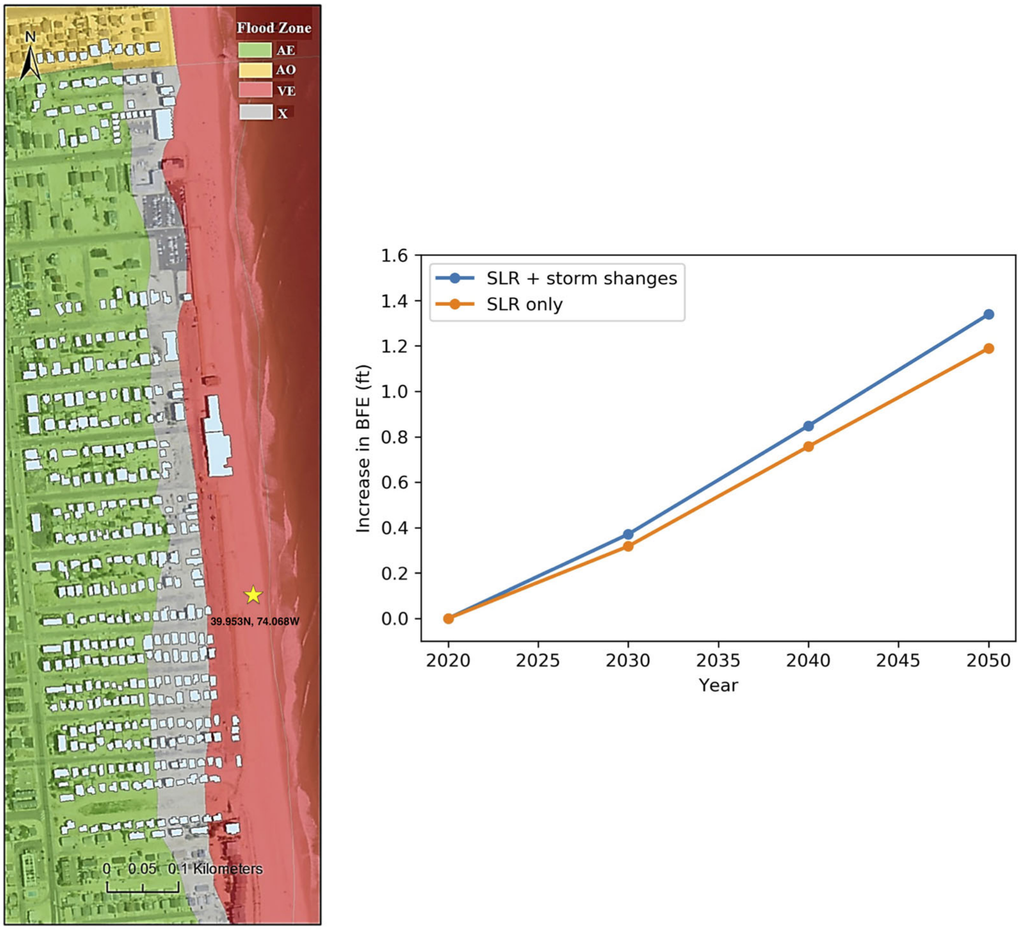

FIGURE 1 Spatial distribution of residential houses in various flood zones in Ortley Beach, NJ. (left) and projection of BFE change at Ortley Beach under effects of SLR + storm changes (blue) and SLR only (red) (right)

not elevated; and (3) homeowners pay the annually updated rates but with the voucher + OEL strategy implemented. Scenarios (1) and (3) represent the static rate situation, where rates are unchanged, and our proposed strategy, respectively. Scenario (2) represents the situation when static rates are replaced by updated rates without a strategy to address affordability and risk mitigation issues. Comparing Scenarios (1) and (2) enables us to identify how much additional premium homeowners need to pay under annually updated premiums. A comparison of Scenario (3) with Scenario (2) reveals the ability of the voucher + OEL strategy to address affordability and flood resilience concerns when annually-updated premiums (henceforth referred to as risk-based premium) are implemented.

3.1 | Future BFE at Ortley Beach

To obtain an accurate BFE projection at Ortley Beach, we extract storm tide data from Marsooli et al. (2019) at the numerical grid point (39.953N, 74.068 W) closest to the community. As shown in Figure 1, the grid point is near the center of the community coastline and can very well represents the local BFE level. By combining the future storm tide with the SLR projection from Kopp et al. (2014), we forecast the BFE at Ortley Beach from 2020 to 2050. Figure 1 shows the map of Ortley Beach community and the projected increase in the future local BFE due to storm change and SLR. We find that by 2050, the BFE is expected to increase by 1.34 ft, with approximately 85–90% of the increase due to SLR while the remainder attributed to storm change. The projected increase is then added to the assumed 2020 BFE for AE (7 ft) and VE zones (10 ft) using the preliminary 2015 FIRM for the area that reflects FEMA's latest estimate of Ortley Beach's flood risk.

Our projection reveals that by 2050, BFE at Ortley Beach will rise to 8.34 ft for the AE zone and 11.34 ft for the VE zone. This increase will have far-reaching effects for both homeowners and the NFIP. For homeowners, higher flood risk will cause more severe and/or more frequent damage to their homes. The NFIP will experience increasing losses if homeowners continue to pay their current rates over the next 30 years instead of the updated risk-based premiums.

TABLE 1 Characteristics of the three sample houses

	Size (ft^2)	House Value ($)	Annual Income ($)	House Level (ft)	Zone	2020 BFE
House #1	1200	201,000	166,700	6	AE	7
House #2	900	86,000	74,740	9	VE	10
House #3	420	23,000	43,700	5	AE	7

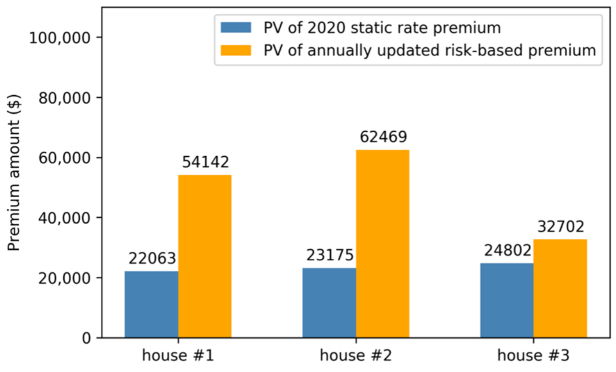

FIGURE 2 Present value of total 2020 static premium and updated risk-based premium over the 30-year period (2020–2050) for Houses #1 to #3, assuming a 3% discount rate

3.2 | Individual house analysis

The data on the three sample houses is presented in Table 1, with Houses #1 and #3 located in the AE zone and House #2 in the VE zone. Annual household income is highest for House #1 and lowest for House #3. The sample houses are analyzed under the three specified future scenarios over the period 2020 to 2050.

Based on the projected BFE, we calculate each house's risk-based premium (based on the projected BFE and the rate table provided in FEMA's flood insurance manual) over the 30-year period. In Figure 2, we compare the present value (PV) of the total static rate premiums and updated risk-based premiums from 2020 to 2050, based on an annual discount rate of 3%, for each of the three houses. The risk-based premiums (no house elevation, Scenario 2) increase over time due to the projected increase of BFE. For all three houses, the total static rate premium is much lower than the total risk-based premium, suggesting a significant deficit to the NFIP if only the former amount is collected. For example, the PV of the static rate premium for House #2 is $23,175 over the 30-year period while the PV of the risk-based premium based on our BFE projection over the same period will be $62,469. This implies that the expected insurance claims over the 30-year period paid by the NFIP for flood damage to House #2 will be $39,294 more than its collected premiums. The cumulative PV of the expected losses to the NFIP from 2020 to 2050 for the three sample houses will be $81,967.

If homeowners were charged risk-based flood insurance premiums, it would be economically optimal for them to elevate their houses to the OEL to minimize their total cost. Figure 3 shows the PV of the risk-based premium cost, elevation cost, and total cost for different elevation heights for the three sample houses. The elevation cost for each house is estimated from FEMA's "Homeowners' Guide to Retrofitting" (FEMA, 2014) and depends on the foundation type, elevation height, and footprint of the house. The risk-based insurance premium over the 30 years is calculated as the PV of total

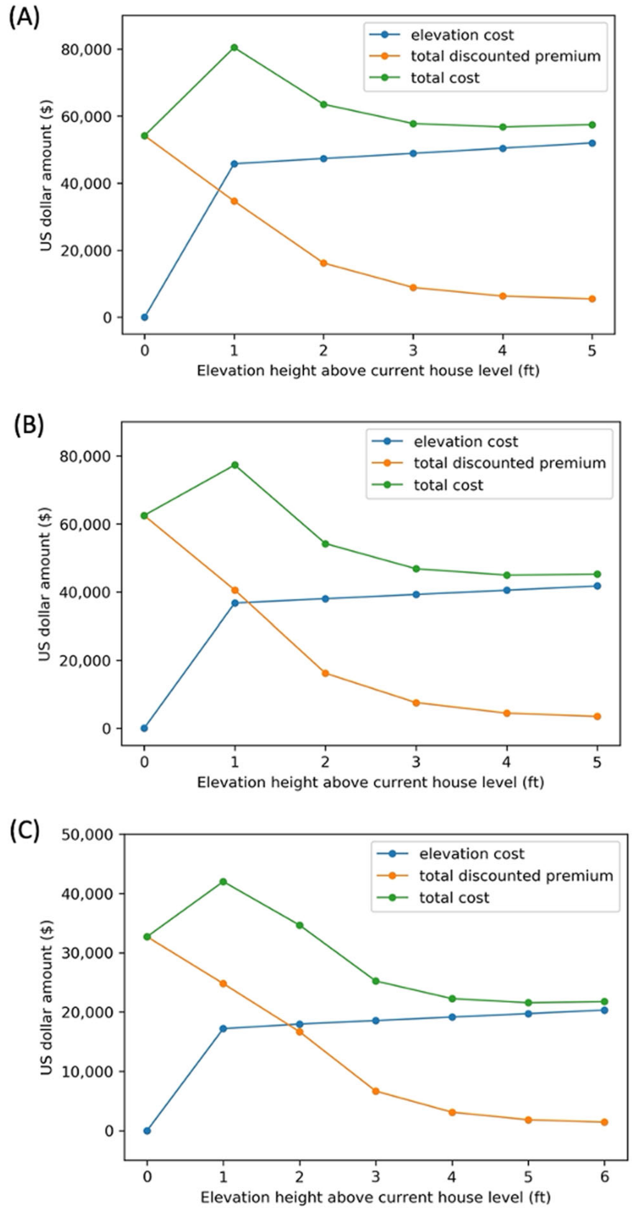

FIGURE 3 Present value of total cost, annual risk-based premium cost and elevation cost at different elevation height for House #1 (A), House #2 (B), and House #3 (C), assuming a 3% discount rate

premium payments by the homeowner over the study period. The total cost is the sum of the PV of the aggregate risk-based premium and the upfront elevation cost. The OEL is determined as the house elevation level with the minimum total cost (Equation 1). For House #1, the risk-based insurance premium and elevation cost at OEL will be minimized at the house's current ground level. The OELs for Houses #2 and #3 are found to be 4 and 5 ft above their current ground level, respectively, and 3 ft above their BFE. Elevating their houses to one foot above the BFE, as suggested by FEMA, would reduce House #2 and #3's flood risk, but elevating to their OEL would further reduce their risk and also significantly reduce their total cost. If Houses #2 and #3 are elevated to their OEL, the PV of reduced total costs for them will be $17,500 and $11,300, respectively, compared to no elevation and $9260 and $3660, respectively, compared to elevating to 1 foot above BFE. The OEL cost reduction would also benefit the NFIP by reducing the voucher cost it would pay to address the affordability issue due to the updated risk-based rates; since the total cost is minimized at OEL and the maximum amount paid by each household is constant, the voucher cost for each house is also minimized at OEL.

To show how our strategy could economically benefit the NFIP, we calculate the program's costs under Scenario 1 (keeping current rates static) and Scenario 3 (replacing static rates by risk-based premium coupled with voucher and OEL strategies) and present the results in Figure 4. The annual premium loss is calculated as the difference between the risk-based premium and static premium for each year. For example, the risk-based premium for House #2 in 2035 is $2,080 higher than the static premium, and the voucher subsidy needed for homeowners in 2035 is $980, resulting in a $1100 savings for the NFIP in 2035. For House #1, the voucher cost will be zero because homeowners can afford the risk-based premium. Results in Figure 4 show that the premium loss from static rates exceeds the incurred voucher cost for all three houses for the study period, and the NFIP would save money during this period if the voucher + OEL strategy is adopted.

Figure 5(A) presents the total cost to the NFIP under the three different scenarios. The PV of total premium losses under Scenario 1 is greater than the PV of total voucher costs under Scenario 3 over the 30-year study period for each of the three houses, with a difference ranging from $3350 to $32,078. (There is no premium loss or voucher cost incurred to the NFIP under Scenario 2, where all homeowners pay the risk-based premium.) To evaluate how total costs to homeowners vary under the different scenarios, we plot the PV of total payments by homeowners over the study period in Figure 5(B). For Scenario 1, the payments by homeowners are the static premium in 2020; for Scenario 2, the payments are the risk-based premium, and no voucher subsidy or house elevation is assumed; for Scenario 3, the payments include the risk-based premium (accounting for premium reduction due to elevation) plus the elevation cost minus the voucher subsidy. Comparing the results, we find that owners of Houses #2 and #3 will pay significantly less under Scenario 3 than Scenario 2 because they will receive a means-tested voucher. The owners of House #1 will pay the same amount under these two scenarios because their annual income is high enough so as not to require a voucher subsidy to partially cover the risk-based premium. Compared to Scenario 1 (static rate), when the risk-based premium is applied in Scenario 3, the high-income House #1 would pay much more, the middle-income House #2 would pay slightly more, and the low-income House #3 would pay less. Thus, without static rate, people may be economically incentivized to elevate their homes to OEL, but the voucher + OEL strategy reinforces the risk mitigation strategy and also addresses the affordability and equity concerns within the community.

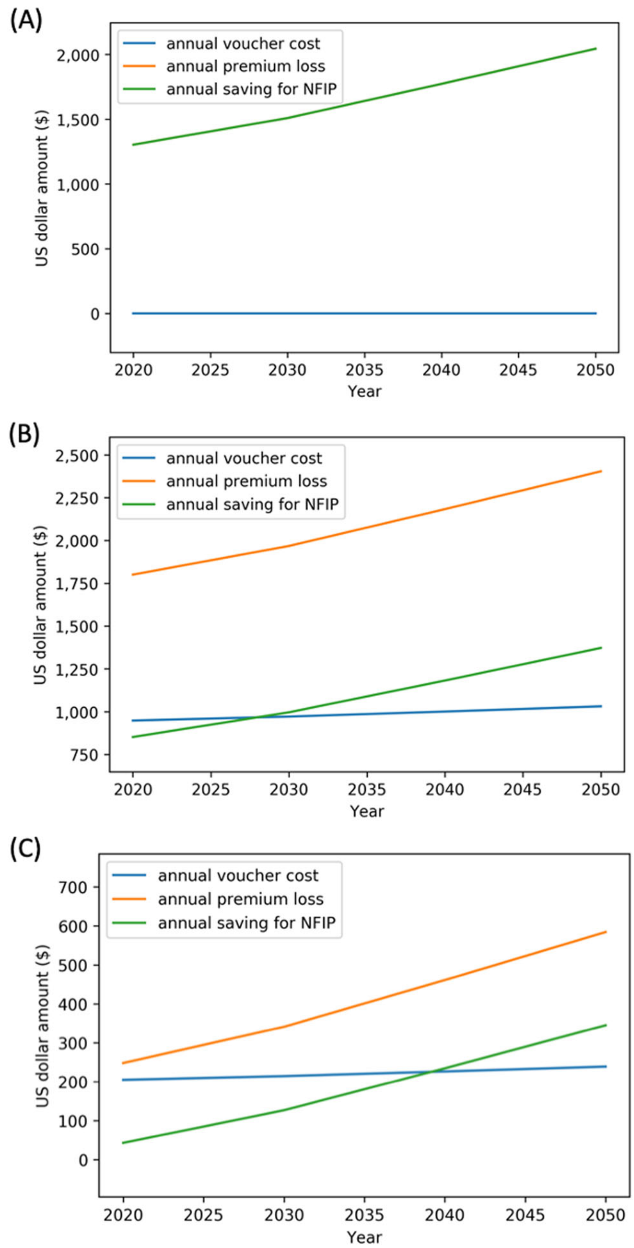

FIGURE 4 Annual premium loss due to static rates, voucher cost, and savings for the NFIP for House #1 (A), House #2 (B), and House #3 (C)

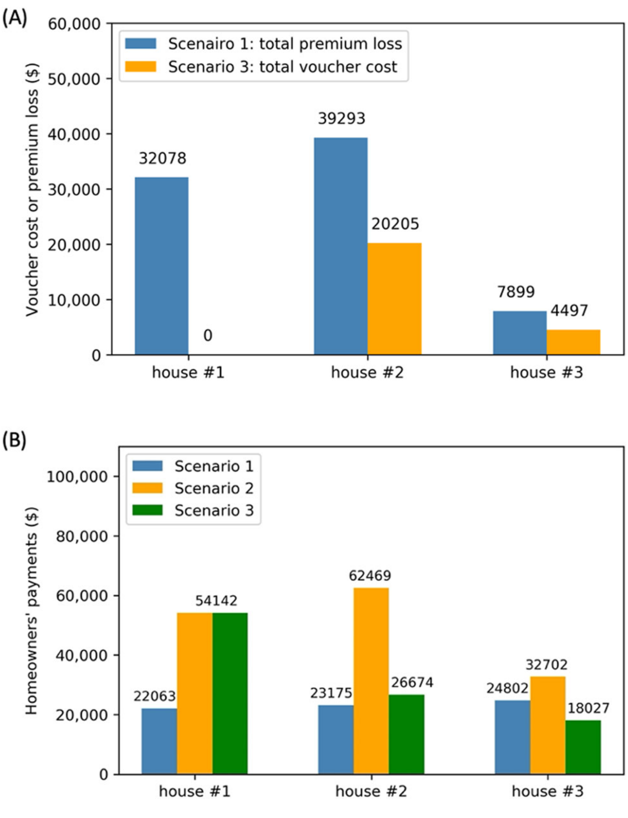

FIGURE 5 Present value of total costs to the NFIP (A) and the homeowners (B) under Scenario (1) 2020 static premium, (2) updated risk-based premium, and (3) updated risk-based premium with voucher + OEL, for Houses #1 to #3

The above results from the sample houses indicate several advantages of the dynamic + voucher + OEL strategy. First, people are incentivized to take optimal risk mitigation measures due to the adoption of a risk-based premium. Second, the NFIP may reduce its potential loss in the future because the voucher costs may be lower than the difference between the risk-based and static premiums. Third, the affordability concern is addressed, and low-income people are likely to economically benefit from the proposed strategy.

3.3 | Community scale analysis

To examine how the voucher + OEL strategy performs at the community level, we conduct the same analysis for all 323 houses (AE and VE zones) in Ortley Beach as shown in Figure 1(A). With increases in the BFE, houses within the community are exposed to a higher flood risk. We find that, over the 30-year period, the number of houses that are at or below BFE will increase from 103 (in 2020) to 208 (in 2050), indicating that the number of houses vulnerable to floods will have more than doubled if no mitigation measures are undertaken. Figure 6(A) shows the distribution of risk-based premiums (without house elevation) for the 323 houses in 2020 and 2050. For most houses, the risk-based premium would increase over the study period because the rising BFE

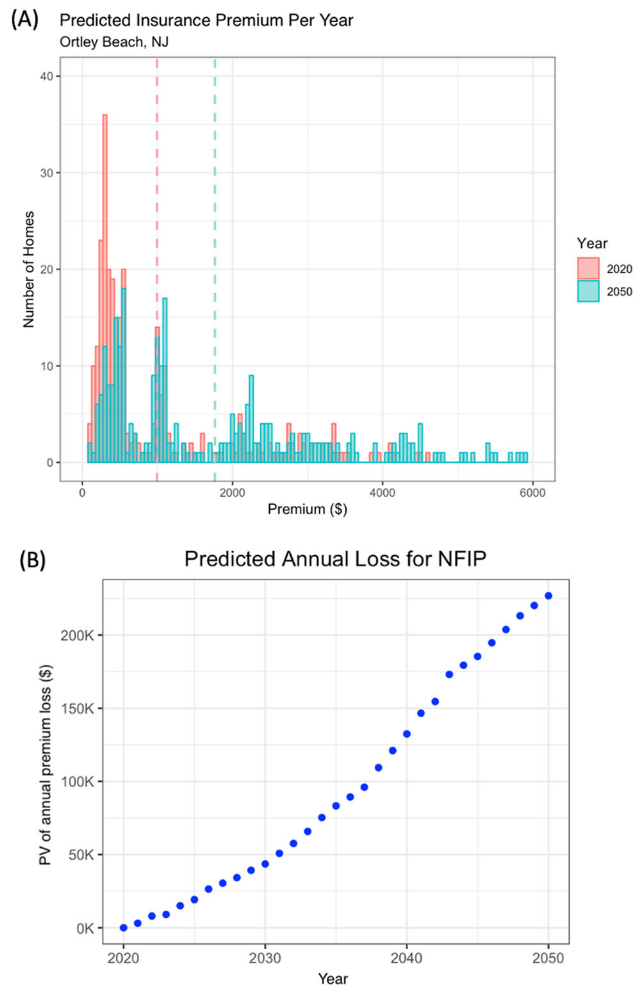

FIGURE 6 Analysis of economic impact on the NFIP of applying 2020 static premiums for the 323 houses at Ortley Beach from 2020 to 2050. (A): Distribution of estimated risk-based premium in 2020 and 2050 (dash lines show the mean premium); (B): Predicted annual loss for the NFIP resulted from not updating rates

would lead to a higher flood risk. Figure 6(B) shows the premium loss from all the 323 houses for each year determined by subtracting today (2020)'s total premium that homeowners are paying from that year's total risk-based premium. We estimate that should the 2020 rates continue for the next 30 years for all the properties in Ortley Beach, the annual loss for NFIP will steadily increase, with the aggregate loss over this period reaching $4.6 million in PV for this community.

In the voucher + OEL strategy (Scenario 3), each year's risk-based premiums are applied, and OEL is calculated for each individual house in the community. Sixty out of the 323 houses will need to be elevated to their OEL for the homeowners to minimize their total payments over the 30-year period. Among these 60 houses, 53 are located in the AE zone (BFE at 7 ft), and seven are in the VE zone (BFE above 10 ft). Also, all 60 houses are at or below their current BFE and have OEL of at least 2 ft above BFE, suggesting that these houses will be exposed to much less flood risk if elevated. Figure 7 compares the distribution of the current level and OEL of the

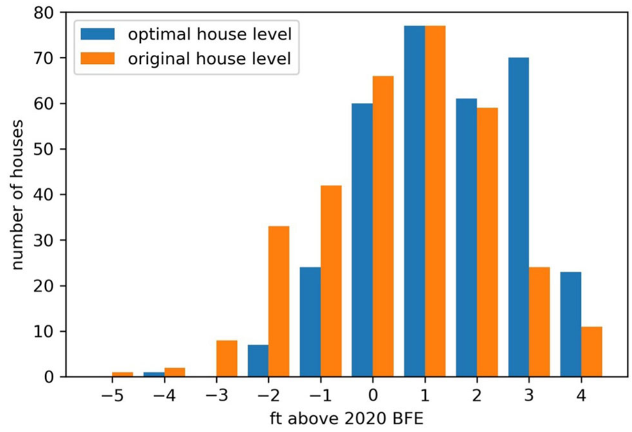

FIGURE 7 Distribution of original and optimal house elevations at Ortley Beach, NJ

323 houses within the community. It shows that the house elevations in the community will be greatly increased if the voucher + OEL strategy is adopted. For example, after elevating to OEL, the number of houses that are 2 ft below BFE will decrease from 33 to 7, and the number of houses that are 3 ft above BFE will increase from 24 to 70. Thus, compared to the static rate scenario, the dynamic + voucher + OEL strategy can lower the flood risk and improve the flood resilience of the community.

In the previous section, we compared the premium loss over three sample houses under Scenario 1 to the total voucher cost under Scenario 3 and found that the NFIP could benefit economically from adopting the voucher + OEL strategy. Figure 8 shows such a comparison at the community level. We find that the annual voucher cost under Scenario 3 for the entire community is always less than the difference between the risk-based and static rate premiums under Scenario 1. Furthermore, cumulated over the study period (2020–2050), the NFIP could avoid a loss of $4.6 million and spend only half of its savings, or $2.3 million, to pay for the vouchers.

Despite higher risk-based premiums, Scenario 3 addresses affordability in that homeowners are paying no more than a small percentage (2%) of their annual income for flood insurance and the costs of elevating their houses to reduce future losses. To present a clearer picture of how the voucher + OEL strategy affects homeowners with different incomes, we partitioned all households into three groups of equal size based on their annual income. Table 2 shows the PV of total homeowners' payments by these three income groups. Similar to the previous analysis of sample houses, a homeowner's total payments are calculated to be the elevation cost plus insurance premium minus the voucher subsidy, cumulated over the study period. The lowest-income families would pay $1.33 million under scenario 1, but $0.11 million less under scenario 3; middle-income families would pay $0.22 million more under Scenario 3; the highest- income families would pay $0.88 million more because most of them are not eligible for a voucher subsidy. Only four high-income group families, whose houses are located in the VE zone, would receive the voucher subsidy. Note that all three income groups would pay less than the risk-based premium in Scenario 2 thanks to the voucher + OEL strategy, which significantly reduces total costs and makes a risk-based premium affordable.

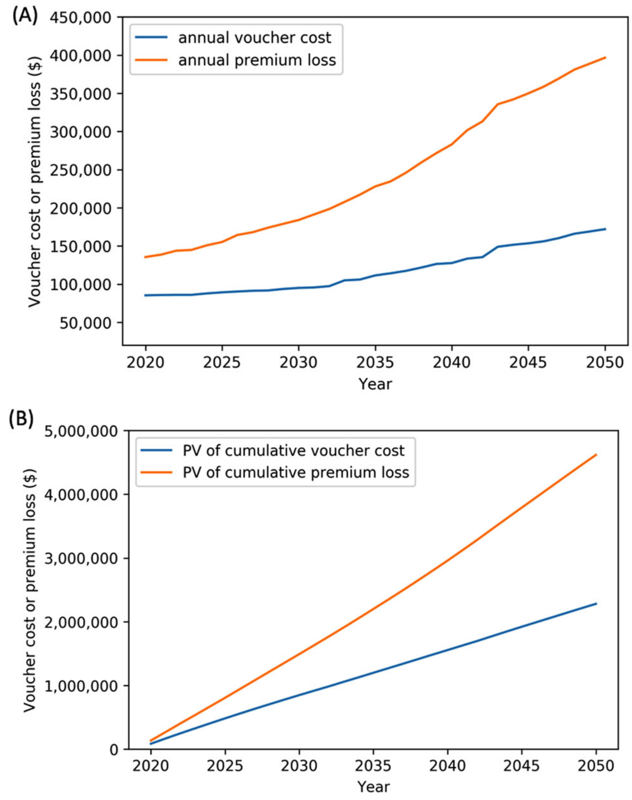

FIGURE 8 Annual voucher cost and premium loss due to not updating rates (A) and PV at 2020 of the cumulated voucher cost and premium loss due to not updating rates (B) for Ortley Beach

TABLE 2 PV ($) of total payments by homeowners in different income groups over the period of 2020 to 2050. All households in Ortley Beach are partitioned into three groups of equal size based on their annual income

Scenarios	Bottom Group	Middle Group	Top Group
(1) Static premium	1,334,311	1,960,153	1,850,785
(2) Dynamic risk-based premium	2,408,984	3,614,118	3,692,426
(3) Dynamic + OEL + Voucher	1,220,988	2,182,457	2,730,917

3.4 | Sensitivity analysis

The community analysis at Ortley Beach reveals that adopting a risk-based premium coupled with the voucher + OEL strategy has certain advantages over the static rate policy. It will improve flood resilience, reduce future loss to the NFIP, and provide affordable insurance to homeowners with relatively low incomes residing in flood-prone areas. Since the NFIP covers thousands of coastal communities in the United States and each one has different characteristics, such as income level or property type, it is worth studying how the strategy works under varying conditions. As the exact information needed for performing the specific analysis for various communities is not readily available, we undertake a sensitivity analysis for the strategy by varying the income level, the most important parameter. We also perform sensitivity analysis on the policy design parameters including the annual loan interest rate and the means-tested voucher condition.

3.4.1 | Income level

The median annual household income of Ortley Beach is around $80,000, which is higher than most other coastal communities in the United States. Since higher community income results in lower voucher cost, it will be useful to explore how the strategy works for lower-income communities. For example, would low-income communities receive a voucher subsidy that exceeds the savings to the NFIP of having a risk-based premium policy instead of a static rate? To answer this and other questions, we investigate the sensitivity to the income level by adjusting the median annual income in the range of $40,000 to $80,000 by shifting the log-normal income distribution in the community level analysis. Specifically, we keep the shape parameter of the fitted log-normal model unchanged and vary the value of the location parameter to obtain the desired median value. Since changes in income do not affect OEL and improved flood resistance, we focus on how they affect loss reduction for the NFIP and affordability to homeowners.

Figure 9 shows that the voucher cost to the NFIP decreases almost linearly as the median annual income of the community increases. The present value of the total voucher cost is $4.25 million when median income is at $40,000, and $2.3 million when the median income is $80,000. For every $10,000 increase in the community median annual income, voucher costs decrease by about $0.6 million. The result is not surprising because homeowners in low-income communities are more likely to need voucher support. However, even for a community with median annual income as low as $40,000, far below the 2018 national median of $61,937 (US Census Bureau, 2018), the voucher cost for the entire community is still $350,000 less than the premium loss of $4.6 million due to not updating rates. Therefore, the proposed strategy is still economically beneficial to the NFIP.

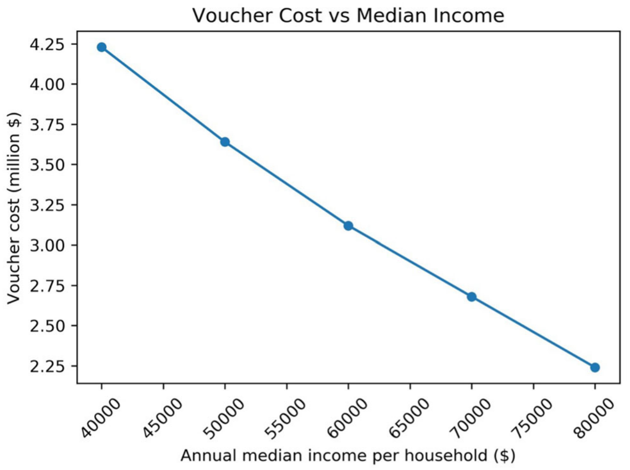

FIGURE 9 Voucher cost incurred at different community income level, in 2020 dollars

TABLE 3 Difference in PV ($) of total payments (Scenario 3 relative to Scenario 1) by homeowners from different income groups. All households in Ortley Beach are partitioned into three groups of equal size based on their annual income

Community median income	40,000	50,000	60,000	70,000	80,000
Bottom Group	−44%	−33%	−23%	−14%	−7%
Middle Group	−27%	−15%	−5%	6%	15%
Top Group	13%	27%	38%	47%	54%

Table 3 compares the discounted total payments by different income groups within the community under scenario 3 relative to scenario 1. We find that regardless of the community's median annual income, the highest-income households pay more under Scenario 3 than Scenario 1, and the lowest-income households pay less under Scenario 3 than Scenario 1. These results occur because under Scenario 1, although many homeowners with relatively low incomes are charged a static premium, it is still above 2% of their annual income. Therefore, when the dynamic + voucher + OEL strategy is adopted (Scenario 3), these homeowners will pay less than the existing static premium, as will all groups when the community's median annual income decreases. In general, as the community is poorer, a larger proportion of homeowners will economically benefit from the dynamic + voucher + OEL strategy.

3.4.2 | Loan interest

Low-interest loans are provided to help homeowners finance their upfront elevation cost as an integral part of the voucher + OEL strategy. In the previous analysis, we assume the loan interest rate to be 3% per annum. However, this parameter may vary depending on the source of funding and economic conditions. Unlike income level, the annual loan interest rate will affect the upfront cost of elevation and thus the OEL.

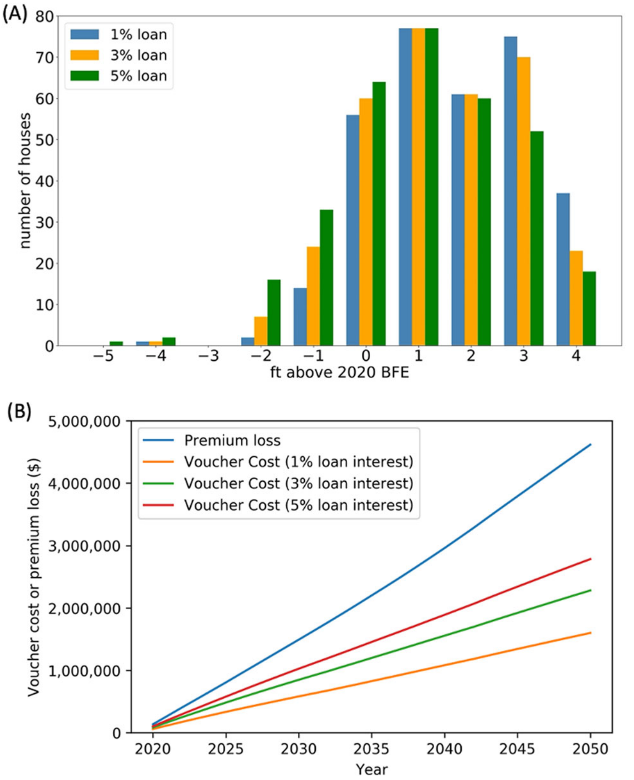

FIGURE 10 OEL distribution (A) and voucher cost (B) for the community when the loan interest rate is assumed to be 1, 3, and 5% per annum

TABLE 4 PV ($) of homeowner payments from 2020 to 2050 under static premium and dynamic + voucher + OEL strategy with 1, 3, and 5% loan interest rate. All households in Ortley Beach are partitioned into three groups of equal size based on their annual income

	Static premium	1% Loan	3% Loan	5% Loan
Bottom Group	1,334,311	1,218,599	1,220,988	1,216,225
Middle Group	1,960,153	2,184,139	2,182,457	2,182,457
Top Group	1,850,785	2,656,726	2,730,917	2,769,162

Keeping the discount rate at 3%, we change the annual loan interest from 1 to 5% and compare their respective outcomes.

Figure 10 shows the OEL distribution and total voucher cost for the community for an annual loan interest rates of 1, 3, and 5%. Higher interest rates discourage homeowners from elevating their houses because of the more expensive annual loan cost. We find that 79 houses in the community will be elevated to the OEL under the 1% interest rate, 60 under the 3% interest rate, and only 36 under the 5% interest rate. For this reason, higher annual interest rates will lead to a higher voucher cost for the NFIP. More specifically, the voucher cost varies from $1.5 to $2.5 million when the interest rate increases from 1 to 5%, but it is still much lower than the premium loss of $4.6 million due to not updating rates.

We also look into the homeowners' payments associated with different loan interest rates (Table 4). Homeowners' total costs are not greatly affected by the annual loan interest rate.

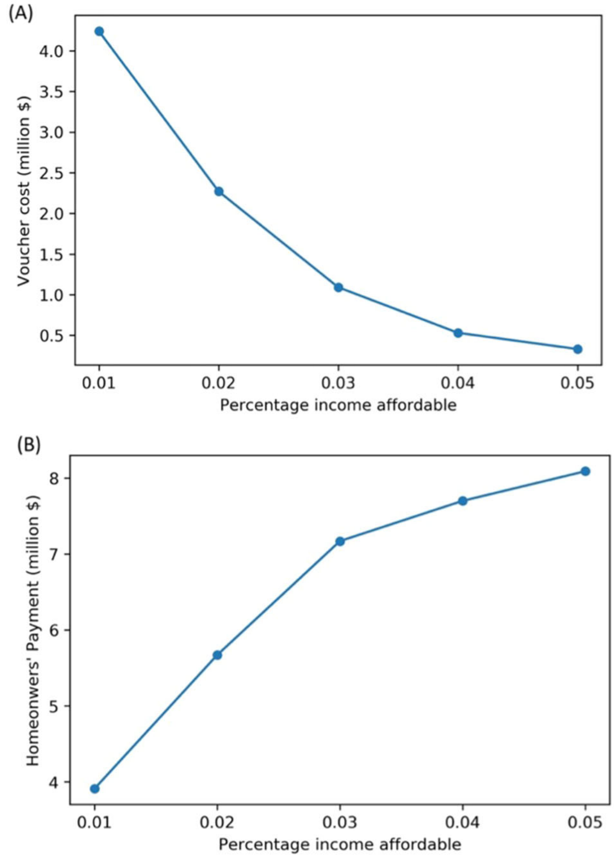

FIGURE 11 PV of total voucher cost (A) and total homeowner's payments (B) for the community versus affordable rate of income

More specifically, the bottom, middle, and top groups are paying in total approximately $1.2, $2.2, and $2.7 million, respectively, under the different loan interest rates.

3.4.3 | Means-tested voucher condition

Another variable that may affect the analysis results is the means-tested voucher condition. In previous analyses, we indicated that a voucher would be provided if the total cost of risk-based insurance premium and loan payment were greater than 2% of annual household income. Similar to the income level, changing the affordable percentage will not affect the determination of the OEL and improved flood resistance. Figure 11 illustrates how the voucher cost and homeowners' payment will change when the means-tested voucher condition varies from 1 to 5% of annual household income. As one would expect, the voucher cost for the community decreases rapidly as the means-tested voucher condition becomes more stringent and homeowners will be required to bear a larger percentage of the cost. The strategy is always economically beneficial to the NFIP because even when the voucher threshold is as generous as 1% of annual income, the total voucher cost of $4.3 million is still less than the premium loss of $4.6 million due to not updating rates.

4 | CONCLUSION AND FUTURE RESEARCH

In recent decades, floods have been the most devastating natural disaster in the United States. Meanwhile, the country's NFIP has so far accumulated over $20 billion in debt due to its generous offering of discounted premiums (Horn, 2021). As stronger storms are expected to hit the United States coasts and sea level continues to rise under global warming, the program launched Risk Rating 2.0 to help deliver more accurate and equitable rates to the public. Although the new rating methodology could help the program become more solvent and adaptable to climate change for the time being, it could still fall short in the future if rates are not updated timely to reflect the impact of climate change.

We test the strategy of applying the dynamically updated risk-based flood insurance rates coupled with a means-tested voucher program (Kousky & Kunreuther, 2014) and risk mitigation based on optimal house elevation (Xian et al., 2017) to reduce future flood losses due to climate change. With risk-based premiums, it will be economically rational for property owners to elevate to the OEL to minimize the sum of the upfront elevation cost and cumulative insurance premium. We also recommend that houses be elevated to their OEL to be eligible for a means-tested voucher, provided to those who cannot afford the annual payment of the mitigation loan and risk-based insurance premium.

To illustrate, we conduct a case study using the sample community of Ortley Beach, NJ. The community consists of 323 houses in the 100-year flood inundation area. We found that the local BFE is expected to rise by 1.34 ft by 2050. As a result, the number of houses at or below the BFE will increase from 103 to 208, and the total static rate premium paid by homeowners will be much lower than the total risk-based premium. If 2020 rates are maintained over the next 30 years for all 323 houses, the NFIP will receive $4.6 million less in premiums than it would if they were charging these properties a risk-based premium. Under the means-tested voucher + OEL strategy, if all homeowners pay no more than 2% of their annual income, the total voucher costs will be only half of the increased revenue from charging all properties a risk-based premium.

The case study also reveals other advantages of the dynamic + voucher + OEL strategy over the static rate policy. First, homeowners are incentivized to elevate their homes, thus improving the flood resistance of the community. With risk-based premiums, elevating homes to their OEL would be beneficial. In the case of Ortley Beach, of the 152 houses at or below BFE, 60 would be elevated to at least 2 ft above BFE, contributing significantly to the community's flood resilience as these houses are the most vulnerable ones to flood hazard. In addition, low-income families are found to be the major beneficiaries of this strategy as their total cost is lower than their original 2020 premium. High-income families will pay much more than the static premium and contribute most of the additional premium collected by the NFIP, revealing that the dynamic + voucher + OEL strategy achieves a more equitable distribution of costs within the community.

Sensitivity analyses were conducted on changes in community median annual income level as well as in policy design parameters including the annual loan interest rate and the condition for obtaining a means-tested voucher. The voucher cost is most sensitive to the means-tested voucher condition and least sensitive to the loan interest rate. However, within the sensitivity range for all three parameters, the voucher cost is always lower than the premium loss of $4.6 million from the static rate policy, indicating that the NFIP would benefit from updating premium rates regularly while addressing affordability issues. Among the three factors, only the annual loan interest rate will affect the OEL and thus the community's flood resistance, with fewer houses elevated with a higher interest rate. Homeowners' payments are not greatly affected by the annual loan interest rate but are sensitive to the other two parameters. Regardless of how these parameters vary, lower-income people will see their total costs reduced under the dynamic + voucher + OEL strategy while higher-income people will likely pay more than their 2020 static rates. The sensitivity analysis indicates that for communities with different levels of income, the strategy is likely to work as expected and bring benefits to both the NFIP and homeowners. However, the sensitivity analysis did not cover all parameters. For example, results could vary in other areas that use different types of foundations (slab-on-grade, crawlspace) than what's typical in Ortley Beach, NJ. In the future, a large-scale, nationwide analysis could be conducted. Such an analysis requires the collection of more detailed house and income information from many representative coastal communities across the country.

Although house elevation is considered the most effective way to mitigate flood risk, it is also the most expensive approach. Among other options, voluntary buyouts that allow property owners to "sell" the properties to the government have been gaining popularity since Superstorm Sandy (Marino, 2018). Homeowners can choose to accept the buyout offer and cannot be evicted from their properties. The buyout is typically offered to properties that have repetitively flooded and are extremely vulnerable to future SLR. It is estimated that although properties subject to repetitive flooding account for only 1% of NFIP policies, they represent 25–30% of all flood claims (Simpson, 2017). One could compare the total voucher cost under OEL to the buyout price for the property to determine which option is more cost-effective. New Jersey's Hurricane Sandy Blue Acres Program, which spent $300 million to buy approximately 1300 repetitively flooded properties (State of New Jersey, 2017) could be a source of data for conducting relevant research in this area.

Consistent with FEMA's insurance framework we based our analysis on the 100-year flood level (BFE), which in this study is estimated by combining projected probability distributions of storm tide and SLR. Using a different BFE projection, the analysis can be repeated with the same framework. Furthermore, it would also be insightful for FEMA to consider treating climate change effects such as SLR and storm change as variables of deep uncertainties that may not be characterize by single probability distributions when estimating risk-based premium. The framework we applied in this study may be revised under this circumstance, and methods such as robust decision-making (Lempert & Collins, 2007; Groves & Lempert, 2007) may be applied to determine the house elevation that provides the "best" protection under numerous future scenarios. For example, instead of using a set of deterministic values, Zarekarizi et al. (2020) conducted multiobjective robust decision analysis on the optimal elevation level for houses when deep uncertainties such as in future flood hazard and discount rate are considered. Also, Ramm et al. (2018) adopted an approach of combining robust decision making and dynamic adaptive policy pathways to improve flood resilience. These approaches may provide insights into more extensive coastal risk management strategies that complement the flood insurance framework discussed in this paper.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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