**Whether (and how high) to elevate a building to manage deeply uncertain riverine flood risks?**

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Projected Journal:

* Journal of hydrology (3.72; 2017),
* sustainability (2.075; 2017),
* ~~Risk Analysis (2.89; 2018)~~
* Journal of flood risk management (2.483)
* Environmental Research Letter
* **Journal of water resources planning and management (3.57; 2016)**
* Science of total environment

Highlights:

* Uncertainties influence the homeowner’s decision of raising the house
* FEMA’s recommendation is not always optimal
* In most cases FEMA’s recommendation underestimates the optimal elevation.
* In rest of the cases FEMA is recommendation over estimates because elevating the house is not worth it
* House characteristics such as lifespan, house size, value and ground elevation are important in the optimal decision

# Abstract

A common approach for flood risk mitigation is lifting houses located in flood-prone areas. The only guideline available for these households is Federal Emergency Management Agency (FEMA)’s minimum elevation requirement for National Flood Insurance Program participants. This guideline recommends elevating the house to the Base Flood Elevation (100-yr flood) plus a freeboard. However, this guideline is not specific, and leaves open the question: how high to elevate the building in the face of uncertain flood projections? To answer this question, we conduct a cost-benefit analysis (CBA) and analyze four main options homeowners have: (1) repairing as floods occur, (2) lifting the house to FEMA’s minimum recommendation, (3) elevating the house to a cost-optimal elevation that minimizes the total cost (current cost of elevating plus net present value of expected damages), and (4) elevating the building to the optimal elevation under uncertainty. We use a case study of a community in Pennsylvania and demonstrate the role of uncertainty quantification in the home elevation problem. Results show that considering uncertainty generally leads to higher CBA optimal elevation and that FEMA’s recommendation can often be improved on from a cost-benefit perspective

Keywords: NFIP; FEMA; Home elevation; flood mitigation strategies; GEV; flood hazard uncertainties

# Introduction

As the costliest natural hazard, floods have affected 2,490 million people between 1980 and 2004 over the globe (Strömberg, 2007). From 1900 to 2015, the U.S. had 35,000 disasters out of which 40 percent were floods (Cigler, 2017). According to the Federal Insurance and Mitigation Administration National Flood Insurance Program (FIMA NFIP) Redacted Claims Dataset released on July 16, 2019, between 1970 and 2019, over 68 billion US dollars have been claimed by the NFIP policy holders on building damage and contents loss. The average damage to households has been over 30,000 US dollars per event (over $23,000 in damages to buildings and over $7,000 to contents).

Structural (e.g. elevating) and non-structural (e.g. flood adapted interior fitting) mitigation plans are undertaken to decrease the flood risk (Kreibich et al., 2005) which generally fall into three categories of wet-floodproofing, dry-floodproofing, and structure modification (e.g. relocating or elevating) (de Ruig et al., 2019). Dry proofing prevents water from entering the building by sealing it through closing the openings such as windows and doors or filling the basement. Wet proofing, on the other hand, allows water to flow inside the building and aims at reducing the damages by decreasing the vulnerability of the structure by, for example, moving valuable contents to higher floors (de Ruig et al., 2019; Moel et al., 2014). The effectiveness of these strategies is contingent upon the intensity of the flood. Generally, dry- and wet- proofing are more effective for low inundation depths (Moel et al. 2014) and structure lifting is more effective for extreme floods.

According to FEMA, over 84% of NFIP households do not meet elevation requirements (such as not having a basement or having the lowest floor above the ground) and yet only 20% of the policy holders have managed to obtain FEMA’s elevation certificate. The low interest in structure elevation is motivated by the fact that lifting a building is very expensive and the cost could go as high as the building value. Large expenses of repairing flood damages and elevating a house make it difficult for the homeowners to decide whether to elevate the building or not. The only guideline provided for structure lifting is by FEMA recommending elevating houses in 100-yr flood zones to the BFE (the flood level with an annual exceedance chance of 1%) plus a freeboard; however, this recommendation is not specific and leaves open the question of whether and how high to elevate a building. FEMA’s minimum recommendation is merely based on the flood zone in which the building is located. Xian et al. (2017) argue that this guideline is not sufficient as it ignores specific building vulnerabilities indicated by building’s lifespan or size, for example. Similarly, de Ruig et al. (2019) argue that implementing a unique adaptation measure to all buildings of a community might not provide enough protection for buildings that are located in areas with higher expected inundation. Both studies implement CBA to find an optimal elevation to raise a building (Xiang et al., 2017) and to identify a cost optimal mitigation strategy (de Ruig et al., 2019).

However, CBA relies on the estimation of cost (i.e. cost of elevating the structure) and benefits (money saved in flood damages) which are subject to a great deal of uncertainty (Apel et al., 2004; Merz et al., 2004; Merz et al., 2010; Moel et al., 2010) and is ignored in the previous literature. Prominent sources of uncertainty in the house elevation problem include dollar magnitude to represent future costs and benefit, the discount rate to convert future values of benefit and costs to present value (Graham 1981; Newell and Pizer, 2003), future flooding probability, and the depth-damage relationship. Moel et al. (2014) conduct a sensitivity analysis of expected annual damages (EAD) and conclude that the uncertainty in EAD can mainly be attributed to flooding probability, flooding duration, and depth-damage curves. Identifying and quantifying these key uncertainties result in more informed decision making (Hadka et al., 2015; Oddo et al., 2017).

This raises the question: what is an economically optimal house elevation decision in the face of uncertain flood projections? To answer this question, we analyze four options a homeowner in a flood-prone area has: (1) implementing no precautionary measures and repair flood damages as they occur, (2) elevating the house to FEMA’s minimum recommended height, (3) elevating the house to the cost-optimal elevation neglecting the flood hazard uncertainty, and (4) elevating the structure to the optimal elevation under uncertainty.

Therefore, we aim to assess the effects of flood hazard uncertainty quantification on the home elevation decision. We start the paper with exploring the levers, objectives, and uncertainty sources in the decision of elevating a house. After explaining our method of calculating the objectives under uncertainty, we illustrate our method with a case study of a community in Pennsylvania which is vulnerable to flooding from Susquehanna river.

# Methods

Estimations of cost, benefit, and optimal elevation are explained in this section. We start with mapping the objectives, levers, and uncertainties in the decision of elevating a house and then we will address calculation of total cost including upfront cost and expected damages.

## Decision framework

Figure 1 shows the XLRM diagram of the home elevation problem. XLRM demonstrates the logical relationships between external factors (X), Levers (L), Relationships (R), and Metrics (M) (Ceres et al., 2019). The levers in this decision include “elevating a house or not?” and if yes, “how high to elevate the house?”. External factors or uncertainties included in this study is the flooding frequency uncertainty; however, more uncertainty factors such as the damage function are possible to consider (Moel et al., 2014). The stakeholder community involved in the home elevation problem include homeowner communities with a diverse range of (usually conflicting) values ranging from preserving the house safety to investing as little as possible. For example, one homeowner might put more value about the safety of the house regardless of money should be spent on elevating it. Or another homeowner might not be able to afford the upfront cost of elevating the house and is limited by the construction cost. Therefore, we consider the home elevation problem to be a multi-objective (Kwakkel, 2017; Kasprzyk et al., 2013; Hadka et al., 2015) problem. Objectives (boxes on the right in figure 1) include (1) total cost, (2) benefit-to-cost ratio, (3) the upfront cost with respect to the building current value, and (4) the safety of the building in extreme floods.



Figure 1: The XLRM framework of the home elevation problem. The lever in such a decision is whether to elevate a house or not and if yes, how high to elevate it? Uncertainties that affect this decision include the flooding frequency and objectives are minimizing total cost and upfront cost and maximizing safety and benefit-to-cost ratio.

## Flooding frequency

We use the Generalized Extreme Value (GEV) distribution which is commonly used for modeling the extremes (Coles, 2001; Lee et al., 2017; Hogan et al., 2019) to estimate the flooding frequency. Non-exceedance probability of a certain water level is obtained by the GEV Cumulative Distribution Function (CDF) as

|  |  |
| --- | --- |
|  | (1) |

where h is annual maximum flood level and μ, σ, and ξ are location, scale, and shape parameters, respectively. For a specific return period (T), the return level is estimated by

|  |  |
| --- | --- |
|  | (2) |

where m is the non-exceedance probability or

|  |  |
| --- | --- |
|  | (3) |

We use Markov Chain Monte Carlo (MCMC) for parameter estimation. For scenarios where uncertainty is ignored, we adopt parameters with the highest likelihood (the mode) and for the scenario where parameter uncertainty is considered, we use the entire ensemble of parameters.

## Safety

We define safety as the probability of no floods during the house lifetime. For a building that is elevated by h feet, safety is defined by

|  |  |
| --- | --- |
|  | (4) |

where n is the house lifespan.

## Upfront cost to house value

One of the objectives in our decision framework is the ratio of upfront cost (cost of elevating the house) to house value () where V is the current value of the house (before elevating), is the cost of elevating the building by h feet, and is the upfront cost to house value ratio if the house is to be elevated by h feet. The cost of elevating a single-family home is interpolated from the Coastal Louisiana Risk Assessment (CLARA) model (McMann et al., 2017). According to this model, the unit cost of elevating a house to 3-7, 7-10, and 10-14 feet is $82.5, $86.25, and $103.75 per square feet with a $20,745 initial fee that includes items such as administration, survey, and permits. Figure 2 depicts the interpolated construction costs for three hypothetical 1,000-, 2,000-, and 3,000-square feet houses.



Figure 2: Construction cost for three sample houses with sizes of 1,000, 2,000, and 3,000 ft2. The gray area indicates elevation of less than three feet which we assume to be impractical. These cost estimates are adopted from the CLARA model (McMann et al., 2017). Units are in 2017 US$ values.

## Total cost

The optimal elevation minimizes the total cost (O1h) defined as the upfront cost of lifting plus the net present value of lifetime expected damages (LED) of cumulative expected damages over the house lifetime (; where n is house lifespan). NPV is a function of EAD and is calculated by

|  |  |
| --- | --- |
|  | (5) |

where r is the discount rate which is assumed to be 4% in this study (de Ruig et al., 2019; Newell and Pizer, 2003) and EADh is the expected annual damages when house is elevated by h feet. Xian et al. (2017) substitute EAD with NFIP insurance premiums assuming that it reflects the actual risk. However, NFIP was originally designed to subsidize the cost of flood insurance on existing homes (Michel-Kerjan, 2010; Kousky and Kunreuther, 2014; Miller et al., 2019; Dinan et al., 2019) and is not risk-based especially for pre-FIRM homes (structures that were built before the FEMA flood maps). To reflect the actual expected damages, we follow de Ruig et al. (2019), Moel et al. (2014) and Arnell (1988) and calculate EAD as the area under the graph of damage against exceedance probability which is called an Exceedance Probability Loss (EPL) curve. Therefore EAD is (de Ruig et al, 2019)

|  |  |
| --- | --- |
|  | (6) |

where p is exceedance probability derived from GEV distribution parameters of which are maximum likelihood estimations of MCMC realizations and D(p) is the damage caused by a flood with exceedance probability of p. D is derived from the depth-damage function which relates the water level to monetary value of damages. We adopted the depth-damage function from European Commission’s science and knowledge service (<https://ec.europa.eu/jrc/en/publication/global-flood-depth-damage-functions-methodology-and-database-guidelines>; accessed on July 29, 2019) (Huizinga et al., 2017) as shown in figure 3 and table 1. This depth-damage function is an average of damage functions for residential buildings in USA and Canada. For USA, the damage estimates are from FEMA’s Hazard U.S. (HAZUS) software and since buildings with and without basements are averaged, the damage at depth of 0 is greater than zero.



Figure 3: The depth-damage function used in this study. The x axis is the water level in the structure and the y axis is the damages as a percent of the total house value (including the contents)

Table 1: The depth-damage relationship used in this study. Contents of the house is also considered in the fraction of damages.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Depth of water in the house [ft] | 0 | 1.64 | 3.28 | 4.92 | 6.56 | 9.84 | 13.12 | 16.40 |
| Damage as a fraction of the house value | 0.2 | 0.44 | 0.58 | 0.68 | 0.78 | 0.85 | 0.92 | 0.96 |

## Benefit-to-cost ratio

Most NFIP participants (that are mainly motivated by the lower insurance premiums) elevate the structure to FEMA’s minimum requirement. In most cases, a cost-benefit analysis (CBA) is not required in such a decision (because if the total cost of elevation is less than 100,000 USD, the requirement of conducting a cost-benefit analysis is waived). Therefore, most homeowners choose to elevate the building to FEMA’s recommendation over conducting a thorough CBA and elevating to an optimal elevation. However, not all households in flood-prone areas participate in NFIP and they do not have to elevate their houses to FEMA’s minimum requirement. We conduct a CBA and the ratio of benefit to cost is one of our decision objectives. In our CBA, cost is the upfront cost (Ch) and benefit is the money saved in expected damages after elevating the house. Therefore, the benefit-to-cost ratio is calculated by

|  |  |
| --- | --- |
|  | (7) |

where Bh is the benefits of elevating a structure by h feet which is damages over the structure lifetime after elevating (by h feet) minus the lifetime expected damages before lifting.

## Decision objectives under uncertainty

We use the criteria listed in table 2 to calculate the decision objectives under uncertainty.

Table 2: Equations for calculating the decision objectives under uncertainty.

|  |  |  |
| --- | --- | --- |
| **Objective** | **Neglecting uncertainty** | **Considering uncertainty** |
| Total cost (O1) |  |  |
| Benefit-to-cost ratio (O2) |  |  |
| Upfront cost to house value (O3) |  |  |
| Safety (O4) |  |  |

## Optimal height calculation with(out) uncertainty quantification

Equations 8 and 9 indicate how we calculate the optimal elevation.

|  |  |
| --- | --- |
|  | (8) |
|  | (9) |

# Results

We demonstrate the effects of uncertainty quantification on the decision of house elevation via a riverine community in Selinsgrove located in central Pennsylvania. In this section, we will present an overview of this community. Then, we will exhibit and discuss the optimal elevation with and without uncertainty quantification.

## Study area and data

The closest USGS gage to the community of Selinsgrove is USGS gage 01554000 collecting water data at Susquehanna River at Sunbury, Pennsylvania. The latitude and longitude of the gage are 40° 50′ 04″ and 76° 49′ 37″, respectively and the drainage area is 18,300 (mi2). The gage datum is at 408.61 feet above NGVD29. Daily discharge data at this location are available for the period of 1937 to 2019 but daily gage height data are limited to 2000-2019. Therefore, in order to take advantage of the rather long record of discharge data, the stage-discharge rating curve for this location was used to convert discharge to gage height.

## Flood frequency and expected damages under uncertainty

Return levels of water depth are estimated under two scenarios of neglecting uncertainty and considering uncertainty. For both cases, MCMC is used to estimate the parameters. For the neglecting uncertainty scenario, the mode (maximum likelihood) of the MCMC distribution is adopted while for the considering uncertainty scenario, all parameter sets in the last 10,000 iterations are used. The expected value (mean) and 90% confidence intervals of the return levels under uncertainty for Selinsgrove, PA is shown in figure 4 by red. The ignoring-uncertainty return levels are shown in blue. For a specific return period (100-year, for example), considering uncertainty leads to higher return levels than the ignoring uncertainty scenario. In the following paragraphs we show that this increase in the water level leads to higher expected damages.



Figure 4: Flooding frequency analysis for two scenarios: 1. Neglecting uncertainty (red line) and 2. Considering uncertainty (blue line and bounds). The uncertainty is indicated by the bounds and the expected water level is indicated by the blue line.

Considering uncertainty increases the return level estimates which in turn increases the expected damages. This is demonstrated through figure 5. As shown in panel b, the expected exceedance probability (i.e. the probability that the water level exceeds the house living elevation; shown by a red line) is higher than the best-guess estimation of exceedance probability. When this exceedance probability is multiplied by the fixed depth-damage function (as shown in panel c), the histogram of the expected damages will look like the curve in panel d. The mean of this histogram is shown by a red line. The black vertical line shows the deterministic expected damages obtained from the deterministic exceedance probability (black line in panel b). In summary, figure 4 and figure 5 demonstrate the value of uncertainty quantification in estimation of expected damages and highlight its importance in assessment of risk and mitigation strategies.



Figure 5: A demonstration to show that including parametric uncertainty in the analysis of extreme water level frequency increases the annual expected damages. a: PDF of each parameter set in the MCMC chain is shown with a light gray line and the expected PDF of the GEV distribution (mean of gray lines) is shown in red. The black line shows the PDF of the GEV distribution under “neglecting uncertainty” scenario. b: 1-CDF of the lines in panel a which shows the exceedance probability associated with each line. c: The depth-damage function d: the annual expected damages under uncertainty shown via the black pdf and its expected value shown via the red line. The annual expected damages neglecting uncertainty is shown by the black line.



Figure 6: Sobol sensitivity analysis diagram. First order and second order.

## Analysis of the optimal elevation for a typical house

We assume that a typical house in Selinsgrove area is worth $350,000, is 1,500 square feet and is 5 feet below the base flood elevation. We also assume that its lifetime is 30 years. In this section we analyze the optimal elevation neglecting and considering uncertainty for such a house. Then, we will compare the results with FEMA’s recommendation and map the trade-offs between objectives in such a decision. As shown in figure 6, the optimal elevation under uncertainty is around eight feet while the optimal elevation neglecting uncertaitty is zero. A simple cost-benefit analysis without uncertainty quantification suggests not elevating the house; however, cost-benefit analysis under uncertainty suggests elevating the house to eight feet. FEMA, on the other hand, recommends elevating the house to one foot above the BFE; in other words, by six feet. Simialry, according to panel b of this figure, the conventional cost-benefit analysis indicates that for non of the policies, the benefit-to-cost ratio is above one. While the cost-benefit analysis under uncertainty indicates that for some policies (5-14 ft), the benefit-to-cost ratio is above one and passes the cost-benefit test. The third panel of this figure shows safety or the probability of no floods in the house lifetime. Neglecting uncertainty appears to show higher safety for all policies which is resulted from the lower exceedence probabilities under “neglecting uncertainty” condition.

It is worth noting that recommending one policy over another is beyond the scope of this study. Instead, we demonstrate the trade-offs and scenarios for the decision-maker and leave the final decision making to them. To this end, we map the tradeoff-s between objectives in figures 7 and 8. Figure 7 uses a parallel axes plot to show the trade-offs between all the objectives (as shown in figure 1). Each line in this plot represents a heightening policy. Green lines represent lower lifting policies and blue lines indicate higher lifting policies. The one left-alone green line indicates the “not elevating” policy. Policies with high (low) safety are associated wih low (high) expected damages, high (low) upfront costs, and high (low) benefit-to-cost ratio. These policies are shown in blue (green) and are related to high (low) lifting scenarios. Two important objectives are the upfront cost of elevating the house and the expected damages. The trade-offs between these two objectives are shown in Figure 8. For a certain upfront cost, the expected damages are higher if uncertainty is taken into account. Also, under certainty, the optimal elevation is zero while under uncertainty is higher than eight feet. Additionally, under certainty, none of the policies pass the cost-benefit test which confirms the results from figure 6.



Figure 6: Variation of total cost, benefit to cost ratio and safety with respect to house heightening level. a: the solid and hollow dots indicate the cost optimal policy considering and neglecting uncertainty, respectively. The horizontal gray area indicates costs that are equal to the house value. The hatched gray area on the left refers to elevating a house to less than three feet which is ignored in this study (this is not practical and cost information are not available for this elevation range). Thus, the black line that shows the construction cost starts from three feet. b: benefit-to-cost ratio for range of heightening policies (0-14 ft). The gray area indicates that benefit to cost ratio is less than one and policies in that area are not cost effective. c: safety for a range of lifting policies. The gray area indicates policies that lead to less than 50% safety. The two vertical dashed lines represent the 100-yr flood (base flood elevation) and FEMA’s recommendation (base flood elevation plus one foot of freeboard). In all the panels, dotted red line indicates ignoring uncertainty and the solid red line indicates considering uncertainty.



Figure 7: Prallel plot demonstrating the trade-offs between objectives in the decision of elevating a typical house in Selinsgrove, PA. Each line indicates a heightening policy (as indicated by its color). The left-out line indicates the policy of “not elevating the house”.



Figure 8: Trade-offs between the upfront cost and expected damages with and without uncertainty quantification. The scenario with uncertainty quantification is shown by red and the neglecting uncertainty condition is shown by blue. Along each line, the dashed parts indicate that the policy does not pass the cost-benefit test (i.e. the benefit-to-cost ratio is less than one). Heightening policies of 0-3 feet are blocked by the gray area as it is impractical to elevate a house to less than three feet. “not elevating” policies are shown by dots and the optimal elevations are shown by squares.

## Analysis of optimal elevation for a range of house characteristics

Given the plausible ranges for house value, house size, and location with respect to the BFE (as listed in table 3), we created a set of 1,000 hypothetical houses using Latin hypercube sampling and analyzed the optimal elevation for each of them.

Table 3: Ranges for house value, elevation, and size considered in this study

|  |  |  |
| --- | --- | --- |
| House characteristic | Lower bound | Upper bound |
| Size (ft2) | 100 | 3000 |
| Value (USD) | 100,000 | 500,000 |
| Initial elevation w.r.t. BFE (ft) | -10 | 0 |
| Lifespan (years) | 5 | 100 |

The optimal elevation under certainty and uncertainty were calculated for all 10,000 houses. Figure 9 plots the optimal elevation under uncertainty versus optimal elevation neglecting uncertainty. It is observed that the all the cases the optimal elevation under uncertainty is greater than or equal to the optimal elevation neglecting uncertainty. In ? percent of houses, the cost of elevating the house to the optimal elevation ignoring uncertainty is higher than the house value. Similarly, in ? percent of houses the cost of elevating the house to the optimal elevation under uncertainty is higher than the house value. In figure 9, these houses are marked with red triangles. In cases where a star is formed (an upward triangle overlaps a downward triangle), the cost of elevating to any of those elevation is more than the current value of the house (before elevating). It should be noted that we ignore the added value to the house after elevating.



Figure 9: The scatter plot of the optimal elevation under uncertainty versus the optimal elevation under certainty. The upward red triangle denotes houses where optimal elevation under certainty cost more than house value. The downward triangle shows houses where elevating to the optimal elevation under uncertainty costs more than house value.



Figure 10: Similar to figure 6 but for a house with value, size, elevation, and lifespan of ?, ?, ?, and ?.



Figure 11: Similar to figure 6 but for a house with size, value, and initial elevation of ?,?, and ?.



Figure 12: Classification and regression tree (CART) diagram to classify the characteristics of the houses where elevating is recommended.

## Analysis of FEMA’s recommendation versus the economic optimal elevation

In the following section we compare the optimal elevation with(out) considering the uncertainty in flooding frequency with FEMA’s recommendation (the BFE plus a freeboard of one foot). Figure 13 shows plots the optimal elevation under uncertainty versus FEMA’s recommendation for the set of sample houses discussed in the previous section. For almost half of the houses the optimal elevation is higher than FEMA’s recommendation. This means that the homeowner can save more money in the expected damages by raising the hose by couple of feet. For around 46% of the houses, the optimal elevation under uncertainty is zero but FEMA recommends elevating this house. A sampel house is presented in figure 11. Finally, in about 4% of the houses, the optimal elevation is less than FEMA’s recommendation. In all the cases, the optimal elevation passes the cost-benefit test but this is not the case for FEMA’s recommendation. Houses where FEMA’s recommendation does not pass the test are denoted by red dots in figure 13. The CART diagram shown in figure 14 classifies the characteristics of the hoses where FEMA does not pass the cost-benefit test (benefit-to-cost ratio is less than one) Based on this classification houses whose initial elevation is close to the BFE are more likely not to pass the b-c test for FEMA’s recommendation. The threshold estimated by the CART method is 4.7. Thus, if a house is less that 4.7 below the base flood elevation is more likely not pass FEMA’s recommendation from a b-c test.



Figure 13: The economic optimal elevation versus FEMA’s recommendation (the BFE plus a freeboard of one foot). Each dot represents a house. Red dots indicate that FEMA’s recommended policy does not pass the cost-benefit test (i.e. the benefit is less that the cost). The diagonal green line is the 1:1 line.



Figure 14: The CART diagram to classify the characteristics of houses where FEMA does not pass the cost-benefit test.

# Discussion and conclusion

One common flood risk mitigation strategy is elevating houses. The United States Federal Emergency Management Agency (FEMA) recommends elevating houses to at least one foot above the Base Flood Elevation (BFE), the water elevation associated with the 100-year flood. This recommendation still leaves open the question whether (and if so by how much) to elevate the houses. This problem is typically addressed in a single objective cost-benefit framework that often neglects key uncertainties.  Here we use a multi-objective decision analysis that considers key deep uncertainties. We show how considering uncertainty changes the trade-offs and the acceptable decisions and identify the key drivers of poor outcomes. The main conclusions of this study include:

* Considering uncertainty leads to higher expected damages in riverine flood-prone communities which in turn leads to higher optimal elevation. Additionally, considering uncertainty of flooding frequency might change the decision outcome.
* Amongst house characteristics such as house value, size, lifespan, and elevation, elevation with respect to the base flood elevation plays the most important role in making the decision of elevating a house or not and if yes, how much.
* FEMA’s recommended heightening policy (elevating to the base flood elevation plus a foot of free board) is not always cost optimal. For majority of the houses, if the homeowner raises the house a couple of feet above FEMA’s recommendation, significantly more money will be saved in the expected damages. On the other hand, in many houses (mainly those whose lowest elevation is close to the base flood elevation), raising the house is neither cost-optimal nor cost-effective while FEMA still recommends elevating.
* An open-source code is distributed along the paper for estimation of flood frequency, the optimal elevation with(out) uncertainty quantification, and plotting the trade-offs between four objectives (total cost, upfront cost to house value, safety, and benefit-to-cost ratio)

The results of this study suggest taking house characteristics such as house value, house size, and initial elevation into account to issue elevation recommendation (currently FEMA’s recommendation is only based on the zone and elevation w.r.t. BFE). Also, quantification of uncertainty in flooding frequency should be considered. In many cases, the homeowners can save considerably more in future expected damages if they raise the house by a couple of feet more now. The accompanied code is accessible by a variety of audience from homeowners to researchers and FEMA as a guideline for estimation of optimal elevation under uncertainty.

Limitaitons and future extensions of this study include:

* Insurance dimension paly san importna trole in elevating houses which is ignored in this study. Accounting for insurance premiums and the amount of money the homeowner can save by elevating the house is an important questions that need to be answer in future extensions of this work. The cost of construction with and without insurance would be different. The cost of construction depends if the money comes out of pocket or is from federal funds.
* Cost of construction estimates are uncertain and this uncertainty is not considered in this study. The cost of construviton estimates are old and are for the state of Luisiana.
* House material is also an important factor in the cost of construction which is not considered in this study.
* The added value to the house price after elevating the house is ignoired
* Just one depth-damage funcrion is used and the uncertainty in the depth-damage function is ignored.
* Real house data are not used
* Other mitigation strategies such as filling the basement and/or adding vents are not considered in this study. An extension of this work will considering other mitigation strategies as well as elevating.
* Discounting rate is considered to be constant which is not the case in reality.
* Non-stationarity of flooding frequency due to climate change is ignored
* The length of the loan which is usually 30 years is ignored
* Lifesopan should be considered as one of the uncertainties
* We ignore the fact that in most of the cases the homeowner
* Other uncertainties are ignored.

# Code and data availability

Code and data are distributed under GNU license through the following repository:

# Acknowledgements

Partial funding for this study is provided by PSIRC

Thank the Keller research group

# Author contribution

Mahkameh Zarekarizi and Klaus Keller devised the study. Mahkameh Zarekarizi conducted the study and wrote the initial draft. Both authors revised and edited the manuscript.

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# Supplementary materials