Economically optimizing elevation of new, single-family residences 1 for flood mitigation via life-cycle benefit-cost analysis

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Abstract

Construction with freeboard – vertical height of a structure above the minimum required – is commonly accepted as a sound investment for flood hazard mitigation. However, determining the optimal height of freeboard poses a major decision problem. This research introduces a life-cycle benefit-cost analysis (LCBCA) approach for optimizing freeboard height for a new, single-family residence, while incorporating uncertainty, and, in the case of insured homes, considering the costs from losses, insurance, and freeboard (if any) to the homeowner and National Flood Insurance Program (NFIP) separately. Using a hypothetical, case study home in Metairie, Louisiana, results show that adding 2 ft. of freeboard at the time of construction might be considered the optimal option given that it yields the highest net benefit, but the highest net benefit-cost ratio occurs for the 1 ft. freeboard. Even if flood loss reduction is not considered when adding freeboard, the savings in annual insurance premiums alone are sufficient to recover the construction costs paid by the homeowner if at least one foot of freeboard is included at construction. Collectively, these results based on conservative assumptions suggest that at the time of construction, even a small amount of freeboard provides a huge savings for the homeowner and (especially) for the financially-strapped NFIP. For community planners, the results suggest that wise planning with reasonable expectations on the front end makes for a more sustainable community.

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Abstract

Construction with freeboard – vertical height of a structure above the minimum required – is commonly accepted as a sound investment for flood hazard mitigation. However, determining the optimal height of freeboard poses a major decision problem. This research introduces a life-cycle benefit-cost analysis (LCBCA) approach for optimizing freeboard height for a new, single-family residence, while incorporating uncertainty, and, in the case of insured homes, considering the costs from losses, insurance, and freeboard (if any) to the homeowner and National Flood Insurance Program (NFIP) separately. Using a hypothetical, case study home in Metairie, Louisiana, results show that adding 2 ft. of freeboard at the time of construction might be considered the optimal option given that it yields the highest net benefit, but the highest net benefit-cost ratio occurs for the 1 ft. freeboard. Even if flood loss reduction is not considered when adding freeboard, the savings in annual insurance premiums alone are sufficient to recover the construction costs paid by the homeowner if at least one foot of freeboard is included at construction. Collectively, these results based on conservative assumptions suggest that at the time of construction, even a small amount of freeboard provides a huge savings for the homeowner and (especially) for the financially-strapped NFIP. For community planners, the results suggest that wise planning with reasonable expectations on the front end makes for a more sustainable community.

1. Introduction

Although adding freeboard – vertical height of a structure above the minimum required – as a flood mitigation measure represents a sound investment (Multihazard Mitigation Council, 2017), determining the optimal height of freeboard poses a significant decision problem (Zarekarizi et al., 2020). The lack of robust benefit-cost analysis (BCA) that quantifies costs and benefits of freeboard at the micro- (i.e., individual building) scale discourages investment in flood mitigation (de Ruig et al., 2019), including the freeboard decision. Moreover, as flooding is a low-probability but high-impact event, it is prudent to evaluate flood loss, with and without retrofit actions, across a long time frame, such as over the building's useful lifespan (Dong and Frangopol, 2017; Taghi Nezhad Bilandi, 2018). Thus, the development of a comprehensive methodology that determines the optimal freeboard height at the micro-scale level through a life-cycle BCA (LCBCA; i.e., across the entire useful lifespan of the building) is valuable in flood risk assessment, by quantifying the cost effectiveness of mitigation measures (De Risi et al., 2018).

LCBCA (e.g., Kappos & Dimitrakopoulos, 2008; Orooji et al., 2022) as it pertains to freeboard and flood mitigation involves weighing the total expected benefits against the total expected costs over the home's useful life in order to determine the best alternative. It builds on a well-established principles of economic analysis to evaluate the life-cycle efficiency between mitigation scenarios. For example, Santos and Ferreira (2013) and Satvati et al. (2021) used LCBCA to enhance decision making regarding pavement solutions and granular aggregate materials on highways, respectively.

Although LCBCA has been conducted in numerous studies, only a few focus on its use for establishing the economically optimal elevation for single-family residences. Xian et al. (2017) introduced the calculation of the economically optimal elevation levels through LCBCA, by substituting the expected annual loss (EAL) with risk-based annual insurance premium based on the National Flood Insurance Program (NFIP) flood insurance manual, even while integrating climate change effects. While the analysis of Xian et al. (2017) was helpful, their estimation of optimal home elevation was based only on freeboard cost and savings on NFIP flood premiums, instead of also considering the EAL.

More recently, Zarekarizi et al. (2020) developed a framework to analyze the home elevation decision, by identifying important sources of uncertainties and characterizing trade-offs between decision objectives such as minimizing the total costs and maximizing the benefit-cost ratio (BCR). While Zarekarizi et al. (2020) represents a substantial step forward, the approach considers only flood reduction in its decision criteria, ignoring the premium savings. The inclusion of flood premium reduction as a function of elevation increase in such analyses allows for a more effective evaluation of freeboard benefits (FEMA, 2008).

Another research gap in the use of LCBCA for optimizing freeboard height for a new, single-family residence is the disaggregation of costs between the affected parties. While the freeboard cost and flood premiums are considered owner costs, the expected average annual loss (AAL) should be assessed while determining the proportions allocated to the owner and the NFIP (Rahim et al., 2021), as insured homeowners are liable only for the deductible and losses exceeding the coverage amount in the case of a flood and NFIP covers the outstanding costs less the deductible. Disaggregation of the costs is important not only for identifying expenses to the affected parties but also to ensure more accuracy for the decision-making process (Sayers, 2013). Thus, while these studies provide useful analyses, further improvement is needed.

This paper presents a methodology for determining the economically optimal elevation of single-family residences using stochastic LCBCA based on the net benefit (NB) and net benefit-cost ratio (NBCR), by freeboard scenario. NBs are the differences in costs between "with" and "without elevation increase" scenarios. The "cost" consists of the sum of the expected AALs, annual insurance premiums, and (in the "with" scenario) freeboard costs, discounted to the present value (DPV) and accumulated over the home's 30-year mortgage period. The economically optimal elevation as a mitigation measure is defined here as the elevation that maximizes the accumulated life-cycle NB. In the "with" scenario above, the NBs are divided by the freeboard cost, either as an "upfront" cost at the time of construction or amortized into an assumed 30-year mortgage, to compute the NBCRs. NB and NBCR are disaggregated as owner benefit and NFIP benefit.

To calculate AAL, a Gumbel extreme value distribution (e.g., Waylen and Woo 1982; Nadarajah and Kotz 2004) is fit to the flood hazard data, in combination with Monte Carlo simulation (MCS) for incorporating the randomness associated with flood annual occurrence, at the individual building level. The Gumbel distribution is widely accepted for such analyses (Kumar and Bhardwaj, 2015; Malakar, 2020; Patel, 2020; Singh et al., 2018). As severe flood events are not limited to the 100-year or 500-year floods, this probabilistic model extends the available data to a longer time-range of interest. MCS has been commonly used in flood risk analysis (e.g., Rahman et al., 2002; Qi et al., 2013, Yu et al., 2013; Hennequin et al., 2018). The building-level approach is characterized by a high level of spatial detail and accuracy in flood risk analysis (Bubeck et al., 2011; Lorente, 2019). Estimating life-cycle benefits at the building scale also allows for more accurate upscaling to broader spatial levels.

A hypothetical one-story, single-family residence in Metairie, Louisiana, is used to demonstrate the methodology presented here. A sensitivity analysis is conducted over a range of discount rates to examine the extent of the impact of the discount rate selected. The aim of this work is to develop a methodology that delivers actionable recommendations to aid the decision-making process for homeowners and other stakeholders with the goal of enhancing long-term flood resilience.

2. Methodology

Determining the economically optimal freeboard involves a comparison of benefits expected over the life of the building between various first-floor elevation (FFE) scenarios. Freeboard is evaluated over a 30-year useful life of a mitigation project, as suggested by FEMA (2009) guidance. LCBCA is performed for each 0.5-ft. increment above the base flood elevation (BFE) – basis for the regulatory flood elevation standard in the U.S., representative of the 100-year flood event elevation – up to four feet of freeboard incorporated at the time of construction. The analysis covers only direct economic losses (building and its contents), with an assumption that no annual cost is needed to maintain the freeboard.

Life-cycle performance of each freeboard scenario is evaluated in terms of its benefit from flood loss reduction and premium savings as compared to its cost, using LCBCA. The outcome is the NBCR, which is derived from the mitigation scenario's total NB divided by its total cost. NBCR is a numerical expression of the life-cycle cost effectiveness of the mitigation scenario, or benefit per dollar spent (Daigneault et al., 2016), in contrast to NB, which measures the overall benefit.

If the resulting NB and NBCR exceed zero, the mitigation scenario is considered cost effective. The scenario with the highest NB represents the economically optimal option. However, NBCR is used as a deciding factor when multiple alternatives have equal NBs. The methodology consists of the following steps: (i) determine the cost of freeboard construction, (ii) calculate NFIP premiums, (iii) calculate AAL and allocate to owner or NFIP, and (iv) conduct the BCA.

2.1 Expected Costs

The financial benefit of adding freeboard is evaluated through consideration of construction cost, flood insurance premiums, and AAL. Costs are divided into two classes: one-time upfront cost and recurring costs that is expected to recur regularly during the analysis timeframe. One-time cost represents the cost of freeboard when it is paid "upfront." The recurring costs are the cost of freeboard built into the mortgage, flood premium, and the expected AAL. All recurring costs are estimated on annualized bases. While cost of freeboard construction and flood premiums are considered owner's costs, the expected AAL is assessed to determine the proportions allocated to the owner and the NFIP.

2.1.1 Cost of Freeboard Construction

The cost of additional increase in elevation is calculated and applied to the LCBCA. Freeboard cost is estimated as a percentage of the total construction cost. FEMA (2008) reports the cost of each freeboard increment as a range of percentage estimates of total construction cost; however, this study uses the upper limit for each freeboard increment to provide a conservative estimate of total cost (Table 1). Freeboard costs are provided in one-foot increments above BFE up to four feet, with half-foot increments being the average of the adjacent whole-foot costs.

Table 1. Upper Limit of Mean Cost of Construction Increase (%), by FEMA Flood Zone and Freeboard (FEMA 2008).

Freeboard (ft.)	A-Zone	Coastal A-Zone	V-Zone
BFE + 1	2.3	3.9	1.8
BFE + 2	4.5	4.8	3.6
BFE + 3	6.8	6.1	5.4
BFE + 4	9.1	8.1	7.2

Upfront freeboard cost depends only on the building's construction replacement cost and is expressed as a percentage of the building value (BV; i.e., building's construction replacement cost). To obtain the upfront construction cost of each freeboard scenario C_{U_I}, the percentage of increase in construction cost associated with each freeboard scenario (I) provided in Table 1 (F_I) is multiplied by the building's value at BFE (BV_{BFE}), or

$$C_{U_I} = F_I \times BV_{BFE} \tag{1}$$

To calculate freeboard construction cost as a recurring cost, 30-year fixed-rate mortgage was applied, as it is the typical length for a standard residential loan. The standard loan amortization formula is used to calculate the amortized base monthly amount C_{BM_I} for each freeboard scenario such that

$$C_{BM_I} = \frac{C_{U_I}\left(\frac{r}{n}\right)}{1 - \left(1+\frac{r}{n}\right)^{-nt}} \tag{2}$$

where r is the interest rate, n is the number of payments per year, and, t is the loan term in years.

The resulting amortized base monthly amount C_{BM_I} is added to the monthly loan fees LF_M to obtain total monthly loan payment for the freeboard C_{M_I}.

$$C_{M_I} = C_{BM_I} + LF_M \tag{3}$$

Because benefits and cost are annualized, the freeboard monthly loan payment C_{M_I} is multiplied by the number of payments per year n to obtain the annual amount C_{Y_I}.

$$C_{Y_I} = C_{M_I} \times n \tag{4}$$

2.1.2 NFIP Premiums

For homes located in special flood hazard areas (SFHA) – floodplain management regulations must be enforced – insurance purchase is mandatory (Senate, 2011). Flood insurance premiums vary based on the location of the property, the flood zone, FFE, building characteristics, and the BFE. The higher the elevation compared to BFE, the less likely the home is to flood and the lower the premium. For each flood zone, the BFE is obtained from the Flood Insurance Rate Map (FIRM) and rates are estimated by comparing the building's elevation to BFE. In the present work, premiums are calculated using Appendix J (Rate Tables) of the NFIP (2021) post-firm construction rates for a single-family residence, for multiple elevation levels. Basic rates for a building and its contents are applied to every $100 of the basic building and content coverage limits, and separate additional rates for building and contents are used for every $100 of additional coverage. For single-family homes, $60,000 is the basic building coverage and $25,000 is the basic content coverage, with maximum limits of $250,000 for building and $100,000 for content (NFIP 2021). NFIP requires a minimum deductible of $1,250 for both building and contents if the coverage exceeds $100,000 (NFIP, 2021); therefore, $1,250 was chosen as a conservative value.

2.1.3 Average Annual Loss (AAL)

This study addresses the randomness of flood occurrence by applying a probabilistic approach. To estimate the expected flood loss, AAL is calculated by integrating the flood loss function (loss-exceedance probability curve) over all probabilities, such that

$$AAL = \int_0^1 L(P)dP \qquad (5)$$

where $L(P)$ represents economic loss as a function of flood exceedance probability.

This methodology derives flood depths for multiple return periods using an inverse cumulative distribution function (CDF), which is then transformed to loss as a function of flood depth using a depth-loss function. Losses associated with each return period expressed as a percentage of the building value are then integrated to estimate total AAL. The two-parameter Gumbel extreme value probability distribution is used to estimate flood occurrence, or

$$f(E) = \left(\frac{1}{\alpha}\right) exp\left[-\left(\frac{E-u}{\alpha}\right) - exp\left(-\left(\frac{E-u}{\alpha}\right)\right)\right] \quad (6)$$

The CDF of the distribution is equal to the exceedance probability, P:

$$P = F(E) = exp\left[-exp\left(\frac{E-u}{\alpha}\right)\right] \quad (7)$$

Solving for E yields the Gumbel inverse CDF, where flood elevation E is obtained as a function of flood probability and Gumbel parameters:

$$E = F^{-1}\big(F(E)\big) = u - \alpha\ \ln(-\ln(P)) \quad (8)$$

In Equations (6), (7) and (8), $f(E)$ is the Gumbel PDF, $F(E)$ is the CDF, $F^{-1}(E)$ is the inverse CDF, and u and α are the calculated (Mostafiz et al., 2021), site-specific location parameter and scale parameter, respectively.

The relationship between flood depth and loss is determined using the U.S. Army Corps of Engineers (USACE; 2000) depth-damage functions for a one-story home with no basement. Although the USACE depth-damage functions begin at –2 ft. depth to account for structures built below FFE, in this work the function is truncated to only calculate building losses beginning at –1 ft. to avoid overestimation of building losses. However, content losses at negative flood depths (i.e., below the building’s first floor) are considered to have no losses. These functions are referred to as depth-loss functions in this paper as the dependent variable is relative loss corresponding to building and contents values, respectively.

To further represent the stochastic nature of the flood hazard, AAL for each freeboard scenario is estimated using MCS, which integrates the loss function with flood elevations. The MCS process can reproduce characteristics of observed floods (e.g., frequency distributions) with relative accuracy across a broad range of frequencies, in addition to circumventing any assumption of linearity (Rahman et al., 2002). The MCS generates scenarios based on the fitted Gumbel inverse CDF for annual occurrences of events having return periods that are rightskewed, such as floods, for which greater depths occur substantially less frequently than lesser depths. For each simulation, an annual probability of exceedance is generated and used as input in the inverse CDF ($F^{-1}(P)$) to calculate the corresponding flood elevation (Equation 9).

$$E_i = F^{-1}[Rand(i)] = u - \alpha \ln(-\ln(Rand(i))) \quad (9)$$

The freeboard scenario FFE_I is subtracted from the resulting simulated flood elevations to obtain the depths and flood loss for building and contents using the appropriate depth-loss functions, where $L_b(E_i - FFE_I)$ and $L_c(E_i - FFE_I)$ is the relative building and content loss, respectively, as a function of flood depth within the building. For each simulation i within freeboard scenario I, the building loss ($l_{b_{i_I}}$) and content loss ($l_{c_{i_I}}$) are determined using the BV

$$l_{b_{i_I}} = L_b(E_i - FFE_I) \cdot BV \quad (10)$$

$$l_{c_{i_I}} = L_c(E_i - FFE_I) \cdot BV \quad (11)$$

The building and content losses that a flood event would cost the homeowner and/or NFIP in a given year is determined. Flood insurance deductibles are represented within total loss, as homeowners are liable for the deductible, specified for building and contents, in the case of a flood regardless of the location or characteristics of the home, while NFIP covers the outstanding costs. Therefore, total loss for each simulation ($L_{Total_{i_I}}$) is apportioned as either owner loss $L_{Owner_{i_I}}$ and/or NFIP loss $L_{NFIP_{i_I}}$, depending on whether or not the policy deductible W_O has been exceeded (Equations 12-16). $L_{Total_{i_I}}$ is a function of the building loss, content loss, and depth in simulation $E_i - FFE_I$.

$$L_{Total_{i_I}} = l_{b_{i_I}} + l_{c_{i_I}} \quad (12)$$

$$L_{Owner_{i_I}} = L_{Total_{i_I}} \qquad \text{for } L_{Total_{i_I}} \leq W_O \quad (13)$$

$$L_{NFIP_{i_I}} = 0 \qquad \text{for } L_{Total_{i_I}} \leq W_O \quad (14)$$

$$L_{Owner_{i_I}} = W_O \qquad \text{for } L_{Total_{i_I}} > W_O \tag{15}$$

$$L_{NFIP_{i_I}} = L_{Total_{i_I}} - W_O \quad \text{for } L_{Total_{i_I}} > W_O \tag{16}$$

In the case of flood total loss $L_{Total_{i_I}}$ exceeding the total insurance coverage G_T, the owner is responsible for W_O plus the loss amount that exceeds the total insurance coverage, such that

$$L_{Owner_{i_I}} = L_{Total_{i_I}} - (G_T - W_O) \tag{17}$$

While the NFIP loss L_{NFIP_i} is the total insurance coverage less the deductible, or

$$L_{NFIP_{i_I}} = G_T - W_O \tag{18}$$

The expected losses of all simulated events with different probabilities for building and contents are averaged to estimate the total (owner plus NFIP) AAL_{Total_I}, that for the owner (AAL_{Owner_I}), and that for the NFIP (AAL_{NFIP_I}), such that

$$AAL_{Total_I} = \frac{1}{N}\sum_{i=1}^{N} L_{Total_{i_I}} \tag{19}$$

$$AAL_{Owner_I} = \frac{1}{N}\sum_{i=1}^{N} L_{Owner_{i_I}} \tag{20}$$

$$AAL_{NFIP_I} = \frac{1}{N}\sum_{i=1}^{N} L_{NFIP_{i_I}} \tag{21}$$

2.2 Benefit-Cost Analysis (BCA)

While the calculated annual costs can be used for benefit comparison, they neglect the life-cycle element of the mitigation scenarios. To determine whether a mitigation scenario actually results in life-cycle economic benefit, all costs are in DPV, and BCA is conducted.

While BCR, and similarly NBCR, are used for comparing multiple alternatives, they do not provide a sense of the economic magnitude since they do not indicate the absolute size of the NB. NB, in contrast, yields the overall magnitude of the benefit but does not convey the relationship between benefits and costs (Cooper et al., 2016). Thus, combining NB with BCR or

NBCR enables a more informed decision-making process. This is one of the advantages of NBCR since NB is a part of its formula, as opposed to BCR, which neglects NB in its calculation.

Although BCR and NBCR are used for similar rule of alternatives prioritization, the traditional BCR method is not an ideal, as BCR compares benefits to costs directly, while NBCR evaluates options based on returns on investment. NBCR is used in this study as an alternative to the traditional BCR since it has the advantage of communicating clear results to homeowners and decision-makers in their language, and BCA is evaluated through consideration of the DPV, NB, and NBCR.

NB is used for mutually exclusive alternative selection, where the decision is independent and expected for only one option. By contrast, NBCR is a metric of alternative prioritization for multiple scenarios competing for limited resources, where funds are allocated based on NBCR rankings to enable several projects to be finished. An elevation increase for a single residence is considered a mutually exclusive project, where only one alternative is considered. Thus, it was decided that for this topic (single-family residence) the scenario with the highest NB represents the economically optimal option.

2.2.1 Discounted Present Value (DPV)

Since costs and benefits of a project accrue over time, the BCA is conducted on a DPV basis, which is the discounted value of all expected future costs and benefits. DPV enables the comparison of current mitigation costs with the expected future benefits resulting from avoided losses (Tate et al., 2016). It transforms benefits and costs occurring in different times to present-value terms (Frank, 2000).

As future costs are being in DPV, the choice of a proper discount rate is a vital decision (Kshirsagar et al., 2010). Discount rates may include the effect of inflation, depending on whether nominal or real discount rate is used. A nominal discount rate incorporates an inflation component. By contrast, the real discount rate is adjusted (i.e., inflation removed from its figure) to eliminate the impact of expected inflation (Office of Management and Budget, 1992).

In this study, real discount rate is selected for several reasons. Because LCBCA often covers extended periods, the real discount rate is recommended since forecasting future inflation is difficult and introduces additional uncertainty into the analysis (Moges et al., 2017; Waheed et al., 1997). This use of the real discount rate is consistent with the recommendation of the Office of Management and Budget (1992) to avoid an inflation assumption whenever possible in LCBCA due to the high uncertainty associated with inflation. Using the real discount rate removes inflation from the present value estimates and obviates the need to calculate its rate (Fuller and Petersen, 1996; van den Boomen et al., 2017). As a result, the estimations are less affected by uncertainty and subjective influences (Zimmerman et al., 2000). In addition, netting out inflation to a constant rate while applying multiple nominal discount rates can result in inconsistency since the proportion of the inflation component within different nominal discount rates varies. These considerations, together with the fact that both types of the discount rates yield similar present values when applied properly (Babusiaux and Pierru, 2005; Fuller and Petersen, 1996), support the decision to use real discount rates.

DPV of a general annual expense (X_{DPV}) serves the purpose of returning the annualized expense X_t over a time horizon T using the discount rate R_D (Equation 21). This general equation is used to calculate the DPV of insurance premiums, AAL, and annual loan payments, which are used to calculate discounted present value total and owner costs in Equations 22 through 27.

$$X_{DPV} = \sum_{t=1}^{T} \frac{X_t}{(1+R_D)^t} \tag{21}$$

Benefits of freeboard are the future costs reduced or prevented by the mitigation measure and are calculated as the difference in the DPV of annual costs over the useful life of the home with versus without freeboard. The total DPV at BFE "no action" scenario ($C_{Total_{DPV\,BFE}}$) is calculated as the sum of life-cycle cumulative DPVs of annual insurance premium $P_{DPV\,BFE}$ and the total $AAL_{Total_{DPV\,BFE}}$, such that

$$C_{Total_{DPV\,BFE}} = \left(\sum_{t=1}^{T} P_{DPV}\right)_{BFE} + \left(\sum_{t=1}^{T} AAL_{Total_{DPV}}\right)_{BFE} \tag{22}$$

$AAL_{Total_{DPV}}$ is the sum of AAL DPVs allocated to owner $AAL_{Owner_{DPV}}$ and NFIP $AAL_{NFIP_{DPV}}$. The owner DPV at BFE "no action" scenario ($C_{owner_{DPV\,BFE}}$) is calculated as the sum of life-cycle cumulative DPVs of annual insurance premium $P_{DPV\,BFE}$ and the owner DPV $AAL_{owner_{DPV\,BFE}}$, such that

$$C_{Owner_{DPV\,BFE}} = \left(\sum_{t=1}^{T} P_{DPV}\right)_{BFE} + \left(\sum_{t=1}^{T} AAL_{Owner_{DPV}}\right)_{BFE} \tag{23}$$

Because loan-based freeboard cost C_{Loan_I} accumulates over the life of the loan, it is assessed on an annualized basis DPV. By contrast, upfront freeboard cost is a one-time cost expressed as a percentage of the total building value only. The total DPV of each freeboard scenario with upfront freeboard cost $DPV_{Total_{U_I}}$ is calculated as the upfront cost of freeboard C_{U_I} plus the sum of life-cycle cumulative of the P_{DPV} and the $AAL_{Total_{DPV}}$.

$$DPV_{Total_{U_I}} = C_{U_I} + \left(\sum_{t=1}^{T} P_{DPV}\right)_I + \left(\sum_{t=1}^{T} AAL_{Total_{DPV}}\right)_I \tag{24}$$

The owner DPV of each freeboard scenario with upfront freeboard cost $DPV_{Owner_{U_I}}$ is calculated as the upfront cost of freeboard C_{U_I} plus the sum of life-cycle cumulative of the P_{DPV} and the $AAL_{Owner_{DPV}}$.

$$DPV_{Owner_{U_I}} = C_{U_I} + \left(\sum_{t=1}^{T} P_{DPV}\right)_I + \left(\sum_{t=1}^{T} AAL_{Owner_{DPV}}\right)_I \tag{25}$$

The total DPV of each freeboard scenario with loan-based cost $DPV_{Total_{L_I}}$ is calculated as the sum of the life-cycle cumulative of the loan annual freeboard payment discounted to the present value $DPV_{C_{Y_I}}$, the P_{DPV}, and the $AAL_{Total_{DPV}}$.

$$DPV_{Total_{L_I}} = \sum_{t=1}^{T} DPV_{C_{Y_I}} + (\sum_{t=1}^{T} P_{DPV})_I + \left(\sum_{t=1}^{T} AAL_{Total_{DPV}}\right)_I \quad (26)$$

The owner DPV of each freeboard scenario with loan-based cost $DPV_{owner_{L_I}}$ is calculated as the sum of the life-cycle cumulative of the loan annual freeboard payment discounted to the present value $DPV_{C_{Y_I}}$, the P_{DPV}, and the $AAL_{owner_{DPV}}$.

$$DPV_{owner_{L_I}} = \left(\sum_{t=1}^{T} DPV_{C_{Y_I}}\right)_I + (\sum_{t=1}^{T} P_{DPV})_I + \left(\sum_{t=1}^{T} AAL_{owner_{DPV}}\right)_I \quad (27)$$

2.2.2 The Net Benefit (NB)

The NB of mitigation is the difference in life-cycle cost between the current and the mitigated scenarios (Orooji and Friedland, 2017). The benefits of freeboard mitigation scenarios are the future reduced or prevented losses by the elevation increase. The NB of adding freeboard NB_I is determined by subtracting the life-cycle cumulative DPV of the freeboard scenario (represented generally in Equation 28 as DPV_I) from the life-cycle cumulative DPV of "at BFE no action" scenario $\left(C_{DPV_{BFE}}\right)$.

$$NB_I = C_{DPV_{BFE}} - DPV_I \quad (28)$$

A positive value of NB_I indicates that the mitigated scenario is more cost beneficial than "the scenario under consideration."

2.2.3 Net Benefit-cost Ratio (NBCR)

The cost effectiveness of adding freeboard (i.e., benefit per dollar spent) is quantified using NBCR. Calculating the NBCR provides a single value showing the relationship between

NB and cost. NBCR for the freeboard is represented generally as the total NB of the freeboard scenario (NB_I) divided by its total cost (C_I), or

$$NBCR_I = \frac{NB_I}{C_I} \tag{29}$$

3. Sensitivity Analysis

BCA is a useful method of appraising projects and examining their long-term financial efficiency. However, the uncertainty caused by key variables that may deviate often acts as an impediment to its successful application (Maravas and Pantouvakis, 2018). The importance of the discount rate in LCBCA has been widely acknowledged (Emmerling et al., 2019). The choice of discount rate has an important role when determining the present value of benefits (Shreve and Kelman, 2014; Tate et al., 2016). However, a growing body of literature argues that the use of a particular discount rate for long-term projects has only limited justification (Ermolieva et al., 2012; Frederick et al., 2002; Tóth, 2000). In Fiscal Year 2018, USACE recommended a 2.875% discount rate for its projects; this is a substantial decline from a peak of 8.875% in 1990 (Fischbach et al., 2019). Cline (1999) and Ermolieva et al. (2012) argued for discount rate fluctuation during the years and that failing to consider such fluctuations may increase vulnerability and losses. Furthermore, U.S. Office of Management and Budget (1992) recommends using a variation of discount rates to assess the sensitivity of the results to the discount rate choice.

To address this problem, this LCBCA is evaluated over a range of discount rates instead of advocating for a particular one. This will serve as a sensitivity analysis, which is a widely used approach in economic impact studies to acknowledge uncertainties and test the effect of changing variable values for which there is uncertainty (Ruegg and Jordan, 2011). Using a range ensures more transparency in the interpretation of benefits involved and also enhances the awareness by highlighting the sensitivity of the results to the discount rate choice (Kozack, 2005). In this study, real discount rates are formed in a range that marks the upper and lower bounds over which they can be varied. The range is bounded at the lower end by the highest NB that occurs at the point when the discount rate is zero (undiscounted case) where all future benefits are at their total value. For the upper end of the range, real discount rates of 4, 8, and 12 percent are used in financial formulas to represent a range when investigating the best investment alternative (Chizmar et al., 2019). Internationally, real discount rates of 3, 7, and 10 percent are suggested for the BCA sensitive analysis (Australian Office of Best Practice Regulation, 2020). Note that the use of a 7% real discount rate as a baseline with a 3% real discount rate to test the sensitivity of results is consistent with the requirements of U.S. Office of Management and Budget (1992) for BCA analyses. Thus, a 7% real discount rate is adopted as the baseline in this study, with real discount rates of 0%, 3%, 10%, and 12% to test the sensitivity of results to the baseline rate.

4. Case Study

A case study was carried out in Metairie, Louisiana, to demonstrate the methodology presented in this work, considering freeboard in half-foot increments. The building is a one-story, single-family residence with 2,500 ft^2 of living area. The site is located in the metropolitan New Orleans area within Jefferson Parish (County) at coordinates 29°59'39.8"N, 90°10'05.7"W. The ground elevation at the location is –7.0 ft. (NAVD88). The site is located on NFIP Map Panel 22051C0185F within flood zone AE –4, indicating that the required BFE of the building is –4 ft. (NAVD 88). In addition, Jefferson Parish requires an additional 0.5 ft. of freeboard to ensure a "code compliant" FFE of –3.5 ft. (NAVD88).

The average construction cost of a single-family residence in the New Orleans area is \$92.47 per square foot for a 2,500 ft^2 residence (Moselle, 2019). Also, 2,500 ft^2 is the average size for a single-family home in the southern U.S. (U.S. Census Bureau, 2020). Accordingly, the total estimated construction cost is $231,175. To calculate cost of construction at the half-foot increments not provided in Table 1, an interpolated value was used. The insurance coverage for structure and content is selected as $231,175 and $100,000, respectively. A minimum deductible of $1,250 for both structure and contents is required. Therefore, $1,250 was chosen as a conservative value.

Using the multi-frequency depth grids provided by Federal Emergency Management Agency's Risk Mapping, Assessment and Planning (RiskMAP) project, the site's flood elevations for the 10%, 2%, 1%, and 0.2% annual chance flood events are –4.7, –4.2, –3.9, and –3.4 ft., respectively. The corresponding above ground flood depths are 2.3, 2.8, 3.1, and 3.6 feet.

5. Results and Discussion

Results are presented in two steps: (i) determine the expected costs at BFE versus costs of each freeboard scenario, (ii) conduct the BCA, where NBs and NBCRs are obtained for various combinations of freeboard, their cost options, benefit allocations, and discount rates. LCBCA of freeboard insurance savings is performed separately.

5.1 Expected Costs

The benefit of adding freeboard is evaluated through consideration of construction cost, flood insurance premiums, and AAL.

5.1.1 Cost of Freeboard Construction

Construction cost for each freeboard increment is calculated as an upfront cost and as a loan (Table 2). For upfront option, the cost of freeboard is calculated as a direct percentage of the total building value. In the loan option, freeboard cost is calculated as a part of a 30-year mortgage with fixed rate of 3.375% and 7% payment-related fees (current rates used by Federal National Mortgage Association (Fannie Mae)). Because all recurring costs are estimated in an annualized bases, the monthly loan payment is multiplied by the number of payments per year to obtain the annual estimate. The loan annual estimate is multiplied by the loan's term to obtain the total cost of the freeboard.

Table 2. Freeboard Cost for Upfront and Loan Options.

Freeboard (ft.)	First-Floor Elevation (ft.)	Freeboard Cost (Upfront)	Freeboard Cost (Loan – Yearly)	Freeboard Cost (Loan – Total)
0.0	–4.0	$0	$0	$0
0.5	–3.5	$2,659	$158	$4,743
1.0	–3.0	$5,317	$316	$9,485
1.5	–2.5	$7,860	$467	$14,022
2.0	–2.0	$10,403	$619	$18,558
2.5	–1.5	$13,061	$777	$23,300
3.0	–1.0	$15,720	$935	$28,043
3.5	–0.5	$18,378	$1,093	$32,786
4.0	0.0	$21,037	$1,251	$37,528

5.1.2 NFIP Premiums

Calculated premiums include the NFIP Community Rating System (CRS) discount of 25% (rating of 5), $6 Increased Cost of Compliance (ICC) premium, reserve fund fee, $25 Homeowner Flood Insurance Affordability Act (HFIAA) surcharge, and $50 federal policy fee. Table 3 shows the calculated flood premiums, where annual premiums decrease with each additional one-foot increment above BFE.

Table 3. Annual Flood Insurance Total Annual Premium (Including $6 for Increased Cost of Compliance (ICC) Premium, $25 Homeowner Flood Insurance Affordability Act (HFIAA) Surcharge, and $50 Federal Policy Fee) by Freeboard Height.

Freeboard (ft.)	First-Floor Elevation (ft.)	Premium	CRS Discount	Reserve Fund Fee	Total Annual Premium
0.0	–4.0	$2,117	$529	$287	$1,954
0.5	–3.5	$2,117	$529	$287	$1,954
1.0	–3.0	$1,070	$268	$146	$1,027
1.5	–2.5	$1,070	$268	$146	$1,027
2.0	–2.0	$665	$166	$91	$669
2.5	–1.5	$665	$166	$91	$669
3.0	–1.0	$538	$135	$74	$556
3.5	–0.5	$538	$135	$74	$556
4.0	0.0	$514	$129	$70	$535

5.1.3 Average Annual Loss (AAL)

AALs are computed for each 0.5-ft. increment of additional freeboard above the BFE up to 4.0 ft., apportioned to the owner and NFIP. Based on the overall results (Table 4), AAL is reduced with each additional freeboard increment, with higher reduction occurring on the smaller increments of freeboard and decreasing reduction as elevation increases.

Table 4. AAL Results for Each Freeboard Height Scenario.

Freeboard (ft.)	First-Floor Elevation (ft.)	Building AAL	Content AAL	Owner Building AAL	Owner Content AAL	NFIP Building AAL	NFIP Content AAL	Total AAL	Avoided Loss
0.0	–4.0	$1006	$137	$56	$13	$950	$124	$1143	$0
0.5	–3.5	$432	$66	$25	$6	$407	$59	$498	$645
1.0	–3.0	$234	$26	$13	$2	$220	$24	$260	$882
1.5	–2.5	$96	$13	$5	$1	$91	$12	$109	$1034
2.0	–2.0	$63	$8	$3	$1	$60	$7	$71	$1072
2.5	–1.5	$25	$3	$1	$0	$24	$3	$28	$1115
3.0	–1.0	$12	$1	$1	$0	$11	$1	$13	$1130
3.5	–0.5	$6	$1	$0	$0	$6	$1	$7	$1136
4.0	0.0	$2	$0	$0	$0	$2	$0	$2	$1141

5.2 Benefit-Cost Analysis (BCA) and Sensitivity Analysis

Tables 5 and 6 show the BCA results presented as life-cycle NB and NBCR for various real discount rates, calculated for each freeboard scenario, as an upfront construction cost and as built into a mortgage, respectively.

Table 5. Results of Life-cycle Benefit-cost Analysis as Shown by Net Benefit (NB) and Net Benefit-cost Ratio (NBCR) Calculated as an Upfront Construction Cost, by Freeboard Scenario and Real Discount Rate.

Freeboard (ft.)		0%	3%	7%	10%	12%
0.5	NB	$16,691	$9,984	$5,345	$3,422	$2,537
	NBCR	6.3	3.8	2.0	1.3	1.0
1.0	NB	$48,983	$30,160	$17,143	$11,746	$9,263
	NBCR	9.2	5.7	3.2	2.2	1.7
1.5	NB	$50,970	$30,577	$16,474	$10,626	$7,936
	NBCR	6.5	3.9	2.1	1.4	1.0
2.0	NB	$60,307	$35,795	$18,845	$11,816	$8,583
	NBCR	5.8	3.4	1.8	1.1	0.8
2.5	NB	$59,779	$34,528	$17,068	$9,827	$6,497
	NBCR	4.6	2.6	1.3	0.8	0.5
3.0	NB	$60,510	$34,085	$15,811	$8,234	$4,748
	NBCR	3.8	2.2	1.0	0.5	0.3
3.5	NB	$57,852	$31,426	$13,153	$5,575	$2,090
	NBCR	3.1	1.7	0.7	0.3	0.1
4.0	NB	$55,823	$29,179	$10,755	$3,115	-$400
	NBCR	2.7	1.4	0.5	0.1	0.0

Table 6. As in Table 5, but Calculated into a Mortgage.

Freeboard (ft.)		0%	3%	7%	10%	12%
0.5	NB	$14,607	$9,544	$6,042	$4,590	$3,922
	NBCR	3.1	3.1	3.1	3.1	3.1
1.0	NB	$44,815	$29,280	$18,537	$14,082	$12,033
	NBCR	4.7	4.7	4.7	4.7	4.7
1.5	NB	$44,808	$29,276	$18,534	$14,080	$12,031
	NBCR	3.2	3.2	3.2	3.2	3.2
2.0	NB	$52,152	$34,073	$21,572	$16,388	$14,003
	NBCR	2.8	2.8	2.8	2.8	2.8
2.5	NB	$49,540	$32,367	$20,491	$15,567	$13,302
	NBCR	2.1	2.1	2.1	2.1	2.1
3.0	NB	$48,187	$31,483	$19,932	$15,142	$12,938
	NBCR	1.7	1.7	1.7	1.7	1.7
3.5	NB	$43,444	$28,384	$17,970	$13,652	$11,665
	NBCR	1.3	1.3	1.3	1.3	1.3
4.0	NB	$39,332	$25,697	$16,269	$12,359	$10,561
	NBCR	1.0	1.0	1.0	1.0	1.0

As shown in Tables 5 and 6, all freeboard scenarios outperform the BFE "no action" scenario. For the upfront option using the baseline real discount rate of 7%, adding freeboard results in NBs ranging from $5,345 to $18,845, with NBCRs ranging from 0.5 to 3.2. The corresponding NBs for the loan option are slightly higher, ranging from $6,042 to $21,572 with considerably higher NBCRs ranging between 1.0 and 4.7.

With the lower 3% real discount rate, the NBs are substantially increased. In the upfront option the range becomes $9,984 and $35,795 with NBCRs ranging from 1.4 to 5.7, representing an increase of approximately 90% from the baseline real discount rate estimates. These numbers are slightly higher compared to the loan option NBs increase, which ranges between $9,544 and $34,073 with unchanged NBCRs. Note that NBCRs for the loan option remain unchanged when applying various discount rates, because both variables of the ratio (benefits and costs) are discounted using the same discount rates. By contrast, for the upfront option only the benefits are discounted, while the costs are provided as initial one-time payments.

When benefits are not discounted (i.e., at 0% discount rate), all future benefits are at their total value, resulting in the highest NBs and NBCRs, especially in the upfront opinion. At a higher discount rate of 10%, the NBs and NBCRs decrease compared to the baseline estimates, with the upfront option offering more decrease than the loan option. However, when the discount rate is increased to 12%, the NBs decrease substantially, ranging from -$400 to $9,263 with NBCRs ranging from 0 to 1.7. For the mortgage option, NBs drop to a range of $3,922 to $14,003.

As can be observed from the NB results, the upfront option performs better with lower discount rates of 0% and 3%, while the loan option performs better with the higher rates of 7%, 10%, and 12%. This result is due to the inverse relationship between the loan's interest rate for the freeboard cost and the discount rate. The PV of the freeboard cost is lower than its current value when the real discount rate used is higher than the loan's interest rate. Conversely, when the loan's interest rate is higher than the discount rate, the PV of the freeboard cost exceeds its current value, resulting in lower NBs.

The NB continues to increase with every additional half-foot of elevation increase, reaching the highest level at 2 ft. of freeboard and then shows an incremental decline. Beyond 2 ft. of freeboard, AAL values are too low and the estimations depend only on flood premium savings and the cost of elevation, with construction costs outweighing flood premium savings, leading to decreased NB. With no premium savings for half-foot increments, the estimations consider only the reduction in flood loss and the cost of elevation, resulting in low NBs and NBCRs. It should be noted that the greater NB increases are occurring for smaller freeboard and gradually decrease with greater freeboard. NBs decrease as real discount rates increase, with the slope of the curves for larger freeboard being steeper than smaller ones, meaning that the NB results for larger freeboard are more sensitive to discount rate changes. Additionally, as the real discount rate increases, the NB differences between freeboard increments are reduced.

Adding 2 ft. of freeboard might be considered the optimal option given that it yields the highest NB. These results demonstrate the utility of using NB to identify the most beneficial scenario. If NBCR had been chosen as the optimization metric, this alternative (i.e., 2 ft) would be ranked below the other loan scenarios (i.e., 0.5, 1.0, and 1.5 ft). The higher NBCRs of these scenarios (i.e., 0.5, 1.0, and 1.5 ft) indicate that as freeboard increases, its value decreases with respect to the aggregated benefits (i.e., less benefit per dollar of cost). This result is expected since the largest portion of flood losses occur at lower flood elevations. For the homeowner, these results suggest that even a small amount of freeboard provides a huge savings, and the message for community planners is that wise planning with reasonable expectations on the front end makes for a more sustainable community.

5.3 Benefits Allocation to Owner

Among other results, the lifetime benefit for each freeboard is differentiated by the beneficiary, where it is apportioned as a homeowner and/or NFIP benefit. While cost of freeboard and savings in flood premiums are considered in the estimation of owner's benefit, the reduction in AAL benefit is assessed to determine the proportions allocated to the owner and the NFIP. Tables 7 presents the owner- -apportioned NB and NBCR, for various real discount rates, calculated for each freeboard scenario, both as an upfront and as a loan option.

With no premium savings for half-foot increments, the estimations consider only the reduction in flood loss and the cost of elevation, resulting in negative NBs and NBCRs for owner share (Table 7). However, by elevating a home only one foot above BFE at a discount rate of 7%, for example, an owner would experience a lifetime NB of \$6,869 for the upfront option and \$8,262 for the mortgage option (Tables 7). However, as freeboard cost is a part of the NBCR estimations, the owner NBCR result is higher with the lower discount rates for the upfront option, while the loan option results remain unchanged when applying various discount rates.

Table 7. Apportioned Net Benefit (NB) and Net Benefit-cost Ratio (NBCR) by Freeboard Scenario and Discount Rate: Owner Share.

Freeboard		Owner/Upfront					Owner/Loan				
(ft.)		0%	3%	7%	10%	12%	0%	3%	7%	10%	12%
0.5	NB	-$1,519	- $1,914	-$2,187	-$2,300	- $2,352	-$3,603	-$2,354	-$1,490	-$1,132	-$967
	NBCR	-0.6	-0.7	-0.8	-0.9	-0.9	-0.8	-0.8	-0.8	-0.8	-0.8
1.0	NB	$24,143	$13,931	$6,869	$3,940	$2,593	$19,975	$13,051	$8,262	$6,277	$5,363
	NBCR	4.5	2.6	1.3	0.7	0.5	2.1	2.1	2.1	2.1	2.1
1.5	NB	$22,020	$11,662	$4,499	$1,529	$163	$15,858	$10,361	$6,560	$4,983	$4,258
	NBCR	2.8	1.5	0.6	0.2	0.0	1.1	1.1	1.1	1.1	1.1
2.0	NB	$30,217	$16,136	$6,399	$2,361	$504	$22,062	$14,414	$9,126	$6,933	$5,924
	NBCR	2.9	1.6	0.6	0.2	0.0	1.2	1.2	1.2	1.2	1.2
2.5	NB	$27,559	$13,478	$3,740	-$297	-$2,155	$17,320	$11,316	$7,164	$5,442	$4,650
	NBCR	2.1	1.0	0.3	0.0	-0.2	0.7	0.7	0.7	0.7	0.7
3.0	NB	$28,290	$13,034	$2,484	-$1,891	-$3,903	$15,967	$10,432	$6,604	$5,017	$4,287
	NBCR	1.8	0.8	0.2	-0.1	-0.2	0.6	0.6	0.6	0.6	0.6
3.5	NB	$25,632	$10,375	-$174	-$4,549	-$6,561	$11,224	$7,333	$4,643	$3,527	$3,014
	NBCR	1.4	0.6	0.0	-0.2	-0.4	0.3	0.3	0.3	0.3	0.3
4.0	NB	$23,603	$8,129	-$2,572	-$7,010	-$9,051	$7,112	$4,646	$2,942	$2,235	$1,910
	NBCR	1.1	0.4	-0.1	-0.3	-0.4	0.2	0.2	0.2	0.2	0.2

The NB for the owner continues to rise up to 2 ft. and gradually declines beyond 2 ft. as AALs are minimal and the estimations start to depend only on premium and the freeboard cost.

5.4 BCA of Freeboard Insurance Savings Only

As flood occurrence is uncertain, if flood loss reduction is not considered when adding freeboard, the savings in annual insurance premiums alone are sufficient to recover the construction costs paid by the homeowner, for one foot of freeboard and above. Table 8 shows the life-cycle NB from annual flood premium savings, with, for example, a range of $11,503 to $17,608 when using a 7% real discount rate. At the same discount rate, the NBCRs range from 0.8 to 2.2. Premium NB results are unaffected by the loan; as a result, there are no differences between estimates in the upfront and loan options. For the first half-foot increment, there are no premium savings.

Table 8. BCA Results of Flood Premiums by Discount Rate, Freeboard Scenario, and Upfront vs. Mortgage Option.

Freeboard (ft.)		Upfront 0%	Upfront 3%	Upfront 7%	Upfront 10%	Upfront 12%
0.5	NB	$0	$0	$0	$0	$0
	NBCR	0.0	0.0	0.0	0.0	0.0
1.0	NB	$27,810	$18,170	$11,503	$8,739	$7,467
	NBCR	5.2	3.4	2.2	1.6	1.4
1.5	NB	$27,810	$18,170	$11,503	$8,739	$7,467
	NBCR	3.5	2.3	1.5	1.1	1.0
2.0	NB	$38,550	$25,187	$15,946	$12,114	$10,351
	NBCR	3.7	2.4	1.5	1.2	1.0
2.5	NB	$38,550	$25,187	$15,946	$12,114	$10,351
	NBCR	3.0	1.9	1.2	0.9	0.8
3.0	NB	$41,940	$27,401	$17,348	$13,179	$11,261
	NBCR	2.7	1.7	1.1	0.8	0.7
3.5	NB	$41,940	$27,401	$17,348	$13,179	$11,261
	NBCR	2.3	1.5	0.9	0.7	0.6
4.0	NB	$42,570	$27,813	$17,608	$13,377	$11,430
	NBCR	2.0	1.3	0.8	0.6	0.5
		Loan				
0.5	NB	$0	$0	$0	$0	$0
	NBCR	0.0	0.0	0.0	0.0	0.0
1.0	NB	$27,810	$18,170	$11,503	$8,739	$7,467
	NBCR	2.9	2.9	2.9	2.9	2.9
1.5	NB	$27,810	$18,170	$11,503	$8,739	$7,467
	NBCR	2.0	2.0	2.0	2.0	2.0
2.0	NB	$38,550	$25,187	$15,946	$12,114	$10,351
	NBCR	2.1	2.1	2.1	2.1	2.1
2.5	NB	$38,550	$25,187	$15,946	$12,114	$10,351
	NBCR	1.7	1.7	1.7	1.7	1.7
3.0	NB	$41,940	$27,401	$17,348	$13,179	$11,261
	NBCR	1.5	1.5	1.5	1.5	1.5
3.5	NB	$41,940	$27,401	$17,348	$13,179	$11,261
	NBCR	1.3	1.3	1.3	1.3	1.3
4.0	NB	$42,570	$27,813	$17,608	$13,377	$11,430
	NBCR	1.1	1.1	1.1	1.1	1.1

6 Assumptions and Limitations

This study relies on several assumptions. First, the depth-loss functions are assumed to be comprehensive of all loss experienced and are accurate. This assumption is known to be questionable, as Wing et al. (2020) have evaluated the sensitivity of flood loss avoidance to depth-loss functions. This remains an area of significant future research that will enhance the accuracy of results produced through the presented LCBCA methodology. Second, the allocation of owner and NFIP benefit implicitly assumes that flood insurance provides replacement value for damaged items. While this is true for NFIP building coverage, NFIP contents coverage only compensates actual cash value (Kousky, 2018), resulting in an unquantified burden upon the homeowner. This issue has not been robustly addressed in flood loss reduction research and is also an area that merits further attention. More generalized understanding is needed to know how insurance affect owner loss (i.e., building and content). Third, FEMA (2008) values for construction cost estimates were used in the calculation. These values should ideally be replaced by robust cost estimates that consider varying foundation types and more research in this area is encouraged as these improved estimates would enhance the quality of all flood mitigation research. Finally, while a sensitivity analysis was performed to evaluate the robustness of the calculations under varying real discount rates, the NB and NBCR are very sensitive to these rates, indicating more research into representative scenarios would be appropriate.

While results provide strong evidence for the value of freeboard, some limitations of the research must be considered. Life-cycle benefit-cost estimations are impacted by high uncertainty since they rely on uncertain variables related to the unpredicted nature of flood occurrence and generality of flood loss functions. Moreover, LCBCA requires future projections of variables such as discount rates that are highly uncertain. While acknowledging the limitations, the methodology proposed in this study offers an improvement to the topic of establishment of the economically optimal elevation of single-family residences through LCBCA.

Furthermore, flood risk reduction and savings in premiums are only some of the apparent gains from including a modest amount of freeboard at the time of construction. Other lifetime benefits that are either unquantifiable or not addressed here include the reduction of inconvenience, health impacts, and suffering, reduced loss of items of sentimental value and other intangible losses such as the environmental and social costs, and faster recovery time from flood disaster, along with increased curb appeal and therefore property values. Also, because this work neglected the possible future effects of climate change (Aerts and Wouter Botzen, 2011) and increase in asset values, the estimates are considerably conservative and underrepresent the true benefits of adding freeboard. The savings at the community level are also substantial, as communities can receive further reductions in insurance premiums from CRS, where elevation increase is one of the conditions for reduced premiums. Yet despite these evident benefits, many homeowners and communities do not take mitigation into account, suggesting that the benefits are not communicated effectively. As a result, benefits are underutilized.

7. Summary and Conclusions

A probabilistic LCBCA is performed to identify the economically optimal elevation of single-family residences at the time of construction by evaluating the performance of various freeboard scenarios. Life-cycle NB are disaggregated as owner benefit and NFIP benefit, and the decision criteria consider both flood AALs and annual premiums. The aim is to support effective decision making with a reliable methodology that improves the quantification, provides actionable information, and communicates clear results to stakeholders.

Results suggest that adding a reasonable amount of freeboard at the time of construction is a wise investment for the individual, community, and NFIP. For example, a case study analysis of a 2,000 square foot home in Metairie, Louisiana, shows that adding two feet of freeboard at an investment cost of $10,403, or 4.5% of the at-BFE construction cost of the home, optimizes the total life-cycle NB at $21,572, with a 2.8 NBCR in the loan option, assuming the baseline real discount rate of 7%. The corresponding NB from annual flood premium savings alone is $15,536 with a 2.1 NBCR.

This optimal two feet of freeboard would add only $52 to the monthly payment of the 30-year mortgage with a fixed rate of 3.375%, while resulting in a reduction in NFIP premium of $107 on a monthly basis. This result demonstrates that even if the value of flood loss reduction is neglected, NFIP premium savings alone are sufficient to offset the increased initial construction cost, resulting in monthly owner savings. This benefit increases after mortgage payments are complete, as there is no offsetting cost.

Significant future work remains to refine the individual elements of the LCBCA calculation. Results highlight the need to perform the LCBCA using a range of real discount rates to ensure better interpretation of the benefits by highlighting the sensitivity of the results to the used discount rate. While this work is restricted to the single-building level, upscaling the LCBCA methodology is an important next step, while making use of the life-cycle NB results at the building scale, which allows aggregation to larger spatial levels with a higher level of accuracy. Future research should also consider the impacts of climate change, following Xian et al. (2017), and its economic costs. Regardless, the research provides a strong first step in ensuring greater financial and community resilience to the flood hazard.

Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Author Contributions

EG developed the methodology, collected and analyzed the data, interpreted the findings, and drafted the manuscript. CF conceptualized the research idea, helped refine the methodology, and reviewed and edited the manuscript. RBM selected the study area, prepared the base flood data, organized the paper, and edited the manuscript. MAR improved the method, verified the results, edited the Monte Carlo simulation, and edited the manuscript. TG coded the Monte Carlo simulation and helped in the calculations. RR reviewed and edited earlier versions of the manuscript. AT provided advice and contributed to the literature review.

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Data Availability Statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation, to any qualified researcher.

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