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Single-Family Residential Flood Loss Reduction through Freeboard

Ehab Said Gnan

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SINGLE-FAMILY RESIDENTIAL FLOOD LOSS REDUCTION THROUGH FREEBOARD

A Dissertation

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

in

The Donald W. Clayton Graduate Program in
Engineering Science

by

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for my parents

for my family

for all those affected by floods

for TamaXight, my inspiration

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Table of Contents

Acknowledgments.....	iii
List of Tables	vii
List of Figures	ix
Abstract	x
Chapter 1. Introduction	1
1.1. Problem Statement	3
1.2. Goals of the Study.....	3
1.3. Scope of the Study	3
1.4. Limitations of the Study.....	4
1.5. Organization of the Dissertation	4
Chapter 2. Micro-Scale Average Annual Loss (AAL) for Single-Family Homes	6
2.1. Introduction.....	6
2.2. Methodology	8
2.3. Sensitivity Analysis	11
2.4. Methods Comparison	13
2.5. Case Study	15
2.6. Results and Discussion	16
2.7. Conclusions.....	24
Chapter 3. Economically Optimal Freeboard for Single-Family Homes	27
3.1. Introduction.....	27
3.2. Methodology	30
3.3. Sensitivity Analysis	41
3.4. Case Study	43
3.5. Results.....	44
3.6. Conclusions.....	53
Chapter 4. Freeboard Life-Cycle Benefit-Cost Analysis for Landlord and Tenant.....	57
4.1. Introduction.....	57
4.2. Methodology	58
4.3. Case Study	67
4.4. Results.....	68
4.5. Conclusions.....	73
Chapter 5. Conclusions	76
5.1. Introduction.....	76
5.2. Flood Risk Assessment	76
5.3. Determining the Optimal Freeboard through Life-Cycle BCA	77
5.4. Freeboard Life-Cycle Benefit-Cost Analysis for Landlord and Tenant	79
5.5. Limitations and Future Work.....	80

References	82
Vita.....	90

List of Tables

2.1. Case Study Flood Depths and Elevations	16
2.2. AAL Results for Each Freeboard Scenario for Metairie, Louisiana, Case Study.....	17
2.3. AAL Results Using USACE (2000), USACE (2006), Wing et al. (2020), and Nofal et al. (2020).....	18
2.4. AAL Results for Elevations Above FFE Using USACE (2000), USACE (2006), Wing et al. (2020), and Nofal et al. (2020).....	20
2.5. AAL Results Calculated as Piecewise Product of Annual Probability of Exceedance and Loss, for the Metairie, Louisiana, Case Study.....	21
2.6. AALs using Log-Linear Extrapolation, for Metairie, Louisiana, Case Study	22
2.7. AAL Results Calculated using Monte Carlo Simulation	22
3.1. Average Cost of Construction Increase (%), by FEMA Flood Zone and Foot of Freeboard .	32
3.2. Site's Flood Elevations and Corresponding Depths Above Ground	44
3.3. Freeboard Cost for Upfront and Loan Options	45
3.4. Annual Flood Insurance Premium by Freeboard Height	45
3.5. AAL Results for Each Freeboard Height Scenario.....	46
3.6. Life-cycle BCA Results for Each Freeboard Scenario – Upfront.....	47
3.7. Life-cycle BCA Results for Each Freeboard Scenario – Loan	48
3.8. Apportioned NB and NBCR for Each Freeboard Scenario – Owner	51
3.9. Apportioned NB and NBCR for Each Freeboard Scenario – NFIP.....	52
3.10. BCA Results of Flood Premiums for Each Freeboard Scenario.....	54
4.1. Average Cost of Construction Increase (%), by FEMA Flood Zone and Foot of Freeboard .	60
4.2. FEMA's Depth-Restoration Time for Multiple Flood Depths	63
4.3. Site Flood Elevations and Corresponding Depth Above Ground.....	67
4.4. Landlord's Expected Annual Costs by Freeboard Height	69

4.5. Tenant Annual Costs for Each Freeboard Height Scenario	70
4.6. BCA Results for Each Freeboard Scenario.....	71
4.7. Premium BCA Results for Each Freeboard Scenario by Discount Rate	73

List of Figures

2.1. USACE (2000) Depth-Damage Curve for a One-Story Home without Basement.....	10
2.2. Comparison of AALs from All Functions for Each Freeboard Scenario, for the Metairie, Louisiana, Case Study.....	19
2.3. Loss-Probability Relationship for BFE.....	21
2.4. Comparison of Results from Various Methods for Each Freeboard Scenario, for the Metairie, Louisiana, Case Study.....	23
3.1. NB and NBCR Results for (a) Upfront (b) Loan.	49

Abstract

The lack of flood loss estimation methods conducted on a micro-scale level that consider the full loss-exceedance probabilities curve poses a significant problem in flood risk assessment. Also, the lack of robust benefit-cost analysis (BCA) that quantifies benefits at the micro-scale level leads to sub-optimal results, and therefore sub-optimal decisions when determining the optimal freeboard. Further, flood loss assessments focus on owner-occupied housing and neglect rental housing. These loss assessment deficiencies underscore the need for a robust assessment that quantifies the life-cycle benefits for all stakeholders and provides actionable information to enable informed decisions.

This research presents a comprehensive methodology such that the life-cycle benefits of adding freeboard for homeowners, landlords, and tenants are evaluated at the single-residence building level using life-cycle BCA. The expected average annual loss (AAL) from flooding is determined through the numerical integration of the full loss-exceedance probabilities curve. The optimal freeboard is determined through a micro-scale BCA with life-cycle benefits disaggregated and allocated to the proper parties.

The results show that while the construction cost of adding freeboard is modest, the life-cycle benefits of avoided losses and savings are substantial. Results highlight the need to assess flood risk at the micro-scale level for a more localized and accurate assessment, where it can be upscaled in a “bottom-up” approach for a higher degree of accuracy. The results also highlight the need to include rental housing and underscore the need for a robust life-cycle BCA that provides actionable recommendations to landlords and tenants.

The numerical integration AAL estimation method introduced in this research is fundamental, with only few parameters required to reduce the increased prediction uncertainty

associated with more complex models requiring more input parameters. Further, this research provides a robust, generalized methodology to evaluate the benefits of adding freeboard through a micro-scale life-cycle BCA. Moreover, this work provides a novel framework for quantifying life-cycle benefits of freeboard for landlord and tenant in a single-family rental housing. All methodologies introduced in this research are developed generally and can be adapted for new data, loss functions, and other input.

Chapter 1. Introduction

A recent report suggests that average annual losses (AALs) from floods are currently \$104 billion worldwide (United Nations Office for Disaster Risk Reduction, 2015). These losses are projected to increase as a combined result of increased economic vulnerability and increasing severity and frequency of extreme weather events (Botzen and van Den Bergh, 2008; Evans et al., 2006; Hino and Hall, 2017; Kunreuther and Michel-Kerjan, 2007). Yet many individuals and communities continue to underestimate the possibility of flood losses, indicating that flood frequency and possible losses are not understood clearly and that the potential benefits of mitigation measures are not communicated effectively (Burningham et al., 2008; Merz et al., 2015; Mol et al., 2020; Parker et al., 2009). Furthermore, the lack of robust flood risk assessment that quantifies flood losses at the micro-scale (i.e., individual building) level discourages investment in flood mitigation (de Ruig et al., 2019). To increase the availability of information and enhance individual and community resilience and sustainability by planning for and adapting to flood hazard exposure, a robust flood risk assessment that quantifies losses at the micro-scale and provides actionable information for stakeholders is needed.

AAL is used as the basis for risk evaluation in risk mitigation measures (Dalezios, 2017). However, it is common practice in flood risk assessment to use only the available data of exceedance probabilities, despite the fact that flood losses arise from all possible flood events (Oliver et al., 2019). Additionally, failure to characterize flood risk at the single-building level limits the amount of information provided about the building's flood risk (Armal et al., 2020). Thus, a comprehensive assessment that quantifies AAL at the micro-scale level and covers the full loss-exceedance probabilities curve is needed to provide actionable information to stakeholders and enable informed decisions about their flood risk reduction management.

Elevation increase of a building's first floor above the 1% annual probability of exceedance event – in the U.S., the base flood elevation (BFE) – is known as “freeboard”. Although freeboard represents a sound investment as a mitigation measure (Multihazard Mitigation Council, 2017), determining the optimal height of freeboard poses a significant decision problem (Zarekarizi et al., 2020). Also, as flooding is a low-probability with high-impact event, it is prudent to evaluate the flood loss within a long time frame, such as the building's life-cycle (Dong and Frangopol, 2017). Integrating flood risk assessment and life-cycle benefit-cost analysis provides an ideal approach for quantifying the cost-effectiveness of mitigation measures (de Risi et al., 2018). Therefore, the development of a comprehensive methodology that determines the optimal freeboard height at the micro-scale level through a life-cycle BCA is essential.

In addition to single-family home owners, many landlords and tenants in single-family rental housing do not understand their flood risk (Hollar, 2017). Single-family home rental represents an increasing share of the housing industry in the U.S. (Charles, 2020), with 14.9 million renter-occupied single-family homes as of 2017 (Rosen, 2018). Nevertheless, flood risk to single-family rental housing has been neglected by decision makers and the scientific community. FEMA has acknowledged that the nation's flood policies neglect rental housing and focus only on owner-occupied housing (Hamideh et al., 2018). The absence of studies conducted on this subject leaves a large segment of the population without adequate protection due to the lack of information. This necessitates the need to develop a comprehensive flood risk assessment that quantifies flood losses for single-family rentals at the micro-scale level and provides actionable information to landlords and tenants.

1.1. Problem Statement

The lack of AAL estimation methods conducted on a micro-scale level basis that accounts for the uncertainties surrounding flood event probabilities poses a substantial problem in flood risk assessment. Also, the lack of robust benefit-cost analysis (BCA) that quantifies costs and benefits at the micro-scale level leads to sub-optimal results, and therefore sub-optimal decisions when determining the optimal freeboard height. This together with the fact that flood loss assessments focus only on owner-occupied housing and neglect rental housing underscores the need for a robust flood risk assessment that provides actionable recommendations to the affected parties.

1.2. Goals of the Study

The goal of this dissertation research is to improve the ability to estimate the flood losses to enhance the understanding of the flood risk. As a step toward achieving this goal, the following objectives are undertaken:

- Develop a methodology to estimate flood AAL for single-family homes at the micro-scale level in a way that covers the full loss-exceedance probabilities curve.
- Develop a methodology to determine the optimal freeboard height for single-family homes through a micro-scale life-cycle BCA, disaggregating and allocating life-cycle benefits to the proper parties (policyholder and/or National Flood Insurance Program (NFIP)).
- Develop a methodology to evaluate the benefits of adding freeboard through a micro-scale life-cycle BCA for both landlord and tenant in single-family rental housing.

1.3. Scope of the Study

This work targets the one-story, single-family home and focuses on flood loss reduction through freeboard. This dissertation quantifies the life-cycle costs of flood hazards to homeowners, landlords, and tenants as compared to the mitigation cost at the single-residence

building level. Life-cycle performance of adding freeboard is evaluated in terms of its benefits from loss reduction as compared to its cost using life-cycle BCA, in which the future benefits of the mitigated scenario are calculated and compared to its total cost. The outcome, net benefit (NB) and net benefit to cost ratio (NBCR) are the two metrics used to aid stakeholders to decide which freeboard scenario results in the highest life-cycle benefits. A one-story, single-family residence in Metairie, Louisiana, is used to demonstrate the methodologies presented in the study.

1.4. Limitations of the Study

This study is limited to one-story, single-family homes. These types of risk assessments are highly constrained by data available, where the accuracy and reliability of results are limited by the quality of data and availability. Also, the estimations are impacted by high uncertainty related to the unpredicted nature of flood occurrence and the generality of flood loss functions. Additionally, the analysis requires future projections of variables such as discount rates that are highly uncertain. Further, the study does not consider the environmental and social impacts, future asset value increase, and the potential negative effects of climate change. As a result, the estimates are considerably conservative and underrepresent the true benefits of adding freeboard. However, the methodology is developed generally and can be adapted for new data, loss functions, and other input. While acknowledging the limitations, this work offers an improvement to flood loss modeling and freeboard life-cycle BCA.

1.5. Organization of the Dissertation

This dissertation is organized by objective topic. Chapter 2 presents a micro-scale level AAL estimation for single-family homes using numerical integration and extreme value probability function. Chapter 3 determines the economically optimal freeboard for single-family

residences through a life-cycle BCA. Chapter 4 presents a freeboard life-cycle BCA for landlord and tenant.

Chapter 2. Micro-Scale Average Annual Loss (AAL) for Single-Family Homes

2.1. Introduction

AAL is used as the basis for risk evaluation in risk mitigation measures (Dalezios, 2017). However, it is common practice in flood risk assessments to use only the available data of exceedance probabilities, despite the fact that flood losses arise from all possible flood events (Oliver et al., 2019). Additionally, failure to characterize flood risk at the single-building level limits the amount of information provided about the building's flood risk (Armal et al., 2020). Thus, a comprehensive assessment that quantifies AAL at the micro-scale level and covers the full loss-exceedance probabilities curve is needed to provide actionable information to stakeholders and enable informed decisions about flood risk reduction management.

As the probability of disastrous flood events in any given year is low, communities and individual property owners often perceive these potential risks to be below the threshold level of concern and deem protection unnecessary (United States Senate, 2011). Studies on risk perception have shown that most individuals do not understand low probabilities well when considering protection against risks (United States Senate, 2011). The language used to communicate flood risks also influences the way communities and individuals perceive these risks. In the U.S., flood risk is typically understood in terms of whether a building is elevated above or below the 1% (i.e., 100-year) annual probability of exceedance (APE) event flood elevation [aka: base flood elevation (BFE)]. The BFE is typically used as the design flood elevation (DFE), even though it may provide a misleading measure of the flood risk. With no additional elevation (i.e., "freeboard") to serve as added protection against flooding, the probability of annual probability of exceedance being exceeded in 70 years (i.e., the life expectancy of a house) is 50.3%. Thus, without freeboard, half of all houses in the special flood hazard area (SFHA; area of the 1% APE flood) are expected to flood at least once, with 15.6%

expected to flood twice during their expected life span (Hawkesbury-Nepean Floodplain Management Steering Committee, 2006). This startling fact underscores the need for improved communication regarding the hazard, as, in addition to the unnecessary danger to life, wise economic investment in buildings and communities should come with the expectation that far less than half will be flood damaged during their life span.

Although flood risk assessment has been investigated in numerous studies, only a few have been focused at the individual building level. Risk assessment at single-building level informs community-level risk reduction decisions effectively, as vulnerability within urban regions is generally assessed at the object level (Arrighi et al., 2018). To capture spatial characteristics having buildings with different levels of exposure, a micro-scale level flood risk assessment is needed (Molua, 2012; Rehan, 2018). Micro-scale flood risk assessment is characterized by a higher degree of detail and accuracy (Aerts and Wouter Botzen, 2011; Bubeck et al., 2011; Kebede and Nicholls, 2012; Lorente, 2019). Such an approach supports customized decision-making by location, building configuration, and budget (Orooji and Friedland, 2017).

A few recent, micro-level studies of flood risk modeling are particularly relevant to this research. However, each have some potential limitations. Montgomery and Kunreuther (2018) estimated AAL from flood hazards for single-family residences based on U-surge flood hazard data and Hazus depth-damage functions. Armal et al. (2020) introduced a climate-adjusted, economic-focused environmental impact assessment that uses a parcel-specific flood depth. While these studies provide useful analyses and represent an important innovation, it is still possible to further improve. The studies excluded events that have an annual probability of exceedance of less than 0.02-percent (i.e., greater than 500-year flood). Severe flood events are

not limited to the 500-year floods. Moreover, the annual probabilities are based on observed data without considering the associated uncertainty or modeling the probability of different outcomes.

The proposed work presents a comprehensive methodology that quantifies AAL at the micro-scale level and covers the full loss-exceedance probabilities curve. The Gumbel distribution is fitted to determine the corresponding annual probability of exceedance for given flood depths. The AAL is determined through a numerical integration of the product of flood probability and loss functions. The estimations are carried out for each half-foot increment of additional elevation (i.e., freeboard), to allow for loss comparison.

A hypothetical one-story, single-family residence in Metairie, Louisiana, is selected to demonstrate the methodology. A sensitivity analysis is conducted to examine the extent of the uncertainty linked to the depth–damage function. Additionally, this study’s results are contrasted with three other methods used for estimating the expected AAL from flooding.

2.2. Methodology

AAL is calculated by integrating the product of the probability density function (PDF) of flood event annual probability of exceedance and the flood loss function, across a range of flood elevations, such that

$$AAL = \int_{-\infty}^{\infty} f(E)L(E)dE \quad (2.1)$$

where E represents the flood elevation [North American Vertical Datum of 1988 (NAVD 88)], $f(E)$ is the PDF, and $L(E)$ is the loss curve as a function of flood elevation.

While theoretically the range of flood elevations is infinite, in reality the flood magnitude in any given area lies within a range of finite minimum and maximum flood elevations estimated for various return periods.

2.2.1. Return Periods and Flood Elevations

An extreme value distribution function is needed to define the return periods and their corresponding flood elevations. Driven by the right-skewed nature of flood return periods, exceedance probabilities for the expected flood elevations are modeled using the two-parameter Gumbel extreme value distribution, which is the most accepted method for flood frequency analysis (Kumar and Bhardwaj, 2015; Malakar, 2020; Patel, 2020; Singh et al., 2018):

$$f(E) = \left(\frac{1}{\alpha}\right) \exp\left[-\left(\frac{E-u}{\alpha}\right) - \exp\left(-\left(\frac{E-u}{\alpha}\right)\right)\right] \quad (2.2)$$

where u and α are the calculated, site-specific location parameter and scale parameter, respectively. The parameters are obtained by fitting the available data using logarithmic regression.

2.2.2. Depth-Damage Function

The relationship between flood depth and loss (in percentage of building) is determined using the depth-damage functions for a one-story home with no basement. United States Army Corps of Engineers (USACE) is considered the main source of depth-damage functions (Multihazard Mitigation Council, 2017). USACE depth-damage curves return the mean percentage of building and content loss that a residence is expected to encounter given a specific flood depth. As shown in Figure 2.1, the middle trendline in both the top and bottom groups represents the mean damage amount expected to be experienced at a given flood depth above first floor, while the trendlines directly above and below the mean represent the 95% confidence interval.

Flood depth above first floor, D , is determined from the predicted flood elevation (E) less first floor elevation (FFE) of the building, or

$$D = E - FFE \quad (2.3)$$

USACE depth-damage functions account for the structure below FFE by assigning percent losses to negative flood depths for buildings without basement, as shown in Figure 2.1. This procedure accounts for the impacts to floor structure and other structural elements including electrical, plumbing, and mechanical systems that may be located below the building's FFE. Although the USACE depth-damage functions start at -2 ft. flood depth, in this work the building loss is truncated to only calculate losses starting at -1 ft., and content losses at negative flood depths (i.e., below the building's first floor) are assumed to be zero.

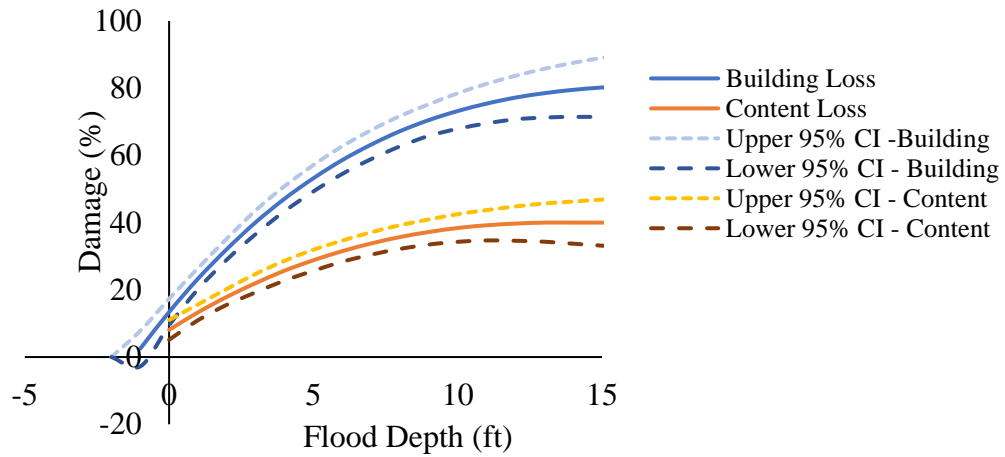


Figure 2.1. USACE (2000) Depth-Damage Curve for a One-Story Home without Basement

2.2.3. Average Annual Loss

A fitted Gumbel distribution is utilized to sample flood probabilities corresponding to various flood depths. The product of these probabilities and the corresponding flood loss PL are integrated using piecewise, numerical Riemann sums to obtain the AAL, or

$$AAL = \sum_{i=1}^n \left(\frac{PL_i + PL_{i+1}}{2} \right) \cdot (D_{i+1} - D_i) \quad (2.4)$$

where n and D are the return periods and flood depth, respectively, and i is the numerator for different return periods.

Resulted $AAL_{b\%}$ and $AAL_{c\%}$ represent the building and content AAL, respectively. Total $AAL_{\%}$ is the accumulation of building and content AAL percentages based on the building's value, such that

$$AAL_{\%} = AAL_{b\%} + AAL_{c\%} \quad (2.5)$$

AAL is general, while $AAL_{\%}$ and $AAL_{\$}$ are percentages of the value and absolute currency, respectively. To calculate AAL in absolute currency, $AAL_{\$}$ is the product of $AAL_{\%}$ and building value (BV), or

$$AAL_{\$} = AAL_{\%} \cdot BV \quad (2.6)$$

2.3. Sensitivity Analysis

Depth-damage functions are key components upon which loss assessments are based and are accepted worldwide as the standard method in estimating flood loss (Apel et al., 2009). However, flood loss assessments are affected by considerable uncertainty (Freni et al., 2010; Notaro et al., 2014; Scorzini and Frank, 2017). Uncertainty derived from these functions is the main bottleneck in assessing losses (Wing et al., 2020). To enhance the decision-making process, a sensitivity analysis with regard to the extent of the associated uncertainty is necessary.

In this study, a sensitivity analysis is conducted to examine the uncertainty related to the depth-damage function choice. AAL is quantified as a function of flood depths and their expected losses determined by the adopted USACE (2000) depth-damage function. The AAL is then estimated further using three additional depth-damage functions, and the results are then contrasted as described in the next paragraph.

The degree to which the local conditions of the studied site influence the outcome of loss assessment is examined by comparing the results of the generic USACE (2000) depth-damage function to the results of an area-specific USACE (2006) depth-damage function developed by

USACE for southern Louisiana, which includes the study site. USACE (2000) is based on actual losses from flood victims' records using data collected from major flooding events that occurred across the U.S. between 1996 and 1998. By contrast, USACE (2006) is derived as average loss percentages from multiple freshwater depth-damage functions with various hydrologic conditions and foundation types that are specific to that area. USACE (2006) was developed using local expert opinion estimates and interviews of the homeowner and commercial sector in southern Louisiana. The results of applying USACE (2000) are also contrasted with the results of two depth-damage functions developed recently by Wing et al. (2020) and (Nofal et al., 2020). For Wing et al. (2020), the function is a derived set of distributions of structural losses from NFIP flood damage claims over the 1972 to 2014 period. Nofal et al. (2020) used expert-based data derived from literature, online sources, and others that are applied within a Monte Carlo framework. While Nofal et al. (2020) developed loss functions for multiple archetypes, the loss function corresponding to a one-story, single-family residential building on a crawlspace foundation is adopted here, as it is comparable with the other functions.

While other depth–damage functions are available, USACE (2006) is selected for this sensitivity analysis as it is specific to the area where the case study is located. Wing et al. (2020) and Nofal et al. (2020) are selected for this sensitivity analysis as they are considered the most recent comprehensive work in loss function area. Moreover, all these functions are comparable with the classification (e.g., occupancy type, number of stories, presence of basement, measured by depth, loss as a percentage of building replacement cost) of the adopted USACE (2000) function. This to ensure a consistent and effective comparison between the functions. It is noteworthy that Wing et al. (2020) consider only building loss, whereas all the other functions

consider both the building and content losses. While USACE (2000) and USACE (2006) separate building loss from content loss, Nofal et al. (2020) integrates both in one function.

Although the USACE depth-damage functions begin at -2 ft. depth and at -3 for Nofal et al. (2020), to provide a conservative measure these functions are truncated in the present study to only calculate building losses beginning at -1 ft. Wing et al. (2020) attributes no loss percentages below the building's first floor. However, in this study, all content losses at negative flood depths (i.e., below the building's first floor) are considered to have no losses. Additionally, building AAL estimates from all the functions are provided for only above FFE (i.e., building losses beginning at 0 ft.), to examine the effects of excluding floor structure and other structural elements that may be located below the building's FFE.

2.4. Methods Comparison

This study's results are contrasted with three other methods for estimating the expected AAL from flooding. The three methods are: (i) AAL is calculated as traditional piecewise product of annual probability of exceedance and loss in which results are integrated by means of a Riemann sum using only the available return periods for the site, (ii) a piecewise approach with log-linear extrapolation to extend the record to longer return periods of interest with estimates then integrated using Riemann sum approximation, and (iii) a Monte Carlo simulation process with fitted probability distribution.

2.4.1. AAL as Traditional Piecewise Product of Probability and Loss

This paper's results are contrasted with a traditional method used in the area of flood risk loss assessment (e.g., FEMA, 2013; Montgomery and Kunreuther, 2018), in which AAL is calculated as piecewise product of annual probability of exceedance and loss using only the available return periods for the site.

To estimate AAL using the traditional method, losses associated with the site's available return periods (10-, 50-, 100-, and 500-year return periods, with 0.1, 0.02, 0.01, and 0.002 annual exceedance probabilities, respectively) are calculated directly as piecewise of annual probability of exceedance and loss using depth-loss functions and the value of the building. Result of annual probability of exceedance and loss products are aggregated using the (FEMA, 2013) Riemann sum equation to obtain the total AAL, as

$$AAL = (f_{10} - f_{50}) \cdot \frac{L_{10} + L_{50}}{2} + (f_{50} - f_{100}) \cdot \frac{L_{50} + L_{100}}{2} + (f_{100} - f_{500}) \cdot \frac{L_{100} + L_{500}}{2} + (f_{500} \cdot L_{500}) \quad (2.7)$$

where, f_i is the flood frequency (i.e., annual probability of exceedance) of the return period, and L_i is the loss corresponding to the return period.

2.4.2. AAL Using Log-linear Relationship

A piecewise approach with log-linear extrapolation is used to extend the time range of the return periods (e.g., Arnbjerg-Nielsen and Fleischer, 2009), with losses at new flood depths determined. AAL estimates are obtained by Riemann sum approximation. In this method, trendlines obtained through regression analyses of the available data are used to derive multiple equations that represent losses from flood elevations in relation to the freeboard heights. Values of available return periods' annual probabilities are plotted against their expected losses to obtain the regression equation, such that

$$L = u + \alpha \ln(P) \quad (2.8)$$

where L represents loss (\$), P is the annual probability of exceedance of the return period, and u and α are the site-specific location and scale parameters, respectively.

From the derived equations, losses are extrapolated to a higher return period time range. The expected losses of all events with different probabilities are aggregated using Riemann sums to estimate the overall AAL.

2.4.3. Monte Carlo Simulation

A synthetic flood record is generated using Monte Carlo simulation with the fitted distribution function (e.g., Zarekarizi et al., 2020). The relationship between flood depth and its expected loss is determined using the depth-damage function. The expected annual losses for building and content from all simulated flood events with randomly varied probabilities are accumulated and averaged to estimate the overall AAL of each elevation increase.

Using the generated simulation over the total number of simulations, N , AAL for building and content is the summation of all losses divided by total simulations, N , or

$$AAL = \frac{1}{N} \sum_{i=1}^N F^{-1}[Rand(i)] L(E_i) \quad (2.9)$$

where i is the simulated event between N simulations, $Rand(i)$ is a random value between zero and one, $F^{-1}[Rand(i)]$ is the inverse cumulative distribution function of the simulated event, and $L(E_i)$ is the loss corresponding to annual flood elevation of that event (E_i).

2.5. Case Study

A case study was performed in Metairie, Louisiana, to demonstrate the scenario for new construction of a one-story, single-family home with 1,800 ft² of living area. The case study is located in the metropolitan New Orleans area within Jefferson Parish (County) at coordinates 29.994385°N, -90.168238°W. The ground elevation of the site is -7.0 ft. (NAVD88), obtained from the 1/9 arc second digital elevation model (DEM), determined by FEMA-developed Lidar. The site is located on NFIP Map Panel 22051C0185F within zone AE -4, indicating that the BFE is -4 ft. (NAVD 88). Note that much of the metropolitan New Orleans area is protected by

various flood protection systems, such as levees, pumping stations, and flood gates (Wilkins et al., 2008). Jefferson Parish requires 0.5 ft. of freeboard, yielding a “code compliant” top of lowest floor of −3.5 ft. NAVD88.

In 2019, the average cost of constructing a single-family residence in the New Orleans area was \$92.47 per square foot (Moselle, 2019), which yields an estimated construction cost for a 1,800 ft² residence of \$166,446.

From the Jefferson Parish, Louisiana, flood depth grids developed by the Risk Mapping, Assessment and Planning (RiskMAP) program, flood depths of the 10-, 50-, 100-, and 500-year return periods, with 0.1, 0.02, 0.01, and 0.002 annual probability of exceedance (APE) are 2.3-, 2.8-, 3.1-, and 3.6-ft. above local ground, respectively. The site’s ground level and flood depth values for each return period are calculated using bilinear interpolation, which is a weighted average of all values of the cells covering the site. Weights are applied based on distance of the cell from the center of the site, where the centroid cell represents the site’s geometric center and has the greatest weight. The corresponding flood depths above ground are calculated as shown in Table 2.1.

Table 2.1. Case Study Flood Depths and Elevations

Annual Probability Of Exceedance	Flood Elevation (NAVD88)	Flood Depth (ft.)
0.002	−3.4	3.6
0.01	−3.9	3.1
0.02	−4.2	2.8
0.1	−4.7	2.3

2.6. Results and Discussion

AAL estimations are carried out for each half-foot increment of additional freeboard above the BFE up to 4.0 ft., to allow for loss comparison. A sensitivity analysis is conducted to examine the extent of the uncertainty linked to the depth–damage function. The results of this

study are further contrasted with the three other methods used for estimating the expected AAL of flooding.

2.6.1. AAL and Avoided Losses

To evaluate freeboard effectiveness in risk reduction and determine the avoided losses, the performance of each additional elevation increase is investigated. The estimations are carried out for each half-foot increment of additional freeboard, to allow for loss comparison. A fitted Gumbel distribution is used to sample flood probabilities corresponding to various flood depths. The product of the probabilities and the corresponding loss percentages from the loss function are integrated using piecewise, numerical Riemann sums to calculate the AAL. The expected AALs for building and content are accumulated to estimate the overall AAL of each freeboard increment. The results summarized in Table 2.2 show that AAL is reduced with each additional 0.5 ft. of freeboard increase until it is eliminated at 2 ft., with greater reduction occurring for smaller freeboard and the reduction decreasing gradually as freeboard increases. However, the cumulative reduction in AAL continues to increase with each additional freeboard increase until reaching 2 ft., where AALs are eliminated and continue unchanged beyond that freeboard amount.

Table 2.2. AAL Results for Each Freeboard Scenario for Metairie, Louisiana, Case Study

Freeboard (ft.)	First-Floor Elevation (ft.)	Building AAL	Content AAL	Total AAL	Avoided Loss
0.0	-4.0	\$2,237	\$186	\$2,423	\$0
0.5	-3.5	\$534	\$42	\$576	\$1,847
1.0	-3.0	\$122	\$0	\$122	\$2,301
1.5	-2.5	\$27	\$0	\$27	\$2,396
2.0	-2.0	\$0	\$0	\$0	\$2,423

Constructing the single-family home with additional freeboard reduces flood losses in flooding events considerably. Adding one half-foot of freeboard decreases annual losses by 76%

and offsets the cost of that increase in elevation in just one year. Similarly, increasing the elevation by 1 ft. results in 95% of decreased annual losses and the cost of the freeboard is offset in less than two years. Adding 2 ft. of freeboard eliminates flood annual losses and the associated cost is recovered in just three years. Although the AAL analysis covers the full loss-exceedance probabilities curve including larger flood events with very low frequencies, elevating the home an additional 2 ft. above that required provides an adequate protection.

2.6.2. Sensitivity Analysis

Sensitivity analysis is carried out to examine the effect of uncertainty related to the depth–damage function choice and its effect on results. AALs were further computed for each half-foot increment of additional elevation increase using USACE (2006), Wing et al. (2020), and Nofal et al. (2020) functions. The results are summarized in Table 2.3.

Table 2.3. AAL Results Using USACE (2000), USACE (2006), Wing et al. (2020), and Nofal et al. (2020)

Freeboard (ft.)	USACE (2000) AAL	USACE (2006) AAL	Wing et al. (2020) Building AAL	Nofal et al. (2020) AAL
0.0	\$2,423	\$3,651	\$150	\$2,792
0.5	\$576	\$862	\$8	\$674
1.0	\$122	\$196	\$0	\$154
1.5	\$27	\$44	\$0	\$35
2.0	\$0	\$0	\$0	\$0

Figure 2.2 compares the results from all loss functions in terms of relative variations in the expected AAL estimates for each freeboard scenario. With respect to total AAL results of the functions, USACE (2000) and Nofal et al. (2020) estimates are very similar in all flood depths. However, area-specific USACE (2006) function consistently overestimates the AAL compared to the generic USACE (2000) and Nofal et al. (2020) functions, with the variance between them decreases slightly with every additional elevation increase. Thus, for this case study, the adopted generic USACE (2000) and Nofal et al. (2020) functions produce slightly lower avoided loss

benefits than the area-specific USACE (2006) function. By contrast, Wing et al. (2020) estimates are very small. These results are expected given that the largest proportion of flood losses for the case study occurs with smaller flood depths. At this range of depths, the other functions attribute higher loss percentages than the Wing et al. (2020) function. Unlike the other functions, Wing et al. (2020) attributes no loss percentages for depths at and below the FFE, leaving the entire floor structure (including the floor-top) and other structural elements that may be located below the building's FFE out of the loss estimations.

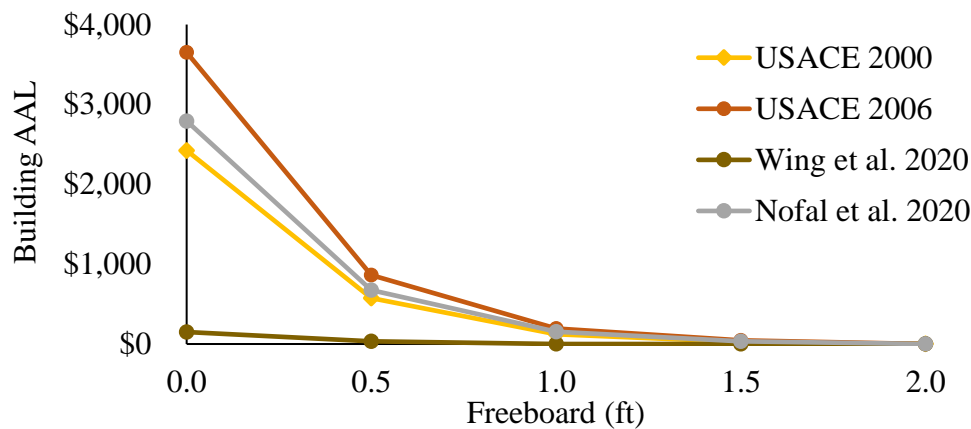


Figure 2.2. Comparison of AALs from All Functions for Each Freeboard Scenario, for the Metairie, Louisiana, Case Study

Additionally, building AAL estimates from all the functions are provided for only elevations at and above the FFE, to examine the effects of excluding floor structure and other structural elements that may be located below the building's FFE. The results are shown in Table 2.4. These low AAL estimates are expected given that they exclude the floor structure, which is the most vulnerable part to the flooding. Depths below the top of the first floor can impact the entire floor structure and other structural elements below the first-floor level. At these depths, flooring can be fully submerged in floodwater and sustain damage as it absorbs water, swells, and buckles (Chung and Adeyeye, 2018).

Table 2.4. AAL Results for Elevations Above FFE Using USACE (2000), USACE (2006), Wing et al. (2020), and Nofal et al. (2020)

Freeboard (ft.)	USACE (2000) Building AAL	USACE (2006) Building AAL	Wing et al. (2020) Building AAL	Nofal et al. (2020) Building AAL
0.0	\$318	\$474	\$145	\$334
0.5	\$16	\$24	\$7	\$17
1.0	\$0	\$0	\$0	\$0
1.5	\$0	\$0	\$0	\$0
2.0	\$0	\$0	\$0	\$0

2.6.3. Methods Comparison

This study's results are contrasted with three other methods for estimating the expected AAL of flooding. The three methods are: (i) AAL is calculated as traditional piecewise product of annual probability of exceedance and loss using only the available return periods for the site, (ii) a piecewise approach with log-linear extrapolation, and (iii) a Monte Carlo simulation process with fitted probability distribution.

2.6.3.1. AAL as Traditional Piecewise Product of Probability and Loss

To estimate AAL using the traditional method, losses associated with the site's available return periods with 0.1, 0.02, 0.01, and 0.002 annual exceedance probabilities are calculated directly as the loss percentages per depth corresponding to a flood annual probability of exceedance estimated using USACE depth-loss functions and the value of the building. AAL is calculated as piecewise product of annual probability of exceedance and the calculated losses where the results are integrated by means of a Riemann sum. The results are shown in Table 2.5.

Table 2.5. AAL Results Calculated as Piecewise Product of Annual Probability of Exceedance and Loss, for the Metairie, Louisiana, Case Study

Freeboard (ft.)	Building AAL	Content AAL	Total AAL
0.0	\$1,649	\$243	\$1,892
0.5	\$721	\$87	\$808
1.0	\$146	\$0	\$146
1.5	\$36	\$0	\$36
2.0	\$0	\$0	\$0

2.6.3.2. AAL Using Log-linear Relationship

To calculate the building and content losses for the case study, trendlines obtained through regression analyses of the available data are used to derive multiple equations that represent losses from flood elevations in relation to freeboard heights. Values of available return periods' annual probability of exceedance are plotted against their expected losses as shown in Figure 2.3. Building loss from the BFE scenario is selected as an example.

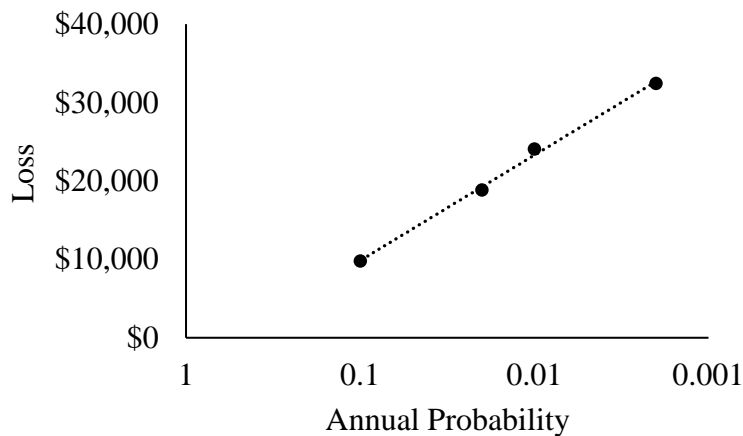


Figure 2.3. Loss-Probability Relationship for BFE

The regression equation for that scenario is:

$$L = -5840 \ln(P) - 3600.9$$

where L represents loss and P is the annual probability of exceedance of the return period.

From the derived equations, losses are extrapolated to a higher return period time range and AALs were computed for each half-foot increment of additional elevation increase. The expected losses of all events with different annual probability of exceedance are aggregated using Riemann sums to estimate the overall AAL of each freeboard (Table 2.6).

Table 2.6. AALs using Log-Linear Extrapolation, for Metairie, Louisiana, Case Study

Freeboard (ft.)	Building AAL	Content AAL	Total AAL
0.0	\$6,469	\$457	\$6,926
0.5	\$882	\$160	\$1,042
1.0	\$258	\$0	\$258
1.5	\$67	\$0	\$67
2.0	\$0	\$0	\$0

2.6.3.3. Monte Carlo Simulation

A synthetic flood record is generated using Monte Carlo simulation with the Gumbel distribution fitted. The relationship between flood depth and its expected loss is determined using the USACE (2000) depth-damage function. AALs for building and content are estimated for each freeboard increment. The results are summarized in Table 2.7.

Table 2.7. AAL Results Calculated using Monte Carlo Simulation

Freeboard (ft.)	Building AAL	Content AAL	Total AAL
0.0	\$2,454	\$ \$197	\$2,651
0.5	\$1,036	\$44	\$1,080
1.0	\$123	\$0	\$123
1.5	\$26	\$0	\$26
2.0	\$0	\$0	\$0

2.6.3.4. Methods Comparison Discussion

Figure 2.4 compares the results from all methods in terms of relative variations in the expected AAL estimates for each freeboard scenario.

The comparison shows that the piecewise product using only the available data underestimates AAL when compared with results of methods using longer time ranges. Better estimates are achieved when a higher range of return periods is used. Estimates from the numerical integration methodology developed in this study and the Monte Carlo simulation approach are similar. However, log-linear regression method produces considerably higher estimates. Flood exhibits highly nonlinear behavior, whereby the behavior of some flood events differs from others, and thus the applied dataset may not be represented appropriately by a log-linear function.

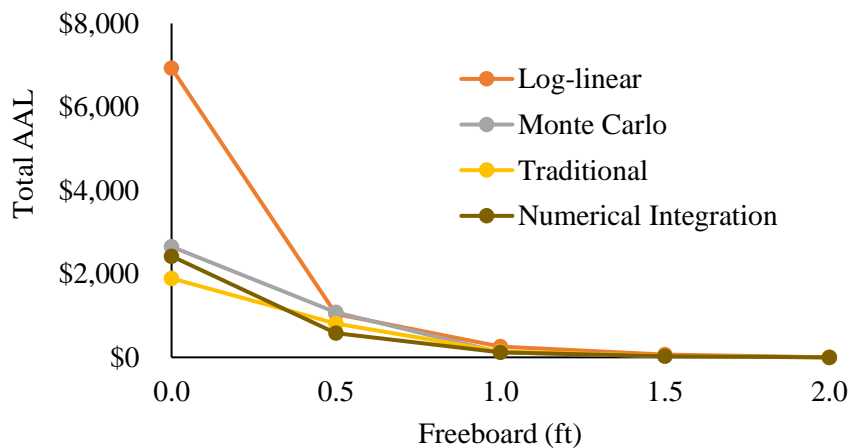


Figure 2.4. Comparison of Results from Various Methods for Each Freeboard Scenario, for the Metairie, Louisiana, Case Study

Although Monte Carlo simulation and numerical integration methods provide comparable results, the required computation time using Monte Carlo simulation is considerably long, limiting its applicability. Monte Carlo simulation is a proper approach when a large number of variables are involved. However, in this study the number of variables used in calculations is relatively small, which allows for the use of numerical integration without resorting to the time-consuming methods.

Furthermore, in flood models used for predictive purposes, it is necessary to consider prediction uncertainty to ensure the most reliable estimation procedure (Rasmussen and Rosbjerg, 1991). Models with fewer parameters – such as the numerical integration method developed in this chapter – are preferable to complex models with increased prediction uncertainty due to a larger number of parameters (Rasmussen and Rosbjerg, 1991).

2.7. Conclusions

Motivated by the increased need to improve the reliability of loss assessment due to flood and flood mitigation, the aim of this research was to translate numerical flood modeling results to a representation of cost-effectiveness with the goal of enhancing individual and community resilience. This research established a methodological framework for quantitatively assessing potential flood losses at a single building-scale.

The results of this work demonstrated that flood protection is achievable with added freeboard. Flood loss reduction is an immediate benefit to be gained by increasing elevation. Other benefits include savings on insurance premiums, less suffering, faster recovery, and increase in home value. Despite the benefits, many homeowners and communities fail to consider mitigation strategies, which suggests that the potential benefits are not communicated in an effective way. As a result, benefits are largely unrealized by many homeowners and communities.

Results also highlight the need to assess flood risk at a single-building level, using its specific flood exposure, as it allows for a more localized and accurate assessment. AAL evaluations conducted on an aggregated spatial basis, where a particular flood exposure (i.e., flood inundation depth) is applied to all properties in the area, leads to suboptimal results. As the flood depths may vary within one area, the risk assessment will rely on assumptions (de Ruig et al., 2019). In contrast, applying building-level assessments as a part of larger-scale risk

estimations can yield more accurate and factual results. This can encourage homeowners and communities to consider mitigation measures and firmly support political decision-makers who promote flood mitigation investments and building code changes.

The results show that a large proportion of flood losses occur below the top of the first floor, signifying that adding freeboard should take in the consideration the floor structure and other structural elements below the first-floor level.

Furthermore, the results show that a fundamental flood risk assessment model such as the numerical integration method developed in this chapter can perform better than the more complex models with increased prediction uncertainty due to larger number of parameters.

Due to the nature of the study, the risk assessment covered only direct economic losses and did not consider the indirect economic losses. While characteristics of individual buildings may vary considerably in the same area, it remains unfeasible to develop individualized loss functions for each building. To enhance the reliability and accuracy of flood loss estimates, more research should be focused on reducing the uncertainties associated with loss functions. Also, these types of risk assessment models are highly constrained by flood data availability, where the accuracy and reliability of results are limited by the quality of data available. While acknowledging the limitations, this work offers an improvement to flood loss modeling.

Moving forward, it is beneficial to integrate the life-cycle cost-benefit aspect with this risk assessment. This model focused exclusively on single-property risk assessment. It is essential to undertake the same assessments on the community level by applying the risk model on a large number of buildings across space. A broader risk analysis could help in identifying potentially vulnerable areas within the targeted region, which could help prioritize future flood

risk management strategies. Future work may also consider the effects of climate change in this risk model by updating the predicted annual probability of exceedance of flood events.

Chapter 3. Economically Optimal Freeboard for Single-Family Homes

3.1. Introduction

Although adding freeboard as a mitigation measure generally represents a sound investment (Multihazard Mitigation Council, 2017), determining the optimal height of freeboard poses a major decision problem (Zarekarizi et al., 2020). Also, the lack of robust benefit-cost analysis (BCA) that quantifies costs and benefits at the micro-scale level discourages investment in flood mitigation (de Ruig et al., 2019). Thus, the development of a comprehensive methodology that determines the optimal freeboard height at the micro-scale level through a life-cycle BCA is essential.

As flooding is a low-probability but high-impact event, it is prudent to evaluate the flood loss within a long time frame, such as the building's life-cycle (Dong and Frangopol, 2017). Integrating flood risk assessment and life-cycle BCA provides an ideal approach for quantifying the cost-effectiveness of mitigation measures (de Risi et al., 2018). Life-cycle BCA involves weighing the total expected benefits against the total expected costs over the home's useful life in order to determine the best alternative (CWCB, 2010; Mikulik and Zajdel, 2009; Thoft-Christensen, 2010). It builds on a well-established principles of economic analysis to evaluate the life-cycle efficiency between mitigation scenarios (Santos and Ferreira, 2013).

Although life-cycle BCA has been investigated by numerous studies, only a few focus on establishing the economically optimal elevation for single-family residences using a life-cycle BCA. Xian et al. (2017) introduced the calculation of the economically optimal elevation levels through life-cycle BCA. The methodology integrated climate change analysis for flooding approaches developed by other studies to consider the dynamic climate effects. The study substituted the expected AAL with risk-based annual insurance premium calculated based on the National Flood Insurance Program (NFIP) flood insurance manual. However, NFIP flood

premiums estimated for a building's various first floor elevation heights do not reflect the expected AAL because the incremental increase in NFIP premiums for various freeboard heights is uniform across the United States rather than as a function of the hazard. Thus, the optimal elevation level is determined in relation to annual premiums only and not the expected annual flood loss. Zarekarizi et al. (2020) developed a framework to analyze the house elevation decision. The study identified important sources of uncertainties and characterized trade-offs between decision objectives such as minimizing the total costs and maximizing the benefit-cost ratio (BCR). While the study represented a substantial step forward, it considered only flood reduction in its decision criteria, ignoring the premium savings. The inclusion of reduction in flood premiums with elevation increase in such analyses allows for a more effective evaluation of freeboard benefits (FEMA, 2008). Also, neither study disaggregated costs between the affected parties. While the freeboard cost and flood premiums are considered owner costs, the expected AAL should be assessed while determining the proportions allocated to the owner and the NFIP, as homeowners are liable for the deductible in the case of a flood and NFIP covers only the outstanding costs. For a robust analysis, costs and benefits must be disaggregated and allocated to the proper parties. Disaggregation is important to identify affected parties and ensure the reliability of the decision making process (Sayers, 2013). Thus, while these studies provide useful analyses, further improvement is needed.

This chapter is motivated by the increased need to establish a reliable methodology for determining the economically optimal elevation of single-family residences. The optimal freeboard height for single-family homes is determined through a life-cycle BCA. The life-cycle BCA includes the net benefit (NB) and net BCR (NBCR), which are the two metrics used to aid stakeholders to decide the optimal freeboard scenario that maximizes life-cycle benefits. Each

freeboard scenario is evaluated in terms of its benefit from flood loss reduction and premium savings as compared to its cost. The expected AALs, annual premiums, and freeboard costs are estimated and discounted to the present value (PV) and accumulated; NBs are the differences between “with” and “without elevation increase” scenarios. An economically optimal elevation as a mitigation measure is the elevation that maximizes the accumulated life-cycle NB. The NBs are divided by the freeboard cost to compute the NBCRs. This work calculates the economically optimal elevation for two options: when freeboard cost is an upfront cost, and when freeboard cost is built into the mortgage. Additionally, the life-cycle benefit-cost is disaggregated as owner benefit and NFIP benefit.

In this work, Monte Carlo simulation with a fitted Gumbel extreme value distribution is used to handle the uncertainty associated with flood annual probabilities. As severe flood events are not limited to the 100-year or 500-year floods, this probabilistic model extends the available dataset to reach a higher time-range of interest. Also, this life-cycle BCA is developed for a particular building level. Such an approach is characterized by a high level of spatial detail and accuracy (Bubeck et al., 2011; Lorente, 2019). Estimating life-cycle benefits at a building scale allows aggregation to larger spatial levels with increased accuracy.

A hypothetical one-story, single-family residence in Metairie, Louisiana, is used as the basis for the life-cycle BCA to demonstrate the methodology presented in this chapter. A sensitivity analysis is conducted over a range of discount rates to examine the extent of the uncertainty linked to the choice of discount rate. 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 establishing long-term flood resilience.

3.2. Methodology

Determining the economically optimal freeboard involves a comparison of benefits expected over the life of the building between various first-floor elevation scenarios. Freeboard is evaluated over a 30-year period, as this is the useful life of a mitigation project suggested by FEMA (2009) guidance. Life-cycle BCA is performed for each 0.5-ft. increment above BFE up to four feet of additional freeboard at the time of construction. In this chapter, the analysis covers only direct economic losses (building and content). It is assumed that no annual cost is used to maintain the freeboard, and therefore, maintenance cost is not considered.

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 BCA, in which the future benefits of the mitigated scenario are calculated and compared to its total cost. The outcome is a 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, whereas NB is a measure of the overall benefit. Life-cycle BCA estimates all relevant benefits and costs throughout the life of a building at their PV. NB of the mitigation using freeboard NB_{F_i} is determined by subtracting the sum of the annual costs (at the PV) for the freeboard scenario $F_{i_{PV}}$ from the sum of the annual costs (at the PV) at BFE “no action” scenario BFE_{PV} . Total NB is divided by the cost of the freeboard F_{i_C} to obtain $NBCR_{F_i}$ for adding the freeboard, or

$$NBCR_{F_i} = \frac{BFE_{i_{PV}} - F_{i_{PV}}}{F_{i_C}} \quad (3.1)$$

where i is the freeboard increment.

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 expected costs at BFE versus costs of each freeboard scenario, (ii) conduct the BCA.

3.2.1. 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 continual cost that is expected to recur regularly during the building's useful life. One-time cost represents the cost of freeboard when it is made up front. The continual costs are the cost of freeboard built into the mortgage, flood premium, and the expected AAL. As AAL is a loss that is expected to occur, it is important to integrate it as a cost into the analysis. These two classes are further divided into owner cost or/and NFIP cost. 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. All continual costs are estimated on annualized bases.

3.2.1.1. Cost of Freeboard Construction

The cost of each additional increase in elevation is calculated to be applied to the life-cycle BCA. Freeboard cost is estimated as a percentage of the total construction cost. FEMA (2008) guidance is used to estimate the freeboard construction cost for new buildings. While FEMA (2008) reports the cost of each freeboard increment as a range of percentage estimates of total construction cost, this study uses the upper limit for each freeboard increment to provide a conservative estimate of total cost (Table 3.1). 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. Cost of home elevation is calculated as a one-time upfront cost and as a loan that spreads the cost of elevation over time.

Table 3.1. Average Cost of Construction Increase (%), by FEMA Flood Zone and Foot of Freeboard

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

3.2.1.1.1. Upfront Freeboard Cost

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 F_{CU} , the percentage of increase in construction cost associated with each freeboard height F_{PI} provided in Table 3.1 is multiplied by the building's value at BFE (BV_{BFE}), or

$$F_{CU} = F_{PI} \times BV_{BFE} \quad (3.2)$$

3.2.1.1.2. Loan Freeboard Cost

Freeboard cost is also calculated as a loan. A long-term loan allows homeowners to spread the large upfront cost of construction over the length of the mortgage term (Aerts and Wouter Botzen, 2011). In this work, a 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 freeboard's amortized base monthly amount F_{CBM} , such that

$$F_{CBM} = \frac{F_{CU} \left(\frac{r}{n} \right)}{1 - \left(1 + \frac{r}{n} \right)^{-nt}} \quad (3.3)$$

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

The resulting amortized base monthly amount F_{CBM} is added to the monthly loan fees LF_M to obtain total monthly loan payment for the freeboard F_{CM} .

$$F_{CM} = F_{CBM} + LF_M \quad (3.4)$$

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

$$F_{CY} = F_{CM} \times n \quad (3.5)$$

3.2.1.2. NFIP Insurance Premiums

For homes located in “special flood hazard” areas, the purchase of NFIP coverage is mandatory (Senate, 2011). Flood insurance premiums vary based on the location of the property, the flood zone, first floor elevation, 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. To assess the potential benefits of adding freeboard, the estimated reduction in annual flood premiums is added to its expected flood AAL. Although reduction in flood premiums with elevation increase is not typically addressed in such studies, its inclusion allows for a more comprehensive evaluation of benefits associated with adding freeboard (FEMA, 2008). For each flood zone, Flood Insurance Rate Map (FIRM) assigns the 100-year flood as BFE, and rates are estimated by comparing the building’s elevation to BFE. In this work, premiums are calculated using the rate tables published in the NFIP (2021) Flood Insurance Manual’s post-firm construction rates for a single-family residence, for multiple elevation levels. Basic rates for building and content are applied to every \$100 of the basic building and content coverage limits, and separate additional rates for building and content 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 requires a minimum deductible of \$1,250 for both building and content if the coverage exceeds \$100,000 (NFIP, 2021); therefore, \$1,250 was chosen as a conservative value.

3.2.1.3. Average Annual Loss (AAL)

The unpredictable nature of floods carries uncertainty; this study addresses uncertainty by applying a probabilistic approach (Hennequin et al., 2018). To estimate the expected flood loss, AAL is calculated by integrating the product of the probability density function (PDF) of flood event annual occurrence and the flood loss function, such that

$$AAL = \int_{-\infty}^{\infty} f(E)L(E)dE \quad (3.6)$$

where E represents the flood elevation (ft., NAVD88), $f(E)$ is the PDF, $L(E)$ is the loss as a function of flood elevation, and FFE is the first floor elevation. While flood elevation is expressed as an infinite range, in reality the flood elevations in any given area lies within a finite range.

This methodology derives flood depths for multiple return periods using inverse cumulative distribution function, which then transformed to loss as a function of flood depth using depth-damage function. Losses associated with each return period expressed as a percentage of the building value are then integrated to estimate total AAL. Extreme value probability function was utilized to represent the uncertainty surrounding flood event probabilities. Driven by the right-skewed nature of flood return periods, two-parameter Gumbel extreme value distribution is used, or

$$f(E) = \left(\frac{1}{\alpha}\right) \exp\left[-\left(\frac{E-u}{\alpha}\right) - \exp\left(-\left(\frac{E-u}{\alpha}\right)\right)\right] \quad (3.7)$$

The cumulative distribution function (CDF) of the distribution is equal to the exceedance probability, P :

$$P = F(E) = \exp\left[-\exp\left(\frac{E-u}{\alpha}\right)\right] \quad (3.8)$$

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

$$E = F^{-1}(F(E)) = u - \alpha \ln(F(E)) \quad (3.9)$$

In Eq. (3.7), (3.8) and (3.9), $f(E)$ is Gumbel PDF, $F(E)$ is the CDF, $F^{-1}(E)$ is the inverse CDF, and u and α are the calculated, site-specific location parameter and scale parameter, respectively. The parameters are obtained by fitting the available data using logarithmic regression.

The relationship between flood depth and loss is determined using the 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 the structure below FFE, in this work the function is truncated to only calculate building losses beginning at -1 ft. However, content losses at negative flood depths (i.e., below the building's first floor) are considered to have no losses.

AAL is estimated using Monte Carlo simulation, which integrates the loss function with flood elevations. A Monte Carlo simulation process can reproduce characteristics of observed floods (e.g., frequency distributions) and their skewed nature with relative accuracy across a broad range of frequencies, in addition to circumventing any assumption of linearity (Rahman et al., 2002). The Monte Carlo simulation generates scenarios based on the fitted Gumbel inverse CDF for annual occurrences of events having return periods that are right-skewed, 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 ($F^{-1}(E)$) to calculate the corresponding flood elevation. Simulations are executed whereby the return periods are chosen randomly. The FFEs are subtracted from the resulted simulated flood elevations to obtain the depths and flood loss is considered for building and content using

the depth-loss functions. The expected losses for all simulated events are accumulated and averaged to estimate the overall AAL of each freeboard.

AAL for each type of loss function is the summation of all generated simulation losses divided by total simulations N , or

$$AAL_{b\%} = \frac{1}{N} \sum_{i=1}^N F^{-1}[Rand(i)] L_b(E_i) \quad (3.10)$$

$$AAL_{c\%} = \frac{1}{N} \sum_{i=1}^N F^{-1}[Rand(i)] L_c(E_i) \quad (3.11)$$

where $AAL_{b\%}$ and $AAL_{c\%}$ represent the building and content AAL, respectively, i is the simulated event between N simulations, $Rand(i)$ is a random annual probability of exceedance between zero and one chosen according to the given Gumbel inverse CDF, $F^{-1}[Rand(i)]$ is the inverse CDF of the flood elevation for each simulated event, and $L(E_i)dE$ is the loss function corresponding to annual flood elevation of a simulated event (E_i).

$AAL_{\%}$ is the accumulation of building and content AAL percentages based on the building's value.

$$AAL_{\%} = AAL_{b\%} + AAL_{c\%} \quad (3.12)$$

AAL is general, while $AAL_{\%}$ and $AAL_{\$}$ are percentages of the value and absolute currency, respectively. To calculate AAL in absolute currency, $AAL_{\$}$ is the product of $AAL_{\%}$ and building value (BV), or

$$AAL_{\$} = AAL_{\%} \cdot BV \quad (3.13)$$

3.2.2. AAL Loss Allocation to Owner and NFIP

For each freeboard height, the building and content losses that a flood event would cost both the homeowner and/or NFIP in a given year is determined. Building loss (l_b) and content loss (l_c) are determined using the building value. Flood insurance deductibles are represented within total loss, as homeowners are liable for the deductible in the case of a flood regardless of

the location or characteristics of the home. Owners are liable for the deductibles specified for building and content while NFIP covers the outstanding costs. Therefore, total loss for each simulation L_T is apportioned as either owner loss L_O and/or NFIP loss L_{NFIP} , depending on whether or not the policy deductible W_O has been exceeded (Eq. 3.14-3.16). L_T is a function of the building loss, content loss, and depth in simulation D_s .

$$L_T = l_b(D_s) + l_c(D_s) \quad (3.14)$$

$$L_O = L_T \quad \text{for } L_T \leq W_O \quad \text{Owner loss} \quad (3.15)$$

$$L_O = W_O \quad \text{for } L_T > W_O$$

$$L_{NFIP} = L_T - W_O \quad \text{for } L_T > W_O \quad \text{NFIP loss} \quad (3.16)$$

$$L_{NFIP} = 0 \quad \text{for } L_T \leq W_O$$

In case that flood total loss L_T exceeds the total insurance coverage G_T , the owner is responsible for the deductible specified W_O and the loss amount greater than the total insurance coverage, such that

$$L_O = L_T - (G_T - W_O) \quad (3.17)$$

On the other hand, the NFIP loss L_{NFIP} is the total insurance coverage less the deductible W_O , or

$$L_{NFIP} = G_T - W_O \quad (3.18)$$

The expected losses of all simulated events with different probabilities for building and content are averaged to estimate the total AAL AAL_O for owner and NFIP AAL_{NFIP} , such that

$$AAL_O = \frac{1}{N} \sum_{i=1}^N L_O \quad (3.19)$$

$$AAL_{NFIP} = \frac{1}{N} \sum_{i=1}^N L_{NFIP} \quad (3.20)$$

3.2.3. 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. In order to determine whether a mitigation scenario actually results in life-cycle economic benefit, all costs are discounted to the PV, and BCA is conducted.

NB, BCR, and NBCR are some of the metrics used in the BCA to compare the cost-effectiveness of different alternatives. NB (i.e., net PV) is a measure of overall benefit, i.e., overall return. The BCR – and similarly NBCR – measure the economic efficiency, i.e., benefit per dollar spent (Daigneault et al., 2016). 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 net benefit. 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 approach. BCR compares benefits to costs directly, while NBCR evaluates options based on returns on investment where it presents the return (net benefit) as compared to the cost. 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. Thus, BCA is evaluated through consideration of the PV, 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.

3.2.3.1. Present Value (PV)

Since costs and benefits of a project accrue over time, the BCA is conducted on a discounted present value (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 discounted to the PV, 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 used for several reasons. For life-cycle BCA which often covers extended periods, the real discount rate is recommended since forecasting future inflation is difficult and that 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) Circular A-94 to avoid an inflation assumption whenever possible in life-cycle BCA due to the high uncertainty associated with inflation. Using the real discount rate removes inflation from the PV estimates and obviates the need to calculate its rate (Fuller and Petersen, 1996; Van den Boomen et al., 2016). 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 is not the same. These considerations, together with the fact that both types of the discount rates yield similar PV results when applied properly (Babusiaux and Pierru, 2005; Fuller and Petersen, 1996), support the decision to use real discount rates.

DPV of the annual cost C_{DPV} serves the purpose of returning the annualized costs C_t over a time horizon t using the discount rate R_D , or

$$C_{DPV} = \sum_{t=1}^t \frac{C_t}{(1+R_D)^t} \quad (3.21)$$

Benefits of freeboard are the future costs reduced or prevented by the mitigation measure and are calculated as the difference in the PV of annual costs over the useful life of the home with versus without freeboard. The PV at BFE “no action” scenario (BFE_{PV}) is calculated as the sums of life-cycle cumulative PVs of annual insurance premium P_{DPV} and the total AAL_{DPV_T} , such that

$$BFE_{PV} = (\sum_{t=1}^t P_{DPV})_{BFE} + (\sum_{t=1}^t AAL_{DPV_T})_{BFE} \quad (3.22)$$

AAL_{DPV_T} is the sum of AAL PVs allocated to owner AAL_{DPV_O} and NFIP AAL_{DPV_N} .

$$BFE_{PV} = (\sum_{t=1}^t P_{DPV})_{BFE} + (\sum_{t=1}^t (AAL_{DPV_O} + AAL_{DPV_N}))_{BFE} \quad (3.23)$$

Because loan-based freeboard cost $F_{C_{Loan}}$ accumulates over the life of the loan, it is assessed on an annualized basis discounted to the PV. By contrast, upfront freeboard cost is a one-time cost expressed as a percentage of the total building value only. The PV of each freeboard scenario with upfront freeboard cost F_{PV_U} is calculated as the upfront cost of freeboard F_{C_U} plus the sums of life-cycle cumulative of the P_{DPV} and the AAL_{DPV_T} .

$$F_{PV_U} = F_{C_U} + (\sum_{t=1}^t P_{DPV})_F + (\sum_{t=1}^t AAL_{DPV_T})_F \quad (3.24)$$

The PV of each freeboard scenario with loan-based cost F_{PV_L} is calculated as the sums of the life-cycle cumulative of the loan annual freeboard payment discounted to the present value $F_{CY_{DPV}}$, the P_{DPV} , and the AAL_{DPV_T} .

$$F_{PV_L} = \left(\sum_{t=1}^t F_{CY_{DPV}} \right)_F + \left(\sum_{t=1}^t P_{DPV} \right)_F + \left(\sum_{t=1}^t AAL_{DPV_T} \right)_F \quad (3.25)$$

3.2.3.2. 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_F is determined by subtracting the life-cycle cumulative PV of the freeboard scenario (F_{PV}) from the life-cycle cumulative PV of “at BFE no action” scenario (BFE_{PV}).

$$NB_F = BFE_{PV} - F_{PV} \quad (3.26)$$

A positive value indicates that the present value of the mitigated scenario is more cost beneficial than the current scenario.

3.2.3.3. Net Benefit to 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 net benefit and cost. NBCR for the freeboard is the total net benefit of the freeboard scenario (NB_F) divided by its total cost (F_C), or

$$NBCR_F = \frac{NB_F}{F_C} \quad (3.27)$$

3.3. Sensitivity Analysis

CBA 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 act as an impediment to its successful application (Maravas and Pantouvakis, 2018). The importance of

the discount rate in life-cycle BCA 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, the U.S. Army Corp of Engineers (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, Circular No. A-94 of 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 life-cycle BCA 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 which occurs at the point when the discount rate is zero (undiscounted case) where all future benefits are at their total value. As for the upper range, 4%, 8%, and 12% of real discount rates are used in financial formulas to represent a range when investigating the best investment alternative (Chizmar et al., 2019). Internationally, 3%, 7%, and 10% of real discount

rates 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 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.

3.4. Case Study

A case study was carried out in Metairie, Louisiana, to demonstrate the methodology presented in this work. The building is a one-story, single-family residence with 2,500 ft² of living area. The site is located in the metro 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” first floor elevation of -3.5 ft. (NAVD88).

The average construction cost of a single-family residence in the New Orleans area is \$92.47 per square feet for a 2,500 ft² residence (Moselle, 2019). Also, 2,500 ft² is the average size for a single-family home in southern U.S. (U.S. Census Bureau, 2020). Accordingly, the total estimated construction cost is \$231,175.

Using the multi-frequency depth grids provided by Risk Mapping, Assessment and Planning (RiskMAP), 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 calculated as shown in Table 3.2.

Table 3.2. Site's Flood Elevations and Corresponding Depths Above Ground

Annual Probability of Exceedance	Flood Elevation (NAVD88)	Flood Depth (ft.)
0.002	-3.4	3.6
0.01	-3.9	3.1
0.02	-4.2	2.8
0.1	-4.7	2.3

3.5. Results

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. Life-cycle BCA of freeboard insurance savings is performed separately.

3.5.1. Expected Costs

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

3.5.1.1. Cost of Freeboard Construction

Construction cost for each freeboard increment is calculated as an upfront cost and as a loan (Table 3.3). For upfront option, the cost of freeboard is calculated as a direct percentage of the total building value. On the other hand, 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 continual 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 3.3. 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	\$151	\$4,528
1.0	–3.0	\$5,317	\$302	\$9,055
1.5	–2.5	\$7,860	\$446	\$13,385
2.0	–2.0	\$10,403	\$591	\$17,716
2.5	–1.5	\$13,061	\$741	\$22,242
3.0	–1.0	\$15,720	\$892	\$26,770
3.5	–0.5	\$18,378	\$1,043	\$31,297
4.0	0.0	\$21,037	\$1,194	\$35,825

3.5.1.2. NFIP Insurance Premiums

The case study site is located in an AE-Zone special flood hazard area, with a maximum structure and content value of \$231,175 and \$92,470, respectively. A minimum deductible of \$1,250 for both structure and contents is required. Therefore, \$1,250 was chosen as a conservative value. Calculated premiums include the NFIP Community Rating System (CRS) discount of 25% (rating of 5), \$6 ICC premium, reserve fund fee, \$25 HFIAA surcharge, and \$50 federal policy fee. Table 3.4 shows the calculated flood premiums, where annual premiums decrease with each additional one-foot increment above BFE.

Table 3.4. Annual Flood Insurance Premium by Freeboard Height

Freeboard (ft.)	First-Floor Elevation (ft.)	Premium	CRS Discount	Reserve Fund Fee	Total Annual Premium
0.0	–4.0	\$2,065	\$518	\$280	\$1,908
0.5	–3.5	\$2,065	\$518	\$280	\$1,908
1.0	–3.0	\$1,047	\$263	\$142	\$1,007
1.5	–2.5	\$1,047	\$263	\$142	\$1,007
2.0	–2.0	\$650	\$164	\$89	\$656
2.5	–1.5	\$650	\$164	\$89	\$656
3.0	–1.0	\$523	\$132	\$71	\$543
3.5	–0.5	\$523	\$132	\$71	\$543
4.0	0.0	\$489	\$124	\$67	\$513

3.5.1.3. Average Annual Loss (AAL)

AALs are estimated for flood depths of return periods up to 2000-year flood events. Any further increase in return period results in an insignificant change in the estimates, as flood frequencies approach nullity. AALs are computed for each 0.5-ft. increment of additional freeboard above the BFE up to 4.0 ft. AAL is apportioned to the owner AAL and NFIP AAL.

Based on the overall results (Table 3.5), AAL is reduced with each additional freeboard increment until it is eliminated totally at 2 ft. of freeboard, with higher reduction occurring on the smaller increments of freeboard and decrease in reduction as elevation increases. Nevertheless, the cumulative reduction in AALs rises with each elevation increase until reaching the eliminating level.

Table 3.5. AAL Results for Each Freeboard Height Scenario

Freeboard (ft.)	First-Floor Elevation (ft.)	Building Content AAL	Content AAL	Owner	Owner	NFIP	NFIP	Total AAL	Avoided Loss
				Building	Content	Building	Content		
0.0	−4.0	\$3,383	\$258	\$298	\$15	\$3,085	\$243	\$3,641	\$0
0.5	−3.5	\$738	\$48	\$66	\$0	\$672	\$48	\$786	\$2,855
1.0	−3.0	\$154	\$0	\$15	\$0	\$139	\$0	\$154	\$3,487
1.5	−2.5	\$24	\$0	\$0	\$0	\$24	\$0	\$24	\$3,617
2.0	−2.0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$3,641
2.5	−1.5	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$3,641
3.0	−1.0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$3,641
3.5	−0.5	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$3,641
4.0	0.0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$3,641

3.5.2. Benefit-Cost Analysis (BCA) and Sensitivity Analysis

BCA is conducted to evaluate the life-cycle performance of adding freeboard to determine the economically optimal elevation for the residence. Once all annual cost estimates for the life of the building are aggregated, BCA is conducted on a present value basis. The life-cycle net benefits of adding freeboard are compared to their construction costs as an upfront payment and as a 30-year loan. This is carried out together with a sensitivity analysis to examine

the sensitivity of the results to various real discount rates. The BCA assumes a 7% real discount rate as the baseline, with 0%, 3%, 10%, and 12% real discount rates to test the sensitivity of results. Tables 3.6 and 3.7 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 a loan, respectively.

Table 3.6. Life-cycle BCA Results for Each Freeboard Scenario – Upfront

Freeboard (ft.)		0%	3%	7%	10%	12%
0.5	NB	\$82,997	\$53,304	\$32,771	\$24,257	\$20,340
	NBCR	31.2	20.0	12.3	9.1	7.6
1.0	NB	\$126,238	\$80,634	\$49,099	\$36,021	\$30,006
	NBCR	23.7	15.2	9.2	6.8	5.6
1.5	NB	\$127,667	\$80,686	\$48,199	\$34,727	\$28,530
	NBCR	16.2	10.3	6.1	4.4	3.6
2.0	NB	\$136,357	\$85,482	\$50,302	\$35,713	\$29,003
	NBCR	13.1	8.2	4.8	3.4	2.8
2.5	NB	\$130,694	\$80,861	\$46,401	\$32,111	\$25,538
	NBCR	10.0	6.2	3.6	2.5	2.0
3.0	NB	\$131,425	\$80,417	\$45,144	\$30,517	\$23,789
	NBCR	8.4	5.1	2.9	1.9	1.5
3.5	NB	\$128,767	\$77,759	\$42,486	\$27,859	\$21,131
	NBCR	7.0	4.2	2.3	1.5	1.1
4.0	NB	\$127,008	\$75,688	\$40,199	\$25,483	\$18,714
	NBCR	6.0	3.6	1.9	1.2	0.9

As shown in Tables 3.6 and 3.7, all freeboard scenarios outperform the BFE “no action” scenario. For the upfront option, adding freeboard results in NBs ranging from \$32,771 to \$50,302, with NBCRs ranging from 12:1 to 2:1 when applying the baseline real discount rate of 7%, while the corresponding NBs for the loan option are slightly higher, ranging from \$33,557 to \$46,418 with considerably higher NBCRs ranging between 18:1 and 3:1. With the lower 3% real discount rate, the NBs are substantially increased to a range between \$53,304 and \$85,482 for the upfront option with NBCRs ranging from 20:1 to 4:1. That is an increase of approximately 60% up from the baseline real discount rate estimates.

Table 3.7. Life-cycle BCA Results for Each Freeboard Scenario – Loan

Freeboard (ft.)		0%	3%	7%	10%	12%
0.5	NB	\$81,128	\$53,005	\$33,557	\$25,493	\$21,783
	NBCR	17.9	17.9	17.9	17.9	17.9
1.0	NB	\$122,500	\$80,035	\$50,670	\$38,493	\$32,892
	NBCR	13.5	13.5	13.5	13.5	13.5
1.5	NB	\$122,142	\$79,801	\$50,522	\$38,381	\$32,796
	NBCR	9.1	9.1	9.1	9.1	9.1
2.0	NB	\$129,044	\$84,311	\$53,377	\$40,550	\$34,649
	NBCR	7.3	7.3	7.3	7.3	7.3
2.5	NB	\$121,513	\$79,390	\$50,262	\$38,183	\$32,627
	NBCR	5.5	5.5	5.5	5.5	5.5
3.0	NB	\$120,374	\$78,646	\$49,791	\$37,825	\$32,321
	NBCR	4.5	4.5	4.5	4.5	4.5
3.5	NB	\$115,848	\$75,689	\$47,919	\$36,403	\$31,106
	NBCR	3.7	3.7	3.7	3.7	3.7
4.0	NB	\$112,220	\$73,319	\$46,418	\$35,263	\$30,132
	NBCR	3.1	3.1	3.1	3.1	3.1

These numbers are slightly higher compared to the loan option NBs increase, which ranges between \$53,005 and \$84,311 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 seeing more decrease than the loan option. However, when the discount rate is increased to 12%, the NB results see a substantial decrease, ranging between \$18,714 to \$30,006 for the upfront option with corresponding NBCRs ranging from 8:1 to 1:1. That is a decrease of around 42%, down from the baseline estimates. For the loan option, NBs decline to a range from \$21,783 to \$34,649.

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 used 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. Oppositely, 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.

As shown in Figure 3.1, the cumulative 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, AALs are eliminated 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. It should be noted that the greater NB increases are occurring for smaller freeboard and gradually decrease with greater freeboard.

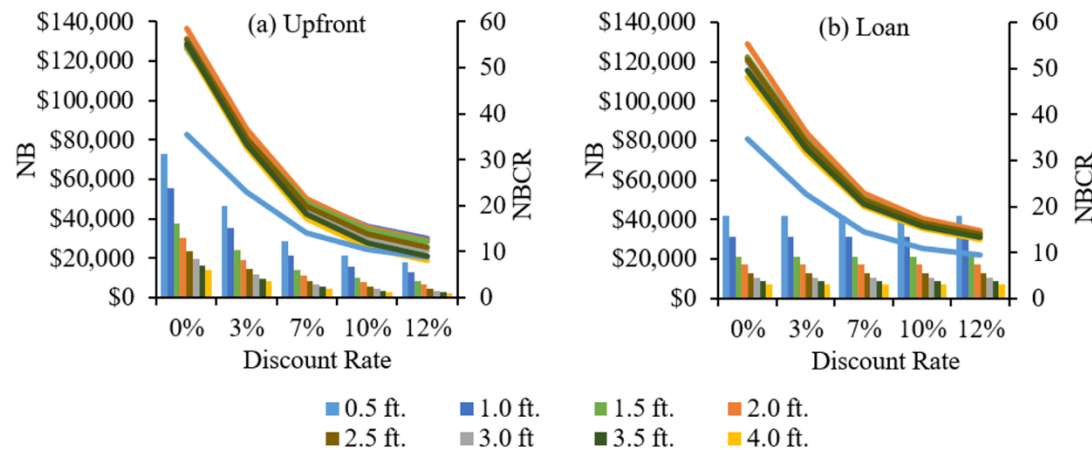


Figure 3.1. NB and NBCR Results for (a) Upfront (b) Loan.

It is clear from Figure 3.1 that 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.

From the overall results, using the NB metric to determine the economically optimal elevation indicates that adding 2 ft. of freeboard is the optimal option given that it yields the highest NB. Yet this alternative would be ranked below the other loan scenarios, 0.5, 1.0, and 1.5 ft. when applying the NBCR metric, as these alternatives have higher NBCRs, with the highest NBCR seen in the smallest freeboard, 0.5 ft., indicating 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.

3.5.2.1. Benefits Allocation to Owner and NFIP

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 3.8 and 3.9 present the owner- and NFIP-apportioned NB and NBCR, respectively, 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 low NBs and NBCRs. However, by raising a home only one foot above BFE, an owner would experience a lifetime NB of \$9,554 for the upfront option and \$11,126 for loan when applying the baseline real discount rate of 7%, while NFIP experiences benefits of \$39,544 for both upfront and loan option. Note that for NFIP, the NB estimates are similar for both upfront and the loan. This is because freeboard cost is not considered in its estimation; therefore, results are not affected by the loan's interest rates.

Table 3.8. Apportioned NB and NBCR for Each Freeboard Scenario – Owner

Freeboard (ft.)		Owner/Upfront					Owner/Loan				
		0%	3%	7%	10%	12%	0%	3%	7%	10%	12%
0.5	NB	\$4,657	\$2,121	\$367	-\$360	-\$695	\$2,787	\$1,821	\$1,153	\$876	\$748
	NBCR	1.8	0.8	0.1	-0.1	-0.3	0.6	0.6	0.6	0.6	0.6
1.0	NB	\$30,636	\$18,173	\$9,554	\$5,980	\$4,337	\$26,898	\$17,574	\$11,126	\$8,452	\$7,222
	NBCR	5.8	3.4	1.8	1.1	0.8	3.0	3.0	3.0	3.0	3.0
1.5	NB	\$28,447	\$15,861	\$7,158	\$3,549	\$1,889	\$22,922	\$14,976	\$9,481	\$7,203	\$6,155
	NBCR	3.6	2.0	0.9	0.5	0.2	1.7	1.7	1.7	1.7	1.7
2.0	NB	\$36,516	\$20,251	\$9,004	\$4,340	\$2,195	\$29,203	\$19,080	\$12,079	\$9,176	\$7,841
	NBCR	3.5	1.9	0.9	0.4	0.2	1.6	1.6	1.6	1.6	1.6
2.5	NB	\$30,832	\$15,616	\$5,095	\$732	-\$1,275	\$21,651	\$14,145	\$8,955	\$6,803	\$5,813
	NBCR	2.4	1.2	0.4	0.1	-0.1	1.0	1.0	1.0	1.0	1.0
3.0	NB	\$31,563	\$15,172	\$3,838	-\$862	-\$3,024	\$20,513	\$13,402	\$8,485	\$6,446	\$5,508
	NBCR	2.0	1.0	0.2	-0.1	-0.2	0.8	0.8	0.8	0.8	0.8
3.5	NB	\$28,905	\$12,514	\$1,180	-\$3,520	-\$5,682	\$15,986	\$10,444	\$6,612	\$5,023	\$4,292
	NBCR	1.6	0.7	0.1	-0.2	-0.3	0.5	0.5	0.5	0.5	0.5
4.0	NB	\$27,146	\$10,443	-\$1,107	-\$5,896	-\$8,100	\$12,358	\$8,074	\$5,112	\$3,883	\$3,318
	NBCR	1.3	0.5	-0.1	-0.3	-0.4	0.3	0.3	0.3	0.3	0.3

Table 3.9. Apportioned NB and NBCR for Each Freeboard Scenario – NFIP

Freeboard (ft.)		NFIP/Upfront					NFIP/Loan				
		0%	3%	7%	10%	12%	0%	3%	7%	10%	12%
0.5	NB	\$78,340	\$51,183	\$32,404	\$24,617	\$21,035	\$78,340	\$51,183	\$32,404	\$24,617	\$21,035
	NBCR	29.5	19.2	12.2	9.3	7.9	17.3	17.3	17.3	17.3	17.3
1.0	NB	\$95,602	\$62,461	\$39,544	\$30,041	\$25,670	\$95,602	\$62,461	\$39,544	\$30,041	\$25,670
	NBCR	18.0	11.7	7.4	5.6	4.8	10.6	10.6	10.6	10.6	10.6
1.5	NB	\$99,220	\$64,825	\$41,041	\$31,178	\$26,641	\$99,220	\$64,825	\$41,041	\$31,178	\$26,641
	NBCR	12.6	8.2	5.2	4.0	3.4	7.4	7.4	7.4	7.4	7.4
2.0	NB	\$99,841	\$65,231	\$41,298	\$31,373	\$26,808	\$99,841	\$65,231	\$41,298	\$31,373	\$26,808
	NBCR	9.6	6.3	4.0	3.0	2.6	5.6	5.6	5.6	5.6	5.6
2.5	NB	\$99,862	\$65,245	\$41,306	\$31,380	\$26,814	\$99,862	\$65,245	\$41,306	\$31,380	\$26,814
	NBCR	7.6	5.0	3.2	2.4	2.1	4.5	4.5	4.5	4.5	4.5
3.0	NB	\$99,862	\$65,245	\$41,306	\$31,380	\$26,814	\$99,862	\$65,245	\$41,306	\$31,380	\$26,814
	NBCR	6.4	4.2	2.6	2.0	1.7	3.7	3.7	3.7	3.7	3.7
3.5	NB	\$99,862	\$65,245	\$41,306	\$31,380	\$26,814	\$99,862	\$65,245	\$41,306	\$31,380	\$26,814
	NBCR	5.4	3.6	2.2	1.7	1.5	3.2	3.2	3.2	3.2	3.2
4.0	NB	\$99,862	\$65,245	\$41,306	\$31,380	\$26,814	\$99,862	\$65,245	\$41,306	\$31,380	\$26,814
	NBCR	4.7	3.1	2.0	1.5	1.3	2.8	2.8	2.8	2.8	2.8

However, as freeboard cost is a part of the NBCR estimations, the owner and NFIP NBCR results are higher with the lower discount rates for the upfront option, while the loan option results remain unchanged when applying various discount rates.

The cumulative NB for the owner continues to rise with every additional increment of elevation increase, reaching the highest value at 2 ft. and gradually declining as AALs are eliminated and the estimations start to depend only on premium and the freeboard cost. By contrast, NB for the NFIP continues to increase until reaching their highest estimate at 2 ft. of freeboard, where AALs are eliminated and continue unchanged beyond that. Although results show that adding freeboard yields substantial lifetime benefits to both the homeowner and NFIP, it was established that the flood losses are primarily borne by NFIP and therefore, the savings are primarily allocated to the NFIP.

3.5.2.2. BCA of Freeboard Insurance Savings

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, unless only a half-foot increment is added, which provides no premium savings. Table 3.10 shows that the life-cycle NB from annual flood premium savings ranges from \$11,181 to \$17,311 when using a 7% real discount rate. At the same discount rate, the NBCRs, representing the ratio of premium savings to the cost of adding the freeboard, range from 1 to 2. Premium NB results are unaffected by the loan; as a result, there are no differences between estimates in the upfront and loan options.

3.6. Conclusions

In this work, a probabilistic life-cycle BCA is performed to identify the economically optimal elevation of single-family residences by evaluating the performance of various freeboard scenarios. Life-cycle benefits are disaggregated as owner benefit and NFIP benefit and the

decision criteria consider both flood average annual losses 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.

Table 3.10. BCA Results of Flood Premiums for Each Freeboard Scenario

Freeboard (ft.)		Upfront				
		0%	3%	7%	10%	12%
0.5	NB	\$0	\$0	\$0	\$0	\$0
	NBCR	0.0	0.0	0.0	0.0	0.0
1.0	NB	\$27,030	\$17,660	\$11,181	\$8,494	\$7,258
	NBCR	5.1	3.3	2.1	1.6	1.4
1.5	NB	\$27,030	\$17,660	\$11,181	\$8,494	\$7,258
	NBCR	3.4	2.2	1.4	1.1	0.9
2.0	NB	\$37,560	\$24,540	\$15,536	\$11,802	\$10,085
	NBCR	3.6	2.4	1.5	1.1	1.0
2.5	NB	\$37,560	\$24,540	\$15,536	\$11,802	\$10,085
	NBCR	2.9	1.9	1.2	0.9	0.8
3.0	NB	\$40,950	\$26,755	\$16,938	\$12,868	\$10,995
	NBCR	2.6	1.7	1.1	0.8	0.7
3.5	NB	\$40,950	\$26,755	\$16,938	\$12,868	\$10,995
	NBCR	2.2	1.5	0.9	0.7	0.6
4.0	NB	\$41,850	\$27,343	\$17,311	\$13,151	\$11,237
	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	\$27,030	\$17,660	\$11,181	\$8,494	\$7,258
	NBCR	3.0	3.0	3.0	3.0	3.0
1.5	NB	\$27,030	\$17,660	\$11,181	\$8,494	\$7,258
	NBCR	2.0	2.0	2.0	2.0	2.0
2.0	NB	\$37,560	\$24,540	\$15,536	\$11,802	\$10,085
	NBCR	2.1	2.1	2.1	2.1	2.1
2.5	NB	\$37,560	\$24,540	\$15,536	\$11,802	\$10,085
	NBCR	1.7	1.7	1.7	1.7	1.7
3.0	NB	\$40,950	\$26,755	\$16,938	\$12,868	\$10,995
	NBCR	1.5	1.5	1.5	1.5	1.5
3.5	NB	\$40,950	\$26,755	\$16,938	\$12,868	\$10,995
	NBCR	1.3	1.3	1.3	1.3	1.3
4.0	NB	\$41,850	\$27,343	\$17,311	\$13,151	\$11,237
	NBCR	1.2	1.2	1.2	1.2	1.2

Using the case study, adding two feet of additional freeboard as the optimal choice yields a total life-cycle NB of \$53,377, with a 7:1 NBCR in the loan option, assuming the baseline real discount rate of 7%. The cost associated with adding the freeboard is offset in less than four years. The corresponding NB from annual flood premium savings alone is \$15,536 with a 2:1 NBCR. The initial cost of increasing elevation two feet is \$10,403, or 4.5% of the at-BFE construction cost of the home.

The results of this work demonstrate that flood protection is achievable at a modest cost. The optimal two feet of freeboard add only \$49 to the monthly payment of the 30-year mortgage with a fixed rate of 3.375%. Even if the value of flood loss reduction is neglected, the savings in annual premiums alone are sufficient to offset the freeboard costs paid.

Flood risk reduction and savings in premiums are apparent gains, other lifetime benefits include less inconvenience and suffering, faster recovery, and increased property values. Communities can also receive further reductions in insurance premiums from CRS, where elevation increase is one of the conditions to lower premiums. These avoided losses and savings will be realized by the owner through the life span of the structure. While the freeboard cost is modest, the life-cycle benefits of avoided flood losses and cost savings are substantial. Despite these evident benefits, many homeowners do not take mitigation into account, suggesting that the benefits are not communicated effectively. As a result, benefits are not being realized by many individuals and communities.

While results show that adding freeboard yields substantial lifetime benefits to both the homeowner and NFIP, it is evident that the flood losses are primarily borne by NFIP and therefore enjoys greater lifetime benefits. Results also highlight the need to perform the life-

cycle BCA 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.

Due to the nature of this work, the analysis accounted for only direct economic losses, and did not cover indirect losses such as displacement, relocation, human suffering, and health costs. In addition, this study did not cover indirect intangible losses such as the environmental and social costs. Also, this work did not consider the possible future effects of climate change and increase in asset values. As a result, the estimates are considerably conservative and underrepresent the true benefits of adding freeboard.

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, life-cycle BCA 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 life-cycle BCA.

While this work investigates life-cycle benefit-cost at single-building level, extending the methodology to a larger scale is essential. Estimating life-cycle benefits at a building scale allows aggregation to larger spatial levels with a higher level of accuracy. Future research should also consider the impacts of climate change and their economic costs.

Chapter 4. Freeboard Life-Cycle Benefit-Cost Analysis for Landlord and Tenant

4.1. Introduction

Floods are the most commonly occurring and most costly type of natural disaster (Witt et al., 2015). Single-family home owners and tenants are the most affected by flooding events (Warren-Myers et al., 2018). Single-family home rental represents an increasing share of the housing industry in U.S. (Charles, 2020), with 14.9 million renter-occupied single-family homes as of 2017 (Rosen, 2018). As is the case with homeowners, many landlords and tenants are unaware of their flood risk (Hollar, 2017), and consequently they invest substantial sums without being aware of the full risk (Warren-Myers et al., 2018). Understanding their true risk of flooding, the possible mitigation measures, and the economic implications, or lack thereof, are likely to influence investment choices and occupation decisions (Warren-Myers et al., 2018).

Yet, flood risk to single-family rental housing has been neglected by decision makers and the scientific community. FEMA has acknowledged that the nation's flood policies neglect rental housing and focus only on owner-occupied housing (Hamideh et al., 2018). Moreover, the dearth of studies conducted on rental housing leaves a large segment of the population without adequate protection due to the lack of information. This necessitates development of a comprehensive flood risk assessment that quantifies flood losses for single-family rentals and provides actionable information to landlords and tenants.

While FEMA (2013) Hazus-MH tool and FEMA (2009) BCA Reference Guide provide useful benefit-cost analyses (BCA), their analyses consider losses to landlords only instead of disaggregating losses between the affected parties – landlords and tenants. Also, average annual loss (AAL) estimates are calculated as piecewise product of annual probability of exceedance

and loss based on observed data without considering the associated uncertainty or modeling the probability of different outcomes.

In this chapter, life-cycle BCA is conducted for the landlord and the tenant, with multiple freeboard scenarios evaluated in terms of their benefits as compared to the cost. The expected costs over the useful life of the home for each freeboard are estimated and discounted to the present value (PV) and summed; net benefits (NBs) are the differences in the life-cycle costs between the “with freeboard” scenarios and “at base flood elevation (BFE) no action” scenario. The optimal scenario is the freeboard with the highest life-cycle NB. NB is divided by the construction cost of the freeboard to determine the NBCRs.

For the landlord, adding freeboard is evaluated through life-cycle BCA considering freeboard cost, building flood premiums, building AAL, and loss of rental income. For the tenant, the benefit of freeboard is evaluated through consideration of content AAL, content flood premiums, displacement cost, and moving cost. Additionally, the life-cycle benefit-cost is proportioned to the policyholder and the NFIP as policyholders are liable for the deductible of flood loss while the NFIP covers the remainder of the loss.

In this work, the life-cycle BCA is conducted on a micro-scale (i.e., single-building level) basis, which is characterized by a higher level of detail (Bubeck et al., 2011; Lorente, 2019). A one-story, single-family residence in Metairie, Louisiana, is used to demonstrate the methodology presented. The study is motivated by the need to establish a reliable methodology for estimating freeboard life-cycle benefit-cost for the landlord and the tenant. The methodology delivers actionable information and supports the decision-making process.

4.2. Methodology

Benefits of freeboard are the future costs prevented or reduced by adding the freeboard and are determined by comparing the present value of costs over the useful life of the building

between with and without the mitigation measure. In this work, freeboard life-cycle benefit-cost for the landlord and the tenant are determined through a life-cycle BCA. Life-cycle BCA is used to weigh the expected benefits against the costs over the useful life of the building to decide the best alternative (CWCB, 2010; Mikulik and Zajdel, 2009; Thoft-Christensen, 2010). Freeboard is evaluated over a 30-year period, the expected useful life of a mitigation project (FEMA, 2009).

Life-cycle BCA is performed for each 0.5-ft. increment of freeboard above BFE up to four feet. The methodology consists of the following steps: (i) determine the expected costs at BFE versus costs of each freeboard scenario for both landlord and tenant, with all costs estimated on an annualized basis, (ii) conduct the BCA.

4.2.1. Expected Costs

Flood losses are divided into two categories: direct physical losses and losses due to loss of function. Direct physical losses are the expected loss to building and content. Loss of function is loss that is incurred when the building is damaged by flood and no longer meet its intended purpose (FEMA, 2019). Losses resulting from the loss of function are loss of rental income, displacement cost, and moving cost. Landlord losses include building loss due to flooding and the loss of rental income, while tenant losses are content loss, displacement cost, and moving cost. Building and content losses are presented as average annual loss (AAL). Loss of rental income is based on the length of restoration time required, while displacement cost and moving cost are one-time costs. The life-cycle benefit of adding freeboard for the landlord is evaluated through consideration of freeboard construction cost, flood insurance premiums for building, building AAL, and loss of rental income. For the tenant, the benefit of freeboard is evaluated through consideration of flood insurance premium for content, content AAL, displacement cost, and moving cost.

4.2.1.1. Landlord Losses

The first loss that the landlord is expected to incur is building loss, which is the direct physical loss based on flood depth that the residence is expected to experience. Building loss is estimated as the product of the loss percentage per flood depth and the replacement cost of the building (i.e., building value). However, a flood-damaged building leads to other losses by affecting the building's functionality. For the landlord, such losses include the rental income lost when the rental unit is withdrawn from the market. These are in addition to flood premiums for building and freeboard construction cost that are incurred by the landlord. Therefore, the annual landlord loss L_l is estimated as the sum of annual freeboard cost F_C , building annual premium P_b , building AAL (AAL_b), and the expected annual rental loss R_l , or

$$L_l = F_C + P_b + AAL_b + R_l \quad (4.1)$$

4.2.1.1.1. Cost of Freeboard

Freeboard construction cost is estimated as a percentage of the building value and is based on FEMA (2008) guidance for estimating the freeboard cost for new single-family residences. While FEMA (2008) reports the cost for each freeboard increment as a range of percentage estimates of total building cost, this work applies the upper limit as a conservative measure (Table 4.1).

Table 4.1. Average Cost of Construction Increase (%), by FEMA Flood Zone and Foot of Freeboard

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

Freeboard construction cost of each scenario F_{CU} is the percentage increase in construction cost associated with each freeboard F_{PI} provided in Table 4.1 multiplied by the value of the building at BFE (BV_{BFE}), or

$$F_{CU} = F_{PI} \times BV_{BFE} \quad (4.2)$$

In this study, a 30-year fixed-rate loan is assumed, as it is the standard length for residential mortgages. The standard loan amortization formula is applied to calculate the amortized base monthly amount for freeboard construction cost F_{CBM} , such that

$$F_{CBM} = \frac{F_{CU} \left(\frac{r}{n} \right)}{1 - \left(1 + \frac{r}{n} \right)^{-nt}} \quad (4.3)$$

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

The amortized base monthly amount F_{CBM} is added to the monthly loan fees LF_M to obtain total monthly loan payment for freeboard construction cost F_{CM} .

$$F_{CM} = F_{CBM} + LF_M \quad (4.4)$$

Freeboard monthly loan payment F_{CM} is multiplied by the number of payments per year n to obtain the annual cost of freeboard F_{CY} .

$$F_{CY} = F_{CM} \times n \quad (4.5)$$

4.2.1.1.2. Building Flood Premiums

For buildings with federally backed loans located in a special flood hazard area (SFHA), the landlord is required to have flood insurance on the building only, not the content (Federal Deposit Insurance Corporation, 2016). Annual building premium for each freeboard increment is calculated using the NFIP (2021) Flood Insurance Manual's post-firm for a single-family residence. For single-family homes, \$60,000 is the basic building coverage, with a maximum

limit of \$250,000. A minimum deductible of \$1,250 is required for coverages above \$100,000 (NFIP, 2021).

4.2.1.1.3. Building AAL

Building AAL is estimated using the methodology presented in Chapter 3. To estimate building AAL, flood depths derived from Monte Carlo simulations with fitted Gumbel distribution are translated to building loss percentages using the USACE (2000) depth-damage function. The loss percentages are then multiplied by the structure replacement cost (i.e., building value), and the average of the resulting losses of all simulated flooding events is the AAL.

While the USACE depth-damage functions account for the structure below FFE by contributing losses to negative flood depths (i.e., below the building's first floor), it is assumed that it is unlikely that the tenant will relocate when flood depths are below FFE. In that case, there is no loss of rental income. However, building loss starts at -1 ft. depth and is included in the loss estimations.

The flood premium deductible for a building is represented within the flood loss, as the policyholder is liable for the deductible specified while NFIP covers the remaining balance. Thus, the building AAL is apportioned as either landlord loss or NFIP loss using the methodology presented in Chapter 3.

4.2.1.1.4. Loss of Rental Income

Rental loss is a time-based loss, where loss depends on the expected building's restoration time after being flooded. The building's restoration time is derived from FEMA (2013) depth-restoration time function, which assigns restoration time in months based on the expected flood depth. To estimate rental loss, flood depths derived from Monte Carlo simulations with a fitted Gumbel distribution are translated to restoration times S_{t_i} using the

FEMA (2013) depth-restoration time function. Next, the determined monthly rent loss per-square-foot R_m is multiplied by the building's total square footage B_q to estimate the monthly rental loss. The monthly rental loss is applied to the calculated restoration time to estimate the rental loss R_{l_i} for the simulated annual event. The average of the resulting rental loss of all simulated flooding events is the annual rental loss R_l , such that

$$R_l = \frac{1}{N} \sum_{i=1}^N (S_{t_i}) \cdot (R_m \cdot B_q) \quad (4.6)$$

where i is the simulated event between N simulations.

The depth-restoration time function relates the expected flood depth inside the building to the required time to restore the building, including physical restoration in addition to time needed for clean-up, inspection, permits and approval, and contractor availability. FEMA (2013) depth-restoration times for multiple flood depths are provided in Table 4.2. Although restoration times are evaluated in 4-foot increments of flood depths, these data are interpolated in this study to estimate the restoration time at any point within the data intervals.

Table 4.2. FEMA's Depth-Restoration Time for Multiple Flood Depths

Depth (ft.)	Physical Restoration (Months)	Clean-up (Months)	Inspection Permits Approval (Months)	Contractor Availability (Months)	Total Restoration Time (Months)
0	3	1	2	3	9
4	6	1	2	3	12
8	9	1	2	3	15
8+	18	1	2	3	24

Rental loss per-square-foot is obtained using 2019 housing data from Zillow (Corbin, 2020). Rent per-square-foot of single-family residences in each state is provided with an average monthly rent per-square-foot of \$1.21. However, depending on the location, other sources could be used to obtain rental costs that are relevant to the location of the site.

4.2.1.2. Tenant Losses

Although it is unlikely that the tenant will relocate when flood depths are below FFE, any higher depth is likely to cause the tenant to be displaced. Tenants bear displacement costs due to flood damage to the residence (Arcadis, 2019). However, the tenant likely will cease rent payment to the landlord, and instead look for another place (Arcadis, 2017). Such relocation cost is not included here, but instead only displacement and moving costs are considered in addition to the content loss. Therefore, the annual tenant loss T_l is the sum of the annual premium for content (P_c), content AAL (AAL_c), annual expected displacement cost (D_c), and the annual expected moving cost (M_c), or

$$T_l = P_c + AAL_c + D_c + M_c \quad (4.7)$$

4.2.1.2.1. Content Flood Premiums

Tenants are responsible for any flood loss to their personal belongings (Federal Deposit Insurance Corporation, 2016), and standard renters insurance generally does not cover flood loss (FEMA, 2020). In this study, tenants are assumed to have their separate content-only flood coverage. Annual content premiums are calculated using the NFIP (2021) Flood Insurance Manual's post-FIRM for a single-family residence. For single-family homes, \$25,000 is the basic content coverage, with maximum limits of \$100,000. A minimum deductible of \$1,250 is required for coverages above \$100,000 (NFIP, 2021).

4.2.1.2.2. Content AAL

Content loss is represented as content AAL_c and is estimated using the methodology presented in Chapter 3. To estimate content AAL, depths derived from Monte Carlo simulations with fitted Gumbel distribution are translated to content loss percentages using the USACE (2000) depth-damage function. The loss percentages are then multiplied by the building value, and the average of all the simulated events is the AAL. While the building loss starts at -1 ft.

flood depth, content losses at negative flood depths (i.e., below the FFE) are assumed to have no losses. Content AAL is apportioned to tenant loss or NFIP loss.

4.2.1.2.3. Displacement Cost

tenants impacted due to flood damage to their residence will be temporarily displaced and seek a shelter until finding another place to relocate. While some tenants may use public shelters or stay with families or friends, others will resort to lodging. This study considers only lodging in the loss assessment.

Some other studies have assumed the displacement cost to be linearly proportional to the flooded residence's rental cost, where the displacement cost is estimated also as a one-time (one month) cost on a per-square-foot basis (e.g. Berger, 2017). However, the displacement cost in this study is estimated as a one-time (one month – the minimum time required to find another place (Chaplin, 2019)) cost based on lodging rates. The lodging rate is more reflective of the variable lodging costs than the cost based on the residence's square footage (FEMA, 2016). The U.S. General Service Administration (2021) provides current lodging per day rates for each state with a current average of \$140 per day.

The displacement cost per day (D_{d_i}) is converted to a monthly rate to estimate the one-time displacement cost for each simulated event with flood depth above FFE. The average of the resulting displacement cost of all simulated flooding events is the expected annual displacement cost (D_c), such that

$$D_c = \frac{1}{N} \sum_{i=1}^N (D_{d_i} \cdot 30) \quad (4.8)$$

4.2.1.2.4. Moving Cost

Moving cost is associated with moving the content of the household from the flooded residence to a new location. It is estimated based on the flooded residence square footage, which

often indicates the size of the household. A moving cost of \$1.20 per-square-foot (Arkin, 2021) is used. The moving cost-per-square-foot (M_{cq}) is multiplied by the building's total square footage (B_q) to estimate the moving cost for each simulated event with flood depth above FFE. The average of the resulting moving cost of all simulated flooding events is the annual moving cost (M_c), or

$$M_c = \frac{1}{N} \sum_{i=1}^N (M_{cq} \cdot B_q) \quad (4.9)$$

4.2.2. Benefit-Cost Analysis (BCA)

To determine whether adding freeboard results in life-cycle benefit, all the annualized costs are discounted to the PV, and BCA is performed through consideration of the PV, NB, and NBCR. The scenario with highest life-cycle NB is the optimal option. In contrast, NBCR expresses the life-cycle cost effectiveness of the mitigation scenario by showing the relationship between net benefit and cost.

4.2.2.1. Present Value (PV)

BCA is performed on a discounted present value basis (DPV), which transforms the expected future costs and benefits to present-value terms (Frank, 2000). It enables the comparison of mitigation costs with the expected future benefits (Tate et al., 2016).

The DPV of a cost C_{PV} is the discounted annualized costs C_t using a discount rate R_D over a time horizon t , or

$$C_{PV} = \sum_{t=1}^t \frac{C_t}{(1+R_D)^t} \quad (4.10)$$

Results assuming a 7% real discount rate are contrasted with a 3% real discount rate to test the sensitivity of results in this study. This is consistent with the requirements of U.S. Office of Management and Budget (1992) for BCA analyses.

4.2.2.2. The Net Benefit (NB)

NB of freeboard is the future reduced or prevented losses by the mitigation measure. The NB of adding freeboard NB_F is the difference in life-cycle cost with versus without the freeboard and is determined by subtracting the life-cycle PV of freeboard scenario (F_{PV}) from the life-cycle PV of the “at BFE no action” scenario (BFE_{PV}).

$$NB_F = BFE_{PV} - F_{PV} \quad (4.11)$$

4.2.2.3. Net Benefit to Cost Ratio (NBCR)

The life-cycle cost effectiveness of the freeboard (i.e., benefit per dollar spent) is expressed by NBCR, which is the total NB of the freeboard NB_F divided by its total cost F_C , or

$$NBCR_F = \frac{NB_F}{F_C} \quad (4.12)$$

4.3. Case Study

A one-story, single-family residence with 2,500 ft² of living area located in Metairie, Louisiana, within the AE flood zone, at coordinates 29°59'39.8"N, 90°10'05.7"W, is used to demonstrate the presented methodology. The ground elevation of the site is −7.0 ft. (NAVD88), with −4 ft. BFE and an additional 0.5 ft. of “code compliant” freeboard for a FFE of −3.5 ft. (NAVD88). Using the area’s average construction cost of \$92.47 per square feet (Moselle, 2019), the total estimated construction cost is \$231,175. The site’s flood elevations determined from Risk Mapping, Assessment and Planning (RiskMAP) and the corresponding flood depths above ground are shown in Table 4.3.

Table 4.3. Site Flood Elevations and Corresponding Depth Above Ground

Annual Probability of Exceedance	Flood Elevation (NAVD88)	Flood Depth (ft.)
0.002	−3.4	3.6
0.01	−3.9	3.1
0.02	−4.2	2.8
0.1	−4.7	2.3

4.4. Results

Results are presented in two steps: (i) determine annual costs at BFE versus annual costs of each freeboard scenario for both landlord and tenant, (ii) conduct the BCA, where NBs and NBCRs are obtained for multiple freeboard scenarios and discount rates benefit allocations. NB and NBCR are also apportioned between landlord and tenant. Life-cycle BCA of freeboard insurance savings is performed separately.

4.4.1. Expected Costs

Freeboard life-cycle benefit for the landlord is evaluated through consideration of freeboard construction cost, flood insurance premiums for building, building AAL, and loss of rental income. For the tenant, freeboard life-cycle benefit is evaluated through consideration of flood insurance premium for content, content AAL, displacement cost, and moving cost.

4.4.1.1. Landlord Losses

The cost for each freeboard increment is estimated based on a total construction cost of \$231,175 and as 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)). The corresponding annual building premiums are calculated based on maximum building value of \$231,175, with the minimum deductible of \$1,250 and CRS discount of 25% (rating of 5). For the landlord, direct physical loss is limited to the building loss, whereas loss of rental income resulting from the loss of function is estimated based on the restoration time of the building. Among other results, the building AAL is apportioned as landlord and NFIP AAL. Table 4.4 shows the landlord's expected annual costs for the range of freeboard increments.

As shown in Table 4.4, adding only one foot of freeboard decreases the aggregate annual losses from \$5,327 to \$1,278, yielding an annual avoided loss of \$ 4,049. Based on the results, annual losses are reduced with each additional freeboard increment, with rental loss eliminated at

the first foot of freeboard and building AAL eliminated at 2 ft. of freeboard. Beyond that, landlord annual losses depend only on the cost of freeboard and building premium. It should be noted that higher AALs occur with the smaller freeboard because the largest proportion of losses occurs at smaller flood depths. Loss of rental income is based on the time required to restore the building and increases with the severity of the expected damage. However, it is limited to flood depths above the FFE.

Table 4.4. Landlord's Expected Annual Costs by Freeboard Height

Freeboard (ft.)	Freeboard Cost (Loan/Annual)	Building Annual Premium	Building AAL	Landlord Building AAL	NFIP Building AAL	Annual Rental Loss
0.0	\$0	\$1,616	\$3,383	\$298	\$3,085	\$328
0.5	\$151	\$1,616	\$738	\$66	\$672	\$64
1.0	\$302	\$822	\$154	\$15	\$139	\$0
1.5	\$446	\$822	\$24	\$0	\$24	\$0
2.0	\$591	\$503	\$0	\$0	\$0	\$0
2.5	\$741	\$503	\$0	\$0	\$0	\$0
3.0	\$892	\$391	\$0	\$0	\$0	\$0
3.5	\$1,043	\$391	\$0	\$0	\$0	\$0
4.0	\$1,194	\$361	\$0	\$0	\$0	\$0

4.4.1.2. Tenant Losses

For the tenant, the life-cycle benefit of adding freeboard is evaluated through consideration of content premium savings, flood loss reduction to the content, and prevented or reduced displacement and moving costs as compared to the freeboard's construction cost. The annual content premiums are calculated based on maximum content value of \$92,470, with the minimum deductible of \$1,250 and CRS discount of 25%. For the tenant, all losses are estimated based on flood depths above FFE. The direct physical loss is limited to the content loss and is apportioned as tenant AAL and NFIP AAL. Displacement cost is estimated as a one-time (one month) cost based on \$140 per day lodging rate, assuming a conservative one-room estimate with two household members. Moving cost is estimated as a one-time \$1.20 per-square-foot

expense. Table 4.5 shows the tenant’s expected annual costs for each freeboard increment.

Tenant losses are relatively small and are eliminated in the first one foot of freeboard. This is because losses for the tenant are considered only for flood depths above the FFE.

Table 4.5. Tenant Annual Costs for Each Freeboard Height Scenario

Freeboard (ft.)	Content Annual Premium	Content AAL	Tenant Content AAL	NFIP Content AAL	Annual Displacement Cost	Annual Moving Cost
0.0	\$346	\$258	\$15	\$243	\$49	\$35
0.5	\$346	\$48	\$0	\$48	\$10	\$0
1.0	\$240	\$0	\$0	\$0	\$0	\$0
1.5	\$240	\$0	\$0	\$0	\$0	\$0
2.0	\$208	\$0	\$0	\$0	\$0	\$0
2.5	\$208	\$0	\$0	\$0	\$0	\$0
3.0	\$208	\$0	\$0	\$0	\$0	\$0
3.5	\$208	\$0	\$0	\$0	\$0	\$0
4.0	\$208	\$0	\$0	\$0	\$0	\$0

4.4.2. Life-cycle Benefit-Cost Analysis (BCA)

Once all annual loss estimates are discounted to the PV for the life of the building, the cumulative PVs of losses are calculated for the “at BFE no action” scenario and for each freeboard scenario. NB for each freeboard increment is calculated by subtracting the PV of freeboard cumulative cost from the cumulative PV “at BFE baseline scenario.” NB for each freeboard increment is divided by its construction cost to determine the NBCR. The BCA calculations are carried out using a baseline of 7% real discount rate with 3% real discount rate to test the sensitivity of results. As shown in Table 4.6, BCA results are presented as NB and NBCR for each freeboard scenario using both real discount rates.

From the overall results, all freeboard scenarios outperform the “at BFE no action scenario.” Adding freeboard result in total life-cycle NBs ranging between \$37,670 and \$58,479, with total NBCRs ranging from 4:1 to 20:1, when assuming the baseline real discount rate of 7%, and between \$59,500 and \$92,369 with NBCRs ranging between 6:1 and 20:1, assuming a 3%

Table 4.6. BCA Results for Each Freeboard Scenario

Freeboard (ft.)	First-Floor Elevation (ft.)		Tenant		Landlord		NFIP		Total	
			7%	3%	7%	3%	7%	3%	7%	3%
0.5	-3.5	NB	\$978	\$1,544	\$4,288	\$6,773	\$32,404	\$51,183	\$37,670	\$59,500
		NBCR	0.5	0.5	2.3	2.3	17.3	17.3	20.1	20.1
1.0	-3.0	NB	\$2,522	\$3,983	\$13,654	\$21,567	\$39,544	\$62,461	\$55,720	\$88,012
		NBCR	0.7	0.7	3.6	3.6	10.6	10.6	14.9	23.5
1.5	-2.5	NB	\$2,534	\$4,003	\$12,049	\$19,031	\$41,041	\$64,825	\$55,624	\$87,859
		NBCR	0.5	0.5	2.2	2.2	7.4	7.4	10.0	15.9
2.0	-2.0	NB	\$2,931	\$4,630	\$14,250	\$22,508	\$41,298	\$65,231	\$58,479	\$92,369
		NBCR	0.4	0.4	1.9	1.9	5.6	5.6	8.0	12.6
2.5	-1.5	NB	\$2,931	\$4,630	\$12,379	\$19,553	\$41,306	\$65,245	\$56,616	\$89,427
		NBCR	0.3	0.3	1.3	1.3	4.5	4.5	6.2	9.7
3.0	-1.0	NB	\$2,931	\$4,630	\$11,896	\$18,790	\$41,306	\$65,245	\$56,133	\$88,665
		NBCR	0.3	0.3	1.1	1.1	3.7	3.7	5.1	8.0
3.5	-0.5	NB	\$2,931	\$4,630	\$10,023	\$15,832	\$41,306	\$65,245	\$54,260	\$85,707
		NBCR	0.2	0.2	0.8	0.8	3.2	3.2	4.2	6.6
4.0	0.0	NB	\$2,931	\$4,630	\$8,523	\$13,462	\$41,306	\$65,245	\$52,760	\$83,337
		NBCR	0.2	0.2	0.6	0.6	2.8	2.8	3.6	5.6

real discount rate. The total NB continues to increase with each added freeboard increment, reaching the highest value at 2 ft. of freeboard and then gradually declining. This indicates that the economically optimal freeboard is 2 ft. where total life-cycle NB is at its highest value at \$58,479 with NBCR of 8:1, assuming a 7% real discount rate, and \$92,369 in NB with 13:1 NBCR, when assuming a real discount rate of 3%. Yet this freeboard scenario is ranked below the 0.5-, 1.0-, and 1.5-ft. scenarios, when considering the NBCR metric. The highest NBCR is observed in the smallest freeboard scenario and then shows an incremental decrease, indicating that benefit per dollar of cost declines as FFE increases. This is because the largest share of flood losses occurs for lower FFEs.

Elevating the home to the optimal height of 2 ft. results in a life-cycle NB to landlord and tenant, with a landlord NB of \$14,250 using a 7% real discount rate, and \$22,508 when assuming a real discount rate of 3%. For the tenant, the expected life-cycle NB is \$2,931 when assuming a 7% real discount rate and \$4,630 using a 3% real discount rate. The landlord life-cycle NB continues to increase with each additional freeboard increment, reaching the highest level at 2 ft. and gradually decreasing as rental loss and building AAL are eliminated and the calculations start to rely more heavily on freeboard construction cost and building premium, with freeboard cost increase outweighing building premium incremental decrease, resulting in lower NB. On the other hand, NB for the tenant continues to increase reaching the highest value at 2 ft. of freeboard. Displacement and moving costs are eliminated in the first one foot of freeboard and estimates depend only on content premium decrease. However, beyond 2 ft., there is no incremental decrease in content premium, resulting in unchanged NB estimates.

NFIP life-cycle NB is the aggregated NFIP's building and content NB. For a 2-ft. freeboard, the total NFIP NB is \$41,298, assuming a 7% real discount rate, and \$65,231, when

using a 3% real discount rate. NFIP NBs continue to increase with each additional freeboard increment, with the highest estimate achieved at 2 ft. of freeboard and continue unchanged as AALs are eliminated beyond that threshold.

Except for the first half-foot increment for which there is no premiums savings, the life-cycle NB from flood premium savings ranges between \$11,168 and \$17,286 with NBCRs ranging from 1:1 to 3:1, when assuming a 7% real discount rate, and from \$17,640 to \$27,303 with NBCRs ranging between 1:1 and 3:1 when using a 3% real discount rate (Table 4.7).

Table 4.7. Premium BCA Results for Each Freeboard Scenario by Discount Rate

Freeboard (ft.)		7%	3%
0.5	NB	\$0	\$0
	NBCR	0	0
1.0	NB	\$11,168	\$17,640
	NBCR	3.0	3.0
1.5	NB	\$11,168	\$17,640
	NBCR	2.0	2.0
2.0	NB	\$15,524	\$24,520
	NBCR	2.1	2.1
2.5	NB	\$15,524	\$24,520
	NBCR	1.7	1.7
3.0	NB	\$16,914	\$26,715
	NBCR	1.5	1.5
3.5	NB	\$16,914	\$26,715
	NBCR	1.3	1.3
4.0	NB	\$17,286	\$27,303
	NBCR	1.2	1.2

4.5. Conclusions

Landlords and tenants are unlikely to be aware of flood risk to which they are exposed, and with no comprehensive flood risk assessment that quantifies flood losses and provides actionable information to them, they are likely to remain unaware of the risk and the possible benefits from some mitigation measures. Being aware of the full flood risk, the mitigation options, and the economic implications enhances investment and occupation decisions.

For a risk-neutral decision, the rental rate of a home with flood risk should be lower than the risk-free alternative by an amount equal to the expected flood losses (Moser, 1985).

However, for a risk-averse decision, the rental rate of a home with flood risk should be lower than the risk-free alternative by an amount greater than the expected flood losses as it includes the assessed risk premium to compensate for bearing the risk (Moser, 1985).

In this study, a life-cycle BCA is performed to determine the life-cycle benefits of adding freeboard for landlord and tenant in a single-family rental housing. The aim is to support the decision process by providing actionable information to them. Using the case study, elevating the home to the optimal height of 2 ft. reduces annual building premiums by 69% and annual content premiums by 40%. In addition to savings on insurance premiums, landlords and tenants would also enjoy benefits by reducing direct physical loss and the other losses due to loss of function. Elevating the home to the optimal height eliminates annual building and rental losses for landlord, and similarly, eliminates tenant's annual content, displacement, and moving losses, with total life-cycle NB of \$58,479 and 8:1 NBCR, assuming the baseline real discount rate of 7%, and \$92,369 of NB with 13:1 NBCR, assuming a 3% real discount rate.

In addition to the previously discussed benefits, the landlord will experience other benefits from avoiding or reducing flood losses. Increased flood risk to the rental house can result in a loss of demand, increased vacancy, and decreased property value due to the expected risk cost liabilities associated with owning or occupying such a premise (Warren-Myers et al., 2018). Similarly, tenants experience unvalued benefits from the added level of safety and loss reduction, avoiding temporary relocation. Forced displacement on very short notice causes insecurity and stress, both emotionally and physically (Hollar, 2017). Moreover, tenants may not be able to relocate within their immediate area, removing individuals and families from their

communities (Hollar, 2017). Also, this analysis assumes that as soon as the building is restored, it will be rented immediately. Further, the study did not consider the environmental and social impacts, future asset value increase, and the potential negative effects of climate change. Thus, the estimates are considerably conservative and underrepresent the true benefits of adding freeboard.

Due to the limited research on this topic, there is currently a lack of sufficient knowledge and an absence of comprehensive reference sources. Also, these flood loss assessments rely on uncertain variables such as the unpredictable nature of flood and the generality of flood loss and restoration time functions. Furthermore, these types of analyses are highly constrained by flood data quality and availability. Additionally, life-cycle BCA requires future projections of discount rates that are highly uncertain. While acknowledging the limitations, the methodology proposed in this study provides a novel framework for quantifying life-cycle benefit of freeboard for single-family rentals through life-cycle BCA. The results highlight the need to evaluate the life-cycle benefits of freeboard at a single-building level, as this allows for a more localized and detailed assessment. However, it is essential to extend the methodology to multifamily rentals.

Chapter 5. Conclusions

5.1. Introduction

The overarching goal of this dissertation research was to quantify the life-cycle costs of flood hazards to homeowners, landlords, and tenants as compared to the mitigation cost to provide actionable information to stakeholders and enable informed decisions about their flood risk reduction management. Life-cycle performance of adding freeboard is evaluated at the single-residence building level using life-cycle BCA. In order to address the overarching goal, three specific objectives were addressed:

- Develop a methodology to estimate flood AAL for single-family homes at the micro-scale level and in a way that covers the full loss-exceedance probabilities curve.
- Develop a methodology to determine the optimal freeboard height for single-family homes through a micro-scale life-cycle BCA, disaggregating and allocating costs and benefits to the proper parties (homeowner and/or National Flood Insurance Program (NFIP)).
- Develop a methodology to evaluate the benefits of adding freeboard through a micro-scale life-cycle BCA for both landlord and tenant in single-family rental housing.

Chapters 2 through 4 described the necessary research accomplished to achieve these objectives. This chapter presents the summary of key findings of each chapter and outlines the limitations and future work.

5.2. Flood Risk Assessment

It is common practice in flood risk assessments to use the available flood return periods, even though flood losses arise from all possible flood events. Additionally, failure to characterize flood risk at the single-building level restricts the amount of information gained about the risk.

Chapter 2 provides a robust flood loss assessment model that quantifies flood AAL at the single-building level and covers the full loss-exceedance probabilities curve to provide actionable information to stakeholders and enable informed decisions. The results of this chapter demonstrate that flood protection is achievable with elevation increase. Flood loss reduction is an immediate benefit to be gained by adding freeboard. Other benefits include insurance premium savings, less suffering, and increase in home value. Nevertheless, many homeowners fail to consider mitigation measures, indicating that the potential benefits are not communicated effectively. As a result, potential benefits are not realized by many homeowners and communities.

Results also highlight the need to assess flood risk at the micro-scale level for a more localized and accurate assessment, where it can be expanded to larger-scale risk estimations for a higher degree of accuracy. This can encourage homeowners and communities to take actions and support government decision-makers to invest in flood mitigation and consider building code changes. The chapter results show that a large portion of flood losses occur below the top of the first floor, signifying that increasing the elevation should account for the floor structure and other structural elements below the first-floor level.

The results of Chapter 2 provide a robust, generalized flood loss assessment model that can be easily applied to support decision-making at single-building level. This model is very fundamental with only few parameters to address the increased prediction uncertainty associated with more complex models due to the larger number of parameters.

5.3. Determining the Optimal Freeboard through Life-Cycle BCA

Determining the optimal FFE height poses a major decision problem. Also, the lack of robust life-cycle BCA that quantifies costs and benefits at the micro-scale level discourages investment in flood mitigation. Moreover, recent studies considered either the expected flood

annual loss or annual flood premiums in their decision criteria, and at the same time do not disaggregate costs and benefits between the affected parties.

Chapter 3 provides a comprehensive, generalized methodology that determines the optimal freeboard height at the micro-scale level through a life-cycle BCA, where costs and benefits are disaggregated and allocated to the proper parties (homeowner and/or NFIP). This work also considers both the average annual loss and annual premium in the decision criteria for a more effective analysis.

The results of this chapter show that flood protection is achievable at a modest cost. The two feet optimal freeboard adds only \$49 to the monthly payment of the 30-year mortgage with fixed rate of 3.375%. However, the resulting total life-cycle NB is \$53,377, with a NBCR of 7:1 when applying the baseline real discount rate of 7%. The corresponding NB from premium savings alone is \$15,536 with a 2:1 NBCR. Even if flood loss reduction is neglected, annual premium savings alone are sufficient to offset the cost of adding the freeboard.

Flood risk reduction and premium savings are apparent benefits. Other benefits include less suffering, faster recovery, and increased property values. Communities can also benefit from reductions in flood premiums from CRS participation. These avoided losses and savings will be realized through the life of the property. While the construction cost of adding freeboard is modest, the life-cycle benefits of avoided losses and savings are substantial. Despite the benefits, many homeowners do not consider mitigation, suggesting that the life-cycle benefits are not communicated effectively.

While results show that additional freeboard results in substantial lifetime benefits to both the homeowner and NFIP, it is evident that the losses are primarily borne by NFIP and therefore enjoy the most benefits. The results of this chapter also highlight the need to perform the life-

cycle BCA using a range of discount rates to ensure more transparency in the interpretation of benefits and enhances the awareness by highlighting the sensitivity of the results to the discount rate used. The framework developed in this chapter provides a guidance to support effective mitigation decision making by providing actionable information with clear results to stakeholders.

5.4. Freeboard Life-Cycle Benefit-Cost Analysis for Landlord and Tenant

Many landlords and tenants are unaware of flood risk to which they are exposed, substantially impairing their investment choices and occupation decisions. Still, flood risk to single-family rental housing is largely neglected by decision makers and the scientific community, leaving a large segment of the population without adequate flood protection due to the lack of information. With no comprehensive flood risk assessment that quantifies flood losses over the useful life of the rental building and provides actionable information, they are likely to remain unaware of their flood risk and the potential benefits from available flood mitigation measures.

In Chapter 4, a life-cycle BCA is performed to determine freeboard life-cycle benefits for landlord and tenant in a single-family rental housing. The aim is to support an effective decision process with a reliable methodology that provides actionable information and communicates clear results to them. The results of this chapter show that elevating the rental home to the optimal height of 2 ft. eliminates annual building and rental losses for landlord, and similarly, eliminates tenant's annual content, displacement, and moving losses, with total life-cycle NB of \$58,479 and 8:1 NBCR, assuming the baseline real discount rate of 7%. The landlord will experience other benefits from avoiding or reducing flood losses, including higher demand, increased occupancy, and higher property value. Similarly, tenants will experience unvalued

benefits from the added level of safety, preventing forced relocation, and avoiding stress, both physically and emotionally.

The methodology proposed in this chapter provides a novel framework for quantifying life-cycle benefit of freeboard for landlord and tenant in a single-family rental housing. Being informed of the full risk, the mitigation options, and the economic implications enhances investment and occupation decisions. The results highlight the need to consider rental housing in flood mitigation and underscore the need for a robust life-cycle BCA that provides actionable recommendations to landlords and tenants.

5.5. Limitations and Future Work

The analysis covered the direct economic losses (building and content losses), and the main indirect tangible losses (loss of rental income, displacement, and moving cost). However, indirect intangible losses such as the human suffering, environmental, and social costs were not considered due to the nature of this work. In addition, this work did not consider the possible future effects of climate change and increase in asset values. As a result, the estimates are considerably conservative and underrepresent the true benefits of adding freeboard.

Flood loss assessments are impacted by high uncertainty since they rely on uncertain variables related to the flood unpredicted nature and the generality of flood loss and restoration time functions. To enhance the reliability and accuracy of flood loss estimates, more research should be focused on reducing the uncertainties associated with flood loss and also the restoration time functions. Also, these types of flood loss assessments are highly constrained by available flood data, where the accuracy and reliability of results are limited by data quality and/or availability. Moreover, life-cycle BCA requires future projections of variables such as discount rates that are highly uncertain.

Due to the limited research on rental housing flood loss assessments, there is currently a lack of sufficient knowledge and an absence of comprehensive reference sources. While acknowledging the limitations, this work offers an improvement to flood loss modeling and to the topic of establishment of the economically optimal elevation of single-family residences through life-cycle BCA. Equally, it provides a novel framework for quantifying life-cycle benefit of freeboard for single-family rentals through life-cycle BCA.

Moving forward, extending the methodology to a larger scale is essential. Estimating life-cycle BCA at a building scale allows aggregation to larger spatial levels with a higher level of accuracy. Such improvements could help in identifying potentially vulnerable areas within the targeted region, which could help prioritize future flood risk management strategies. Future work should also consider the impacts of climate change and their economic costs. The methodology is developed generally and can be adapted for new data, loss functions, and other input.

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Vita

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