Non-structural Flood Mitigation Optimization at Community Scale: Middle Cedar Case Study

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Abstract

Flooding is the leading natural hazard in Iowa and has resulted in billions of dollars of damage to properties and critical infrastructure over the past couple of decades. Land alterations, urbanization, and changing precipitation regimes increase the magnitude and frequency of flood events. Considering the increasing risk, flood mitigation efforts are significant to reduce future losses. In this study, we present a comprehensive flood mitigation assessment for the cities of Cedar Falls, Cedar Rapids, and Waterloo in Iowa, utilizing various datasets such as property information, flood inundation maps, mitigation costs, and depth-damage functions. The research revealed that flooding has a minimal impact on Waterloo below the 200-year return period flood scenario, but Cedar Falls and Cedar Rapids are significantly vulnerable, requiring more mitigation investments and planning. The study conducted a benefit-cost analysis, indicating that dry floodproofing is the most feasible option to reduce flood impacts in all studied communities. Moreover, the research conducted a climate data-driven analysis, which found that elevating structures significantly increases the number of feasible mitigation options, regardless of various long-term climate projections. The study also analyzed predetermined mitigation budgets, revealing potential avoided losses and benefit-cost ratios for properties with the highest BCRs and prioritizing them to maximize the total benefit to the communities. The findings provide valuable insights for community decision-makers to prioritize flood mitigation measures based on the benefit-cost ratio. Overall, the study provides valuable insights and recommendations for decision-makers, contributing to the development of effective flood mitigation strategies to minimize the potential impact of flooding in the studied regions.

Keywords: Flood, Mitigation, Cost-Benefit Analysis, Optimization

1. Introduction

Increase in frequency and severity of flood events pose a significant threat to human lives and infrastructure globally, particularly in low-lying and coastal regions (Hirabayashi et al., 2013). With rising sea levels, melting glaciers, and increasing precipitation due to climate change, flood events have become more frequent and severe (Milly et al., 2002). Increasing flood magnitudes have been revealed by many recent studies (Das et al., 2013; Kemter et al., 2020; Petrow and Merz, 2009; Gu et al., 2021). Floods can cause significant complications, including loss of property, damage to critical infrastructure, and loss of life (Alabbad and Demir, 2022). They also lead to economic losses, disrupt transportation, and affect food security (Albano et al., 2014). Floods are one of the underlying reasons for increasing the risk of waterborne diseases and vector-borne illnesses, creating public health challenges (Levy et al., 2016). The growing frequency and severity of flood events necessitate a multi-dimensional response, including improving infrastructure, enhancing early warning systems, and implementing comprehensive disaster risk management plans.

Globally, many government agencies have been investing in flood mitigation measures to eliminate or minimize flood impacts in vulnerable communities. While governments are supporting large-scale flood mitigation projects, they also recommend individual efforts through incentive programs. Property buyouts (Zavar, 2015), flood proofing (De Graaf et al., 2012), elevation (Mobley et al., 2020), and flood insurance (Kousky and Kunreuther, 2014) are commonly preferred individual practices to mitigate properties against flood damage. In the United States, the Federal Emergency Management Agency (FEMA) provides grants for flood mitigation projects to support the implementation of cost-effective measures to reduce the risk of flood damage.

FEMA grants for flood mitigation are available for both pre-disaster mitigation and post-disaster mitigation activities through various programs, including the Public Assistance and Individual Assistance Grant Programs (FEMA, 2015). Pre-disaster mitigation grants aim to fund projects that reduce the risk of flood damage before a disaster occurs, while post-disaster mitigation grants aim to fund projects that mitigate the effects of a disaster and help communities recover. The FEMA grants for flood mitigation provide critical funding to support communities in reducing the risk of flood loss, enhancing resilience, and building more sustainable communities (FEMA, 2023). The state of Iowa is one of the top beneficiaries of FEMA grants per capita to support pre- and post-flood preparedness and recovery (FEMA, 2020a). In 2019, Iowa was hit by a flood event that affected the entire state, including the Missouri River, resulting in significant damage (FEMA, 2020b). Many properties, such as homes, businesses, and agricultural lands, were submerged, with an estimated cost of $1.6 billion (Iowa.gov, 2019). Therefore, the state requires extensive mitigation assessment studies to reduce the potential flood damage.

Minimizing flood losses in an effective and affordable way is a critical challenge for communities vulnerable to flood hazards. There are various strategies to reduce flood losses, including structural and non-structural measures. Structural and non-structural mitigation applications are two approaches for managing the risks associated with floods (Thampapillai and Musgrave, 1985). Structural mitigation involves the construction of physical structures such as dams, levees, and flood walls to protect communities and critical infrastructure from the effects of natural disasters. These structures aim to reduce the impacts of floods by either preventing or mitigating their effects (Kundzewicz et al., 2018). Non-structural mitigation, on the other hand, involves activities that do not involve physical infrastructure, such as flood proofing, elevation, zoning regulations, land use planning, and public education. Non-structural mitigation applications focus on reducing the risk of damage and loss caused by floods by improving community preparedness and resilience (Kundzewicz, 2002). Both structural and non-structural mitigation approaches are crucial in managing the risks associated with floods (Meyer et al., 2012). However, it is important to recognize that structural mitigation is not always a feasible or cost-effective option, and non-structural mitigation measures can be just as effective in reducing the potential losses. Therefore, a thorough investigation is needed by conducting benefit-cost assessments to determine a feasible solution.

1.1. Mitigation Feasibility Evaluation

Benefit-cost analysis (BCA) is a widely used economic tool for evaluating the feasibility of flood mitigation applications. The process of conducting a benefit-cost analysis typically involves identifying the benefits and costs associated with different flood mitigation measures and comparing them (Alabbad et al., 2022). Benefits may include avoided damages, reduced flood risk, and increased property values, while costs may include construction and maintenance expenses, social and environmental impacts, and potential loss of revenue (Alves et al., 2020; Kousky and Walls, 2014). The benefit-cost analysis evaluates the ratio of benefits to costs to determine the economic feasibility of the mitigation measure. A benefit-cost ratio greater than one indicates that the benefits of the mitigation measure outweigh the costs and, therefore, it is a worthwhile investment. However, there are limitations to benefit-cost analysis, such as the difficulty of accurately estimating the benefits and costs of a particular mitigation measure and the challenge of accounting for intangible benefits and costs, including the quantification of environmental values and indirect benefits (Tate et al., 2016). Nevertheless, benefit-cost analysis remains a valuable tool for decision-makers to compare the economic impacts of different flood mitigation applications and make informed decisions about which measures to implement.

Several software tools are available for conducting benefit-cost analyses for flood mitigation purposes. These tools help decision-makers evaluate the costs and benefits of different flood mitigation measures and make informed decisions about which measures to implement. One commonly used software is HEC-FIA (Hydrologic Engineering Center's Flood Impact Analysis), which is a user-friendly tool that can be used to evaluate flood damage reduction measures, such as levees and floodwalls (Mokhtari et al., 2017). The software can estimate flood damages for different design alternatives, assess the costs and benefits of each alternative, and determine the optimal alternative based on the benefit-cost ratio. Another widely used software is HAZUS (Hazards US), which is an analytical tool used for estimating potential losses from natural hazards, including floods. HAZUS can estimate the direct and indirect economic losses, estimate the potential number of casualties, and assess the cost-effectiveness of different flood mitigation measures (Yildirim and Demir, 2019). In addition, various GIS-based software, such as ArcGIS and QGIS, are used to visualize the data, assess the risk, and estimate the costs and benefits of flood mitigation measures. These software tools can aid in the decision-making process, providing decision-makers with accurate and reliable information to make informed decisions about the optimal flood mitigation measures to implement. However, these tools are not providing benefit-cost analyses to identify what particular flood mitigation application can be more effective to reduce potential loss.

1.2. Challenges and Solutions in Flood Mitigation

One of the main challenges of benefit cost assessment is to accurately estimate the associated inputs and outputs of a particular flood mitigation measure. Estimating the benefits of a flood mitigation measure is particularly difficult as it requires forecasting potential damage from future floods, which is often uncertain and dependent on several factors. Moreover, non-economic benefits such as environmental and social impacts are challenging to quantify, leading to the exclusion of these factors from the analysis (Mishra et al., 2022). A comprehensive historical flood event database can be helpful for guiding vulnerable communities to understand the potential consequences of a flood event, such as environmental impact and business disruption (Haltas et al., 2021). Additionally, conducting an integrated benefit-cost analysis for flood mitigation applications requires the integration of data from multiple domains, including engineering, hydrology, economics, and the social sciences (Kull et al., 2013; Muste et al., 2017). Such integration can be challenging and may require significant resources, time, and expertise (Alabbad et al., 2023). However, it is critical to inform all parties in order to create mutually agreed-upon solutions. Because voluntary decisions are also important for flood loss reduction efforts, the public should be informed about the existing risk and potential cost of mitigation choices (Yildirim and Demir, 2022).

The combination of flood maps, information, models, and observations can simplify complex data and present a clear picture of disasters, making it easier for individuals to understand and make decisions on mitigation strategies (Yildirim, 2017). A variety of researchers have explored the potential impacts of floods, such as identifying vulnerable areas (Cikmaz et al., 2022; Tanir et al., 2021) and estimating damage (Jongman et al., 2012), and have also developed decision support systems (Horita et al., 2015) for flood risk management. In order to educate the public on flood mitigation and watershed management (Demir and Beck, 2009), serious games that convey the complexity and importance of flood mitigation options are introduced to communities (Meera et al., 2016). However, their focus is generally limited to teaching the concept of flood mitigation. Such systems can be fed with real datasets (i.e., property information, flood inundation, climate forecast) to achieve analysis over a broader area, which many flood-prone regions lack.

Community scale flood mitigation studies are limited for Iowa that consider the property-level associated costs and benefits. Non-structural flood mitigation options have been inadequately explored to generate new insights on optimal mitigation solutions. Web-based data analytics systems paved the way to conduct real-time hydrological analysis (Demir and Szczepanek, 2017), mapping (Hu and Demir, 2021; Li et al., 2022), visualization (Demir et al., 2009), and geoprocessing (Xu et al., 2019), which can help in flood mitigation efforts. Web-based decision support systems provide easily accessible information that can help decision-makers and the public understand the impact of floods (Sermet and Demir, 2022) and ways to mitigate them (Alabbad et al., 2023). Due to their scalable capabilities, thousands of properties can be analyzed to investigate what specific mitigation options are feasible in order to secure properties against potential floods. Multiple flood scenarios, climate projections, and the most recent mitigation costs can be enabled in such systems. Therefore, better planning, increasing public awareness, and determining at-risk regions can be achieved.

1.3. Proposed Study

The goal of this research is to explore the optimal non-structural solutions to protect large communities in eastern Iowa from flooding. In this research, we utilized extensive data to deliver a comprehensive outlook of community scale of flood mitigation, including climate projections, mitigation costs, parcel information, and multiple flood scenarios. FEMA's BCA Toolkit is one of the most commonly used tools for benefit-cost analysis, but it is limited to providing analysis at the single property level. The BCA toolkit was created based on Excel to investigate benefits and costs at single property (FEMA, 2023). The tool relies on user input such as inundation depth, building type, dollar loss, etc. Spatial analytics and climate inputs are not provided within the tool, which are critical to examining the optimal mitigation solution. This study employs an integrated approach to analyze flood damage and mitigation to assess optimal non-structural scenarios at the community scale. The outcomes of this study can be utilized by state and local authorities to prioritize and distribute financial resources for flood mitigation initiatives and execute flood risk management approaches to reduce the impact of floods. Moreover, one of the objectives of this study is to promote participation in the CRS program (FEMA, 2021) by Iowa and other United States communities. This can be achieved by adopting more measures than the minimum requirements set by the National Flood Insurance Program (NFIP) and receiving discounts on flood insurance as a reward.

The next section of the manuscript describes the methodology used to estimate the costs of damage and mitigation. The results section presents the key findings related to the estimated losses for studied communities and the most effective options for mitigating these losses. Finally, the conclusion and challenges encountered during the research will be discussed at the end of the paper.

2. Methodology

In this section, the study area is explained with a brief flood history. Following the data processing framework, damage and mitigation cost estimation procedures are provided. Data and method limitations are elaborated in each subsection.

2.1. Study Area

The study site chosen for this research is the Middle Cedar watershed, situated in eastern Iowa, which covers large urban communities such as Cedar Rapids, Cedar Falls, and Waterloo. The elevation of the city surface ranges between 213 m and 270 m, and the primary economic activities in the area are related to agriculture and agricultural industry. The Cedar River is the primary stream that runs through each city center and has caused several flood events, including the 2008, 2014, 2016, and 2019 floods. The 2008 flood had a significant impact on the communities, leading to the acquisition of over 2,000 damaged properties through a federally supported program. The areas affected by this flood mostly overlapped with affordable housing blocks, leaving residents vulnerable to poverty, marginalization, and exclusion (Tate et al., 2016). Figure 1 shows the studied urban communities within the Middle Cedar watershed.

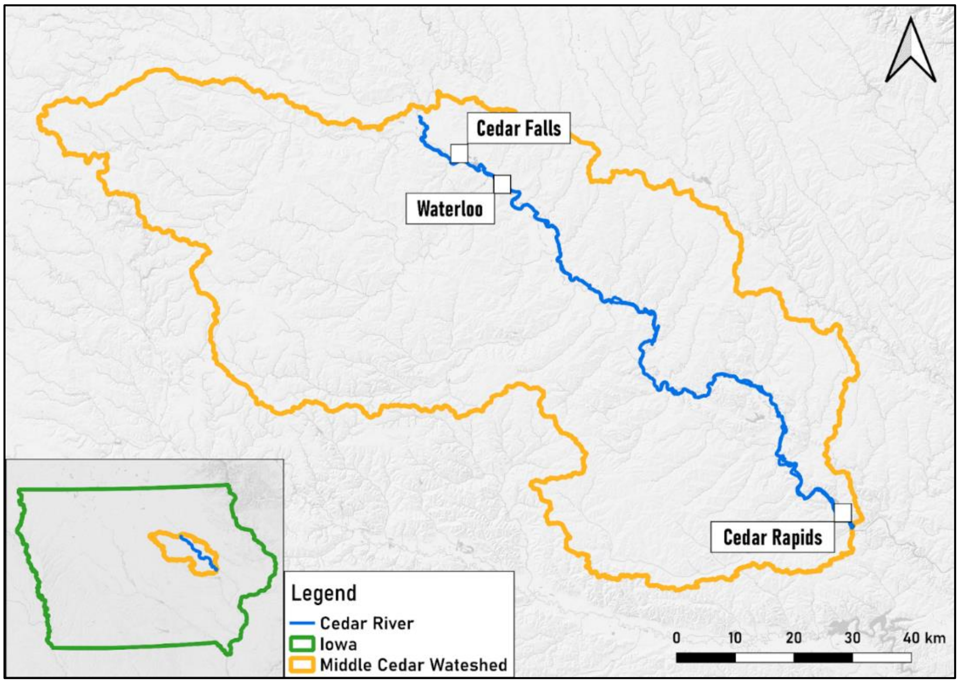


Figure 1. Studied urban communities in Middle Cedar watershed.

2.2. Data Processing

The processing of data is carried out through three main stages which include data collection, analysis and verification, and community mitigation. To begin with, parcel information is gathered from the local tax assessor in the data collection phase, and it is made ready for analysis by identifying occupancy class, square footage, and damage function types. The study employs inundation maps with a 1-meter resolution developed by the Iowa Flood Center, while loss functions, also known as depth-damage functions, are obtained from the U.S. Army Corps of Engineers. Climate projection data, which is a time series of future flood forecasts based on climate projections, is acquired from a study conducted by Quintero et al., 2018. In the analysis stage, PostgreSQL and PostGIS are used to construct databases and carry out queries. Once the collected data is verified for geospatial accuracy and data types, inundation estimation, loss assessment, and mitigation calculations are executed via SQL (Structured Query Language) queries. Finally, detailed summaries for community-scale mitigation are generated, taking into account state-based losses, one-time mitigation, and projected mitigation scenarios. The following sections provide further details on these phases.

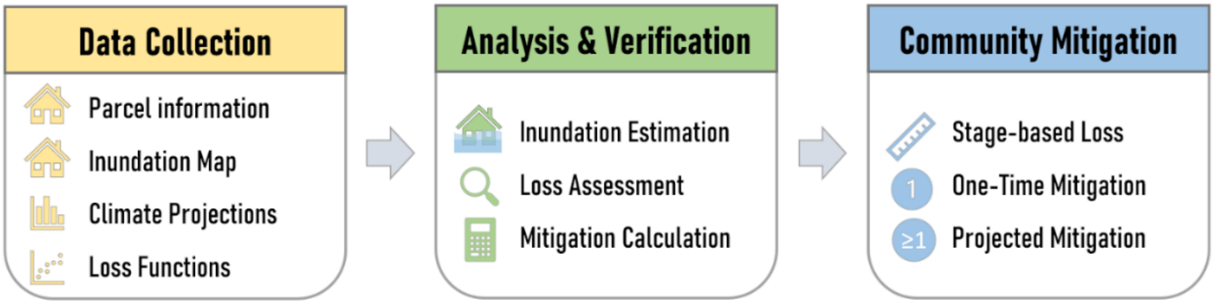


Figure 2. Data processing workflow including data collection, analysis and verification, and community mitigation

2.3. Flood Damage Estimation

During this phase, structural and content losses which are defined as direct flood losses are estimated. To quantify loss at the property level, flood damage functions are adopted to derive depth-damage information. These functions define the relationship between flood depth and the percentage of damage incurred by a property. 36 distinct damage functions are gathered from the USACE, and the module utilizes a unique function for each type of occupancy, such as residential, commercial, or industrial, to calculate structural and content losses. To facilitate the data analysis layer, the functions are converted into a JSON file. Figure. 3 depicts the damage functions for residential and commercial buildings.

In this study, property values are collected from county tax assessors, which contain important details such as the structural and content value, square footage, and occupancy type. The county assessors' data also includes the property's location. However, public buildings are not included in the community-based scenario because they are not taxable, and their structural values are not recorded. The analysis covers more than ten thousand properties, mostly residential. To obtain more accurate flood depth for individual structures, Google Maps satellite imagery is used to geo-correct the tax assessor data on Quantum Geographic Information System (QGIS). This allows for individual properties to be aligned based on the satellite imagery.

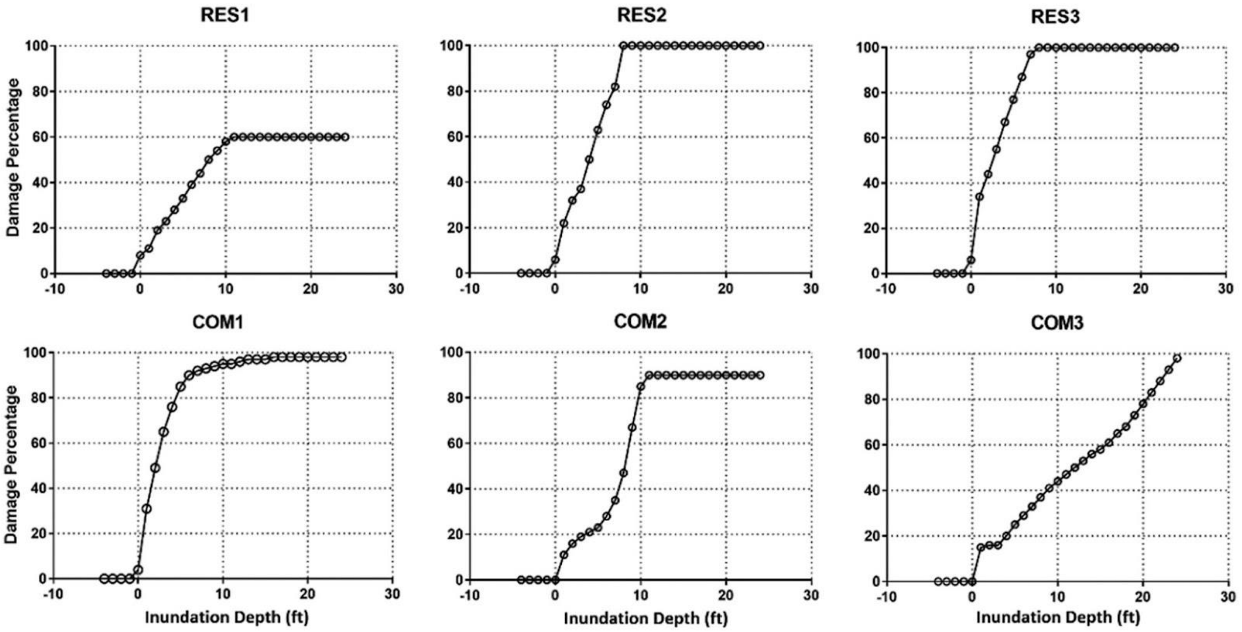


Figure 3. A sample set of flood depth-damage functions used in the study (Yildirim and Demir, 2019)

To assess the overall flood losses for a community, the study estimates the structural and content losses for each property. This is done by calculating the flood depths for each property using community flood map raster generated by the Iowa Flood Center, which are based on the United States Geological Survey gauges installed in the city centers. The damage analysis module utilizes a total of 153 flood inundation maps in the study area. For Cedar Rapids, Cedar Falls, and Waterloo, the number of flood inundation maps are 60, 45, and 48 respectively.

Data on stream projection is obtained from another study conducted in the communities being studied (Quintero et al., 2018), using USGS gauge locations as reference points. The projections are based on two climate scenarios: the A1FI and A2 climate scenarios, which are generated by the CCSM3 (Community Climate System Model) model. The A1FI scenario assumes high fossil fuel emissions, while the A2 scenario assumes lower emissions. Therefore, the system can provide loss projections for both possibilities. The study uses projections for the period 2021-2050. Quintero's study provides further details about the climate scenario-based stream projections. The projected stream data is then classified based on the rating curves developed by the National Weather Service (NWS) to determine the number of flooding events. Since the flood inundation raster is created based on USGS gauges in the study area, suitable flood maps are selected to reflect the classified flood events for projected loss estimates.

2.4. Mitigation Cost Assessment

Individual effort plays a crucial role in flood mitigation. While governments and communities may implement flood control measures, individual actions such as proper disposal of trash, littering, and avoiding activities that contribute to erosion can also help prevent flooding. Additionally, individuals can take steps to protect their properties from flood damage by elevating their homes, installing floodproofing, and purchasing flood insurance. Individual efforts can complement larger-scale flood mitigation efforts and contribute to reducing the risks and impacts of flooding. The public can be informed by community-scale flood mitigation assessments to take action towards reducing flood damage. To determine whether an individual flood mitigation measure is cost-effective, the benefit-cost ratio is calculated by dividing the benefits (i.e., avoided damage costs) by the mitigation cost. As per FEMA (2020), when the ratio is greater than 1, the action is considered cost-effective. The benefit-cost ratio (BCR, Eq. 1) is used to estimate this ratio.

$$BCR = \frac{\text{Benefits (\$ Avoided Damage)}}{\text{Cost (\$ Mitigation Cost)}}, \text{BCR} > 1 \ => \ \text{mitigation is cost effective} \qquad \text{Eq. 1}$$

Various measures can be implemented to reduce the vulnerability of homes to flood events. However, to effectively identify the appropriate measures, multiple data sources need to be analyzed to prepare for future floods. These measures can be divided into three main categories, including avoidance, allowance, and exclusion of floodwater, each with multiple subcategories based on the design and condition of households. The cost of each measure is outlined in Appendix 1. The mitigation solutions vary based on the building area and perimeter, which are estimated using the Microsoft footprint dataset for each building. To calculate the benefit-cost ratio (BCR), the avoided damage, which includes content and structural value, is compared to the average total flood mitigation cost. Some mitigation measures can prevent damage at 100%, such as elevation and relocation, while others can minimize damage to a certain extent, such as dry floodproofing. The expected damage before mitigation minus the expected damage after mitigation is used to calculate the benefits. Flood allowance measures are assumed to reduce structural and content damage by 50%, while flood exclusion measures are assumed to reduce structure damage by 80% and content damage to zero. Our assumptions are derived from (Attems et al., 2020; Owusu et al., 2015; Lasage et al., 2014).

In this study, we evaluated the non-structural flood mitigation options (Table 1) to determine the optimal solutions for potential damage reduction. To determine appropriate mitigation plans and measures, it is crucial to consider the building's condition and flood hazard maps. Some mitigation measures may not be effective for a house exposed to high-water depth, and it may be more beneficial to relocate the building. Maintenance and enforcement are also important considerations for flood mitigation effectiveness, and not all measures are eligible for flood insurance discounts.

Table 1. Non-structural property-level flood mitigation

Mitigation Measures	**Description**
Elevation	Elevating a house to a level where flood risk is minimal is one option, despite its initial high cost, as it can lead to damage reduction. It is recommended to raise a house above the 100-year flood depth plus a 1-foot freeboard.
Relocation	Relocating the vulnerable property outside of the floodplain. Although it requires purchasing new land and ensuring accessibility to the new location.
Reconstruction	The vulnerable property may necessitate being rebuilt up to the most recent code after a flood event, where the house is reconstructed to appropriate standards on the same site to create a risk-free setting.
Wet floodproofing	It allows floodwater to enter a home with low adverse impacts, but it is only practical for areas such as garages, flood depths of less than 3 meters, and flood durations of less than one day.
Dry floodproofing	This mitigation aims to prevent water from reaching a home, but it is only effective for flood depths up to 3 feet, short flood durations of one day, and low water velocity.
Levees and floodwalls	They are also effective measures, with the height of the structures limited to 4 and 6 feet, respectively. However, it is important to consider soil types and slopes when building levees, and they are effective for flood durations up to 4 days.

3. Results and Discussions

In this part, we present a comprehensive evaluation of mitigation measures for Cedar Falls, Cedar Rapids, and Waterloo. Figure 4 displays the number of affected properties and the overall losses in terms of structure and content by flood stage height for the analyzed locations. Our findings suggest that Waterloo experiences minimal flooding damage for scenarios below the 200-year return period flood. However, the estimated losses and impacted properties sharply increase after the 29 feet flood stage, which is just above the 200-year flood in the city. On the other hand, other communities show an increase in the number of affected properties and estimated losses even in less extreme scenarios. Notably, in Cedar Falls, flood damage is significantly higher after the 10-year flood event. Similarly, in Cedar Rapids, the estimated impact becomes considerably high after the 50-year flood scenarios.

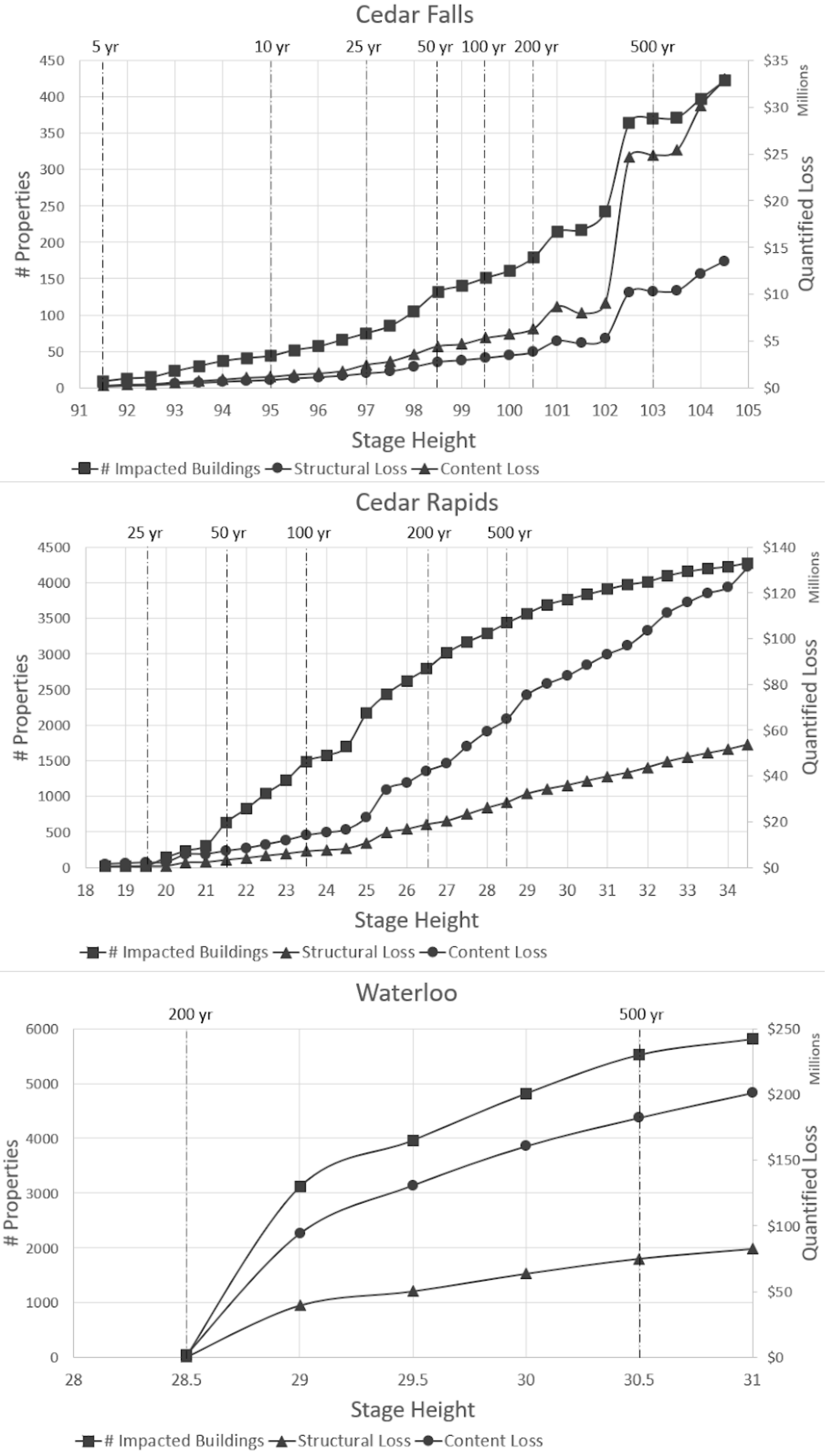
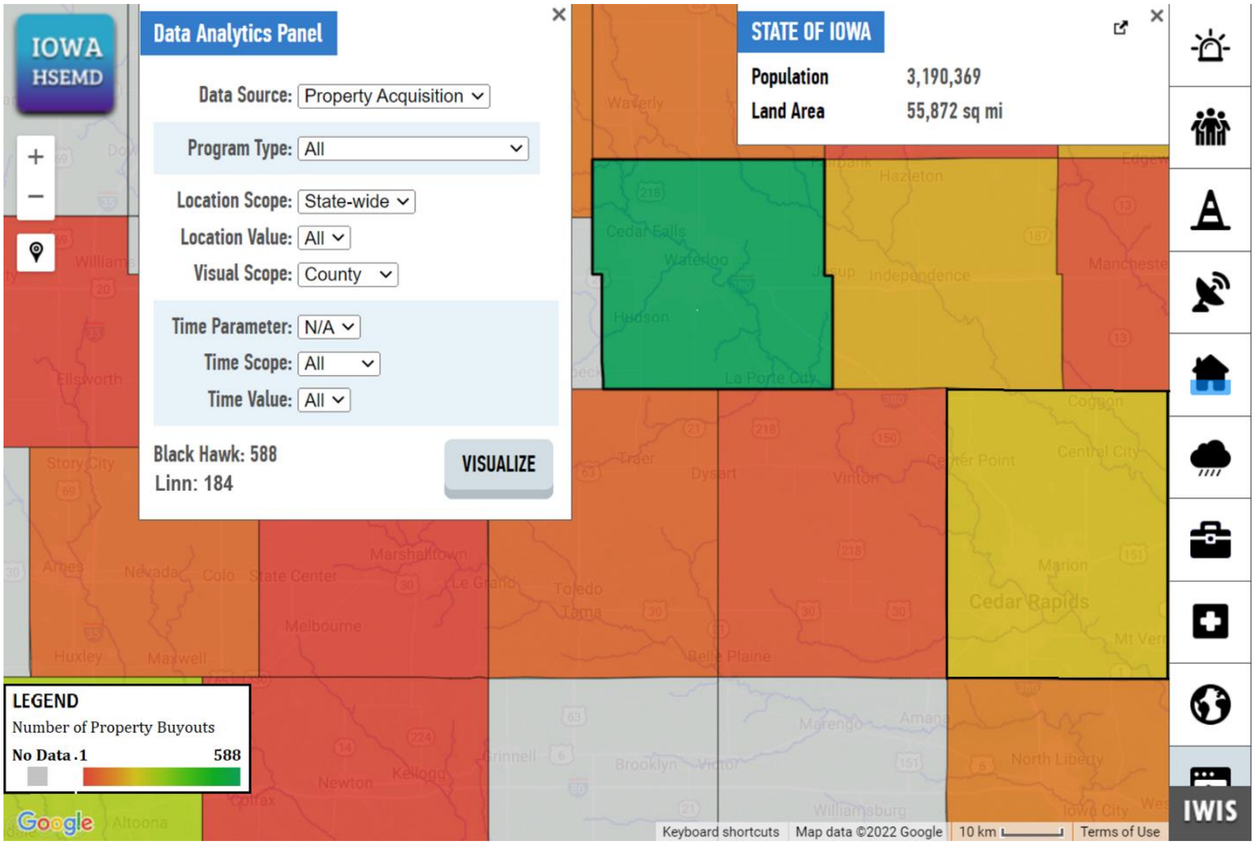


Figure 4. Stage-loss results for communities in the Middle Cedar watershed

The Federal Emergency Management Agency (FEMA) provides mitigation funding to communities to lessen the effects of potential flooding. The counties of Black Hawk and Linn, which are home to Cedar Falls, Waterloo, and Cedar Rapids, received significant support to fund mitigation measures. Table 2 and Figure 5 show property buyouts completed by the Iowa Department of Homeland Security and Emergency Management and major property acquisitions funded by FEMA. Over the past couple of decades, more than 500 property buyouts were completed for Linn and Black Hawk counties where the studied cities are located. Flood damage analysis suggests that property buyouts effectively decreased the impact of flooding in Waterloo. However, Cedar Falls and Cedar Rapids remain at risk, and more measures are necessary to protect properties. As a result, a detailed benefit-cost analysis was conducted to identify the most effective mitigation options for the study area. Different options, such as sandbagging, dry floodproofing, wet floodproofing, and elevation, were assessed to determine their feasibility in various flood zones.


Data Analytics Panel

Data Source: Property Acquisition

Program Type: All

Location Scope: State-wide

Location Value: All

Visual Scope: County

Time Parameter: N/A

Time Scope: All

Time Value: All

Black Hawk: 588

Linn: 184

STATE OF IOWA

Population 3,190,369

Land Area 55,872 sq mi

LEGEND

Number of Property Buyouts

No Data 1 588

Figure 5. Property acquisitions completed by Iowa HSEMD for counties in Middle Cedar

Table 2. Major property buyouts between 1998 and 2019 in communities within Middle Cedar (FEMA, 2022)

Project ID	Type	# Properties	Location	Dates
DR-0996-0023-R	Acquisition	85	Cedar Falls	05/18/1999
DR-0996-0024-R	Acquisition	23	Cedar Falls	05/18/1999
DR-4289-0005-R	Acquisition	14	Cedar Falls	12/11/2019
DR-1763-0086-R	Acquisition	12	Cedar Falls	10/21/2013
DR-1282-0015-R	Acquisition	14	Cedar Falls	01/31/2005
DR-1763-0014-R	Acquisition	161	Cedar Falls	09/26/2013
DR-4386-0016-R	Acquisition	1	Cedar Rapids	09/15/2020
DR-1763-0063-R	Acquisition	91	Cedar Rapids	07/29/2015
DR-4184-0009-R	Acquisition	1	Cedar Rapids	10/30/2017
DR-1763-0036-R	Acquisition	14	Cedar Rapids	05/31/2013
DR-4114-0005-R	Acquisition	1	Cedar Rapids	11/25/2015
DR-1282-0012-R	Acquisition	1	Cedar Rapids	04/30/2004
DR-1277-0003-R	Acquisition	4	Cedar Rapids	01/19/2005
DR-1420-0004-R	Acquisition	2	Cedar Rapids	01/04/2006
DR-0996-0040-R	Acquisition	12	Cedar Rapids	05/28/1998
DR-1763-0050-R	Acquisition	15	Cedar Rapids	06/21/2013
DR-1282-0001-R	Acquisition	3	Waterloo	01/19/2005
DR-1763-0027-R	Acquisition	19	Waterloo	06/06/2013
DR-1763-0046-R	Acquisition	94	Waterloo	04/14/2015

Figure 6 displays the best mitigation strategies for several flood scenarios in the study area. To determine the most effective option, we analyzed the direct losses, including the structural and content damages, as well as the cost of the mitigation process for a one-time flood event. We evaluated hundreds of buildings, flood scenarios, and multiple mitigation depths to identify the optimal solution for communities by comparing hundreds of BCRs for each individual property. Our study found that dry floodproofing is the most practical solution to reduce the flood impact in all areas we analyzed. This is because dry floodproofing provides higher benefit that can withstand high flood levels, making it a feasible option for many properties. Wet floodproofing becomes more viable as the flood scenario becomes more severe, while elevating a structure is only practical for higher flood levels. For properties with a smaller square footage but higher estimated direct losses, elevating the structure may not be cost-effective. We also found that mitigation is not feasible considering a one-time event for several properties which are shown as gray color. These properties will remain vulnerable with regard to one-time flood event and mitigation investment.

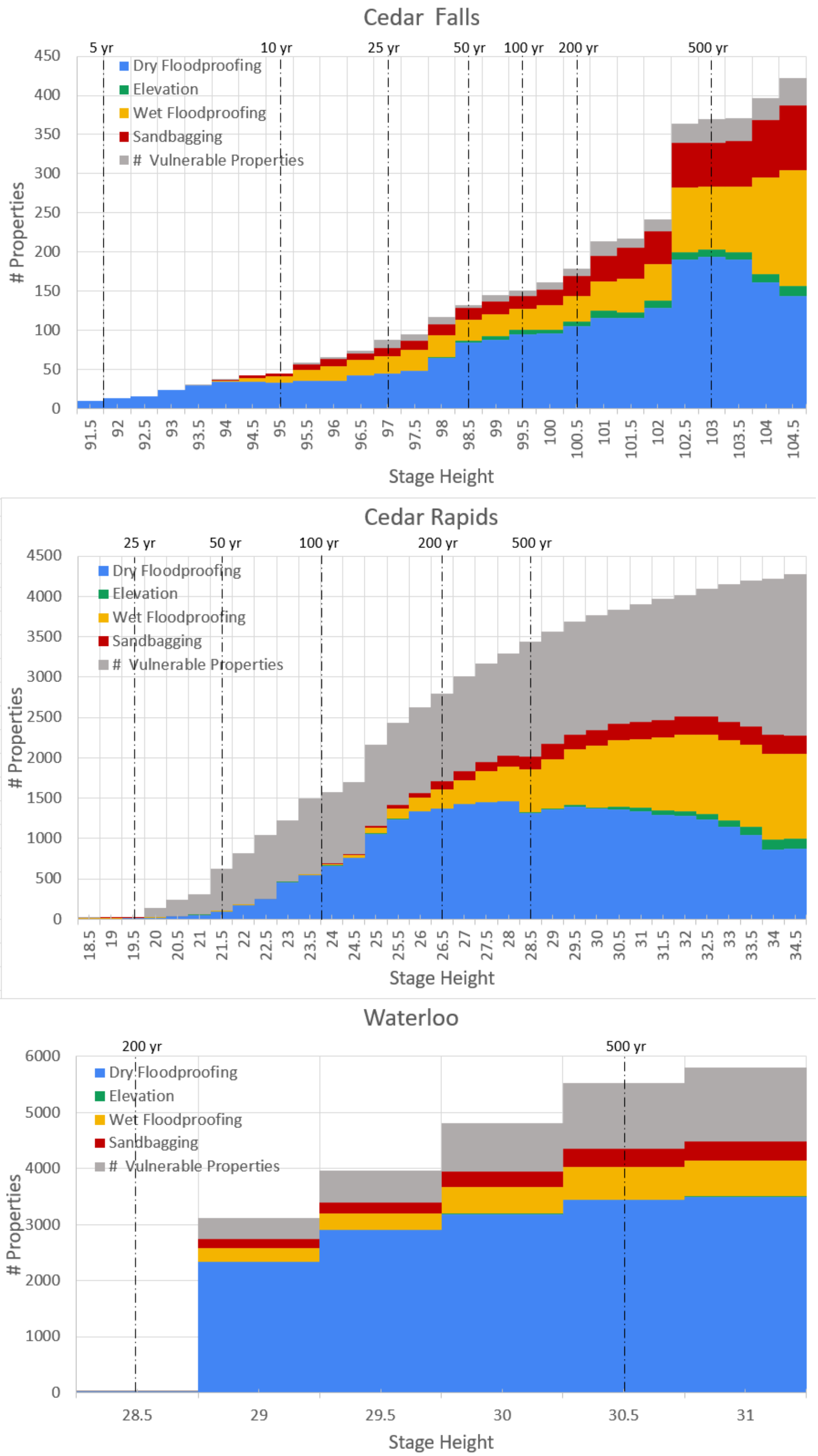


Figure 6. One-time scenario-based mitigation feasibility distribution by flood stages

The study area underwent a climate data-driven mitigation analysis which utilized two climate scenarios, namely the a2 climate scenario as the optimistic and the aif1 climate scenario as the more extreme scenario (Quintero et al., 2018). These scenarios provide useful input for assessing the cost effectiveness of flood reduction measures as lifespan is a crucial factor in determining mitigation options. In order to assess the long-term benefit-cost ratio (BCR) of mitigation strategies, the time frame from 2021 to 2050 was chosen to evaluate the impact of future flood events. However, certain return period floods were not observed during this time frame, so the corresponding mitigation costs and losses were not estimated. Meanwhile, some flood scenarios occurred multiple times, resulting in the amplification of associated costs.

Our findings indicate that elevating structures are a viable mitigation option for flood protection regardless of the type of climate scenario. Due to the one-time cost of implementing elevating structures, it is a cost-effective solution in the long run. On the other hand, the number of feasible sandbagging applications decreased slightly, and it can be inferred that permanent solutions are better for maximizing benefits in the long term. In Cedar Falls, wet floodproofing is a more cost-effective choice for extreme events under the aif1 climate scenario, whereas sandbagging is more feasible for optimistic a2 scenarios. Cedar Rapids has more vulnerable properties than other cities, which is related to a lower benefit-cost ratio. Large-scale protection measures such as flood walls, levees, or buyouts may be more suitable for mitigating flood losses due to the high cost of individual property applications. The limited impact of flooding in the 200-year flood event results in fewer mitigation options for Waterloo, but for aif1, dry and wet floodproofing are the most cost-effective options for the more frequent 500-year flood event. Dry floodproofing is the dominant mitigation type for a2 scenarios due to its BCR. More details are delivered through Figure 7.

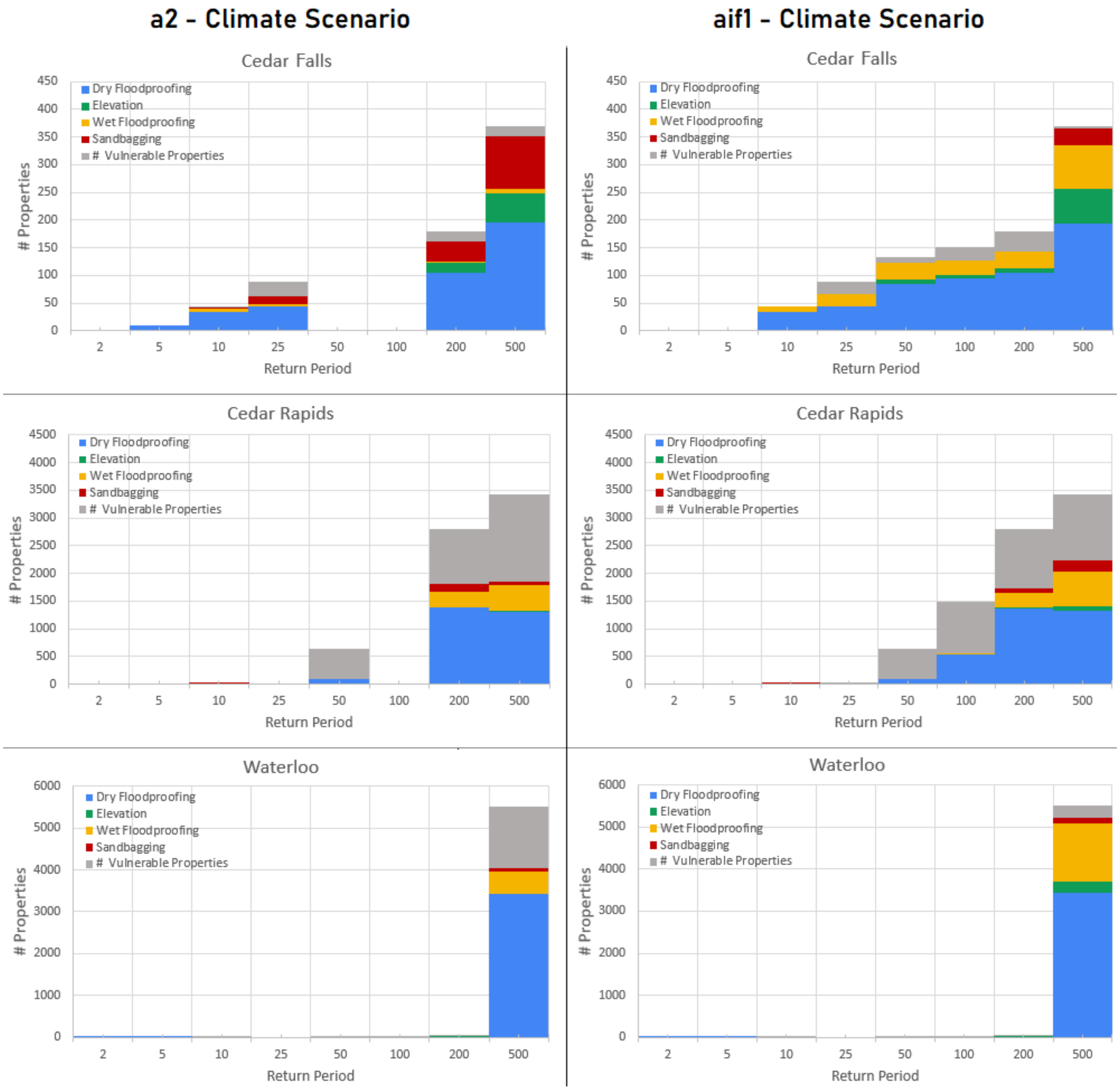


Figure 7. Climate-based mitigation feasibility distribution by different return period floods

FEMA is the primary provider of federal funding for communities that are consistently threatened by flooding. The agency typically focuses on providing resources for communities within the 100-year flood zone, also known as Special Flood Hazard Areas. In Figure 8, we conducted a scenario-based analysis of mitigation strategies for Cedar Falls and Cedar Rapids specifically in the Special Flood Hazard Areas. We did not include Waterloo in this part of the analysis because flooding has minimal impact on the city. We analyzed predetermined mitigation budgets to identify potential avoided losses and benefit-cost ratios, with priority given to properties with the highest benefit cost ratios (BCRs) to maximize benefits to the communities. Our analysis shows a linear relationship between the mitigation budget and the avoided losses in both cities, with a slight increase in net benefit. This increase is mainly due to commercial properties with a high risk of flood losses being included in the mitigation budget because of their high BCRs. We found that each mitigation budget had a high net benefit; however, we assumed that mitigation costs were one-time expenses. As mitigation budgets increases, the net benefits also increase for both cities, but the BCR declines. Because provided BCA only considers direct costs and benefits, the actual benefit cost ratios should be higher than what we present. The underlying reason is indirect benefits which are not straightforward to estimate and require further investigation.

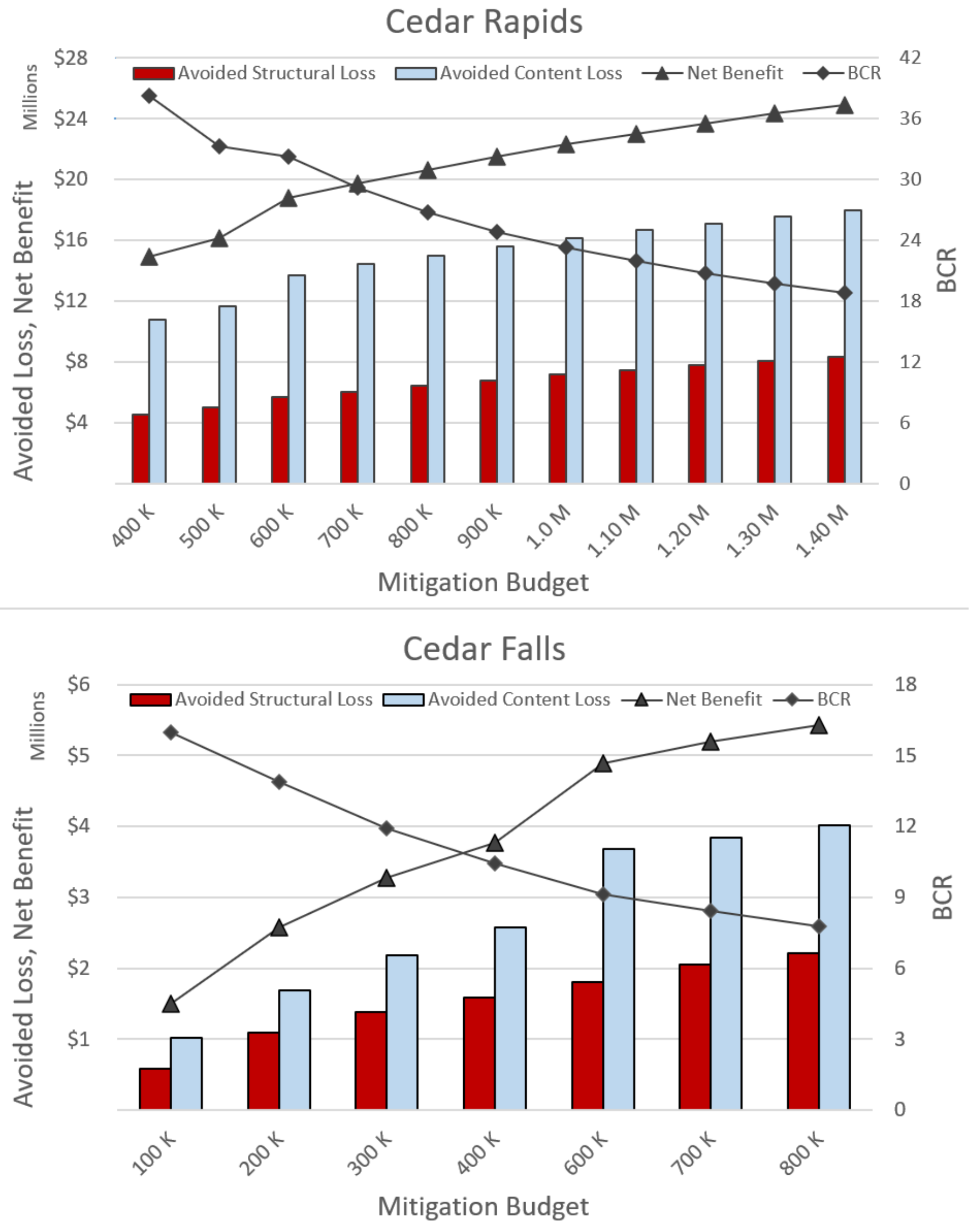


Figure 8. Net benefit and avoided loss distribution under budget constraints

4. Conclusion

This study provides a detailed mitigation assessment for Cedar Falls, Cedar Rapids, and Waterloo using various datasets such as property information, flood inundation maps, mitigation costs, and depth-damage functions. The study found that flooding has minimal impact in Waterloo below the 200-year return period flood. However, Cedar Falls and Cedar Rapids are still vulnerable, and more mitigation efforts are needed to secure properties. Following these results, the authors conducted a detailed benefit-cost analysis to find optimal mitigation options for the study region. The analysis suggests that dry floodproofing is the most feasible option to reduce flood impact in all studied communities. The study also conducted a climate data-driven mitigation analysis and found that elevating structures significantly increases the number of feasible mitigation choices regardless of projected climate scenarios. In addition, the research analyzed predetermined mitigation budgets to reveal potential avoided losses and benefit-cost ratios for properties with the highest BCRs, prioritizing them to maximize the total benefit to the communities.

The research outputs provide valuable information for decision-makers to prioritize flood mitigation measures in communities based on the benefit-cost ratio. Our findings suggest that dry floodproofing is the most feasible option for mitigating the impact of flooding in the studied communities. Additionally, elevating structures are a cost-effective option for long-term mitigation. The research also found that mitigation costs are one-time only, and there is a high net benefit for each mitigation budget. The study provides insight into how FEMA's Hazard Mitigation Assistance grants can be allocated to mitigate potential flooding impacts in the studied regions, and the study suggests that large-scale protection measures or buyouts may be considered for flood loss reduction in vulnerable areas. The integration of detailed property flood impacts, such as income and wage losses or loss of life, as identified by Alabbad and Demir (2022), can be included in the mitigation analysis to optimize the benefits. Additionally, since certain mitigation practices have inherent limitations (e.g., design level), it would be beneficial to conduct further research into the cost-effectiveness of implementing a combination of two or more mitigation practices.

Property data from tax assessors is an essential source of information for flood mitigation analysis as it provides valuable insight into the characteristics of properties and their owners within a given area. However, it is important to note that tax assessor property data has some limitations that can hinder the accuracy of flood mitigation analysis. Firstly, the data may be incomplete, outdated or inaccurate, which can lead to erroneous conclusions. Secondly, the data may not capture important variables such as the presence of flood-prone features on a property, which can impact the risk of flood damage. Additionally, the data may not include information on properties that are exempt from taxation, such as public buildings or religious institutions, which can lead to an underestimation of the overall risk. Lastly, tax assessor property data is often aggregated at the parcel level, which can mask the variability in flood risk at the building or unit level, resulting in a lack of granularity in the analysis. Therefore, it is crucial to acknowledge the limitations of tax assessor data and complement it with other sources of information to conduct a comprehensive flood mitigation analysis.

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Appendix 1: Property-level mitigation costs

Measure	**Design Level**	**Construction Type**	**Existing Foundation**	**Cost[1]**	**Cost Adjusted (2020)[2]**
Floodwater Avoidance					
Elevation add $1.60/sq. ft for each additional foot of elevation.[3]	2ft	frame	Basement or Crawlspace	29/sq. ft	35/sq. ft
	4ft	frame	Basement or Crawlspace	32/sq. ft	38.65/sq. ft
	8ft	frame	Basement or Crawlspace	37/sq. ft	44.69/sq. ft
	2ft	frame	Slab-on-Grade	80/sq. ft	96.62/sq. ft
	4ft	frame	Slab-on-Grade	83/sq. ft	100.24/sq. ft
	8ft	frame	Slab-on-Grade	88/sq. ft	106.28/sq. ft
	2ft	masonry	Basement or Crawlspace	60/sq. ft	72.46/sq. ft
	4ft	masonry	Basement or Crawlspace	63/sq. ft	76.09/sq. ft
	8ft	masonry	Basement or Crawlspace	68/sq. ft	82.13/sq. ft
	2ft	masonry	Slab-on-Grade	88/sq. ft	106.28/sq. ft
	4ft	masonry	Slab-on-Grade	91/sq. ft	109.9/sq. ft
	8ft	masonry	Slab-on-Grade	96/sq. ft	115.94/sq. ft
Allowance of floodwater					
Wet Floodproofing Costs include: Openings Pumps Utility relocation	2ft from basement floor	Frame or Masonry	Basement	$2.9/sq. ft	$3.50/sq. ft
	2ft from the lowest adjacent grade	Frame or Masonry	Crawlspace	$2.204/sq. ft	$2.66/sq. ft
	4ft from basement floor	Frame or Masonry	Basement	$6/sq. ft	$7.25/sq. ft
	4ft from the lowest adjacent grade	Frame or Masonry	Crawlspace	$5.608/sq. ft	$6.76/sq. ft
	8ft from basement floor	Frame or Masonry	Basement	$17/sq. ft	$20.50/sq. ft
	8ft from the lowest adjacent grade	Frame or Masonry	Crawlspace	**N/A**	**N/A**
Waterflood Exclusion					

Dry Floodproofing					
Sprayed-on Cement (above grade)	3 ft	**N/A**	**N/A**	$16.80/Linear Foot of Wall Covered	$20.30/Linear Foot of Wall Covered
Waterproof Membrane (above grade)	3 ft	**N/A**	**N/A**	$5.70/Linear Foot of Wall Covered	$6.88/Linear Foot of Wall Covered
Asphalt (two coats on foundation up to 2 feet below grade)	3 ft	**N/A**	**N/A**	$12/Linear Foot of Wall Covered	$14.50/Linear Foot of Wall Covered
Drainage Line Around Perimeter of House	3 ft	**N/A**	**N/A**	$31/Linear Foot	$37.44/Linear Foot
Plumbing Check Valve	3 ft	**N/A**	**N/A**	$1,060/Each	$1.280/Each
Sump and Sump Pump (with backup battery)	3 ft	**N/A**	**N/A**	$1,710/Lump Sum	$2065/Lump Sum
Metal Flood Shield	3 ft	**N/A**	**N/A**	$375/Linear Foot of Shield Surface	$452.90/Linear Foot of Shield Surface
Wood Flood Shield	3 ft	**N/A**	**N/A**	$117/Linear Foot of Shield Surface	$141.30/Linear Foot of Shield Surface
Sandbag 1 ft height (6 bags)[4]	3 ft	**N/A**	**N/A**	$30/linear foot (bag =$5)[5]	$33/linear foot (bag =$5.50)
[1] FEMA (2009) [2] US Inflation Calculator (2020) [3] FEMA (1998) [4] Heckman (2020) [5] Aerts (2018)					