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OPTIMAL SELECTION OF SHORT- AND LONG-TERM MITIGATION STRATEGIES FOR FLOODING HAZARD

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OPTIMAL SELECTION OF SHORT- AND LONG-TERM MITIGATION STRATEGIES FOR FLOODING HAZARD

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To my family, my mentors, and my friends

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ABSTRACT

Every year, flood hazards cause significant economic losses in different locations worldwide with devastating impacts on the buildings and the physical infrastructure. Therefore, investing in flood mitigation is crucial for communities to protect their physical and socio-economic systems. While there are multiple mitigation options for communities to implement in the floodplain at the building-level, an optimization method is developed to determine the optimal strategy for the buildings to implement for minimizing.

In this research, I propose a mathematical model to study the effects and trade-offs associated with pre-event short-term and long-term mitigation strategies to minimize the expected economic loss associated with flooding hazards in a community. I illustrate the capabilities of the proposed model with a case study on Lumberton, NC, which is a small, socially diverse inland community with around 20,000 buildings. Over the last several decades, Lumberton has been affected by severe flooding events with significant recurring economic loss of more than hundred million dollars. The model uses the cost from a portfolio of mitigation strategies, each representative of a different mitigation level, and the resulting flood-induced monetary losses corresponding to each mitigation strategy/level. Finally, the mathematically optimal building level flood mitigation plan is provided based on available budget level to reduce the total direct economic loss of the community.

1. Introduction

Community resilience is described as a community's ability to withstand any natural calamity and recover to its previous level of functionality following a natural disaster [1]. When a natural hazard strikes a community, there is a wide range of potential consequences. The community may suffer significant losses as a result of damage to the built environment. Though it is better to avoid flood-prone areas to reduce those risks [2], [3] but this is not always a viable option nor a permanent solution to mitigate disaster impacts. Due to climate change and socio-economic growth, the danger of natural hazards such as floods is growing at an alarming rate [4] A community needs more robust solutions to in the face of immediate natural catastrophes in order to reduce economic and social losses. Researchers from many areas, such as social sciences, economics, civil engineering, and industrial engineering, are working to identify effective methods to enhance community resilience. Social science researchers are trying to improve resilience by considering social responsibility [5]. Some also analyzed the impacts of natural hazards like social, psychological, socio-economic, socio-demographic, and political impacts [6]**.** Civil engineers focus on building resilient communities by improving the infrastructure systems [7]. Based on the area of expertise of individuals, researchers of various fields use a variety of advanced methods to enhance resilience of a community. (González, Dueñas-Osorio, Medaglia, & Sánchez-Silva, 2013) Researchers with the expertise of operations research search for the solution by applying various optimization techniques. Lio et al. [8] used optimization techniques to study the resilience of transportation networks in the face of natural and man-made disasters, and they sought to figure out how to employ multi-objective optimization after weighting each objective function. Nozhati, Ellingwood, & Chong employed dynamic programming with reinforcement learning approaches, followed by multi-objective optimization to increase resilience. They used it to reduce the number of days it takes to restore electricity to a given level of functionality and to increase the number of individuals who have power throughout a series of repairs [11]. Sen, Datta and Kabir [12] developed a model using the Bayesian Belief Network (BBN) to increase flood-resilience for residential buildings for a community in India. Gudipati and Cha [13] used artificial neural networks to create community-level optimization of functionally interdependent structures, and they worked with office and hospital buildings to execute seismic hazard mitigation.

However, the method for preparing a community to withstand a natural disaster is determined by the kind or behavior of the event. For example, the nature of earthquakes, tsunamis, and floods are vastly different, thus the appropriate analysis methods for each are unique. We focus on flooding hazards in this study, and one of the most critical components is assessing the economic loss due to flooding. There are different approaches that account for flood damage/losses for buildings and infrastructure, including deterministic approaches that use stage-damage functions [14]–[17] and probabilistic approaches that use fragility functions [18], [19]. Marvi [20] reviewed the developed flood vulnerability functions and identified that the flood-related data scarcity and the inability to propagate uncertainty in the flood damage models are the main challenges to develop a robust flood vulnerability model. Recently, component-based flood fragility functions were introduced to propagate uncertainty in the flood damage models and inform probabilistic safety margins for buildings [14], [21], [22]. For community-level flood damage and loss analysis, Nofal and van de Lindt developed a portfolio of 15 building archetypes to model flood vulnerability for the different building occupancy within the community [23]. This approach depends on dividing the building into components and investigates the flood susceptibility of each component using a Monte Carlo simulation framework to propagate uncertainty in the flood depth and flood duration resistance along with the replacement cost of each component. Afterward, a set of damage states was developed to characterize the building performance during flooding, and the exceedance probability of each damage state (DS) was calculated based on the failure of the component. Such an approach provided a systematic mechanism to model different types of mitigation measures at the building- and community-level [14], [19], [22]. To minimize economic loss, a community must invest in its infrastructure but if the investment exceeds the monetary loss, the investment is not worthwhile; hence, a trade-off between investment and economic loss is critical. Ideally, investments should not exceed their planned budgets nor result in a financial loss [24]. Academics use a variety of methods and strategies to determine the ideal balance between investment and economic loss. Najarian & Lim [25] proposed a mathematical model for natural and human-made disasters to optimize resilience with budgetary constraints. They worked on budget allocation to any infrastructure component. To improve the system's resilience of independent infrastructure networks and reduce the overall cost associated with the restoration process, a multi-objective optimization framework with numerous constraints was presented by [26]. Recently, Wen, Nicholson, & González [27] presented their tornado mitigation model, where they sought to minimize the total economic loss due to the impact of a tornado and then applied their model to Joplin, Missouri. Adluri, Sanderson, González, Nicholson, & Cox [28] also created an optimization model to decrease overall direct economic loss due to building damage in a multi-hazard scenario. Previously, Zhang & Nicholson [29] formulated the optimization model for retrofitting buildings with different mitigation strategies while minimizing the total economic loss of a community for a natural disaster and implemented the earthquake model in Centerville, a virtual community designed to test resilience models. Before them, Wiebe & Cox [30] also analyzed the direct economic loss of the community of Oregon applying fragility curves for the Tsunami hazard though they did not consider the indirect tangible losses of that community and after that Onan, Ülengin, & Sennaroğlu [31]also worked on the bi-objective model for minimizing the economic loss for a natural hazard along with another objective function of reduction of hazardous waste exposure transportation risk.

In this research, I used optimization techniques to minimize a community's economic loss due to floods. Previously, academics used several ways to increase a community's resilience and reduce economic losses caused by natural disasters. Decision-makers can benefit from optimization techniques while deciding on the optimal option for a community's resilience. I concentrate on minimizing economic loss due to building damage caused by flooding hazards. Previously Nofal & van de Lindt [33] worked on the analysis of strategies for making the individual building more resilient, but they did not suggest any separate mitigation strategy for each building or building archetype. It is critical to choose the proper mitigation techniques for decreasing flood damage while also determining which mitigation approach is suitable for a specific infrastructure. The proposed model can inform the decision-maker regarding the optimal mitigation strategy for each individual building in a community.

The flood risk and mitigation model, as well as the optimization model, are discussed in Section two of the article. In Section three, the proposed model is applied to Lumberton, North Carolina in part three, and the findings are described in Section four. After that, Section five contains concluding thoughts and recommendations for further study.

2. Research Methodology

A novel optimization model was developed to minimize the total direct economic loss due to building damage in a community with an optimal building level mitigation plan to help to building owners. Proposed model is fine for taking number of mitigation plans as input to choose the best one from them for saving the buildings. Figure (1) shows a schematic representation of the needed models and input for this optimization model. This approach uses a high-resolution flood loss analysis approach that combines detailed information about the flood hazard and the impacted community to identify the exposed buildings. The flood hazard intensity at each building was then calculated to be used for use in a probabilistic fragility-based flood loss analysis at the building level. An algorithm was developed to use the hazard, exposure, and vulnerability information about each building to calculate the amount of flood losses. This algorithm was then modified to include the impact of different types of mitigation strategies on the amount of flood loss reduction at the building-level. Afterward, an optimization model was developed to optimally allocate these mitigation measure such that the total economic loss can be reduced. The model is designed to support the decision maker to take the correct decision regarding allocation of various mitigation strategies enhancements/modifications to the buildings. The main inputs of this optimization model are various mitigation interventions strategies, the corresponding loss relating to the mitigation strategies effectiveness of the interventions, and total available budget of the decision maker to retrofit buildings.

2.1. Flood Risk and Mitigation Model:

The flood risk components including hazard, exposure, and vulnerability models were developed using high-resolution models based on the concept developed herein [34]. The hazard model wais developed using 2D hydrodynamic analysis that can capture the flood inundation across the community. The community model is developed using a portfolio of 15 building archetypes that can populate the building stock within the community [14]. The developed flood hazard map was then overlaid with the community model to identify the exposed buildings in terms of the hazard intensity at each building. Then, a fragility function corresponding to each building archetype was used to account for building damage in terms of the exceedance probability of a set of five damage states (DS). Table 1 provides a brief description of these damage states along with their damage scale, loss ratio, and the anticipated building functionality and more details about each DS can be found herein [13]. Afterwards, a fragility-based flood loss analysis wais conducted using Eq. (1) which multiply the probability of being in each DS by the replacement cost of each DS.

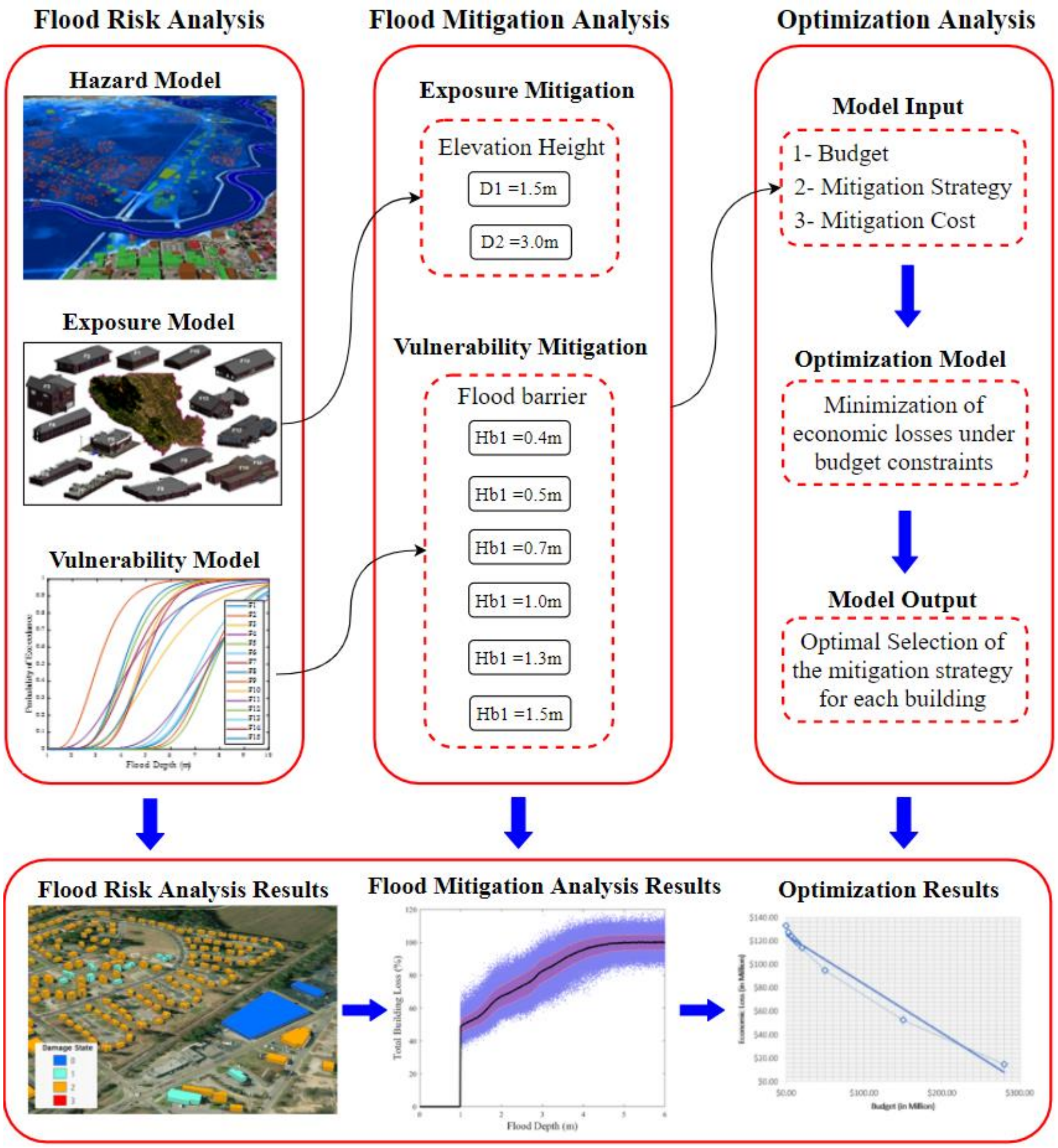

Figure 1: Schematic representation for the needed models and inputs for the optimization model

The analysis resolution used in this approach allowed for investigation of different types of mitigation strategies ranging from the component-level to and the building-level and even to the community-level. These strategies include pre-event, short-term flood mitigation measures for buildings such as using flood barriers with different elevations. Additionally, pre-event, long-term flood mitigation measures (e.g., increasing building elevation) are also modeled such as increasing building elevation. A set of flood mitigation scenarios associated with each mitigation strategy is investigated and the flood loss for each building corresponding to each mitigation scenario is then calculated to be used as an input for the optimization model.

$$L_f\ (IM = x) = \sum_{i=0}^{n} [\ P\ (DS_i|IM = x) - P(DS_{i+1}|IM = x) * Lr_{ci} * V_t \tag{1}$$

where $Lf\ (IM = x)$ =is the total building fragility-based flood losses in monetary terms at $IM = x$ (replacement or repair cost), $P(DS_i|IM = x)$ =is the exceedance probability of DS_i at $IM = x$, $P(DS_{i+1})$ =is the exceedance probability of DS_{i+1} at $IM = x$, Lr_{DSi} =is the cumulative replacement cost ratio corresponding to DS_i, and V_t= is the Total total building cost (replacement cost).

Table 1: Building Damage State Description

Damage State Level	Functionality	Damage Scale	Loss Ratio
DS-0	Operational	Insignificant	0.00-0.03
DS-1	Limited Occupancy	Slight	0.03-0.15
DS-2	Restricted Occupancy	Moderate	0.15-0.50

DS-3	Restricted Use	Extensive	0.50-0.70
DS-4	Restricted Entry	Complete	0.70-1.00

2.2. Optimization Model:

The science of finding the best solutions to mathematically described problems, which may be models of physical reality, is known as mathematical optimization [30]. So, optimization helps to find out the best solution among a lot of feasible or infeasible solution. In this paper, a mathematical optimization model is developed to enhance the resilience of buildings for reducing the total direct economic loss from a flood hazard. The set $\boldsymbol{Z}$ denotes the set of al buildings in the community and the set $\boldsymbol{S}$ denotes the set of all building archetypes. Each building $\boldsymbol{i} \in \boldsymbol{Z}$ is associated with exactly one archetype $\boldsymbol{j} \in \boldsymbol{S}$. The set K denotes all possible building mitigation intervention levels available across the community. The mitigation alternative $\boldsymbol{k}$=0 $\boldsymbol{k} \in \boldsymbol{K}$ implies that no retrofits have been implemented (i.e., the status quo). All buildings are assumed to be in this state prior to the modeling. Additionally, set of valid strategy level changes from strategy level $\boldsymbol{k} \in \boldsymbol{K}$ to level $\boldsymbol{k}' \in \boldsymbol{K}$ is presented by LL.

This optimization model will help the decision maker (i.e., building owners) to take two unknown complex decision, which are known as decision variables. First decision variable of this model is $\boldsymbol{x_{ijk}}$ that is denotes the total number of buildings $\boldsymbol{i} \in \boldsymbol{Z}$, of archetype $\boldsymbol{j} \in \boldsymbol{S}$, which are at strategy level $\boldsymbol{k} \in \boldsymbol{K}$. Another decision variable $\boldsymbol{y_{ijkk'}}$ denotes the total number of buildings $\boldsymbol{i} \in \boldsymbol{Z}$, of archetype $\boldsymbol{j} \in \boldsymbol{S}$, which are to be retrofitted from strategy level $\boldsymbol{k} \in \boldsymbol{K}$ to level $\boldsymbol{k} \in \boldsymbol{k'}$. As a result, for each mitigation option, the model determines the number of buildings that would need to be modified. This model may be used to discover identify the best mitigation strategies for individual buildings, or it can be used when the decision maker considers considering a small number of buildings in a block and electing single mitigation methods for each block.

2.2.1. *Objective of the Optimization Model*

In most of the cases, budget is an essential important factor, and always researchers are always trying to restrict their mathematical model with budgetary constraints [36] and also mentioned that how the budget affects their decision regarding retrofitting. In this model, budget, denoted B, is also considered as a significant factor which is presented by B. The total amount of budget B will be used for retrofitting purposes. As the budget will be used for retrofitting different buildings, so it is very crucial for the model to know the $\boldsymbol{b_{ijk}}$ which is the initial number of buildings which are at a certain mitigation strategy level $\boldsymbol{k} \in \boldsymbol{K}$. Another parameter of this model is strategy cost of $\boldsymbol{SC_{ijkk'}}$ which mainly presents the strategy level retrofitting costs, associated to changing a building $\boldsymbol{i} \in \boldsymbol{Z}$, of archetype $\boldsymbol{j} \in \boldsymbol{S}$, from strategy level $\boldsymbol{k} \in \boldsymbol{K}$ to level $\boldsymbol{k'} \in \boldsymbol{K}$, given that $\boldsymbol{k} \leq \boldsymbol{k'}$. Again, in this model economic loss is vitally important factor, which is directly related to one of the multiple objective functions. Economic loss is presented modeled by $\boldsymbol{l_{ijk}}$ in this optimization mode, where $\boldsymbol{l_{ijk}}$ presents the expected direct economic loss of due to the scenario disaster for building $i \in Z$, of archetype $j \in S$, which are at mitigation strategy level $\boldsymbol{k} \in \boldsymbol{K}$, due to a disaster scenario. Omar and van de lindt [14] mentioned one equation presented their model for calculating the direct economic loss based on flood depth and damage stage of the buildings. That is presented in equation (1). That loss present illustrates the economic loss due to the building damage if that building follows any particular mitigation strategy.

After getting the value of direct economic loss for each building $\boldsymbol{i} \in \boldsymbol{Z}$, of archetype $\boldsymbol{j} \in \boldsymbol{S}$, which are at strategy level $\boldsymbol{k} \in \boldsymbol{K}$, multiplying with a total number of buildings $\boldsymbol{i} \in \boldsymbol{Z}$, of archetype $\boldsymbol{j} \in \boldsymbol{S}$, which are at strategy level $\boldsymbol{k} \in \boldsymbol{K}$, over all the buildings, all the archetypes and all strategy, we can easily find the total direct economic loss of the community. Moreover, our objectives is to minimize this amount which is presented by equation (2).

$$\min \sum_{i \in Z} \sum_{j \in S} \sum_{k \in K} l_{ijk} \, x_{ijk} \tag{2}$$

2.2.2. *Constraints of the Optimization Model*

One of the constraints in this model is budgetary constraints. [25] also emphasized on this type of constraints for a model in their research. As we already know our budget, the main thing is that the entire retrofitting activities have to be completed within this budget. The total cost of all retrofitting activities must be less than or equal to the available budget amount.

$$\sum_{i \in Z} \sum_{j \in S} \sum_{k \in K} \sum_{k':(k',k) \in L} SC_{ijkk'} * y_{ijkk'} \leq B \tag{3}$$

The first constraint of the model is presented in equation (3). The total cost of the model can be calculated by multiplying the strategy cost $\boldsymbol{SC_{ijkk'}}$ with $\mathbf{y_{ijkk'}}$, total number of building i ∈ Z, of archetype j ∈ S, which are retrofitted from strategy level $\boldsymbol{k} \in \boldsymbol{K}$ to level $\boldsymbol{k} \in \boldsymbol{k'}$. This amount has to be less than or equal to the total budget, B.

The one of the purposes of the second constraint of this optimization model shown in equation (4) is to tie total number of buildings $\boldsymbol{i} \in \boldsymbol{Z}$, of archetype $\boldsymbol{j} \in \boldsymbol{S}$, which are at strategy level $\boldsymbol{k} \in \boldsymbol{K}$ with the total number of buildings $\boldsymbol{i} \in \boldsymbol{Z}$, of archetype $\boldsymbol{j} \in \boldsymbol{S}$, which are to be retrofitted from strategy level $\boldsymbol{k} \in \boldsymbol{K}$ to level $\boldsymbol{k} \in \boldsymbol{k'}$ logically. Furthermore, this equation ensures that only (k, k') interventions are allowed. We assumed here that if any mitigation strategy is adopted, then that should be able to reduce the direct economic loss of the buildings. If any buildings of the community are already following one mitigation strategy, then the model will not suggest them to dismiss that by suggestion “do nothing strategy”.

$$x_{ijk} = \sum_{k':(k',k) \in L} y_{ijk'k} + b_{ijk} - \sum_{k':(k',k) \in L} y_{ijkk'} \ , \qquad \forall\, i \in Z, \forall\, j \in S, \forall\, k \in K \tag{1}$$

Again, the last logical constraint of this model is that the total number of buildings $i \in$ Z, of archetype $j \in$ S, must be the same before and after any retrofitting efforts.

$$\sum_{k \in K} x_{ijk} = \sum_{k \in K} b_{ijk} \tag{2}$$

And all the decision variables are non-negative integer variables, so the constraints can be written as in the equation (6) and (7) respectively:

$$x_{ijk} \geq 0, \qquad \forall\, i \in Z, \forall\, j \in S, \forall\, k \in K \tag{3}$$

$$y_{ijkk'} \geq 0, \qquad \forall\, i \in Z, \forall\, j \in S, \forall\, k \in K \tag{4}$$

3. Case Study: Illustrative Example of Lumberton, NC

The developed approach is applied to Lumberton, NC to illustrate the applicability of the developed methodology at the community-level. Lumberton is a small city within Robeson County in southern North Carolina with a population of 20,000 people who live on the banks of Lumber

River as shown in Figure (2). The cascading flooding events following severe hurricanes made Lumberton an ideal location for examining flood damage and investigating the applicability of the developed optimization model. Also, the availability of data about the buildings of North Carolina makes it a perfect example to apply the developed for high-resolution flood risk modeling. Therefore, many researchers have used Lumberton as a testbed for flood risk, mitigation, and recovery analysis [34], [37]–[39]. There are 9,000 buildings within the physical boundary of Lumberton but, in this study, the buildings around Lumberton that share the city facilities are included in the analysis as well. As a result, the number of buildings in the considered community is around 20,000 among which 2857 buildings were impacted by flooding. Figure (2b) shows the spatial location of each building within Lumberton with the buildings color-coded based on their archetypes (e.g., occupancy). There are two main streams that deliver the water to the west side of Lumberton, including Lumber River and Red Springs Creek, as shown In Figure (2c). Table 2 provides a brief description of each one of these archetypes. The flooding event after Hurricane Matthew in 2016 was used as a flood hazard scenario to investigate the developed approach.

3.1. Flood Hazard and Damage Analysis Results

A detailed hydrologic analysis was conducted using the rainfall, land use, and soil information to predict the water flow in the main streams that deliver the water to the study area. This water flow was used as a boundary condition for a hydrodynamic analysis along with a LiDAR-based digital elevation map (DEM) or a resolution of 0.75m. Readers are referred to [34] for more details about the flood hazard analysis. Figure (3a) shows the simulated flood hazard for the flooding event after Hurricane Matthew in 2016 which shows the state of flood inundation and extent concerning with respect to Lumberton, NC. The exposure analysis results revealed that there are 2857 buildings exposed to flooding. Figure (3b) shows the spatial location of the flooded buildings only color-coded based on their archetypes. First, a base flood damage and loss scenario were conducted without applying any mitigation measure. Table 2 provides information about the number of buildings exposed to flooding by archetype along with their market value and the amount of flood losses. Table 3 includes fragility analysis results in terms of the exceedance probability of each DS corresponding to five ranges from 0% up 100% and the number of buildings within each range.

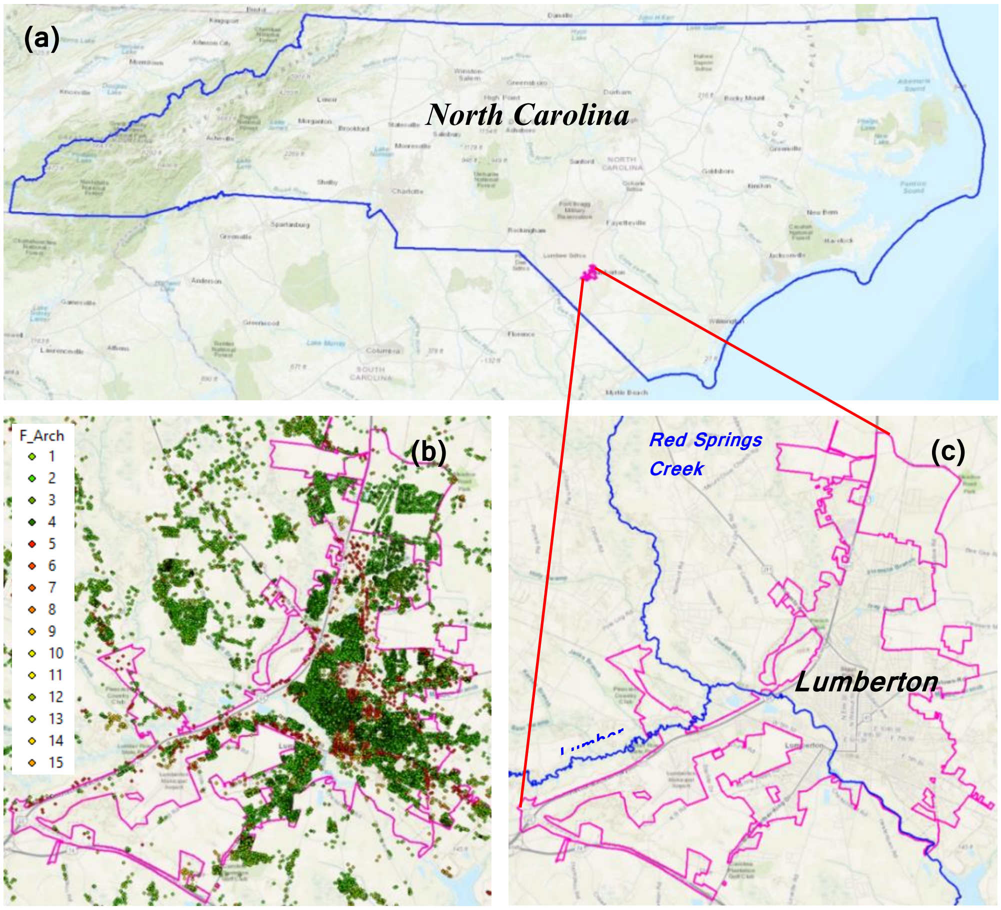

Figure 2: The spatial location of Lumberton city and its buildings with respect to the State of North Carolina: (a) The physical boundary of North Carolina State; (b) The spatial location of the buildings within Lumberton color-coded based on their archetypes; (c) The spatial location of Lumberton city with respect to the state of North Carolina.

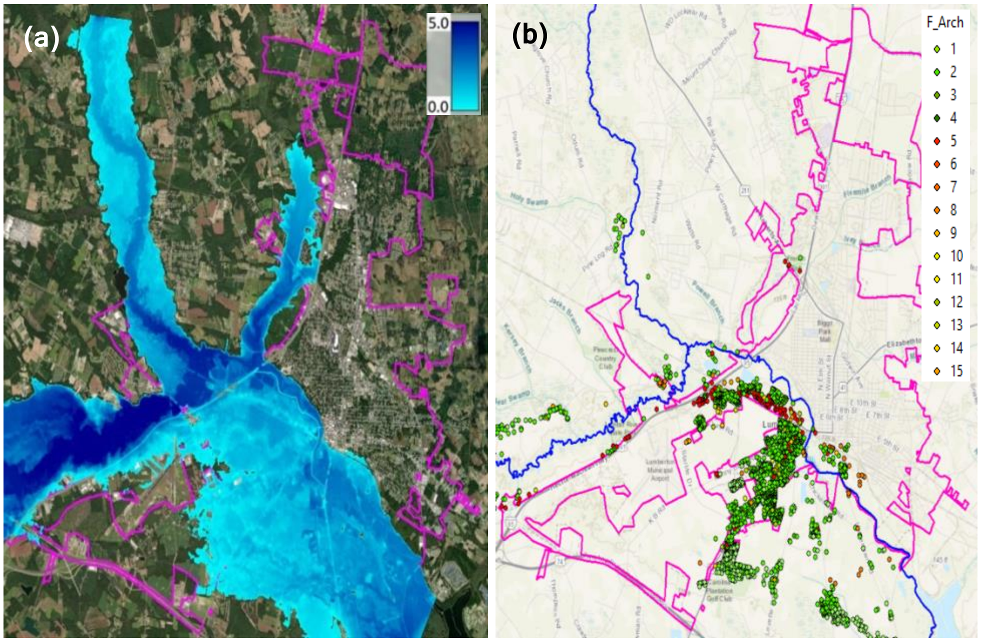

Figure 3: The simulated flood hazard for the flooding event in Lumberton, NC after Hurricane Matthew in 2016 and the exposed buildings: (a) Flood hazard map in terms of the flood extent and flood inundation measured from ground elevation (m); (b) The flood exposed buildings color-coded based on their archetypes.

Table 2: The number of exposed buildings by archetypes along with their current Market value and base flood loss

Archetype	**Number of Buildings**	**Total Current Apprised Value**	**Total Base Flood Losses**
F1: One-Story Single-Family Residential Building	665	$37,527,864	$10,097,519
F2: One-Story Multi-Family Residential Building	1741	$194,990,289	$80,651,358
F3: Two-Story Single-Family Residential Building The	7	$1,059,617	$316,074
F4: Two-Story Multi-Family Residential Building	96	$21,174,848	$5,548,556
F5: Small Grocery Store/Gas Station with a Convenience Store	157	$62,855,685	$7,921,982

F6: Multi-Unit Retail Building (Strip Mall)	1	$7,195,517	$0
F7: Small Multi-Unit Commercial Building	1	$256,600	$157,864
F8: Super Retail Center The	2	$408,318	$176,194
F9: Industrial Building	62	$124,562,628	$12,002,943
F10: One-Story School	8	$7,429,091	$2,495,461
F11: Two-Story School	3	$23,456,627	$3,621,603
F12: Hospital/Clinic The	0	$0	$0
F13: Community Center (Place of Worship)	44	$23,381,452	$6,720,040
F14: Office Building	17	$8,782,066	$2,565,452
F15: Warehouse (Small/Large Box)	53	$40,975,016	$860,940

Table 3: Fragility analysis results in terms of the exceedance probability

Exceedance Probability of a DS (Fragility)	Number of buildings (Total=2858)				
	DS0	DS1	DS2	DS3	DS4
0% < P_DS < 20%	2201	396	567	2071	2822
20% < P_DS < 40%	5	72	115	355	25
40% < P_DS < 60%	7	72	144	293	7
60% < P_DS < 80%	30	108	290	121	3
80% < P_DS < 100%	614	2209	1741	17	0

3.2. Comparative Analysis of Short- and long-term Mitigation Strategies

We tested the model at various budget levels and the findings are summarized in this section. Lumberton's total economic loss will be more than $133 million if the community does not wish to invest anything where they can significantly reduce their economic loss by applying the suggested techniques from our model. However, the choice of various optimal implementation of mitigation techniques has a significant impact on reducing overall direct economic loss. We were quite interested in performing this study in three distinct methods of mitigation modes: (i) long-term methods (i.e., elevating structures), (ii) short-term methods (erecting temporary flood barriers), and (iii) a combination of both long- and short-term interventions. To begin, we employed long-term mitigation techniques to eliminate flood threats, such as elevating structures to a specific height. Second, flood barriers of various sizes, ranging from 0.4 to 1.5 meters, were employed in the mitigation approach. Due to a scarcity of cost information for flood barriers of over 1.5 meters, we had to limit the height of the flood barrier to 1.5 meters. Finally, all of the strategies (long- and short- term) were combined in the model to provide a diverse set of results.

Long-term mitigation strategies include building elevations of 5 ft (1.5 m) and 10 ft (3 m) for reducing the loss of an individual building from flood hazards. If a building owner decides to choose this long-term mitigation option, s/he can save his/her building from flood several times. Table 4 summarizes the optimization model's findings and offers specific building retrofits at different mitigation strategies. Lumberton presently has no retrofitted structures so if any flood happens in that location, all the buildings have to face a significant loss due to that. When the budget was raised, however, the number of buildings that were mitigated climbed dramatically. When all of the buildings are damaged without any mitigating plans in place, they might suffer a direct economic loss of more than $133 million. However, by implementing particular mitigation techniques, this massive economic loss can be reduced. Long-term mitigation techniques are usually costly. The model was tested with the random lowest budget of 3.5 million dollars when the model is able to reduce the economic loss of more than 4 million dollars. With the budget of

$280 million; building owners can only repair 1738 buildings which can reduce the economic loss of more than $118 M USD in each flooding event. This is because long-term measures have a significantly high retrofit cost, but they will assist the community decrease overall building damage for a long time. As a result, anyone considering using this technique will be able to save more money in the long run than their hefty initial expenditure.

Table 4: Result Summary for Long-term Mitigation Strategy

		Number of buildings retrofitted			
Budget	No intervention	Elevate 5ft (1.5m)	Elevate 10ft (3m)	Total Number of Retrofitted Buildings	Economic Loss
$0M	2,857	0	0	0	$133,135,992
$3.5M	2,836	17	4	21	$127,398,555
$7M	2,817	33	7	40	$124,164,674
$10.5M	2,786	57	14	71	$121,268,774
$14M	2,761	81	16	97	$118,517,884
$ 20M	2717	123	18	141	$114,017,769
$50M	2523	288	46	334	$94,973,886
$150M	1796	726	335	1061	$52,520,789
$280M	1119	1329	409	1738	$14,704,547

When we opted to go for long-term mitigation, the model sought to identify a mitigation option for a specific building based on the strategy cost of that mitigation approach. Buildings with a 10 ft elevation have greater mitigation plan costs than those with a 5 ft height. However, 10 feet of elevation can make a structure safer than 5 feet, and in some circumstances, the financial loss will be literally zero if the owner chooses 10 feet of elevation. However, some industrial buildings in Lumberton will not be able to achieve this building elevation since it would require them to invest substantially more money. At various budget levels, Figure **4** depicts the distribution of various long-term mitigation solutions for individual structures in Lumberton, NC at various budget levels. Furthermore, it is clear from the data that the darker dots are increasing when a larger budget is used, implying that more community structures would be converted. One of the most important findings of this study is that we may increase the budget level at any time, and the model is providing the decisions regarding the mitigation strategies for each building, using that budget to minimize overall economic loss. One thing to note is that a mitigation strategy will only be suggested to buildings by the optimization model that assist the community in reducing overall direct economic loss.

While we implemented our optimization model in Lumberton with short time mitigation strategy, results were very different from the long-term strategy. Table 5 reports the various budget levels that we examine along with the number of flood barriers that are selected from 0.4 m to 1.5 m height to retrofit the buildings as well as the resulting estimated direct economic loss to be expected for the scenario. As our optimization model's main objective is to minimize the total economic loss within a given budget level, retrofitting more buildings was not helping to minimize the total economic loss when the user is investing more. So, the model is not suggesting those buildings be retrofitted in those strategy levels. A vital area to notice is that while the community is investing \$50M to retrofit their buildings with a long-term strategy, they can retrofit only 334 buildings. On the contrary, in the case of short-term strategy \$50M budget can help a community to adopt various short-term strategies to 832 buildings, which is a large number. This is because of lower cost of adopting short term strategy which can only support a building during single flooding event. While the community is investing more than \$50M, retrofitting strategy is changing, but the overall economic loss remains the same. Using a flood barrier of 1.5 m is the costliest option among all the short-term strategies, and as the model is getting more money to invest, it is giving more money to use the mitigation strategy of a 1.5 m flood barrier. If one use the flood barrier of more height then they can get better results but in this case due to the lack of pricing information of higher flood barrier we need to stop at 1.5 m. The location of the buildings and the distribution of various short time mitigation strategies are presented in **Figure 5** for different budget levels, respectively.

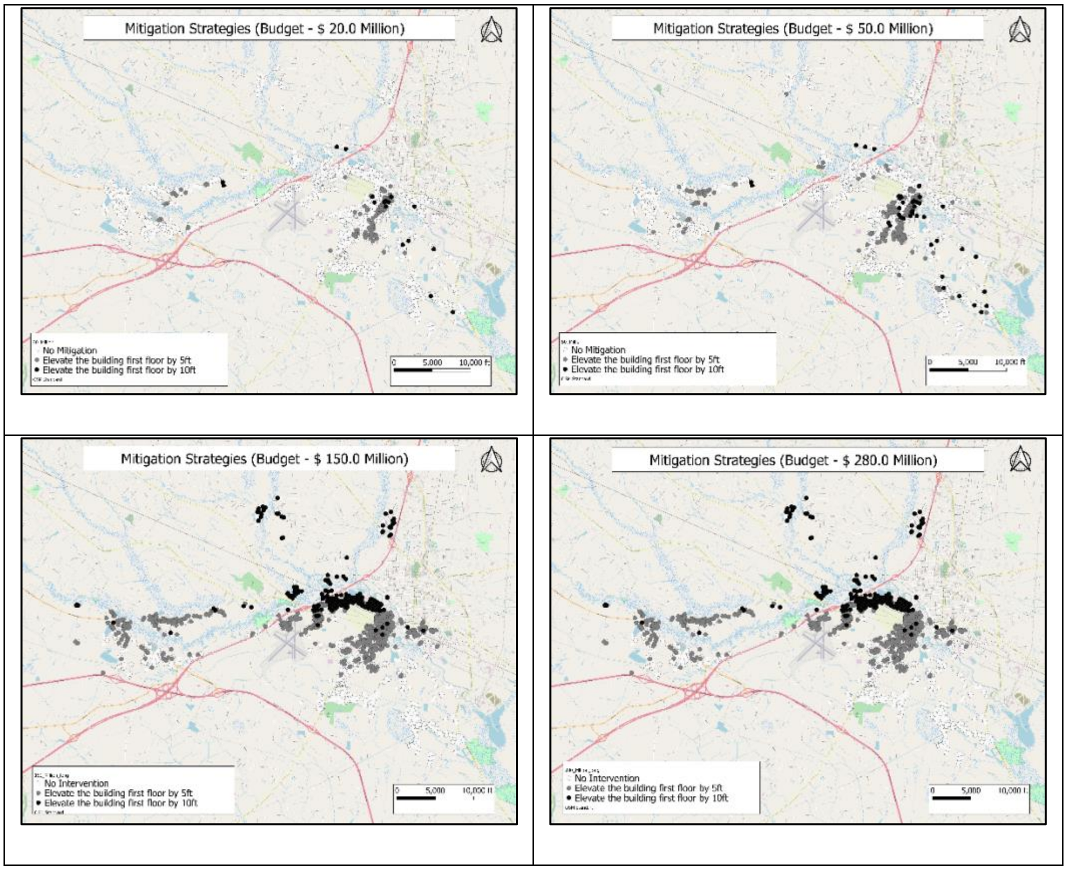

Figure 4: Location of Buildings Based Long-term Strategy Implementation Different Budget Levels

	Number of buildings surrounded by barrier of height (Hb)								
Budget	No intervention	Hb= 0.4m	Hb= 0.5m	Hb= 0.7m	Hb= 1.0m	Hb= 1.3m	Hb= 1.5m	Total Number of Retrofitted Building	Economic Loss
$0M	2857	0	0	0	0	0	0	0	$133,135,992
$3.5M	2826	0	0	5	4	7	15	31	$124,118,022

$7M	2766	1	0	9	16	26	39	91	$119,675,195
$10.5M	2706	1	0	12	29	47	62	151	$116,597,842
$14M	2637	1	0	14	37	74	94	220	$114,059,986
$20M	2513	2	1	16	47	116	162	344	$110,680,315
$50M	2026	33	8	70	146	264	311	832	$107,224,597
$150M	2026	33	8	70	146	264	311	832	$107,224,597
$280M	2026	33	8	70	146	264	311	832	$107,224,597

Table 5: Result Summary for Short-term Mitigation Strategy

The results are also intriguing when the optimization model is used for both short and long-term mitigation options together. Currently, the optimization model is gaining features for recommending buildings for flood barriers and building elevation. Flood barriers may not be advantageous for other buildings after being used in some buildings since they will not help the community lower their overall direct economic loss. In that instance, building elevation as a long-term plan is a fantastic choice. Though it is a costly alternative, it can help reduce the amount of money lost in the community due to floods.

The plot between the total direct economic loss and the invested budget is depicted in Figure 7 and Figure 8 (closoure view), and it is noticeable that the economic loss is decreasing significantly while the community is investing more and more. At the highest budget level of $280 M, the model can help to retrofit almost all the community's buildings. Only 787 buildings will be in no intervention stage when the community invests $280M. In the other budget level, the model suggests elevating the building byfor 5 ft because of two main reasons. Firstly, it is cheaper than elevating 10ft. Secondly, it is reducing the economic loss significantly. However, building elevation is highly dependent on the area of the individual buildings. Typically, commercial buildings hold large areas, which makes the cost of building elevation very high for them. **Figure**

9 depicts the mitigation strategies in the Lumberton map based on budget level while implementing both short- and long-term strategies together.

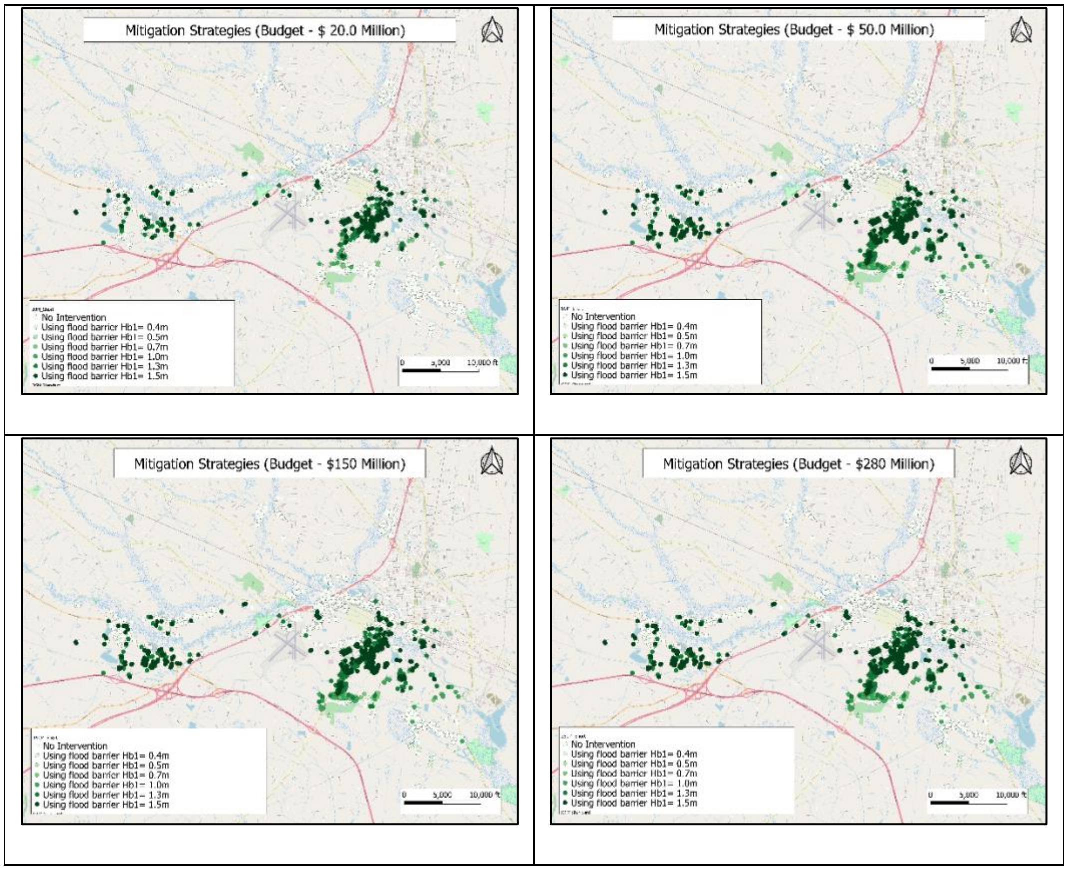

Figure 5: Location of Buildings Based Short-term Strategy Implementation for Various Budget Levels

Table 6: Result Summary for Short and Long-Term Mitigation Strategy

	Number of Buildings Retrofitted									
Budget	No intervention	0.4m	0.5m	0.7m	1.0m	1.3m	1.5m	Elevate 5ft	Elevate 10ft	Economic Loss
$0M	2,857	0	0	0	0	0	0	0	0	$133,135,992
$3.5M	2833	0	0	4	3	4	9	3	1	$123,380,846
$7M	2787	1	0	7	8	15	28	8	3	$118,059,178
$10.5M	2745	1	0	9	16	28	39	15	4	$114,175,819
$14M	2715	1	0	10	22	34	44	24	7	$110,893,178
$20M	2649	1	0	10	27	45	60	51	14	$105,849,491
$50M	2377	2	1	14	39	80	106	212	26	$84,368,342
$150M	1538	2	1	18	53	131	184	601	329	$39,452,522
$280M	787	5	3	23	75	185	239	1091	446	$4,539,084

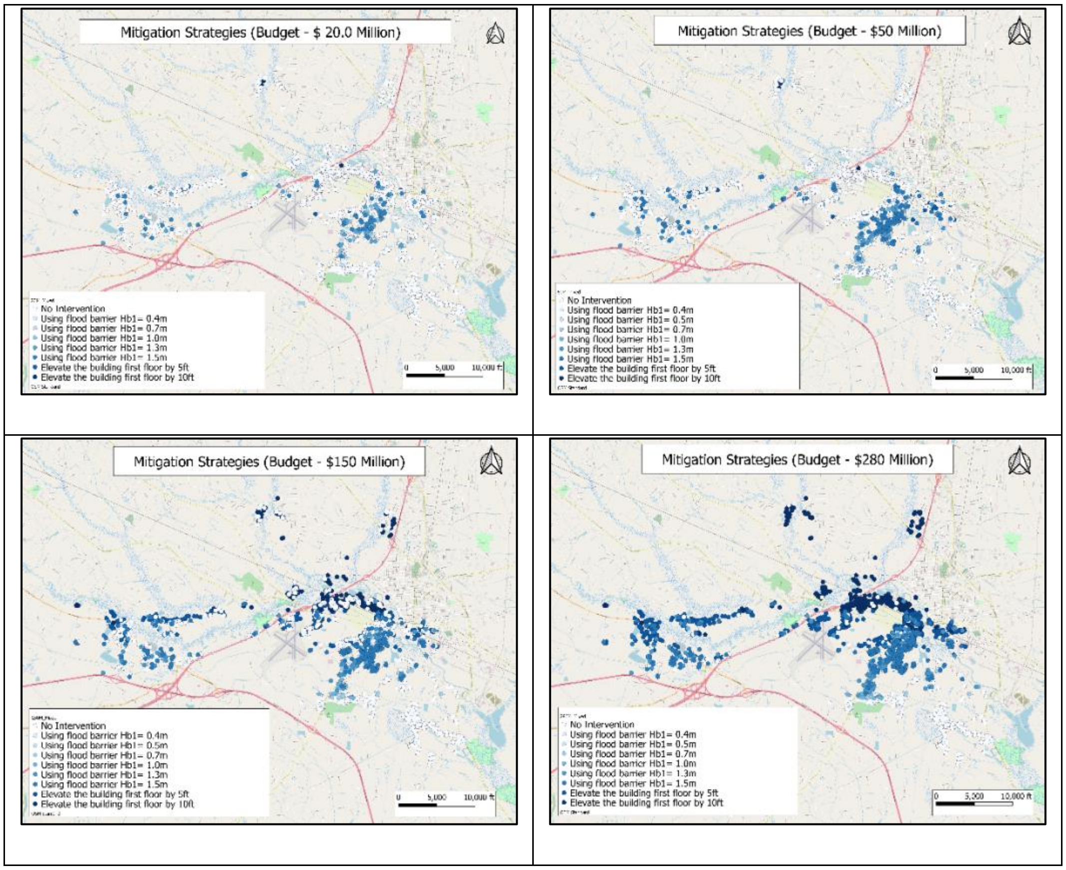

Figure 6: Location of Buildings Based Short- and Long-term Strategy Implementation for Numerous Budget Levels

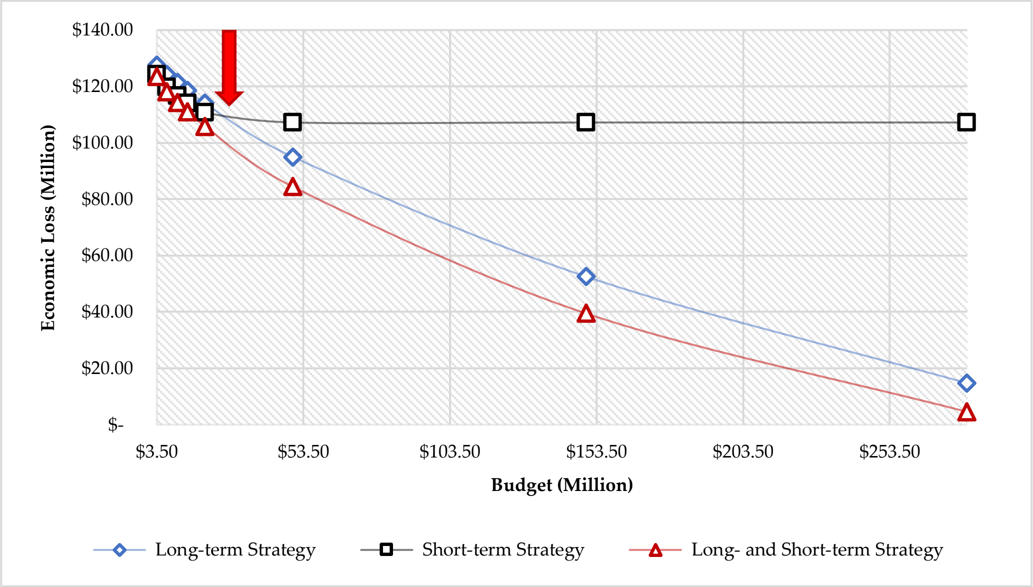

Figure 7: Relationship Between Investment and Corresponding Economic Loss

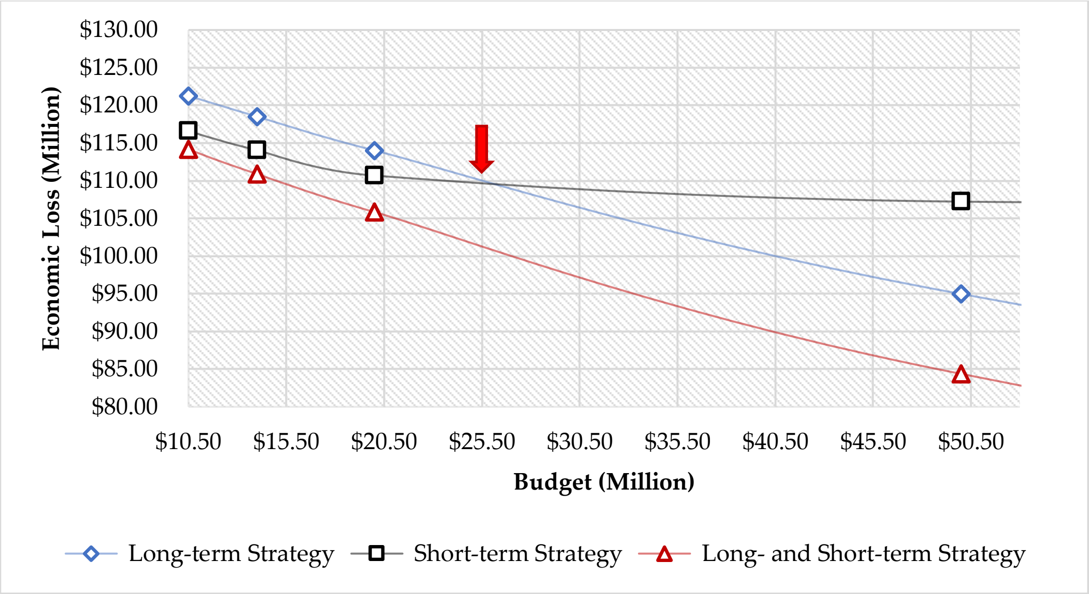

Figure 8: Relationship Between Investment and Coresponding Economic Loss (Close View)

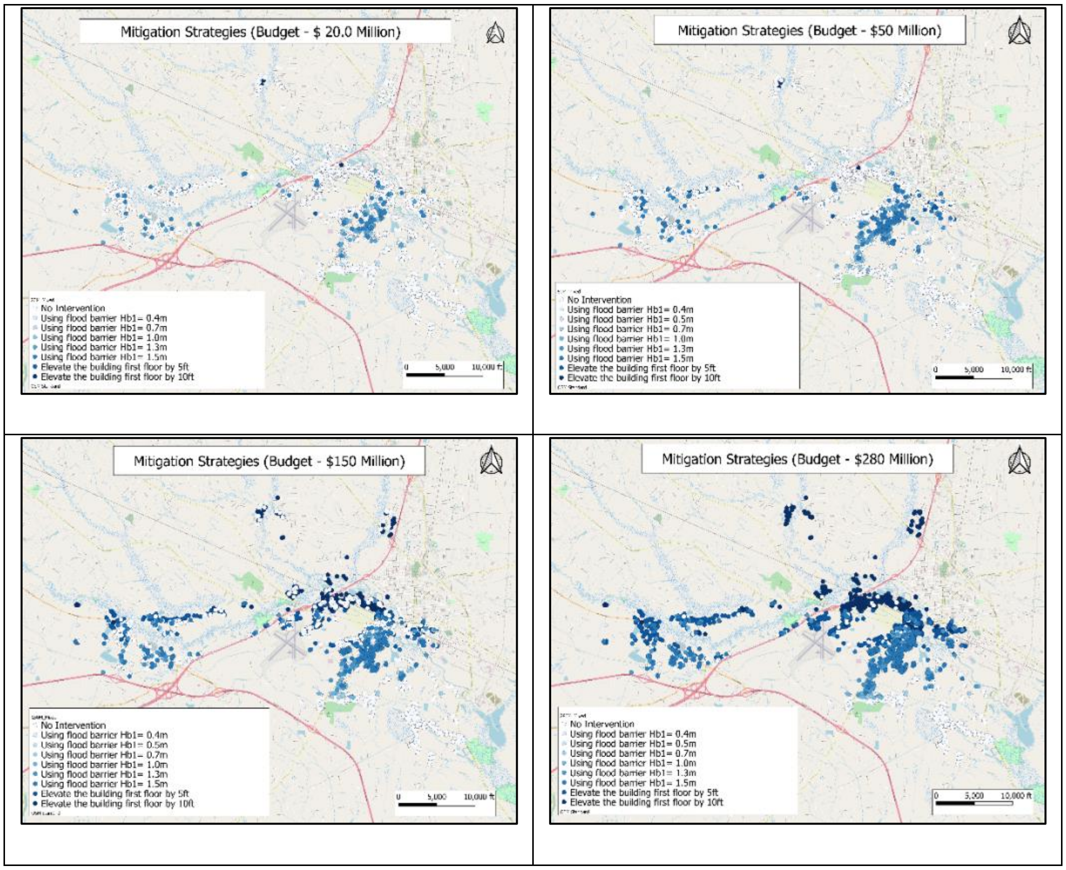

Figure 9: Location of Buildings Based Short- and Long-term Strategy Implementation for Numerous Budget Levels

The link relationship between the reduced economic loss and the employed budget for upgrading buildings in Lumberton is depicted in Figure 7 and Figure 8. This graph depicts how the economic loss decreases as the budget level increases for different increased strategies. When we opted to go for long-term mitigation, the model sought to identify a mitigation option for a specific building based on the strategy cost of that mitigation approach. Figure 7 present the comparison of short- and long-term strategies based on corresponding economic loss. It is noticed that till a specific budget (nearly $25 Million), short-term mitigation measures can help the community to reduce their direct economic loss due to building damage, but after that, long-term strategies are performing better. As short-term strategies are not much costly as long-term ones, the model suggests short-term mitigation measures for lower budget levels. Buildings with a 10 ft elevation have greater mitigation plan costs than those with a 5 ft height. However, 10 feet of elevation can make a structure safer than 5 feet, and in some circumstances, the financial loss will be nil if the owner chooses 10 feet of elevation. However, some industrial buildings in Lumberton will not be able to achieve this building elevation since it would require them to invest substantially more money.

4. Conclusions and Future Research

Each and every day, somewhere in the world, people are suffering a lot due to natural disasters such as flooding, tornedos, tsunami etc. which costs them hundreds of dollars to back into normal life. However, if the community can take some mitigation measures, they can certainly reduce the risk of any natural hazard. Usually for saving the buildings from any unexpected natural events, building owners need to choose particular mitigation strategies. But, selection of mitigation strategy depends on various factors like the natural of any specific natural disaster, building area, impact of the natural hazard on that certain building etc. In this study, the optimization approach was applied to help the decision-maker decide which mitigation strategy should be implemented by which buildings. The model that was created was reasonably fairly universal, meaning that it could be used in any flood affected community subject to availability of the required data. The decision-makers i.e., building owner in this research have the opportunity to pick alternative mitigation techniques for different buildings, but the model may also be employed when a community leader wishes to look at a block of buildings as a whole. The major parameters of the model are the budget, loss of the buildings and the cost of implementing any mitigation strategies in the buildings. The optimization model is using these parameters to suggest the best mitigation strategy for each building which will help the community to reduce the total direct economic loss due to building damage. A data from Lumberton, North Carolina, which is prone to floods, was used to test the model. In this work, we primarily investigate two types of mitigation techniques in this case study. To begin, we examine elevating structures by 5 and 10 feet, and then we consider using flood barriers to keep buildings safe from flooding. This case study can be expanded with more mitigation techniques to reduce the total direct economic loss in the community due to building damage. One of the most challenging difficult aspects of our study was determining the cost of mitigation measures, which was an essential input to our optimization model. One of the study's major limitations is that this optimization model only has one decision-maker decision maker, despite the fact that it may be expanded to include numerous decision makers. The building owner and community leaders will be free to make their own decisions in this situation. In that scenario, the bi-level optimization approach may be employed, and we plan to incorporate the bi-level optimization model in future study to reduce overall direct economic loss.

References

[1] P. Walters, “The problem of community resilience in two flooded cities: Dhaka 1998 and Brisbane 2011,” *Habitat International*, vol. 50, pp. 51–56, Dec. 2015, doi: 10.1016/j.habitatint.2015.08.004.

[2] A. Hooijer, F. Klijn, G. B. M. Pedroli, and A. G. van Os, “Towards sustainable flood risk management in the Rhine and Meuse river basins: Synopsis of the findings of IRMA-SPONGE,” *River Research and Applications*, vol. 20, no. 3, pp. 343–357, 2004, doi: 10.1002/rra.781.

[3] E. Roy, J. Rousselle, and J. Lacroix, “Flood Damage Reduction Program (FDRP) in Québec: Case study of the Chaudière River,” *Natural Hazards*, vol. 28, no. 2–3, pp. 387–405, 2003, doi: 10.1023/A:1022942427248.

[4] M. Hemmati, B. R. Ellingwood, and H. N. Mahmoud, “The Role of Urban Growth in Resilience of Communities Under Flood Risk,” *Earth’s Future*, vol. 8, no. 3, pp. 1–14, 2020, doi: 10.1029/2019EF001382.

[5] A. Mullins and R. Soetanto, “Enhancing community resilience to flooding through social responsibility,” *International Journal of Safety and Security Engineering*, vol. 1, no. 2, pp. 115–125, 2011, doi: 10.2495/SAFE-V1-N2-115-125.

[6] M. K. Lindell and C. S. Prater, “Assessing community impacts of natural disasters,” *Natural Hazards Review*, vol. 4, no. 4, pp. 176–185, 2003, doi: 10.1061/(ASCE)1527-6988(2003)4:4(176).

[7] D. Elms, I. McCahon, and R. Dewhirst, “Improving infrastructure resilience,” *Civil Engineering and Environmental Systems*, vol. 36, no. 1, pp. 83–99, 2019, doi: 10.1080/10286608.2019.1615479.

[8] T. Y. Liao, T. Y. Hu, and Y. N. Ko, “A resilience optimization model for transportation networks under disasters,” *Natural Hazards*, vol. 93, no. 1, pp. 469–489, 2018, doi: 10.1007/s11069-018-3310-3.

[9] S. Nozhati, B. R. Ellingwood, and E. K. P. Chong, “Stochastic optimal control methodologies in risk-informed community resilience planning,” *Structural Safety*, vol. 84, no. October 2019, p. 101920, 2020, doi: 10.1016/j.strusafe.2019.101920.

[10] S. Nozhati, B. R. Ellingwood, and E. K. P. Chong, “Stochastic optimal control methodologies in risk-informed community resilience planning,” *Structural Safety*, vol. 84, no. October 2019, p. 101920, 2020, doi: 10.1016/j.strusafe.2019.101920.

[11] S. Nozhati, Y. Sarkale, B. Ellingwood, E. K.P. Chong, and H. Mahmoud, “Near-optimal planning using approximate dynamic programming to enhance post-hazard community resilience management,” *Reliability Engineering and System Safety*, vol. 181, no. April 2018, pp. 116–126, 2019, doi: 10.1016/j.ress.2018.09.011.

[12] M. K. Sen, S. Dutta, and G. Kabir, “Flood Resilience of Housing Infrastructure Modeling and Quantification Using a Bayesian Belief Network,” *Sustainability*, vol. 13, no. 3, p. 1026, 2021, doi: https://doi.org/10.3390/su13031026.

[13] V. K. Gudipati and E. J. Cha, “A resilience-based framework for design optimization of interdependent buildings,” *13th International Conference on Applications of Statistics and Probability in Civil Engineering, ICASP 2019*, pp. 1–8, 2019.

[14] O. M. Nofal and J. W. van de Lindt, “Minimal building flood fragility and loss function portfolio for resilience analysis at the community level,” *Water (Switzerland)*, vol. 12, no. 8, 2020, doi: 10.3390/w12082277.

[15] A. Pistrika, G. Tsakiris, I. Nalbantis, G. Tsakiris, and I. Nalbantis, “Flood Depth-Damage Functions for Built Environment,” *Environ. Process*, vol. 1, pp. 553–572, 2014, doi: 10.1007/s40710-014-0038-2.

[16] S. Noor, M. @ Romali, S. A. K. Sulaiman, Z. Yusop, and Z. Ismail, “Flood Damage Assessment: A Review of Flood Stage–Damage Function Curve,” *ISFRAM 2014*, pp. 147–159, 2015, doi: 10.1007/978-981-287-365-1_13.

[17] C. Scawthorn *et al.*, “HAZUS-MH Flood Loss Estimation Methodology. II. Damage and Loss Assessment,” *Natural Hazards Review*, vol. 7, no. 2, pp. 72–81, May 2006, doi: 10.1061/(ASCE)1527-6988(2006)7:2(72).

[18] R. de Risi *et al.*, “Flood risk assessment for informal settlements,” *Natural Hazards*, vol. 69, no. 1, pp. 1003–1032, Oct. 2013, doi: 10.1007/S11069-013-0749-0.

[19] O. M. Nofal and J. W. van de Lindt, “High-resolution approach to quantify the impact of building-level flood risk mitigation and adaptation measures on flood losses at the community-level,” *International Journal of Disaster Risk Reduction*, vol. 51. 2020. doi: 10.1016/j.ijdrr.2020.101903.

[20] M. T. Marvi, “A review of flood damage analysis for a building structure and contents,” *Natural Hazards*, pp. 1–29, 2020, doi: https://doi.org/10.1007/s11069-020-03941-w.

[21] R. Figueiredo, X. Romão, and E. Paupério, “Component-based flood vulnerability modelling for cultural heritage buildings,” *undefined*, vol. 61, Jul. 2021, doi: 10.1016/J.IJDRR.2021.102323.

[22] O. M. Nofal and J. W. van de Lindt, “High-resolution flood risk approach to quantify the impact of policy change on flood losses at community-level,” *International Journal of Disaster Risk Reduction*, vol. 62, p. 102429, 2021, doi: 10.1016/j.ijdrr.2021.102429.

[23] O. M. Nofal, “High-Resolution Multi-Hazard Approach to Quantify Hurricane-Induced Risk for Coastal and Inland Communities,” Colorado State University, 2021.

[24] W. Zhang and C. Nicholson, “A multi-objective optimization model for retrofit strategies to mitigate direct economic loss and population dislocation,” *Sustainable and Resilient Infrastructure*, vol. 1, no. 3–4, pp. 123–136, 2016, doi: 10.1080/23789689.2016.1254995.

[25] M. Najarian and G. J. Lim, “Optimizing infrastructure resilience under budgetary constraint,” *Reliability Engineering and System Safety*, vol. 198, no. June 2019, p. 106801, 2020, doi: 10.1016/j.ress.2020.106801.

[26] Y. Almoghathawi, A. D. González, and K. Barker, “Exploring Recovery Strategies for Optimal Interdependent Infrastructure Network Resilience,” *Networks and Spatial Economics*, 2021, doi: 10.1007/s11067-020-09515-4.

[27] Y. Wen, C. Nicholson, and A. González, “A multi-objective optimization model for buildings retrofit strategies to optimize direct economic loss , population dislocation , and building functionality,” 2021.

[28] T. Adluri, D. Sanderson, A. González, C. Nicholson, and D. Cox, “Multi-Objective Optimization of Building Mitigation Strategies to address Multiple Hazards,” 2021.

[29] W. Zhang and C. Nicholson, “A multi-objective optimization model for retrofit strategies to mitigate direct economic loss and population dislocation,” *Sustainable and Resilient Infrastructure,* vol. 1, no. 3–4, pp. 123–136, 2016, doi: 10.1080/23789689.2016.1254995.

[30] D. M. Wiebe and D. T. Cox, “Application of fragility curves to estimate building damage and economic loss at a community scale: A case study of Seaside, Oregon,” *Natural Hazards*, vol. 71, no. 3, pp. 2043–2061, 2014, doi: 10.1007/s11069-013-0995-1.

[31] K. Onan, F. Ülengin, and B. Sennaroğlu, “An evolutionary multi-objective optimization approach to disaster waste management: A case study of Istanbul, Turkey,” *Expert Systems with Applications*, vol. 42, no. 22, pp. 8850–8857, 2015, doi: 10.1016/j.eswa.2015.07.039.

[32] K. Onan, F. Ülengin, and B. Sennaroğlu, “An evolutionary multi-objective optimization approach to disaster waste management: A case study of Istanbul, Turkey,” *Expert Systems with Applications*, vol. 42, no. 22, pp. 8850–8857, 2015, doi: 10.1016/j.eswa.2015.07.039.

[33] O. M. Nofal and J. W. van de Lindt, “High-Resolution Approach to Quantify the Impact of Building-Level Flood Mitigation and Adaptation Measures on Flood Losses at the Community-Level,” *International Journal of Disaster Risk Reduction*, p. 101903, 2020, doi: https://doi.org/10.1016/j.ijdrr.2020.101903.

[34] O. M. Nofal and J. W. van de Lindt, “High-resolution approach to quantify the impact of building-level flood risk mitigation and adaptation measures on flood losses at the community-level,” *International Journal of Disaster Risk Reduction*, vol. 51, no. September, p. 101903, 2020, doi: 10.1016/j.ijdrr.2020.101903.

[35] J. A. Snyman and D. N. Wilke, *Practical Mathematical Optimization*. 2005. doi: 10.1007/b105200.

[36] S. Mejjaouli and M. Alzahrani, “Decision-Making Model for Optimum Energy Retrofitting Strategies in Residential Buildings,” *Sustainable Production and Consumption*, 2020, doi: 10.1016/j.spc.2020.07.008.

[37] D. Deniz *et al.*, “Flood performance and dislocation assessment for Lumberton homes after Hurricane Matthew,” 2019, doi: 10.2/JQUERY.MIN.JS.

[38] “ID. 41 - Modeling business recovery after natural disasters: The case study of Lumberton, NC following Hurricane Matthew - ICONHIC 2019.” https://iconhic.com/2019/2019/11/id-41-

modeling-business-recovery-after-natural-disasters-the-case-study-of-lumberton-nc-following-hurricane-matthew/ (accessed Nov. 16, 2021).

[39] S. Khajehei, “Recovery challenges of public housing residents after disasters: Lumberton, North Carolina after Hurricane Matthew,” *Graduate Theses and Dissertations*, Jan. 2019, Accessed: Nov. 16, 2021. [Online]. Available: https://lib.dr.iastate.edu/etd/17483