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Risk-Based Decision Making Model for the Selection of Flood Mitigation Alternatives

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RISK-BASED DECISION MAKING MODEL FOR THE SELECTION OF FLOOD MITIGATION ALTERNATIVES

BY

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ABSTRACT

In recent years, there has been a noticeable increase in the frequency of natural disasters such as wildfires, hurricanes and flooding, resulting in big economic, environmental, and social impacts. In the case of flood events, impacts such as community anxiety, loss of life, water pollution, and contamination of agricultural land have been found to be equally, if not more important, than the economic impacts of such events. Nevertheless, the literature shows that flood risk assessment studies incorporating economic, environmental, and societal impacts are limited. In addition, flood mitigation measures are typically compared focusing on economic criteria and not considering stakeholders or the implementation characteristics of the flood mitigation alternatives.

This study proposes a holistic framework for watershed flood management that considers economic, social, environmental, and implementation criteria for selecting among flood mitigation alternatives. First, a spatial flood risk assessment framework capable of integrating economic, social, and environmental impacts is introduced in order to assess the possible losses and risks within the communities of a watershed. The risk assessment uses HAZUS software from the Federal Emergency Management Agency (FEMA) and is executed for five different return periods. Second, in order to select from multiple mitigation alternatives, a Decision-Making Models (DMM) is proposed. The first model uses the results from the risk assessment and the mitigation alternatives are evaluated using a Monte Carlo Simulation and probabilistic optimization. The second DMM model incorporates stakeholder's characteristics and opinions using stakeholder theory, network analysis, and the Analytical Hierarchical Process (AHP). Two surveys were developed and deployed to public officials of agencies involved in the planning and implementation of flood mitigation alternatives and to the community, respectively. Along with this information, technical aspects of the flood mitigations alternatives are used as implementation criteria. Three alternatives were evaluated in the decision analysis: (1) no action, (2) flood warning system, and (3) levee. The framework is demonstrated with the case study of the Upper Río Grande of Loíza Watershed in the Commonwealth of Puerto Rico.

The results showed that both stakeholder's input and implementation criteria can have a significant impact when selecting among flood mitigation strategies. For the case study, when considering economic, social, and environmental criteria, the "Levee" was the

alternative that minimized the flood risks. The developed framework was shown to be easily implementable and adaptable to Decision-Maker (DM) requirements. In summary, the model can provide DMs with the information they need in order to forecast the flood risks of a community and study the effects of the mitigation alternatives to be implemented. These results could be used for budget forecast, resource allocation and for establishing flood management priorities for a watershed.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

As the world's population continues to increase at an alarming rate, human's adverse impact on Earth's ecosystem is greater. In turn, this has created major environmental issues such as global warming and depletion of the ozone layer. There has also been a noticeable increase in the frequency and severity of natural disasters, like wildfires, earthquakes, hurricanes, and floods, leaving negative impacts on the economy, the environment, and society. In Figure 1, a history of natural disasters (i.e. geophysical and climate related) throughout the world since 1900 is presented. A clear trend of increase in natural disasters and their economic impacts can be observed.

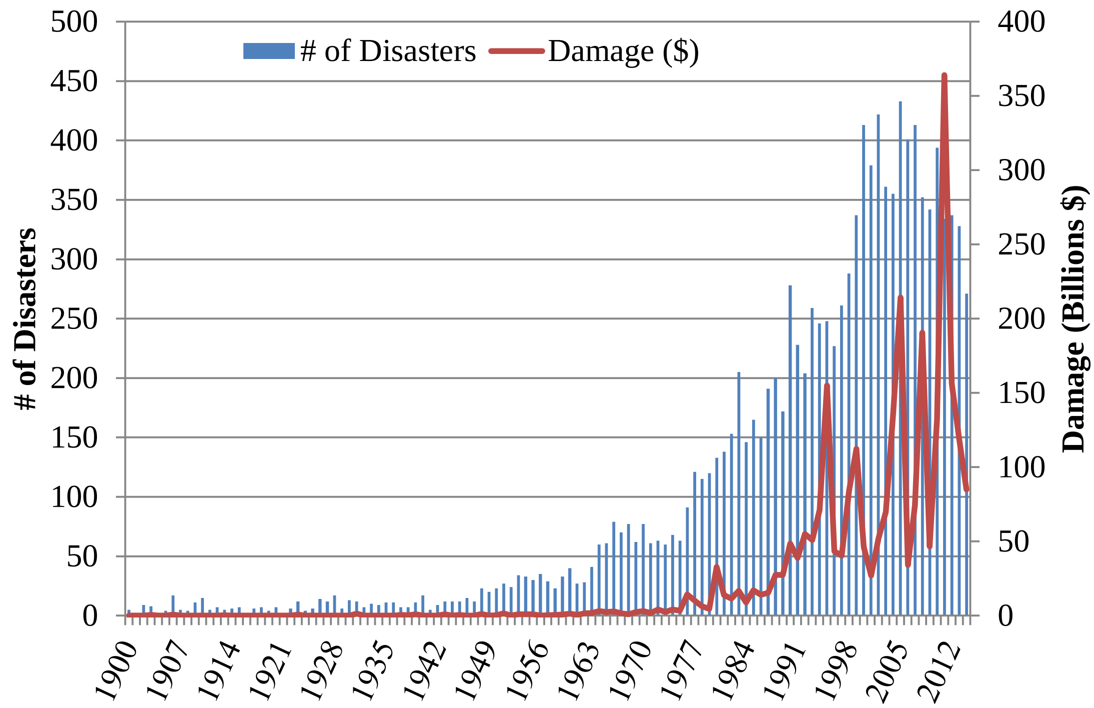


Figure 1. Time series of natural disasters (Data source: EM-DAT)

1.1 Problem Statement

In this era, where technological advances provide us with more data and prediction capabilities of future events, one would believe that a flood event would be manageable and controlled to limit its impact on society. However, flood persists as an increasing problem causing fatalities and billions of dollars in damage.

The impact of a flood event (i.e. damages, deaths, spread of pollutants, etc.) is directly affected by the vulnerability of the receptor. For instance, communities' attributes such as age, income, and literacy, can dictate how much impact a community will be subjected to. Other aspects like uncontrolled land development due to the increasing population, and aging infrastructure can contribute to increase vulnerability of the community. The American Society of Civil Engineers (ASCE) 2013 Report Card for America's Infrastructure graded the United States' infrastructure with a D+ and anticipated an estimated investment of $3.6 trillion for 2020 to improve the aged infrastructure (ASCE, 2013). Vulnerable aging infrastructure (e.g., utilities, telecommunications, transportation, etc.) not able to withstand the consequences of a flood event, can greatly affect the response times and effectiveness of emergency teams, the proper operation of critical facilities, and the quick recovery for citizens to return to their normal way of life.

To deal with the problems associated with laws related to flooding, regulation, public policies as well as decision support systems (DSS) have been implemented**.** The concept of flood management (FM) is commonly used for describing the multiple approaches applied to manage the impacts of floods. FM is considered an integration of multiple mitigation measures with the primary objective of maximizing the efficient use of floodplains, while minimizing the negative impacts of flood. In this research, the focus will be primarily given to the decision-making process of selecting among multiple mitigations alternatives in order to prevent/reduce the impacts from floods.

Deciding which mitigation measures should be put into practice requires the consideration of multiple criteria and multiple stakeholders' preferences and expertise. Some of the criteria tend to conflict with one another creating the decision-making process more complicated and delaying the actual reduction of the risks. For example, the flow regulation of a river can minimize the impacts of floods for a community, but generate a devastating effect on the fish life. There are numerous alternatives available when planning for mitigating the risk of flood; the final decisions will rely on the comparison of multiple criteria and multiple stakeholders' preferences. For these reasons, it is essential to educate decision-makers and supply them the needed tools in order for them to perform efficiently such difficult task of evaluating and selecting from numerous alternatives.

In flood management, there has been an increase use of multi-criteria decision-making (MCDM) models and support systems (Akter & Simonovic, 2005; Escuder-Bueno et al., 2012; Levy, 2005; Raaijmakers, Krywkow, & van der Veen, 2008) where physical and non-physical criteria can be categorized and evaluated. The raise use of MCDM is attributed to the "*dissatisfaction with conventional 'single criterion' methods and the* *emergence of software and algorithms for solving complex environmental problem*" (Levy, 2005).

In this study, a holistic approach is presented for a risk based flood decision-making model, which incorporates three impact categories: economic, social, and environmental. An additional category, which relates to the implementation process of a specific risk mitigation alternative, is also included. In addition, the approach incorporates the use of stakeholders' theory, network analysis, and Analytical Hierarchical Process (AHP) to integrate the opinion and potential decision of stakeholders.

1.2 Background

Much independent research has been conducted assessing the risks and vulnerability to floods as well as studying the impacts of selecting and implementing flood mitigation alternatives (FMA). Most of the research mainly considers the economic impacts of floods, while others have made an attempt to incorporate social and environmental impacts into their methodologies.

Mitigation alternatives are commonly divided into two categories: structural and non-structural. Structural mitigations tend to modify the characteristics of a flood while non-structural measures help reduce the hazard from unavoidable damages (Oliveri & Santoro, 2000).

Structural mitigation alternatives are commonly recognized for actual structural changes or new constructions to reduce flood impact in floodplains. Some structural mitigation alternatives found in the literature and commonly applied in practice are: dams, reservoirs, levees, and channel improvement, among others. Although structural measures have proven to be efficient in reducing or re-routing the effects of floods on communities and individuals, they are subject to failure, costly maintenance and even provide a false sense of security for residents living in the floodplains (Thampapillai & Musgrave, 1985).

Thampapallai and Musgrave (1985) found that there is a general consensus among authors that the structural alternatives alone do not provide optimal floodplain management, which can be achieved with the incorporation of non-structural mitigation measures. Examples of non-structural measures found in the literature are: land use zoning, advance warning systems, building codes and regulations, education of flood hazards, among others (Faisal, Kabir, & Nishat, 1999; Meyer, Priest, & Kuhlicke, 2012; Thampapillai & Musgrave, 1985). An issue with non-structural measures is that they often require inter-agency coordination and active community involvement. Such relations, if not properly managed, can lead to a slow implementation process and even affect the emergency response.

The perspective of the population in danger is an important aspect when performing the risk assessment and selecting flood mitigation alternatives (FMAs). Also, it has been found that for an efficient implementation of the FMAs and effective emergency responses, an optimal communication between stakeholders is necessary. For this reason, we found crucial to conduct a survey to the target population with the purpose to obtain an insight of each stakeholder's perspective on flood risks and current FMAs.

1.3 Research Questions

The main objective of this research is to develop a spatial risk-based framework that will inform flood management officials when selecting from various FMAs. The methodology will be illustrated with a case study of the Upper Río Grande of Loíza Watershed in Puerto Rico. The following are the research questions addressed in this thesis:

- What criteria should be considered when assessing the impacts of flood mitigation alternatives?
- How can the criteria be efficiently estimated in order to assess the impacts of floods and flood mitigation alternatives?
- What is the perspective of the stakeholders and how can it be incorporated into the decision-making model?

1.4 Overview of Methodology

The proposed framework is composed of four main components: (1) a flood model, (2) a risk assessment, (3) survey instruments, and (4) a risk-based decision-making model (DMM). The first component estimates the floods extent and depth for different return periods. The data obtained from the flood model is incorporated into the second component to estimate the impacts of such floods in three different categories: (1) economic, (2) social, and (3) environmental. The survey instruments are integrated in this study in order to identify the perception of the stakeholders towards the flood risks and FMAs. Network analysis and stakeholders' theory is proposed in this study to find the typology of the stakeholders and define which stakeholders' opinion will be included in the risk assessment and DMM. Finally, the information obtained from the risk assessment and the survey instruments are incorporated in the proposed risk-based DMM, which incorporates the evaluation of benefit and cost criteria by combining the Monte Carlo Simulation (MCS) and an Analytical Hierarchical Process (AHP) analysis. The DMM is intended to supply floodplain managers with a tool that provides transparent and defensible results, making the implementation process more effective.

1.5 Organization

The research is comprised of five chapters. Chapter 1 introduces the global issues and the general problems encountered in flood management. Chapter 2 summarizes the literature review on the fields of flooding, flood management, risk assessment, and decision-making. Chapter 3 describes in detail the proposed framework including tools and methods to be used. Chapter 3 also illustrates the proposed framework with a case study of the Upper Río Grande de Loíza Watershed in Puerto Rico. In Chapter 4, the results are summarized and discussed in order to assess the functionality of the proposed methodology. Chapter 5 summarizes the study and discusses the contributions of the research as well as it limitations and proposed future research.

CHAPTER 2: LITERATURE REVIEW

Natural disasters have increased over the past decades leaving behind big economic losses for the affected communities and negative social and environmental impacts. To mitigate the impacts and increase communities' resilience, it is important for stakeholders to understand the risk associated to natural disasters and identify what factors make the community more vulnerable to such hazards. In this chapter, a review of the existing research on flood management alternatives will be presented. In Section 2.1 an overview of floods and flood modeling is presented. After understanding the general concepts associated with floods, their vulnerability is presented in Section 2.2. Section 2.3 introduces the concept of risks and its applicability to this study. Section 2.4 is a review of different methodologies for conducting a risk assessments found in the literature. Since the purpose of this study is to select from multiple FMAs capable of reducing the risk and vulnerability of a community, Section 2.5 reviews the various mitigation alternatives found in the literature and their applicability to reduce the risk of flooding. Finally, Section 2.6 reviews the concept of decision-making in flood management and the different methodologies applied in the literature.

2.1 Flooding

A general definition of flood is provided by the Federal Emergency Management Agency (FEMA) as "*the partial or complete inundation of normally dry land*" (FEMA, 2014). According to FEMA, there are four major types of flood:

1) **Flash flooding**- The rapid flooding of low-lying areas which is usually caused by intense rainfall and can flood an area in less than six hours. Flash floods usually carry debris such as rock and tree branches, causing more impact on its path.
2) **Coastal flooding-** Occurs when intense offshore storm systems push ocean water inland above the normal tide level. The rise in water is the storm surge, which can occur in just a few minutes. Hurricanes, tsunamis, and unusually high tides can cause coastal flooding.
3) **River and stream flooding**- May be triggered by heavy rains, melting snows, and storm surge.
4) **Closed-basin flooding-** Occurs when a lake has no outlet or a relatively small outlet. Seasonal rainfall and storm systems can cause the lake level to rise faster than it can be empty. Floodwaters in closed-basin lakes accumulate over long periods of time and may stay for weeks, months, or years.

Depending on the type of flood expected, emergency management agencies can take different plan of actions to reduce the damages. It is also important for a community to be aware of the different flood hazard that they are subjected to. In this study, we will focus mainly on river and stream flooding.

In order to study the impacts of floods within communities and the ecosystem, government agencies and private institutions have developed a wide variety of flood modeling software. Table 1 presents a summary of the flooding software researched for this study.

Table 1: *Flood Modeling Software*

Software	Description
TUFLOW	One–dimensional (1D) network and two-dimensional (2D) grid-based software for simulating flood and tidal flow.
FLO-2D	Integrated river and floodplain 2-D flood routing model.
ISIS	1D and 2D simulation engine, analysis and visualization tools and innovative flood inundation.
MIKE FLOOD	Includes a wide selection of 1D and 2D flood simulation engines that enables the user to model virtually any flood problem whether it involves rivers, floodplains, floods in streets, drainage networks, coastal areas, dam, and levee breaches or any combination of the above.
HAZUS 2.1	Nationally applicable standardized methodology that contains models for estimating potential losses from earthquakes, floods, and hurricanes.
HEC-RAS	Designed to perform one-dimensional hydraulic calculations for a full network of natural and constructed channels.

2.2 Flood Vulnerability

The effect of a flood event will depend on the vulnerability of the system. A resilient community will be able to absorb the impacts with minimal damage to its components (critical facilities/social hot-spots and infrastructures, buildings, people, etc.). Usually the concepts of hazard risk and vulnerability tend to create confusion. For this reason, it is important to understand the concept of vulnerability and how it is associated to flood management.

Researchers have agreed that the concept of vulnerability has a wide variety of definitions for different scientific communities (Few, 2003; Scheuer, Haase, & Meyer, 2011). Table 2 presents a summary of definitions found in the literature for vulnerability.

Table 2: *Definition of Vulnerability in the Literature*

Source	Definition
FEMA	"*Measure of the capacity to weather, resist, or recover from the impacts of a hazard in the long term as well as the short term*".
Haimes (2006)	*"The manifestation of the inherent states of the system (e.g., physical, technical, organizational, cultural) that can be exploited to adversely affect (cause harm or damage to) that system."*
Adger (1999)	*The exposure of groups or individuals to stress as a result of social and environmental change, where stress refers to unexpected changes and disruption to livelihoods.*
Blaikie et al. (1994)	*"Characteristics of a person or group in terms of their capacity to anticipate, cope with, resist, and recover from the impact of natural hazards"*
Indeed, Adger (2000)	*"The presence or lack of ability to withstand shocks and stresses to livelihood"*
Messner, F., & Meyer, V. (2006)	*"Defined by the characteristics of a system that describes its potential to be harmed. It can be expressed in terms of functional relationships between expected damages regarding all elements at risk and the susceptibility and exposure characteristics of the affected system, referring to the whole range of possible flood hazards.''*
Alexander (1993)	*"Human vulnerability is a function of the costs and benefits of inhabiting areas at risk form natural disaster."*
Pelling (2003)	*"Denotes exposure to risk and the ability to avoid or absorb potential harm.*
UNDRO (1982)	*"The degree of loss to a given element or set of elements at risk resulting from occurrence of a natural phenomenon of a given magnitude."*
Sayers et al. (200)	*Refers to the "resilience of a particular group, people, property, and the environment, and their ability to respond to hazardous conditions."*

From the definitions found in the literature and listed in Table 2**,** vulnerability can be defined as the ability of a system or a person to cope with hazards. Hence, to obtain a quantifiable value of vulnerability we must consider the probability of exposure to the hazard and the capacity of the system or person to sustain such risk. Balica, S. F., Douben, N., and Wright, N. G. (2009) quantifies vulnerability as an expression of susceptibility, exposure to hazard and resilience (see Equation 1).

(1) $$\boldsymbol{Vulnerability = Exposure + Susceptibility - Resilience}$$

In this equation, *exposure* refers to the susceptibility of a community to be impacted by a flood event due to its location; *susceptibility* refers to components of the community exposed to the hazard that can impact the probability of the community being affected; and *resilience* is the capacity of the community to withstand the impacts of a flood event (Balica, et al., 2009).

Being able to quantify the vulnerability of a person, community, or region to a flood hazard can help a decision-maker identify which areas or people are more susceptible to be affected by the event. For this reason, it is important to understand what are the factors affecting and defining vulnerability.

2.3 Flood Risk

The concept of risk has been widely studied by researchers and it has been established that having a specific definition for risk is not possible and therefore each author should explain the term in the context of the research (Kaplan, 1997). Over the years, various definitions have been provided in the literature. Table 3 presents a summary of the definitions supplied by different author throughout the years.

Table 3: *Definition of Risk in the Literature*

Source	Definition
Federal Emergency Management Agency (FEMA)	*"Exposure to an undesired event. It can be expressed in probability that the event will happen, often during a calendar year."*
Rosa, E. A. (2003)	*"A situation or an event where something of human value (including humans themselves) is at stake and where the outcome is uncertain."*
Reid S.G. (1992)	*"Risk refers to the dangers associated with processes with uncertain outcomes."*
Lowrance (1976)	*"A measure of the probability and severity of adverse effects."*
Kaplan (1997)	*"Triplet of conditions: scenario (what can go wrong?), likelihood (how likely it is to happen?), and consequence (what happens?)."*
Lamond, J. (2012)	*"The function of a flood hazard on an exposed receptor that has a certain vulnerability to the hazard."*

As shown in Table 3, all of the definitions found in the literature incorporate the uncertainty of the hazard occurring and the outcome/consequences if the hazard were to occur. The Merriam-Webster dictionary defines hazard as a *"source of danger; chance, risk; a chance event"*, noting that the occurrence of a hazard is directly related to chance which is uncertain (Merriam-Webster, 2014). Kates et. al. (1985) defined hazard as a "*threat to humans and what they value (life, well-being, material goods, and environment)*". More specifically, for this study, the hazard will be defined as the probability of flood occurring. The consequences to be considered are the economical (i.e. buildings and infrastructure damages, loss of businesses, etc.), societal (i.e. loss of life, mental health, quality of life, etc.), and environmental (i.e. loss of habitats, contamination, etc.) impacts if the hazard were to occur.

For this research, risk will be quantified considering two factors: (1) the likelihood that a flood hazard occurs and (2) the consequences related to the flood. For example, a levee is often designed to protect developed areas from flooding, but there is a chance that the levee will fail and there will be consequences associated to that failure. Typically, the simplified equation for obtaining a quantitative value of risk is:

$$Risk = p \times C \qquad (2)$$

In this equation, p is the probability of a hazard or specific event occurring and C is the magnitude of the potential losses (i.e. casualties, economic losses, habitats affected).

2.4 Risk Assessments

In order to understand the associated risks to a flood hazard, a risk assessment is performed. Risk assessment is not a new concept and has been widely applied to different study areas such as insurance (Friedman, 1984), banking (Elsinger, Lehar, & Summer, 2006), medicine (Naghavi et al., 2003; Tuman, McCarthy, March, Najafi, & Ivankovich, 1992), and engineering (Faber & Stewart, 2003; Stewart & Melchers, 1997). Penning-Roswell et al. (2005) define a risk assessment as a *"method of evaluating the likelihood and severity of the adverse events, including identifying associated uncertainties"* (Penning-Rowsell, Floyd, Ramsbottom, & Surendran, 2005).

In reference to natural disasters, FEMA defines a risk assessment as "*a process to identify potential hazards and analyze what could happen if a hazard occurs*". Risk assessments are frequently incorporated in the planning phases for decision-making and resources management. Within a risk assessment the decision-maker is able to identify areas in danger and anticipate possible failure of infrastructure, such as bridges, roads, and drainages and make better decisions for resource allocation applications in infrastructure management. A risk assessment of a levee can evaluate the performance of the affected structures during different possible levee failure scenarios and provide decision-makers with the important information.

A flood risk assessment is based on a numerous sources of data, which create uncertainty in the results. In the literature various sources of uncertainty, such as meteorological data, variability in precipitation, and flood potential, have been identified (Morss, Wilhelmi, Downton, & Gruntfest, 2005).

Over the years, several studies have been published researching the impacts of natural disaster events in communities and critical infrastructures. Haimes et al. (2002) developed a framework to perform a risk assessment for infrastructure protection and aid decision-makers from a Department of Transportation in identifying, prioritizing, assessing, and managing, the risks of a large scale transportation network. The framework included five major considerations: "*(1) a holistic approach to risk identification, (2) prioritization of a large number of risk scenarios, (3) integration of expert judgment, (4) extreme and catastrophic event analysis, and (5) use of multi-objective framework to evaluate management options"* (Haimes, et al., 2002). Apel et al. (2004) developed a stochastic flood risk model that allows decision-makers to calculate the magnitude of possible events and their expected economic damage using a two-layer Monte Carlo Simulation. The model considers two types of uncertainty: aleatory and epistemic. The aleatory uncertainty refers to the variability of natural and human impacts, and the epistemic uncertainty makes up for the incomplete information of the system.

In contrast with the previous studies, Jonkman et al. (2008) presented their study of the risks to flooding of the dike ring area in South Holland in the Netherlands by estimating the loss of life instead of focusing on the economic losses. The researchers performed a risk assessment where it was possible to obtain the individual and societal risk by estimating the loss of life under different flood scenarios. For the estimation of the societal risk, the authors took into account different evacuation scenarios. With the results, the authors were able to ascertain that the risks in their case study exceeded those of the established thresholds providing decision-makers with the necessary information to take action on reducing such risks within a margin of error (Jonkman, et al. 2008).

Zou et al. (2013) developed the Set Pair Analysis-Variable Fuzzy Sets model (SPAVFS), to "*determine the relative membership degree function by using the set pair analysis method*" (Zou et. al., 2013). In their study, they incorporated a fuzzy AHP to obtain the weights for flood hazard and flood vulnerability. Although authors find the SPAVFS easy to be applied and useful for other types of hazards, they find that the uncertainties when using the fuzzy theory are still a limitation requiring further study.

A recent study by Johnson, Fischbach, and Ortiz (2013) presented the Coastal Louisiana Risk Assessment (CLARA) model. The model is able to "*facilitate comparisons of current and future flood risk under a variety of protection system configurations in a wide range of environmental, operational, and economic uncertainties*"(Johnson, et al., 2013). The authors took into consideration the economic damages to the structures and the costs to repair them as the metric to calculate the consequences a flood.

2.5 Flood Mitigation Alternatives

Reducing the risk of floods in communities requires the implementation of mitigation alternatives. Agencies and individuals can greatly benefit from such alternatives, which could be divided in two categories: structural and non-structural. Structural mitigations tend to modify the characteristics of a flood while non-structural alternatives help reduce the hazard from unavoidable damages (Oliveri & Santoro, 2000).

Structural mitigation alternatives are commonly recognized for actual structural changes or new constructions to reduce flood impact in floodplains. Some structural mitigation examples found in the literature and commonly applied are dams, reservoirs, levees, and channel improvement, among others. Although structural alternatives have proven to be efficient in reducing or re-routing the effects of flood on communities and individuals, they are subject to failure, costly maintenance and even provide a false sense of security for residents in living in the floodplains (Thampapillai & Musgrave, 1985). In addition to the "problems" identified above, structural alternatives are also associated with other issues such as the cost of constructions and environmental impacts given the change in course of the rivers.

In 1999, a case study of non-structural FMAs was conducted by Faisal, Kabir, & Nishat, (1999). In their study, the authors identified non-structural alternatives for the city of Dhaka, the capital city of Bangladesh. The city had experienced a disastrous flood in 1988, to which the government’s response was the Dhaka Integrated Flood Protection Project, which focused on structural alternatives. Ten years later the city experienced another catastrophic flood from which 20% of the protected area was inundated. Although the impact was reduced 60%, citizen’s life was greatly affected. The non-structural alternatives identified in the case study were flood forecasting and warning, preservation of retention ponds, land use planning, flood zoning, emergency services, shelters, flood proofing, flood fighting, and post-flood rehabilitations as non-structural alternatives of their case study. An issue with non-structural alternatives is that they often require inter-agency coordination and active community involvement. Such relations, if not properly managed can lead to a slow implementation process and even affect the emergency response process (Faisal et. al., 1999).

Table 4 shows a summary of the mitigations alternatives found in the literature and government agency flood management manuals. The alternatives are identified in the table by the type and purpose. This study proposes the development of a new decision-making model to obtain the best combination of these alternatives given risks and budget thresholds.

Table 4 : *Flood Mitigation Alternatives (FMAs) from the Literature*

Type	Purpose	Mitigation Measure
Structural	Reduce physical hazard	Dam
		Diversion Channels
		Reservoirs
		Retention Basins
		River channelization
		Embankments
		Levee
	Reduce exposure of hazard	Flood Proofing
		Elevation of structure
		Relocation of structures
Non-structural	Reduce exposure of hazard	Land-use planning
	Reduce vulnerability to hazard	Education
		Emergency response preparedness
		Flood warning system
		Flood Insurance
	Reduce physical hazard	Catchment management
		Land-use management
		Urban development control

Performing a flood risk assessment can assist in the decision-making phase by providing information to the decision maker in order to compare flood mitigation alternatives. (Escuder-Bueno et al., 2012).

2.6 Impacts of Floods and Flood Mitigation Alternatives

Risk assessments which incorporate the economic, environmental, and societal impacts, are rare. This study proposes the incorporation of the three impact categories in order to obtain a complete assessment. The following sub-sections will go more into detail on how the aforementioned impacts considered in the risk assessment have been integrated in various researches.

2.6.1 Economic Impacts

The economic impacts of floods and FMAs are the most commonly applied in flood risk assessments (FRA) and FMAs impact assessment. Table 5 presents a summary of the economic criteria commonly considered in the literature.

Table 5: *Economic Criteria Commonly Considered in Flood Mitigation Alternatives (FMAs)*

Source	Economic
Tkach and Simonovic (1997)	- Building Damage
Bana e Costa et al. (2004)	- Cost benefit
Brouwer and Van Ek (2004)	- Costs (land use change, agricultural compensation), - Payments, infrastructure protection, operation, and maintenance) - Benefits (damages avoided, recreational benefits)
de Bruijn (2004)	- Annualized Average Damage - Costs - Economic opportunities
Ash (2005)	- Assets - Land use - Transport - Business development
Levy (2005)	- Flood relief costs - Resettlement costs - Structural prevention costs - Flooding costs
Simonovic & Nirupama (2005)	- Flood damage
Levy et al. (2007)	- Emergency response costs - Damaged property
Meyer et al. (2009)	- Damages on assets (buildings, inventories, etc.)
Scheuer et al. (2011)	- Land value - Transport - Housing - Commerce - Administration - Recreation
Peng et al. 2013) (2013)	- Flood Damage - Evacuation costs
Qi et al. (2013)	- Property damage

2.6.2 Environmental Impacts

Environmental effects of pollutants, chemicals, soil erosion are considerably well researched individually, but studies of short and long-term environmental impacts of floods are rarely considered within risks and vulnerability assessments (Stuyt, L. , Reinders, J., Van der Hoek, E., Hernans, A., de Munick Keizer, M., Kampereveen, J., . . . Icke, J., 2003). In order to perform a complete environmental risk assessment, it is necessary to create an inventory of common pollutants that can be released by buildings, cars, soils, and other sources. The effects on the health of the ecosystem and the community can be critical and need to be anticipated. The release of such pollutants will also require an economic investment for clean-up costs, public health impacts mitigation, and other long-term environmental effects of floods.

Stuyt, L. et. al (2003) introduced a conceptual framework for simulating and quantifying the environmental effects of pollutants transported by a dike breach flooding. The framework assesses flood impacts in the ecosystem; for example, agricultural damage is evaluated by studying the deposit of toxic sediments in the field and its effect on crops and irrigation facilities. The public health can also be affected due to the growth of disease caused by micro-organisms and the spread of pollutants in the water systems. As a result from the case study, the authors found that flooding can cause significant environmental impacts.

Brower and Van Ek (2004) studied the possible environmental impacts of land use changes and floodplain restoration within an integrated (i.e. environmental, economic, and social impacts) assessment of FMAs. To study the environmental impacts of the mitigation alternatives, an environmental impact assessment (EIA) was performed, which included two main impacts: hydrological and ecological. For the hydrological assessment, the authors used the input of experts in order to define the impacts of the alternative in possible "*(1) changes to groundwater level, (2) annual average seepage flux, and (3) water levels of small water systems such as ditches*" (Brouwer & Van Ek, 2004). The ecological assessment was conducted with software capable of predicting changes in the vegetation. The results of the ecological assessment are given as a percentage of the positive/negative effects of a desired situation based on the conservation policies of the area.

Bana e Costa et. al. (2004) considered environmental impacts of risk mitigation alternatives. The criteria were divided in four categories: (1) water, (2) soil, (3) flora and fauna, and (4) landscape. The sub-criteria considered for water included the quality of surface and ground water as well as obstruction due to sedimentation and aquifers level. For soil, the affected agricultural soil and the possible contamination were included. The interest in conserving nature was the criteria for fauna and flora; for landscape the effects of urban integration and enhancement of landscape were considered. Experts scored the criteria with qualitative values. Table 6 summarizes the different criteria studied in the literature.

Table 6: *Environmental Impacts of Floods*

Flood event/Country	Environmental Impacts	Source
1993 Meuse and Rhine River Flood in Southern Netherland	• Suspended matter in rivers (organic contaminants and trace metals) • Eco-toxicological consequences-effect of toxic chemicals on biological organisms	Van Der Heijdt and Zwolsman (1997)
2002 Moldau/Elbe Floods in Prauge, Czech Republic	• Release of heavy metals and chlorine from chemical plant • Debris from building material and contents	Stuyt, L. et. al (2003)
River Elbe Flood, Germany	• Water quality • Spill of diesel and other type of oils	
World	• Debris • Spread of polluted sediments • Spread of diseases	
Red River Flood North Dakota, USA	• Loss of municipal water treatment plant • Oil spill • Mold, mainly in basements	
2002 Dam Failure Flood in Romania	• Release of cyanide-contaminated liquid • Aquatic life affected • Drinking water contaminated	
Case Study	• Immediate and long-term effects of dangerous chemicals released • Suspended sediments • Soil erosion	

2.6.3 Social Impacts

Social impacts of flood are usually overlooked during a risk assessment mainly because of the difficulty in quantifying them in a way that can be used to be compared with other risk criteria. Studies that have incorporated social impacts of floods or FMAs are shown in Table 7. Loss of life and injuries that can occur during a flood event are one of the main criteria when conducting a flood risk analysis other than direct economic criteria. Research on estimating such casualties and injuries are scarce and are commonly developed for specific regions and type of flood events such as dam breaks, levee failure, storm surges, and coastal flooding.

Table 7: *Literature Incorporating Social Impacts of Floods*

Source	Considered Criteria/Impacts	FRA/FMA
Costa et. al. , 2004	· Perception of flood risk · Effects on social fabric · Effects on public health	FMA
Brouwer & Van Ek, 2004	· Impact on functions perception of landscape change risk perception communication efforts · Participation possibilities	FMA
De bruijn, 2004	· Affected population · Casualties	FRA
Ash, 2005	· Recreation · Health and safety · Availability of services · Equity · Sense of community	FMA
Levy, 2005	· Equity (property loss) · Evacuation upheaval · Fairness · Sustainability	FRA
Akter & Simonovic, 2005	· Community involvement · Amount of personal loss	FMA
Levy et. al., 2007	· Anxiety and physical discomfort	
Meyer et. al., 2009	· People affected at their home · Social hot-spots like hospitals, schools, old people's homes, etc.	FRA
Scheuer, et al., 2011	· Population · Children · Pensioners · Social hot-spots	FRA
Mauro, Bruijn, & Meloni, 2012	· Loss of life	FRA
Peng et. al., 2013	· Loss of Life	FRA
Qi et. al. 2013	· Loss of life	FMA

Globally, many studies have been published attempting to develop quantitative methods for estimating the fatalities due to floods. Di Mauro et al. (2012) evaluates the reliability of three different methods for assessing losses of life: (1) Mortality function method commonly applied in the Netherlands, (2) Flood Risk to People (FRP) method developed by HR Wallingford and Middlesex University Floods Hazard Research Centre for the United Kingdom Department of Environment, Food and Rural Affairs (DEFRA), and (3) the Life Safety Model developed by BC Hydro in Canada. The results showed that the FRP method estimated the number of fatalities better than the other two methods when applied to a flood event in the United Kingdom.

Brouwer & Van Ek (2004) studied the social impacts of proposed FMAs mainly based on the judgment of the most important stakeholders. They were required to evaluate the effects of flooding on five social criteria identified by the authors as the most important: inhabitants, agriculture, nature conservation organizations, water supply companies, and recreation. The experts rated the criteria with qualitative scores (i.e. “+” for a positive impact,”0” for neutral and “–” for negative impact). The authors acknowledged that it is hard to express the social impacts in quantitative terms and the results will vary due to experts’ opinions.

2.7 Decision-Making for Flood Management (DMFM)

The process of selecting the best alternatives for mitigating flood risk can be a challenging process which requires the comparison of qualitative and quantitative criteria (Tkach & Simonovic, 1997) and involves a degree of uncertainty when making decisions. Some of the challenges in DMFM mentioned in previous literature include: the uncertainties in the flood models, difficulties in quantifying the risk impacts, rapidly growing society, economic constraints, the amount of stakeholders involved in the process and their different priorities, and most recently, the uncertainties associated with climate change (Jonkman & Dawson, 2012; Morss, et al., 2005; Pereira, Pulhin, & Shaw, 2010). In order to assist with such challenges, various decision-making models (DMMs) have been researched. This section will summarize the researched literature on DMFM.

Selecting from various flood mitigation alternatives requires an assessment and comparison of all them. Most of the time, the criteria used for the decision-making process are based on the economic impacts of the alternatives (i.e. cost of implementation, cost of damages avoided by the measure, employment creation, cost of maintenance, etc.). However, when selecting from various flood mitigation alternatives other impacts such as environmental and social of the proposed alternatives should be integrated. For these reasons, flood management has been increasingly treated as a multi-criteria decision-making (MCDM) process (Akter & Simonovic, 2005; Escuder-Bueno, et al., 2012; Jason K Levy, 2005; Raaijmakers, Krywkow, & van der Veen, 2008), where physical and non-physical factors can be categorized and evaluated. The increase use of MCDM is attributed to the *"dissatisfaction with conventional 'single criterion' methods and the emergence of software and algorithms for solving complex environmental problem*" (Levy, 2005). The non-physical factors tend to be more complicated to evaluate. Lekuthai and Vongvisessomjai (2001) noted that existent need for research to quantify intangible flood damages (i.e. anxiety, hardship, etc.). In 2012, Escuder-Bueno et. al. (2012) proposed integration of social criteria into flood risk analysis in order to assist decision-makers in the evaluation of non-structural protection alternatives. Although some research have proposed a decision-making approach incorporating multiple criteria (Tkach & Simonovic 1997; Bana E Costa et al. 2004; Brouwer & van Ek 2004; Akter & Simonovic 2005; Thinh & Vogel 2006; Meyer & Scheuer 2009, Scheuer, et al., 2011), the incorporation of an integrated assessment for flood risk assessments is relatively rare (Scheuer, et al., 2011). In Table 8, summary of the literature found for flood DMM is presented. The table identifies which type of criteria is considered and what type of analysis theory is applied.

Table 8: *Flood decision-making models**

Source	E	S	EN	DMM
Tkach & Simonovic (1997)	X			• Spatial Compromise Programming (SCP): weighting criteria and distance to best solution
Bana e Costa, et al.(2004)	X	X	X	• Hierarchical additive value-model using VISA and MACBETH (qualitative) software • Simple Multi-Attribute Rating Technique
Brouwer & Van Ek (2004)	X	X	X	• Qualitative scoring for social impact • CBA for economic impact • Weighting of ranking criteria for the MCA
de Bruijn (2004)	X	X	X	• NONE
Ash (2005)	X	X	X	• Scoring and weight • Eliciting weight
Levy (2005)	X	X	X	• Analytic network process • AHP
Akter & Simonovic (2005)		X		• Fuzzy expected value • Multi-objective, multi-participant decision matrix
Simonovic & Nirupama (2005)	X			• Spatial Fuzzy Compromise programming (criteria ranked according to their respective distance metric values
Levy (2007)	X	X	X	• Analytic Network Process
Meyer (2009)	X	X	X	• Disjunctive • MAUT (additive weighting), • FLOOD Calc
Scheuer (2011)	X	X	X	• Weighting criteria
Mauro (2012)		X		• Mortality Function • Flood Risk to People Method • Life Safety Model
Peng (2013)	X	X		• Bayesian Network, Monte Carlo Simulation and Time series
Qi et. al. (2013)	X	X		• Monte Carlo Simulation

* E= Economic, S= Social and EN =Environmental

2.8 Chapter Summary and Point of Departure

This chapter described the current published literature on the various topics used for the decision-making process in flood management. Previous studies have looked at flood risk assessments that incorporate economic, environmental, and social criteria. Important criteria to evaluate the impacts of flood were identified in the literature. Also, an overview of the current methodologies in DM for flood management found that there is increasing use of MCDM frameworks incorporating multiple criteria in the process. However, studies that include all three-impact categories are limited in the literature. It was also found that the incorporation of stakeholders' opinion due to their power and influence is not commonly found in the literature. The particular interest in this research is to propose a holistic approach to the decision-making process when implementing flood mitigation alternatives. A particular contribution is the incorporation of stakeholders' opinion with the use of the network analysis.

CHAPTER 3: METHODOLOGY

The proposed framework for this research (shown in Figure 2) is comprised of four main components: (1) a flood model, (2) a risk assessment, (3) survey instruments, and (4) a risk-based decision making model (DMM). The first component requires the estimation of floodplains and flood depth for a defined return period and a specific flood mitigation alternative. The data obtained from the flood model is used in the second component to estimate the impacts of such floods in three different categories: (1) economic, (2) social, and (3) environmental. The survey instruments are integrated in this study to identify the perception of the stakeholders towards the flood risks and flood mitigation alternatives (FMA). Network analysis and stakeholders' theory is proposed in this study in order to identify the typology of the stakeholders and define which stakeholders' opinion will be included in the risk assessment and DMM. Finally, the information obtained from the risk assessment and the survey instruments is incorporated in the proposed risk-based DMM. The proposed DMM combines the evaluation of benefit and cost criteria by using the Monte Carlo Simulation (MCS) and an Analytical Hierarchical Process (AHP) analysis.

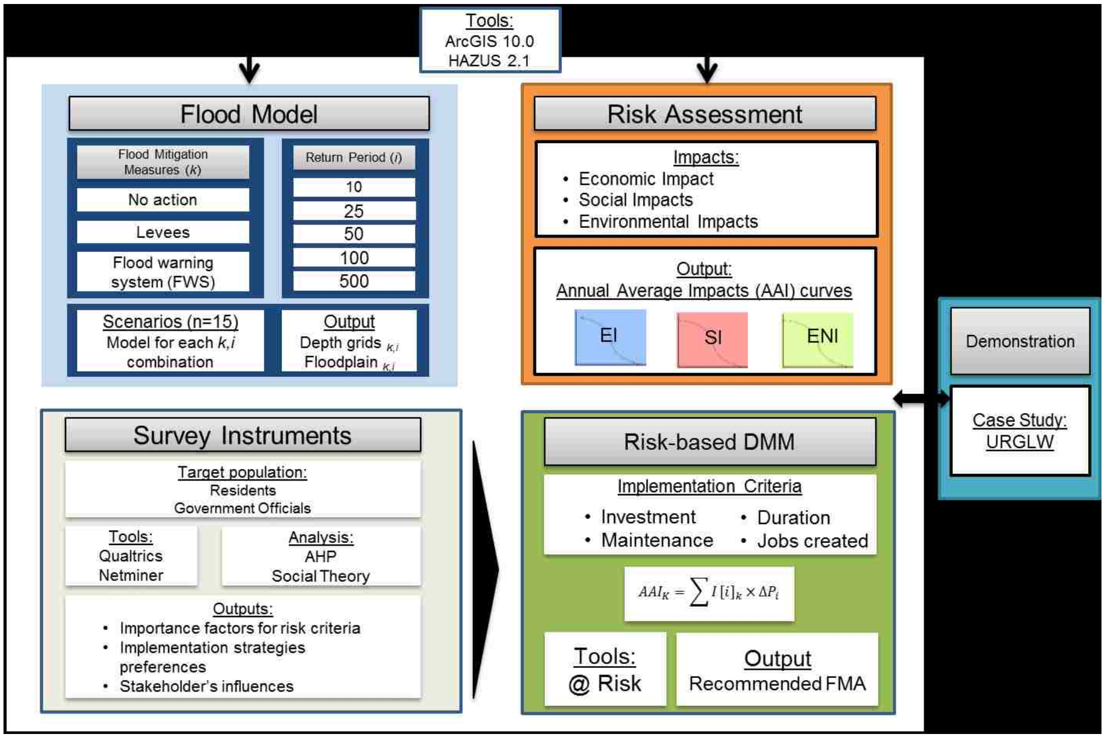


Figure 2. Research framework

This chapter describes the flood model in Section 3.1. In Section 3.2, the risk assessment methodology implemented in the study is presented and a description of the criteria for each impact category is defined. Section 3.3 explains the methodology used to collect and conduct the analysis from the stakeholders' opinion. With the collected data, in Section 3.4 two decision-making models are proposed for the selection of a flood mitigation alternative. Finally, a description of the case study is presented in Section 3.5 to illustrate the risk-based decision-making model proposed in this research.

3.1 Flood Model

A flood model is required to assess the impacts of potential events. The flood model was obtained using the HAZUS 2.1 software by the Federal Emergency Management Agency, which was selected from those discussed in Chapter 2 based on data availability and the expected outputs. HAZUS is multi-hazard loss estimation software that is able to estimate the losses from earthquakes, hurricanes, and floods events (FEMA, 2015). The software does not require the user to have technical background and it is easily implementable because of the training provided online by the developers. As an add-on to ArcGIS, HAZUS is able to spatially delineate the floodplains and calculate the flood depth given a specific return period or discharge rate. In addition, the software calculates the impacts (i.e., economic losses, percent of damage to buildings, affected population, and debris generation, etc.) of the floods by spatially representing the impacts and generating a written report with detailed data of the analysis.

The accuracy of the analysis will depend on the level of the study performed and the data supplied to the model. In HAZUS, the software developers have defined three levels of analysis (Figure 3). The most basic but less accurate analysis is known as a Level 1. A Level 1 analysis only requires the input of terrain data and estimates the flood losses with the built-in data inventory. The analysis is recommended as an initial assessment in order to determine which areas require more detailed analysis. A Level 2 and 3 analyses require more technical knowledge from the user and the compilation of site-specific data. For this study, a Level 1 analysis is performed.

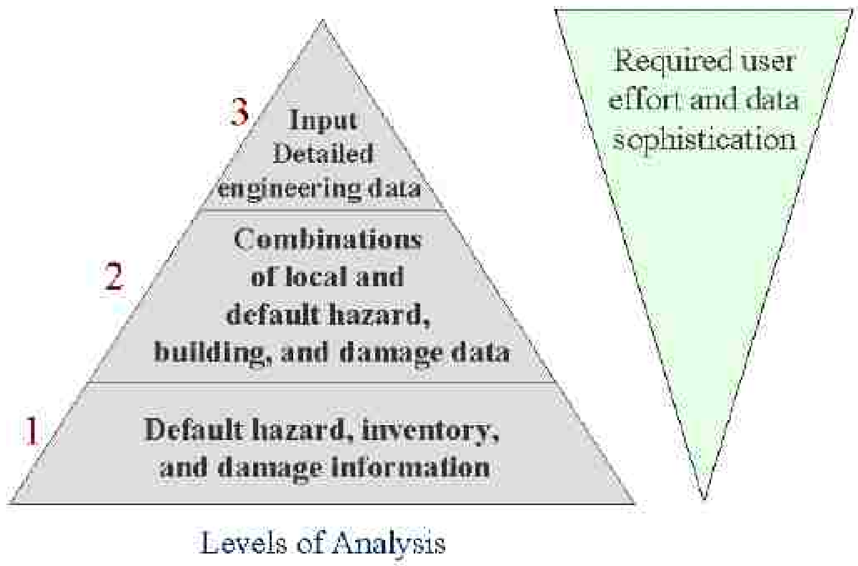


Figure 3. Levels of analysis and user sophistication (HAZUS, 2009)

HAZUS software performs a hydraulic and hydrology (H-H) analysis given the information from the terrain provided by the user and additional built-in data such as USGS gages data, soil type, land use, etc. For more information on the H-H analysis within HAZUS the Flood Model Technical Manual is available online in FEMA.gov (FEMA, 2015).

The terrain data can be provided in different formats: Digital Elevation Model (DEM), HEC-RAS model, a depth grid created by the user or a depth grid created with the flood information tool provided within the software. For a Level 1 analysis only the DEM is necessary.

Once the floodplain is delineated, HAZUS computes the flood height for each cell within the floodplain. The height of the flood is obtained by subtracting the resulting flood elevation from the ground elevation as shown in Figure 4.

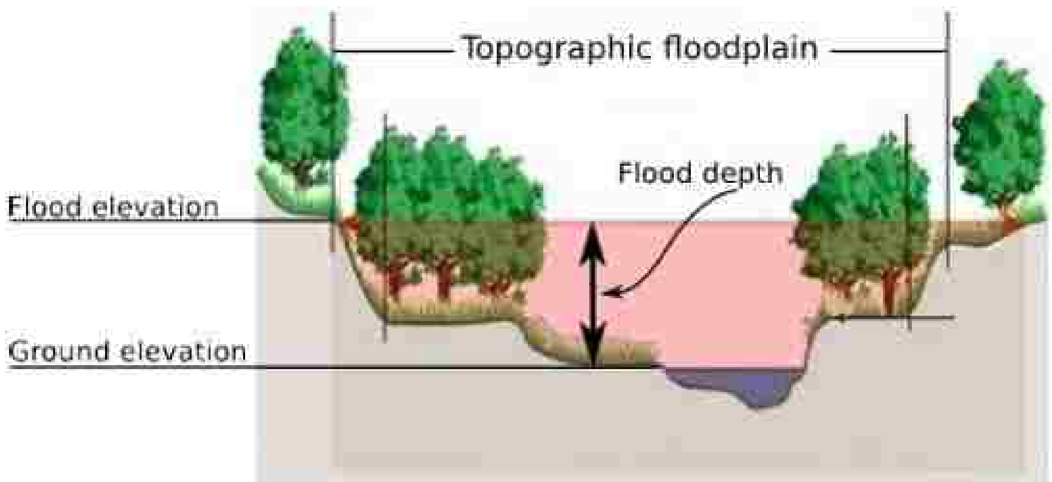


Figure 4. Flood elevation (FEMA, 2015)

The resulting depth grid is in raster formats where each cell within the raster has a flood depth value. The cell size of the depth grid is the same as the cell size provided by the DEM. The floodplain is used as a polygon shapefile that delineates the extent of the flood. Figure 5 presents an example of the resulting floodplain delineation and the depth grid obtained from HAZUS.

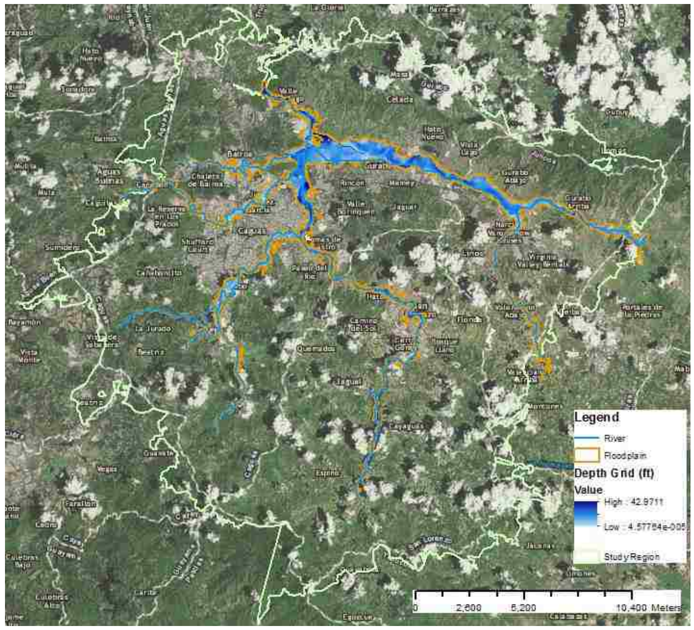


Figure 5. Resulting floodplain delineation and the depth grid

In a Level 1 analysis, HAZUS estimates the flood losses in an aggregate manner using census block information. HAZUS provides a data management platform that allows the user to include site-specific data. Also, demographic information is incorporated in order to assess vulnerable groups and population at risks. Most of this data is already included in the inventory data furnished by HAZUS.

3.2 Risk Assessment

To evaluate the efficiency of a mitigation measure in reducing the risk of floods, a risk assessment is performed for each flood mitigation alternative considered. In this study, the total risk is obtained by calculating the expected annual average impact (AAI). AAI is acquired by computing the damages for each flood event and with the data collected, a probability-damage curve can be generated (see Figure 6). The area below the curve is considered the total flood risk, or in this study, the total AAI (Meyer, et al., 2009;

Scheuer, et al., 2011). It is important to clarify that this is a general approach that assumes that the total annual risk is objective and can be quantified, which in real life this is not often the case due to the many uncertainties in the data, time variations, and peoples actions (Meyer, et al., 2009).

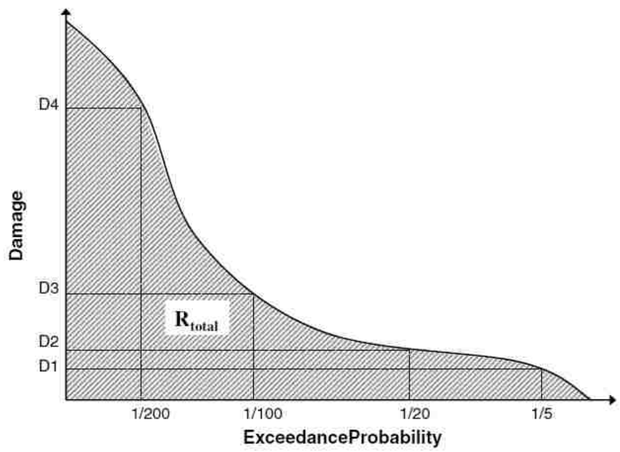


Figure 6. Probability-damage curve (Meyer, et al., 2009)

In order to calculate the risk, the area under the curve is estimated using the following equations *(DVWK 1985; eq. 3, 4 and 5)*:

(3) $$AAI_k = \sum I[i]_k \times \Delta P_i$$

(4) $$I[i]_k = \frac{I_{i-1} + I_i}{2}$$

(5) $$\Delta I_i = |P_i - P_{i-1}|$$

In this equations, AAI is the annual average impact, *the* mean impact between two points, I is the impact, ΔPi is the mean probability between those two points, *i* is the recurrence interval and *k* is the mitigation measure alternative.

Five recurrence intervals *i* were selected: 10 years, 25 years, 50 years, 100 years, and 500 years for the risk assessment. The probability of a flood event occurring for recurrence interval is shown in Table 9**,** for example, the probability of a 100 year event occurring is once every 100 years or 0.01 (1%).

Table 9: *Probability of the Flood Event Occurring*

Recurrence interval (*i*)	Probability (P_i)
500 years	0.002
100 years	0.01
50 years	0.02
25 years	0.04
10 years	0.10

The total impact for each flood event is then obtained with a weighted sum of the impacts' categories:

(6) $$I_{i,k} = \sum_{j=1}^{n} w_j I_{i,j,k} = w_{EI} EI_{i,k} + w_{SI} SI_{i,k} + w_{ENI} ENI_{i,k}$$

In this equation, *k* is the flood mitigation alternative been evaluated for the return period *i*; *w* is the weight of importance given to a specific impact and category ranging from 0 to

1; *j* is the impact category; EI is the economic impact category; SI is the social impact category, and ENI is the environmental impacts category. All three-impact categories are ranked in three categories: (1) low, (2) moderate, and (3) high. More detailed information for each impact category criteria is presented in Section 3.2.1.

3.2.1 Risk Criteria

A summary of the criteria used in previous studies was identified from the literature. For this study, not all the criteria were incorporated due to lack of data availability. In future studies, where more data is available, it is recommended that the criteria mentioned in Chapter 2 is considered and implemented in order to perform a more detailed risk assessment. The following sub-sections will summarize the selected criteria for each impact category and describe how it is evaluated in this research.

3.2.1.1 Economic Criteria

The economic risk analysis is obtained from the HAZUS loss estimation results. HAZUS estimates the economic damages in an aggregated form at the census block level. In this study, only two criteria were used for the analysis: (1) damage to buildings and (2) damaged to infrastructure (i.e. bridges, water utilities). Table 10 describes these criteria.

Table 10: *Economic Risk Criteria Identification*

EI Criteria	Unit	Description
Building Damage	USD ($)	Total cost of repairing/rebuilding the damage buildings (i.e. residential, commercial, and industrial) within a census block.
Infrastructure	USD ($)	The total cost of repairing/rebuilding of repairing/replacing the damage bridge, potable water facility, and wastewater facility.

In order to obtain the total damage of the building, HAZUS has multiple depth-damage curves built-in the model. To estimate the damages, the inventory data within HAZUS is classified and associated to a specific depth-damage curve. For example, the building inventory is classified in the type of occupancy (i.e. residential, commercial, etc.), construction type (i.e. masonry, steel, wood, etc.), and building specific data such as foundation type, building height, and age. HAZUS also integrates the R.S. Means square-foot costs for the general building inventory. For the final estimation, HAZUS considers the following economic losses: repair and replacement costs (structural and non-structural damage), contents losses, inventory losses, relocation expenses, capital related income losses, wage losses, and rental income losses. For the infrastructure economic analysis, only bridges and water utilities were estimated. The economic losses of these utilities are limited to the cost of repairing the damage caused by the flood event (FEMA, 2015). The total economic loss is obtained in two formats: (1) a polygon layer where each polygon is a census blocks containing the total amount of loss ($) for each block, and (2) written reports that include summary of losses and specific criteria information.

3.2.1.2 Social Criteria

Three social criteria were selected based on data availability: (1) displaced population, (2) social hot spots affected, and (3) short term shelters. Table 11 describes the social criteria used in this study.

Table 11: *Social Risk Criteria Identification*

SI Criteria	Unit	Description
Displaced population	Number of people	Population in a census block that would need to vacate their property, but not necessarily requires shelter from the government.
Social hot-spots	Affected (1) or not affected (0).	Number of hospital, police stations, and religious buildings that are expected to be affected by the flood event.
Short Term Shelter	Number of people	Population in a census block that would need to vacate their property that will require short-term shelter from the government.

The risk analysis for the displaced population and short-term shelter needs are conducted within HAZUS. The software estimates the number of people displaced from their homes based on the inundated areas and Census data. According to the HAZUS Flood Model Technical Manual (FEMA, 2015), it is assumed that people will be displaced from their homes if there has been some damage to the building, they have been evacuated, or there is no access to their residence. To determine the number of the population requiring shelter, HAZUS considers individuals who have been displaced and have lower incomes and no family and friends within the immediate. Such population is expected to require short-term shelters. Similar to the economic results, the HAZUS social impact results are obtained in one polygon shapefile that contains the census block ID, the number of people displaced, and the number of people requiring shelter. The results can also be acquired in a written report.

The social hot spots are facilities that provide a quality of life for the population. For example, hospitals and care facilities provide help for the people in need of medical assistance as well as religious buildings offer a place for social gathering and practice of their faith. Not having access to these facilities can physically and mentally affect the individuals. For instance, if a person seeks medical attention and the region's hospital is not accessible, or has been damage, the individual will have to travel further to get the services needed.

For this study, only the spatial information of hospitals, schools, and religious buildings was used. The risk analysis for the social hot spots was performed by overlaying the floodplain shapefiles obtained from HAZUS with the social hot spots shapefile. Facilities that where within the floodplain are given a value of 1, indicating that the facility has been affected; otherwise, it will be given a value of 0 (i.e. not affected by the flood). For each scenario a new layer was created containing the hot spots affected by the flood event.

3.2.1.3 Environmental Criteria

A flood event is capable of not only affecting directly the population and buildings, but it also can have a great impact on the environment. The rapid flood can cause contaminants to be carried by the flowing debris, affecting surface, and groundwater quality downstream. It can also impact habitats not normally flooded, affecting the flora and fauna within the habitat.

A detailed environmental risk assessment is out of scope in this study. In turn, the potential of environmental impacts occurring will be assessed. Given the available information, a set of environmental criteria has been defined in Table 12. Three environmental criteria have been selected based on data availability: (1) critical habitats affected, (2) debris generation, and (3) landslide probability due to erosion potential of the soil.

Table 12: *Environmental Risk Criteria Identification*

Impact	Unit	Description
Critical Habitats	Affected (1) / Not affected (0)	Areas defined by the U.S. Fish and Wildlife Services (USFWS) as critical for the survival and restoration of listed species.
Debris	Tons	Refers to the generation of debris due to the flood event.
Landslide potential	Low (1), Moderate (2) and High (3)	The data represents the susceptibility to landslides in the area.

The data for the critical habitats was obtained from the U.S. Fish and Wildlife Services (USFWS), which represent the areas designated as critical for the survival and restoration of listed species. If the area is affected by a flood event, it is possible that a site-specific assessment will be necessary to determine the specific impacts, if any. In this study only the possibility of the habitat been affected will be evaluated.

The total debris generated by a flood event is obtained from the HAZUS loss estimation model. The model only calculates building-related debris materials (i.e. finishes, structural components, and foundation materials). In order to estimate the debris, flood depth, and square footage of the building are used. First, depending on the building occupancy type, the quantity of debris is generalized. Table 13 shows an example of the debris quantities for residential occupancy. Using the square footage of the buildings in the census blocks, the total debris generated is aggregated. The results are obtained at the census block level and a written report is generated.

Table 13: *HAZUS Debris Generation for Residential Buildings Estimates (FEMA, 2015)*

<table>
<tr><th rowspan="3">Occupancy</th><th rowspan="3">Depth of Flooding</th><th colspan="4">Debris Weight (Tons/1000 sq. ft.)</th></tr>
<tr><th rowspan="2">Finishes</th><th rowspan="2">Structure</th><th colspan="2">Foundations</th></tr>
<tr><th>Footing</th><th>Slab on grade</th></tr>
<tr><td rowspan="3">RES1 (without basement)</td><td>0' to 4'</td><td>4.1</td><td colspan="3" rowspan="2"></td></tr>
<tr><td>4' to 8'</td><td>6.8</td></tr>
<tr><td>8'+</td><td>6.8</td><td>6.5</td><td>12.0</td><td>25.0</td></tr>
<tr><td rowspan="4">RES1 (with basement)</td><td>-8' to -4'</td><td>1.9</td><td colspan="3" rowspan="3"></td></tr>
<tr><td>-4' to 0'</td><td>4.7</td></tr>
<tr><td>0' to 6'</td><td>8.8</td></tr>
<tr><td>6'+</td><td>10.2</td><td>32.0</td><td>12.0</td><td>25.0</td></tr>
<tr><td rowspan="2">RES2</td><td>0' to 1'</td><td>4.1</td><td colspan="3"></td></tr>
<tr><td>1'+</td><td>6.5</td><td>10.0</td><td>12.0</td><td>25.0</td></tr>
<tr><td rowspan="3">RES3 (small 1 to 4 units)</td><td>0' -4'</td><td>4.1</td><td colspan="3" rowspan="2"></td></tr>
<tr><td>4' to 8'</td><td>6.8</td></tr>
<tr><td>8'+</td><td>10.9</td><td>6.5</td><td>12.0</td><td>25.0</td></tr>
</table>

The data for the landslide potential was obtained from United State Geological Survey (USGS). Figure 7 shows an example of the landslide potential map, which is characterized in low (L), moderate (M), high (H) and very high (VH) scale. Areas with high susceptibility to landslides are considered high risk during a flood due to the instability of the soil caused by the rapid water-level changes.

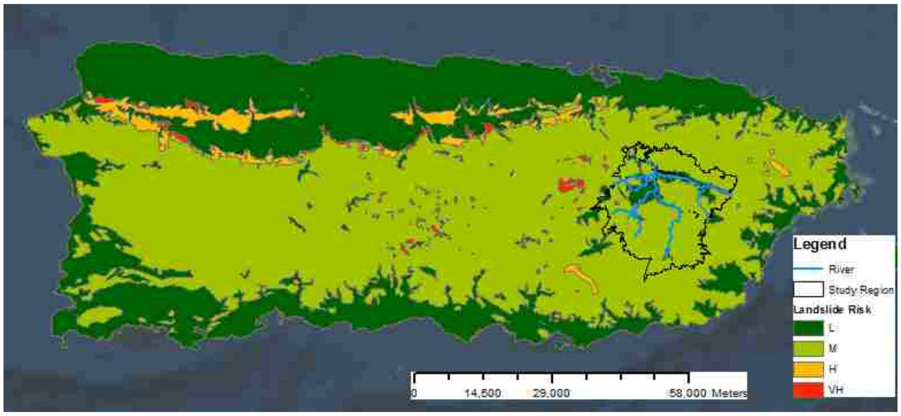


Figure 7. Example of the landslide potential data

3.2.2 Spatial Average Annual Impacts (AAI)

The spatially distributed results for each impact category were processed within ArcMap 10.0 with the purpose to get the annual risk for each alternative. Figure 8 presents the methodology defined in this study to perform the spatial raster risk analysis. First, it is important to define the coordinate system for the study region. Different coordinate systems can generate inconsistencies in the analysis.

Figure 8. Raster risk analysis process

Once all the data is projected to the selected coordinate system, the spatial data obtained for each risk criteria is converted into a raster layer. In order to maintain consistency, the processing extent, snap raster, and raster cell size were defined to be the same as the digital elevation model (DEM). Table 14 summarizes the data obtained for each criterion considered in the risk assessment.

Table 14: *Risk Layers for Each Criterion Defined*

Category	Criteria	Criteria ID	Units	Source
EI	Building Damage	EI_1	USD ($)	HAZUS
	Infrastructure Damage	EI_2	USD ($)	HAZUS
SI	Social Hotspots	SI_1	Affected: Yes (1)/No (0)	PRPB
	Short-term Shelter	SI_2	Number of people	HAZUS
	Displaced Population	SI_3	Number of people	HAZUS
ENI	Debris generation	ENI_1	Tons	HAZUS
	Landslide potential	ENI_2	High, Moderate, Low	USGS
	Critical Habitats	ENI_3	Affected: Yes (1)/No (0)	USFW

As shown in Table 14, the spatial data is provided in different units. In order to process the data with the same units, it was reclassified using a (1) low, (2) moderate, and (3) high risk scale. The "*reclassify*" tool within ArcMap was used for this purpose. In this research, the criteria were reclassified arbitrarily defining ranking criteria. The ranking criteria for each layer are summarized in Table 15. For example, in the debris layer, a grid cell with a value of 150 tons is ranked in the Category 2 (moderate risk).

The value ranges were classified using equal intervals. A decision-maker will be able to redefine the ranges given their preferences. An example of a reclassified layer is shown in Figure 9-B. Figure 9-A shows a layer that has a range of values from low to high. Using the reclassification ranges, the layer was divided into three categories: low, moderate, and high as shown in Figure 9-B.

Table 15: *Proposed Reclassifying Values for Each Criterion*

Criteria_ID	Grid Cell Units	Ranges		Rank
		From	To	
EI_1	USD ($)	0	100	1
		100	400	2
		400	greater	3
EI_2	USD ($)	0	100	1
		100	400	2
		400	greater	3
SI_1	Affected: Yes (1)/No (0)	0	0	0
		1	1	1
SI_2	Number of people	0	200	1
		200	400	2
		400	greater	3
SI_3	Number of people	0	200	1
		200	400	2
		400	greater	3
ENI_1	Tons	0	100	1
		100	400	2
		400	greater	3
ENI_2	High, Moderate, Low	4	4	1
		3	3	2
		1	2	3
ENI_3	Affected: Yes (1)/No (0)	0	0	0
		1	1	1

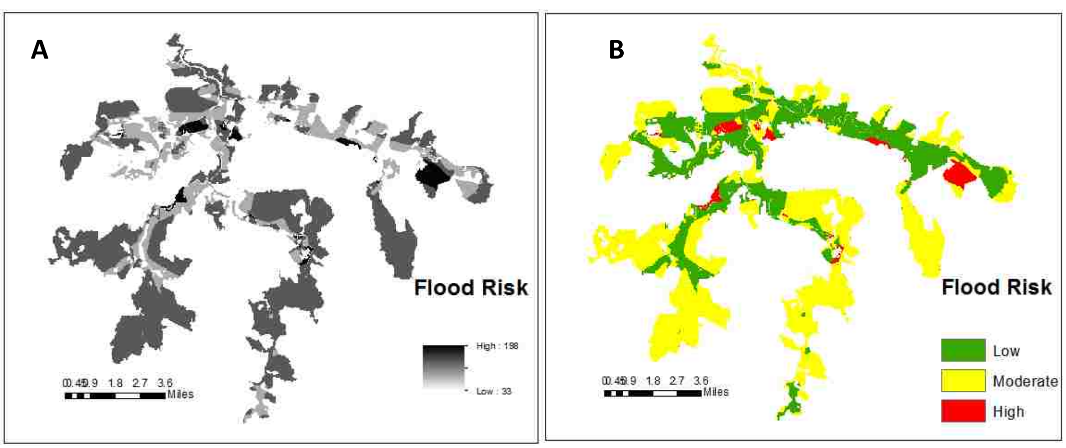


Figure 9. A) Layer with a range of values and B) reclassified layer in three categories (i.e. low, moderate and high)

After reclassifying all layers, the criteria within each impact category were added using a weighted overlay. An example of the weighted overlay method is shown in Figure 10 where two criteria raster datasets were weighted and added to get the total impact. For this process the raster calculator within ArcMap was used, which allows for the no data cell to be treated as 0 or no value cells. The equation used in the raster calculator is:

$$(7) \qquad I_{j,i,k} = \sum_{c=1}^{n} w_c C_{i,j,k} = w_{cI} C_{1,i,k} + \cdots + w_{cn} C_{n,i,k}$$

In this equation, I is the total impact for the alternative k for the return period i, n is the total number of criteria, w_c is the weight for the criteria C, and k is the mitigation measure being evaluated. Stakeholders defined the weight using this equation.

Figure 10 shows an example of the spatial calculations of the total impacts generated by two types of criteria. The cell values in each criteria layer ranges from 0 to 4. In the example, the total impact for the shaded cell was estimated. The weight for each layer is represented at the left of the corresponding raster. Following the expression used in the raster calculator, the result is obtained:

$$Impact = (3 \times 0.80) + (NoData \ \times 0.20) = 2.4$$

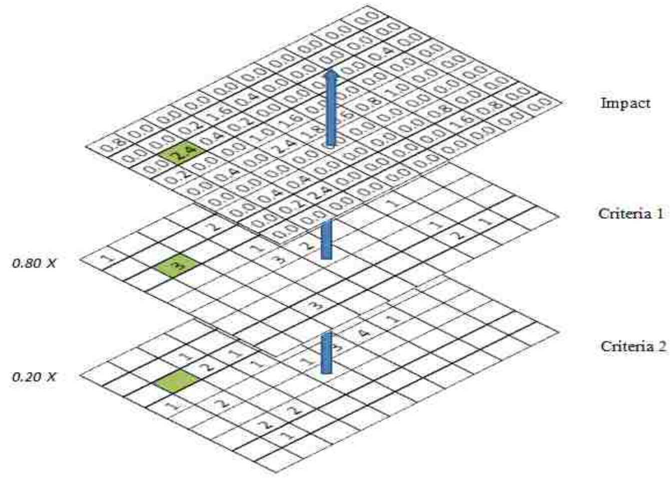


Figure 10. Example of the raster analysis

The spatial impact for every category is calculated by multiplying each cell by its rank and adding all the values. For instance, Figure 11(a) presents an example raster grid for an impact category. Each cell within the grid is given a value according to the ranking criteria. The risk for each criterion is then combined to obtain the total impact for each category. The total spatial impact is the cell value multiplied by the count of cells with the given value (see Figure 11(b)). For example, the grid contains 3 cells with a value of 1; therefore, the impact of cells with a value of 1 is computed as 1 x 3 = 6 and the total impact of the grid is 13.

1	1	2
2	3	3
1	0	0

(a)

Value	Cell count	Impact
1	3	= 1 x 3 = 3
2	2	= 2 x 2 = 4
3	2	= 3 x 2 = 6
Total Impact=		13

(b)

Figure 11. Raster grid

Finally, the probability-damage curve for every mitigation alternative can be generated and the AAI can be calculated using equation 3, previously defined.

This raster analysis was conducted with the model builder (MB) tool within the HAZUS environment. The MB is a tool within ArcMap that helps “*create, edit, and manage workflows that string together sequences of Geoprocessing tools, feeding the output of one tool into another tool as input*” (ESRI 2013). The MB makes it easier to perform the same process for multiple datasets by using iterators. It also provides the user with the ability to create editable parameters and variables that can be changed depending on the user’s preferences. An example of the MB is presented in Figure 12.

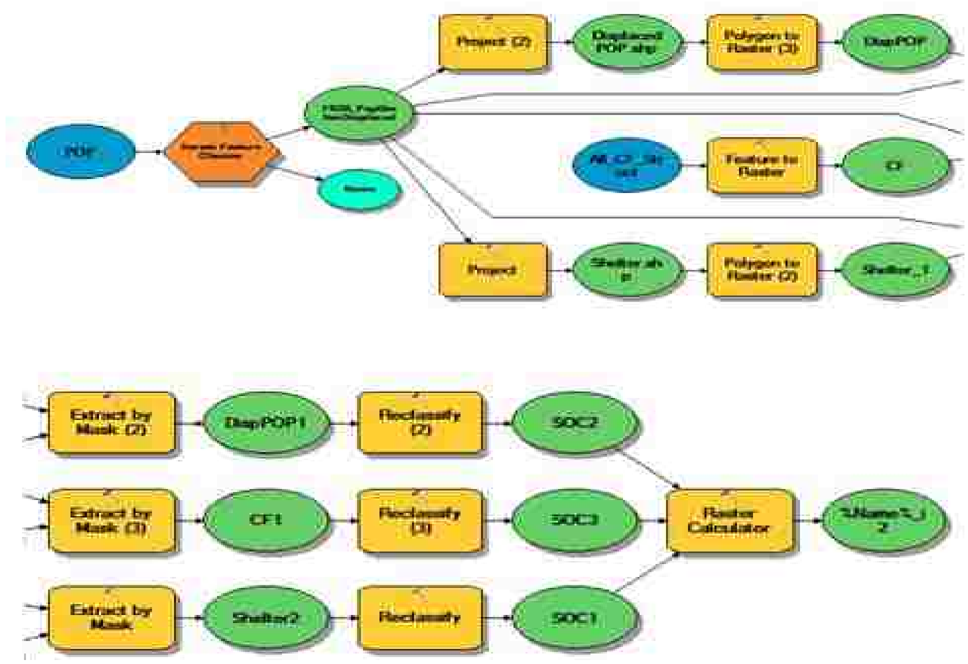


Figure 12. MB for social risk raster analysis.

3.3 Stakeholder Network Analysis

According to the Merriam-Webster dictionary, a stakeholder is someone who is involved in or affected by a course of action (Merriam-Webster, 2014). In terms of flood management, a stakeholder can be defined as anyone who manages the floodplain, lives in the floodplain, or is affected by the activities or FMAs applied to the floodplain. For example, an individual who is not in the floodplain can be affected by the construction of a dam that will provide water supply for his or her area. The interaction between stakeholders can affect the implementation process, causing delays, costs increase, and risk increase. It has become a major challenge incorporating the diversified opinions of a large number of stakeholders where uncertainty plays a major role (Akter & Simonovic, 2005). For this reason, it is necessary in this study to develop a methodology that incorporates the stakeholder's opinion.

In this research, stakeholders were identified from the literature review and interviews with experts in flood management were conducted. The groups of stakeholders consider in this study are presented in Figure 13. In the following sections, an overview of how each stakeholder is characterized and how they interact with each other is presented.

Figure 13. Floodplain stakeholders.

3.3.1 Stakeholder Characterization

Each stakeholder has specific objectives. They may have different attributes or could be classified within different groups. For instance, stakeholders can be categorized according to their level of power, the legitimacy of their operations, or their urgency in the process. The literature also mentions classifications such as whether the stakeholders are external to the process (those affected by the project and not necessarily involved in the execution process) of the project, or internal stakeholders (those actively involved in project execution, but not necessarily affected by the project) (Olander 2006). The typologies considered in this research are summarized in Table 16. These classifications integrate concepts from stakeholder theory and organizational theory.

Table 16: *Typologies of the Organizations (Valentín, 2011)*

Typologies	Description	Evaluation Scale
Power	Linked to the use of coercive, utilitarian, or normative means to obtain their goals in the context of a specific type of conflict *(Mitchell et al. 1997)*.	0 – none, 1- very low, 2 – low, 3- medium, 4 – high, 5-very high
Legitimacy	Legitimacy is associated with appropriate actions according to socially established norms in the context of a specific type of conflict *(Mitchell et al. 1997)*.	0 – none, 1- very low, 2 – low, 3- medium, 4 – high, 5-very high
Urgency	Urgency is based on the time sensitivity and criticality of the stakeholder relationship in the context of a specific type of conflict *(Mitchell et al.1997)*.	0 – none, 1- very low, 2 – low, 3- medium, 4 – high, 5-very high
Level of Involvement	Degree of involvement of the stakeholder	0 – none, 1- very low, 2 – low, 3- medium, 4 – high, 5-very high
Level of Interest	Degree of interest the stakeholder has during the project phase being evaluated.	0 – none, 1- very low, 2 – low, 3- medium, 4 – high, 5-very high
Classifications		
Internal/External	Refers to whether or not the stakeholder is actively involved in the project execution *(Olander, 2006)*.	Internal/External
Level of Representation	Refers to the degree of representation of the stakeholder *(Pahl-Wostl, 2006)*.	Individual/ aggregated/ highly aggregated
Level of Organization	Refers to the degree of organization of the stakeholder (*Pahl-Wostl, 2006)*.	Not organized/informal institutions/formal institutions
Public/Private	Refers to whether the stakeholders pertain to or are a public or private organization *(Pahl-Wostl 2006)*.	Public/Private

3.3.2 Data Collection

Developing an inter-agency network requires the collection of data. For this study, a web-based survey was prepared using the Qualtrics online software (www.qualtrics.com). The two target populations were identified for the study: (A) residents of the commonwealth of Puerto Rico and (B) public officials of agencies who are directly or indirectly responsible for reducing the risk of flooding within the study region. The questionnaire instruments used for this study are included in Appendix B.

To develop the questionnaires, a literature review of the study's objectives and research of past surveys related to current flood risks, vulnerabilities, and flood mitigation alternatives implementation were reviewed. The questions in the survey have different formats such as ranking scales, multiple-choice questions with single and multiple answers, and Likert scales. Any incomplete or missing information was characterized as not applicable (NA) since this is the only form of data incompleteness for the surveys. Since two different target populations were defined, two different questionnaires were prepared:

1) Community Survey: targets residents within the study region and consist of questions related to basic demographic information, the participant's perception of floods risks and his/her knowledge about mitigation alternatives.
2) Agency survey: targets public officials. Consists of questions related to the official's experience and knowledge on flood management alternatives within his/her agency and their interaction with other agencies. In addition, the officials

were asked to characterize the different organizations involved in the decision-making process of selecting flood mitigation alternatives (Table 16).

3.3.2.1 Community Survey

The purpose of the community survey was to obtain the general perspective of the population towards floods and the implementation of mitigation alternatives. The survey consists of 34 questions, which covers topics such as demographic data of the participants, their current perspective of flood risk in the community and the importance of the evaluation criteria for each impact category (i.e. economic, environmental, and social).

The first section of the survey considers the perspective of the participants towards a specific flood risks and their experience with past flood events. At the beginning of the survey, the respondent is given with the following definitions to get familiarize with the concept of risk in this study:

- Flood risk: the consequences that a community is exposed to a given occurrence of a flood event.
- Flood event- the inundation of dry land through the overflowing of a body of water, especially a river.
- Consequences- damage to buildings, loss of life, loss of property, damaged electricity and/or water infrastructure, interruption of services, anxiety, etc.

- Flood mitigation alternatives- alternatives implemented in flood prone areas in order to reduce the risk of flooding. Mitigation alternatives are divided into two main groups: structural and non-structural.
    - Structural mitigations- mitigation alternatives that tend to modify the characteristics of a flood (i.e. dams, levees, retention ponds, etc.).
    - Non-structural alternatives- help to reduce the hazard from unavoidable damages (i.e. warning systems, flood zoning regulations, relocation, etc.).

3.3.2.2 Agency Survey

The purpose of the agency survey is to obtain information about the interaction between agencies during decision-making processes related to flood management. The survey consists of 13 questions, which included general information from the respondent, perception of FMAs and typology characteristics (i.e. power, legitimacy, influences, etc.) of agencies identified as stakeholder in the process of planning and implementing FMAs. The survey was developed using the web-based survey in Qualtrics and is electronically deployed.

3.3.3 Stakeholders Interactions

For this study, an inter-agency network analysis was conducted following the conceptual framework by Valentín (2011). The steps followed in the development of the network are illustrated in Figure 14.

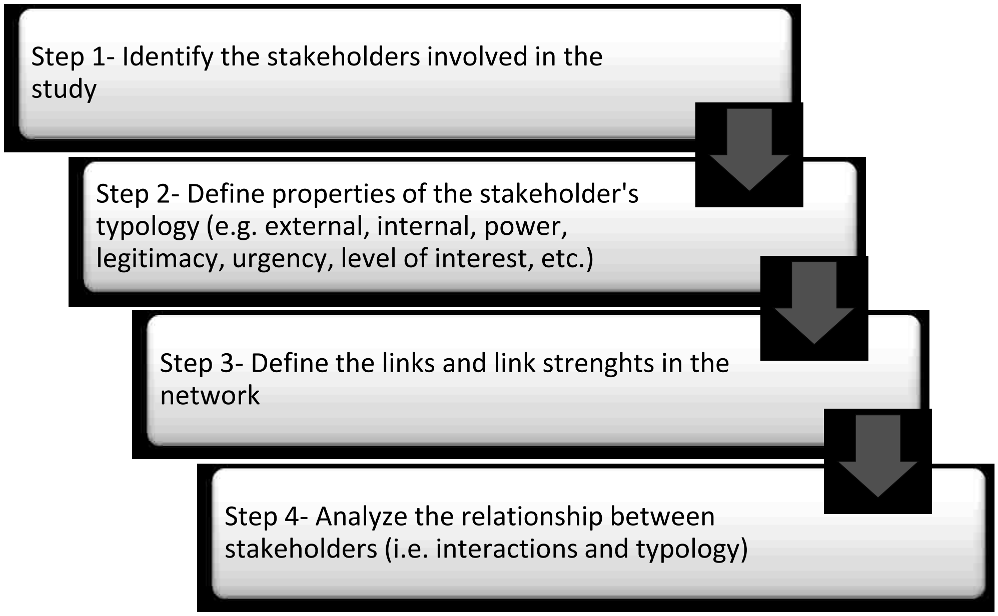
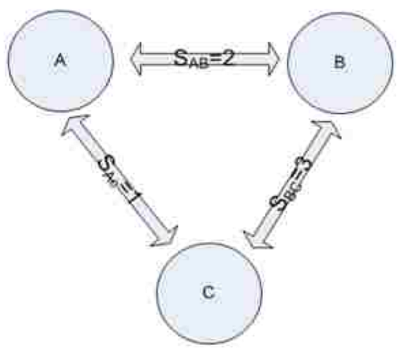


Figure 14. Network analysis framework (adapted from Valentín, 2011)

In Step 1 the stakeholders need to be identified. During the implementation process of the FMAs, interaction with multiple stakeholders is necessary. The stakeholders involved range from federal, state, and local authorities. Also, given that the communities are expected to be positively or negatively affected by the decisions, their input should be taken into consideration during the planning process. Once the stakeholders are identified, Step 2 requires the characterization of the stakeholders using the typology described in Table 16. In order to identify the typology of the stakeholder, data collected from questionnaire B (refer to Section 3.3.2.2) was used.

In Step 3 the strength of the links between stakeholders are defined. In this study, the strength of the links was defined as the importance of stakeholders' interactions during the evaluation and implementation process of FMAs. An expert was consulted to rate the importance of the interaction between the identified stakeholders. A rating scale ranging from 0 to 3 was defined. Interactions between two entities having no importance during the selection and implementation process, were given a value of zero (0), and the interaction between two entities having high importance were given a value of three (3). In Figure 15 an example of the network analysis between three entities is illustrated. The link between each entity defines the strength of the interaction. In the example, the strength of the link between agencies A and B (S_{AB}) is 2.



(a) Defining network links

	A	B	C
A		2	1
B	2		3
C	1	3	

(b) Matrix depicting the strength of links between agencies

Figure 15. Link strengths (adapted from Valentin, 2011)

With the results obtained in step 2 and 3, different network metrics can be calculated in order to conduct an analysis of the interactions between stakeholders (i.e. Step 4). Table 17 describes the structural metrics.

Once the strength of the links and the structural attributes (based on link strength) are calculated, the relationship (if any) between stakeholders' typology and the stakeholders' importance on the decision-making process is investigated.

Table 17: Inter-agency *Network Structural Metrics (Valentin, 2011)*

	Network/Stakeholder Metric	Definition/Algorithm	Interpretation in the inter-organizational context
Network	Density	Number of links in the network divided by the number of all possible links	- This metric can be used to compare the inter-organizational risk levels of networks representing different phases of the capital-intensive project - For undirected networks, the density represents the probability that any given link between two random stakeholders is present (Hanneman and Riddle, 2005)
Stakeholder	Degree	Number of connections a stakeholder has with other stakeholders	- Indicator of the overall inter-organizational conflict of a stakeholder - Stakeholders with a high degree communicate/exchange information with a greater number of stakeholders
	Degree Centrality	Calculated by determining the proportion of stakeholders that are connected to the node being evaluated (Wasserman and Faust, 2004)	- The centrality provides an analytical measure of a stakeholder's ability of negatively affecting the project metrics.

The inter-agency network analysis is performed using the Netminer software. Netminer is a Windows-based program for the analysis and visualization of networks. The program interface is easy to use and adapt for policy and decision-makers to analyze or modify the models and allows importing data from spreadsheets in Microsoft Excel.

3.3.4 Integration of Stakeholders' Opinion

Previous research in flood management has proposed a framework that incorporates the stakeholders' opinion (e.g. Akter et. al, 2004; Akter and Simonovic, 2005; Akter and Simonovic, 2006), but research is very limited as to whose opinion should be included in the analysis. Different types of stakeholder (i.e. internal-external, latent-dormant, etc.)

participate during the decision-making process and most often, their opinions tend to conflict with each other. For the purpose of defining which stakeholders will be considered as important for this study, the theory of Mitchell et. al. (1997) is incorporated. Mitchell et al. (1997) proposed a theory for identifying who really matters in the management process. Their theory identified that salience stakeholders are those that possess power, legitimacy, and urgency. In Figure 16 a representation of the different types of stakeholders defined by their research are shown. The type of stakeholder will depend on which type of attribute it possesses.

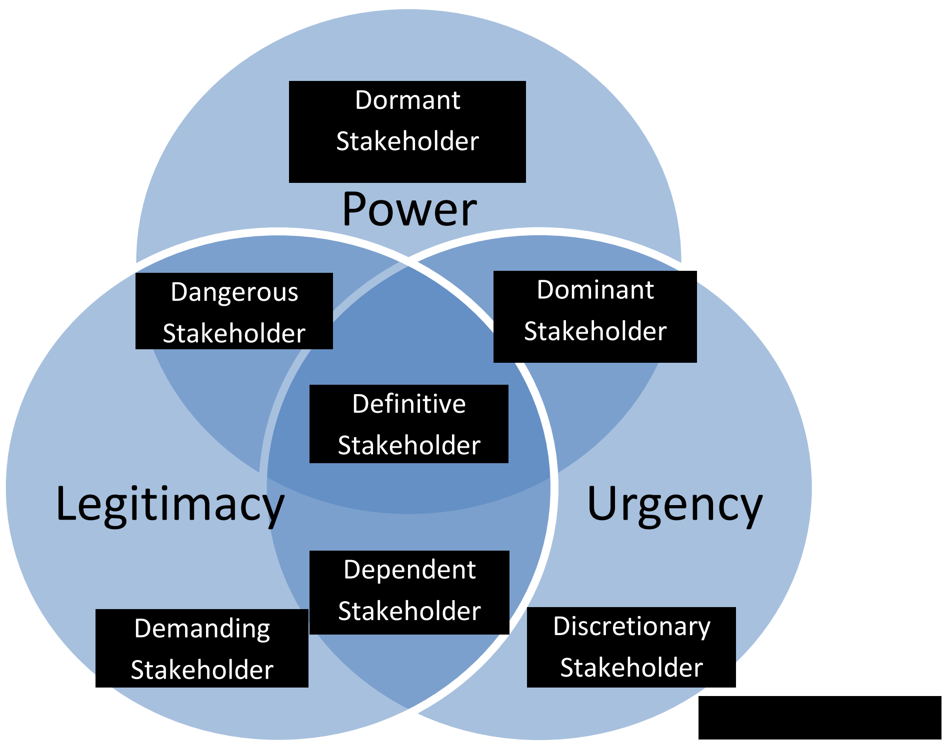


Figure 16. Stakeholder typology (adapted from Mitchell et. al. 1997)

In the survey deployed to agencies (refer to Section 3.3.2.2), the respondents were asked to evaluate the typology of their own agencies and all the other stakeholders identified.

The typology included the evaluation of the stakeholder's legitimacy, urgency, and power. For the purposes of this study, the opinion from the "definitive stakeholders" will be the only information considered when defining the weights for the criteria and impact categories. Mitchell et. al. (1997) defines a "definitive stakeholder" as "*those possessing all three attributes*" (i.e. legitimacy, urgency, and power).

Having defined which stakeholders will be considered in the decision-making process, the Analytical Hierarchical Process (AHP) was integrated for estimating the weights to be given to each criteria and impact category. The AHP was first developed by Thomas L. Saaty in the early 1970's. The process is used to develop "*ratio scales from both discrete and continuous paired comparisons*".

The preference of the definitive stakeholders was obtained by requesting survey respondents to rank the importance of each criterion using a likert-scale form not important (1), to very important (5). The opinion of the stakeholders was converted to weights factors using AHP methodology. For example, if criteria A and B were ranked 2 and 5 respectively by the stakeholder, the rank of criterion A was subtracted from the rank given to criterion B with a result is -3. A pairwise scale value is obtained by using the conversions defined in Table 18. For the example of mentioned above, the difference from A and B was -3. Using the conversion in Table 18 the pairwise comparison for AB is, which means that criterion B is considered by the stakeholder as "*very strongly more important*" than criterion A. Similarly, if the ranking of A and B were 5 and 2 respectively, the subtraction of A from B would yield +3. The pairwise comparison AB is 7 which indicates that criterion A is "very strongly more important" than criterion B.

Table 18: *Pairwise Comparison Scale*

A – B	Scale	Definition
0	1	A and B are equally important
1	3	A is moderately more important
2	5	A is strongly more important
3	7	A is very strongly more important
4	9	A is absolutely more important
-1	1/3	B is moderately more important
-2	1/5	B is strongly more important
-3	1/7	B is very strongly more important
-4	1/9	B is absolutely more important

Once all the N criteria has been converted the pairwise comparison scale, a matrix is developed of size N x N with rows *i* and columns *j*. Each entry in the matrix represents the importance of the criterion in relation with another criterion and is defined as:

(8) $$X_{ji} = \frac{1}{X_{ij}}$$

In this equation, X_{ij} is the pairwise comparison scale values between the criterions in row *i* and the criterion in column *j*. As shown in Table 19, when $i = j$ the same criterion is been compared, and therefore $X= 1$.

Table 19: *Pairwise Comparison Matrix*

	Criterion 1	Criterion 2	…	Criterion N
Criterion 1	1	X_{12}	…	X_{1N}
Criterion 2	X_{21}	1	…	X_{2N}
• • •	• • •	• • •		• • •
Criterion N	X_{N1}	X_{2N}	…	1

For the example discussed earlier, the resulting matrix is shown in Table 20:

Table 20: *Pairwise Comparison Matrix from Example*

	Criterion A	Criterion B
Criterion A	1	1/7
Criterion B	7/1	1

Following Hussein et. al. (2010), the weigh factor of the i^{th} criteria (W_i) is determined by calculating the geometric mean (GM) of the i^{th} row of the matrix depicted in Table 19 and then normalizing these results as follows:

(9) $$GMi = \left\{\prod_{j=1}^{N} cij\right\} 1/N$$

(10) $$Wi = \frac{GMi}{\sum_{i=1}^{N} GMi}$$

3.4 Decision Analysis

The steps followed for selecting a FMA are presented in Figure 17. First, the criteria to evaluate the FMAs were defined. As defined in Section 3.2, each criterion is grouped into the economic, social, and environmental categories. Then, the impact of each FMA that has in every category for a specific return period is calculated with a risk assessment. (Refer to Section 3.2.2). With the information obtained from risk assessment, the risk reduction benefits for each FMA in the different scenarios are obtained.

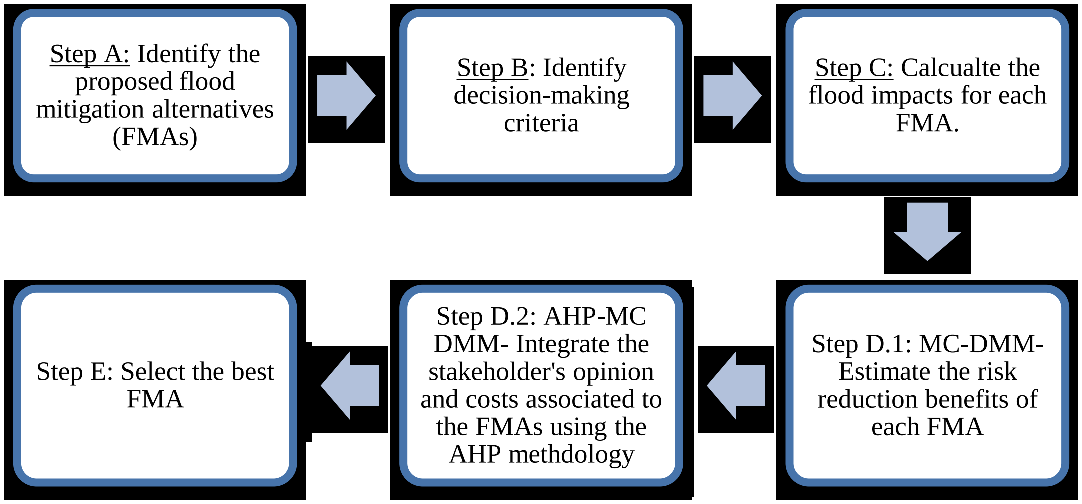


Figure 17. Risk-based decision-making framework

3.4.1 Step A: Proposed Flood Mitigation Alternatives (FMAs)

There are numerous alternatives that can be implemented to reduce the risk of flooding in a specific area. In order to compare the different alternatives, their respective impacts on the study region need to be defined. HAZUS allows the incorporation of mitigation alternatives such as levees, flow regulation, flood warning systems (FWS), and policy changes (i.e. changes in land use, base flood elevation, etc.). In this study, two alternatives are evaluated: (1) levees and (2) FWS. These alternatives are compared to the "no action" alternative.

A levee "*is an embankment whose primary purpose is to furnish protection from high water due to river floods*" (Pagliara & Pozzolini, 2005). The construction of the levee requires a considerable amount of earthworks. A FWS provides emergency responders and flood managers a lead-time to evacuate and protect the population and properties at risk, hence, minimizing the impacts of a flood. The system integrates three major components: (1) data collection equipment (i.e. automated gages), (2) computer software capable of processing the information, and (3) means for broadcasting the information such as communication services (i.e. cable, satellite, telephone, etc.) (National Weather Service, 2012).

3.4.2 Step B: Decision-Making Criteria

The decision-making criteria used to evaluate the alternatives are those economic, social, and environmental identified in Section 3.2.1. A decision-maker would be able to add or remove any criteria considering the data available and the evaluation requirements. In addition to the risk assessment criteria, implementation criteria were also included. The implementation criteria refer to any consideration involving the implementation, operation, and maintenance of the FMA. A description of the implementation criteria considered in this study is presented in Table 21. The importance of each criterion was evaluated by the agency official questionnaire described in Section 3.3.2.2.

Table 21: *Implementation Criteria*

Criteria	Description	Units
Investment	The cost of planning and implementing the proposed alternative.	USD $
Operation and Maintenance	The cost of operating and maintaining the proposed alternative.	USD $
Creation of employments	The amount of jobs expected to be created by the alternative. Depending on the available information, it can include direct and indirect job creations.	# jobs
Duration of the project	Time it takes to implement the proposed	Months

	alternative.	

3.4.3 Step C: Impacts of FMA on Criteria

The flood impacts associated to the FMA are required to estimate the risk reducing benefit of each alternative. The methodology for estimating the impacts of each FMA is presented in Section 3.2.1.

3.4.4 Step D: Decision-Making Model (DMM)

The proposal and demonstration of a new decision-making framework for evaluating FMAs is the main contribution of this study. From the methods evaluated in the literature review, the decision-making in flood mitigation is a result of the evaluation of multiple criteria and multiple stakeholders' opinions. Also, much uncertainty is involved in the process due to the data provided for the models and the variability, objectives, and typologies of the stakeholders. In this study, two DMMs were developed in order to incorporate the multiple criteria, multiple stakeholders, and uncertainty identified in the literature review. First a DMM using a Monte-Carlo Simulation is proposed (MC-DMM) and presented in Section 3.4.4.1. The suggested model account for the uncertainties related to the input data and includes the risk criteria identified in Section 3.2.13.2.1. The objective of this model is to estimate the risk reduction benefits of the FMAs.

The second model incorporates the AHP methodology to the MC-DMM (AHP-MC-DMM) in which the benefit-cost ratio for each FMA is estimated by adding a fourth impact category. As previously described, the fourth impact category considers implementation criteria (i.e. cost of implementation, maintenance, etc.). Figure 18 depicts a diagram of the AHP-MC-DMM. Within this model, multiple cost and benefit criteria can be evaluated for a definite numbers of alternatives. The methodology for the AHP-MC-DMM is introduced in Section 3.4.4.2.

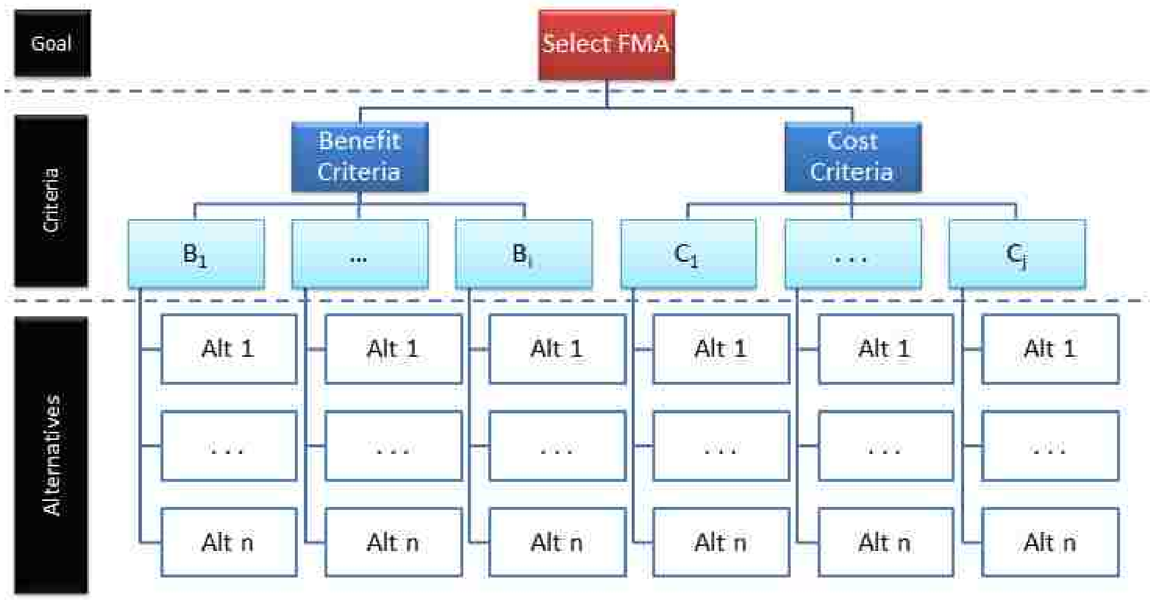


Figure 18. AHP-MC DMM Diagram

3.4.4.1 Step D.1: Monte-Carlo Decision-Making Model (MC-DMM)

Traditional analysis selects a single deterministic value, such as the average of an occurrence, to represent uncertain or variable inputs. The problem with this approach is that the deterministic results may only represent one outcome of the range of possible results. A Monte Carlo Simulation (MCS) is a tool that allows the incorporation of uncertainties within a risk assessment by including probability distributions. The method was firstly introduced by researches working on the Manhattan Project at Los Alamos

National Laboratory, for solving problems related to the physics of nuclear explosions. As described by Rezaie et. al (2007) the MCS is a "*statistical technique that could become increasingly important as a mean for risk assessors to evaluate the uncertainty*" (Rezaie et al. 2007). The range of the uncertainties can be defined from historic and more realistic data and the results are a distribution of the results obtained from multiple iterations.

The MC-DMM integrates the results collected from the risk assessment analysis (Section 3.2) and a weight factor that reference the importance that will be given to each impact category. To perform the analysis, the variables, objective functions, and constraints are defined as follow:

Variables

- I_i = annual average impact (AAI) expected for each return period *i* (i.e. 10, 25, 50, 100 and 500 return periods) for each alternative *k.*
- P_i = Probability of a flood event occurring given a return period *i.*
- EI= Economic impact for return period *i.*
- SI = Social impact for return period *i.*
- ENI = Environmental impact for return period *i.*

Objective function

The objective function minimizes the AAI associated with the alternative, *k*. Thus the objective function is defined as:

(11) $$\min AAI_k = \sum \frac{I_{i-1} + I_i}{2} \times |P_i - P_{i-1}|$$

In this equation, I is the total impact of alternative *k* for return period *i* and *P* is the probability of an event with a return period *i* occurring.

The AAI was previously defined in Equation 6 as:

$$AAI_k = \sum_{j=1}^{n} w_j I_{i,j,k} = w_{EI} EI_{i,k} + w_{SI} SI_{i,k} + w_{ENI} ENI_{i,k}$$

<u>Constraints</u>

The constraint for this model was defined so that only one alternative was to be selected. It is possible to include additional alternatives within the model and select more than one by changing the constraints. To define the constraint, the selection of the alternative was defined with binary numbers where 0 means the alternative is not selected and 1 means that alternative was selected.

With the use of the Monte Carlo Simulation, uncertainties are considered in the proposed model. Distributions were defined for the AAI results and the probability of an event occurring. The estimation of the AAI (Section 3.2) is a result of user data provided to the model and the loss estimations based on algorithms and aggregated data. Hence, there is an expected margin of error in the final results. In this study, a 10% margin of error was assumed for the AAI. The user could change the margin of error at any time. For this study, a triangular distribution was defined for the AAI. An example of the triangular distribution is shown in Figure 19.

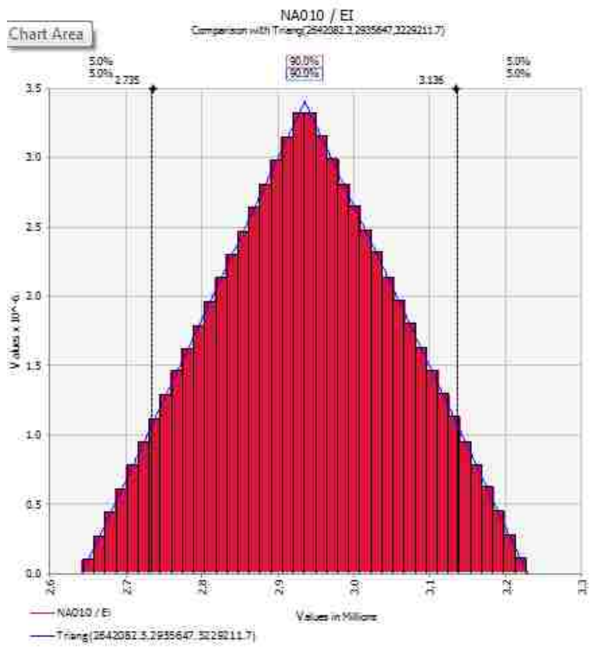


Figure 19. Economic impact triangular distribution for scenario NA010

Finally, the recommended FMA would be selected as the alternative that is able to mitigate the majority of the flood risks, in other words, gives the most risk reducing benefit to the community.

To account for the probability of a specific flood event occurring, a binomial distribution is defined in order to account for the probability of the event happening during the year in evaluation (Refer to Table 9).

3.4.4.2 Step D.2: AHP Monte-Carlo Aided Decision-Making Model (AHP-MC DMM)

The AHP–MC DMM was modeled using the Excel software from Microsoft Office and considered the following input data:

- Total risk reduction benefit for each alternative (from MC-DMM).
- Pairwise comparison of the implementation criteria, which account for the costs associated to the implementation of the FMAs.

In order to rank the FMAs, the weights for the implementation criteria are calculated (refer to Equation 10). Additionally, the FMAs are compared to one another given their effectiveness in reducing flood impacts and the opinion and expertise of the "definitive stakeholders" defined in Section 3.3.4 for each implementation criteria. With this data, a matrix is generated where the FMAs is compared to one another for each specific criterion. For instance, if alternative 1 and alternative 2 are being compared considering criterion A and criterion B, a matrix for each criterion is generated as shown in Table 22. In this case, when comparing both alternatives within the criterion A, alternative 2 was considered "very strongly more important" than alternative 1, which yields a pairwise comparison of 1/7. For criterion B, the pairwise comparison between alternative is 1/5.

Table 22: *Pairwise Comparison for Criterion A and B*

Matrix for Criterion A

	Alternative 1	Alternative 2
Alternative 1	1	1/7
Alternative 2	7/1	1

Matrix for Criterion B

	Alternative 1	Alternative 2
Alternative 1	1	1/5
Alternative 2	5/1	1

For this study, two types of implementation criteria were defined: quantitative and qualitative (refer to Table 23). The quantitative criteria include the costs of investment and maintenance, expected number of jobs to be created, and the duration of the project. These criteria are estimated during the planning process. The qualitative criteria refer to the perception of the stakeholders on the implementation efficiency of a specific FMA. For example, if the “definitive stakeholder’s” perspective is that the FMA is easily implementable, very efficient at reducing the risk of floods, and less costly, he or she would tend to prefer such alternative.

Table 23: *Implementation Criteria for Each Alternative*

Criteria			Description	UNITS
Quantitative	1	Cost of maintenance/year	The total cost in of operating and maintaining the FMA.	USD $
	2	Investment	Total cost to evaluate and implement the FMA. (i.e. feasibility studies, permits documentation, construction, etc.	USD $
	3	Job creation	The amount of jobs generated during the construction period.	# of jobs
	4	Duration	The duration for implementing the FMA.	Months
Qualitative	5	Implementation Easiness	Rating of from stakeholders on their perception of the criteria.	Pairwise comparison scale
	6	Most efficient decreasing flooding impacts		
	7	Costly		

The preferable FMA will be the one that provides greater benefits with fewer costs. To evaluate how each FMA ranks in terms of benefits and cost, a benefit-cost (B-C) ratio analysis is performed. Previously, different criteria are identified for the performance evaluation of the FMAs. Before computing the AHP matrices, it is important to differentiate which criteria represent a benefit and which criteria represent costs. The benefit criteria refer to criterions that give an advantage such as reducing the risk of flooding. In contrast, cost criteria refer to the ones that represent a cost like the investments required for implementing, operating, and maintaining the proposed FMA. A summary of the criteria to be considered for the AHP-MC DMM is presented in Table 24.

Table 24: *Identification of Benefit and Cost Criteria for the AHP*

	Criteria	AHP Category
Quantitative	Implementation Cost	Cost
	Maintenance Costs	Cost
	Duration	Cost
	Job Creation	Benefit
	Risk Reduction	Benefit
Qualitative	Implementation easiness	Benefit
	Most efficient decreasing flooding impacts	Benefit
	Costly	Cost

Once the goal has been defined (i.e. select FMA), the alternatives have been proposed, and the evaluation criteria have been determined, it is possible to represent the AHP-MC DMM diagram. As shown in Figure 20, the main goal of the model is to select a FMA. The criteria have been divided into benefit criteria and cost criteria. To estimate the reduced risk criteria, the “no action” alternative results are defined as the base risk.

The risk reduction benefits for the other two alternatives were obtained by subtracting their AAI from the "no action" alternative AAI. For example, if the total AAI for the "no action" and the "levee" alternatives is 3 and 2 respectively, the risk reduction value for the "levee" would be 1. The "*costly*" and "*most efficient decreasing flooding*" qualitative criteria are not included in the analysis. For each criteria and FMA, the weigh factor (W_i) is calculated following the AHP methodology in Section 3.3.4.

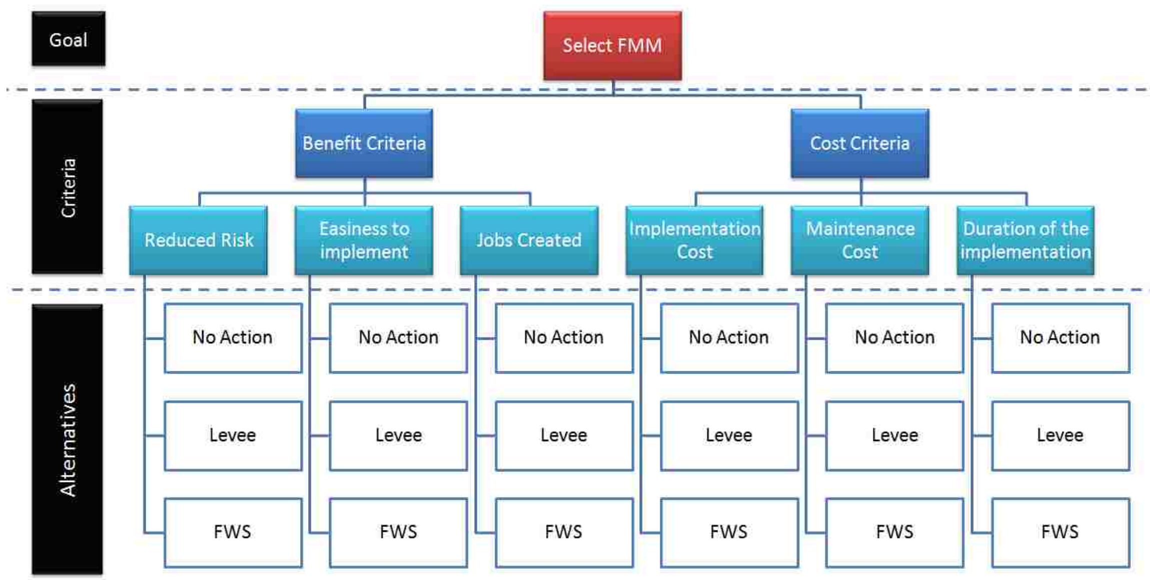


Figure 20. Study's AHP-MC DMM diagram

The evaluation of the qualitative criteria for this study is obtained from questionnaire B (Appendix B). In the questionnaire, were agency officials (listed in Table 33) are asked to use their best judgment to rank structural and non-structural FMA in three categories: the FMA's effectiveness in reducing the flood risk, (2) implementation costs, and (3) easiness to implement. The ranking scale in the questionnaire was from 1 to 8 were 1 was the easier to implement, most efficient in reducing risk, and most costly to implement. The survey results collected to use for suggested alternatives are converted into weights factors using the AHP methodology defined in Section 3.3.4. The output of the model is a B/C ratio of the FMAs providing the decision-maker even more information than the MC-DMM.

3.5 Case Study: Upper Río Grande of Loíza Watershed, Puerto Rico

The island of Puerto Rico is located in the Caribbean (Figure 21). The island has approximately 3,500 square miles and has an estimated population of 3.72 million (CENSUS, 2010).

Figure 21. Location of Puerto Rico

Given its position in the Caribbean, the island is subject to several and intense rainfall events, tropical storms, and hurricanes making it susceptible to flooding. In Figure 22, the mean annual rainfall from 1981 to 2010 is spatially represented. The tropical rainforest, El Yunque, is located in the northeastern part of the island and receives up to 170 inches of rain annually. The topography of the island is composed of a central ridge from which many of the rivers are born.

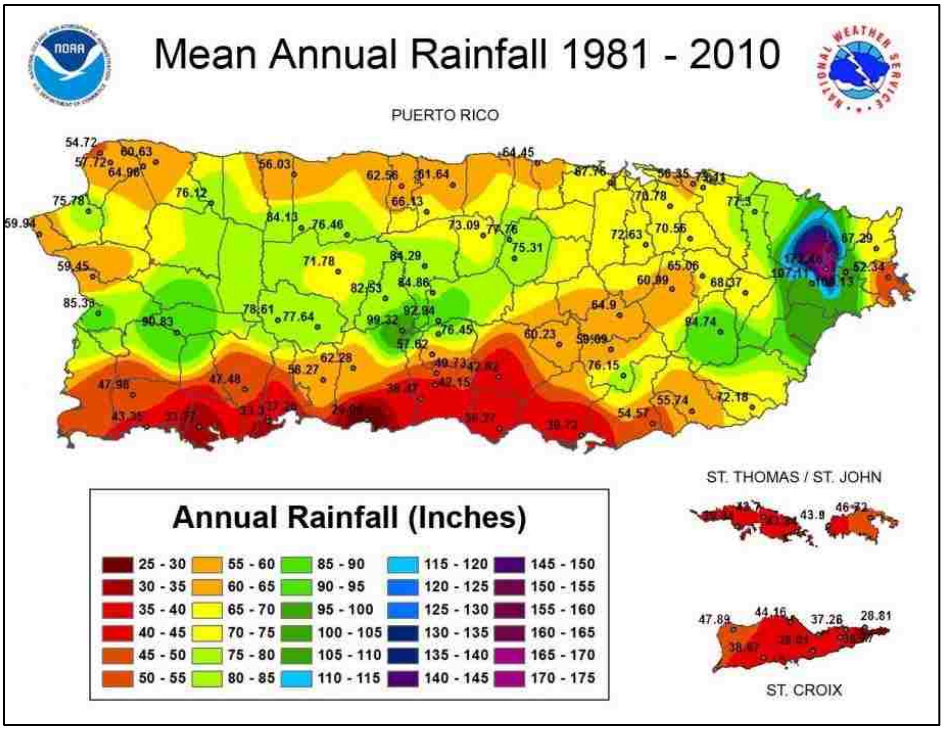


Figure 22. Mean annual precipitation in Puerto Rico from 1981-2010 (SJU Webmaster, 2013)

There are a total of 22 watersheds in Puerto Rico and the Río Grande de Loíza Watershed (RGLW) is the largest one with a total drainage area of 310 square miles to the Atlantic Ocean. The watershed is located on the northeastern coast of Puerto Rico (Figure 23) originating from the east-central area of the island. Nearly all of the major tributaries join the Río Grande de Loíza near the upstream end of Lago Loíza in the municipality of Caguas area. The primary exception is the Valenciano River, which joins Gurabo River at Juncos. The watershed is composed of 10 municipalities: Aguas Buenas, Carolina, Caguas, Gurabo, Juncos, Las Piedras, Loíza, Río Grande, San Lorenzo, and Trujillo Alto.

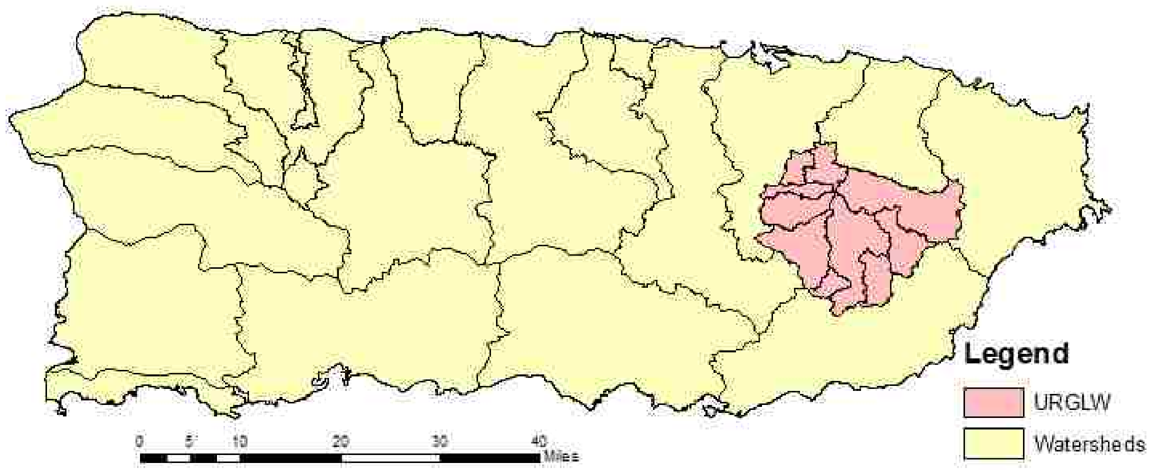


Figure 23. Upper Río Grande of Loíza Watershed (URGLW)

The Upper Río Grande de Loíza Basin change from agricultural use to residential, commercial, and industrial use around the 1980s. The major cities in the basin are Caguas, Carolina, and Trujillo Alto. Smaller cities located in the basin are Gurabo, Juncos, and San Lorenzo. The increase of developments near rivers and in low laying areas has increase the risk of floods to the population.

3.4.5 Past Flood Events in the Río Grande de Loíza Basin

The largest known flood to occur on Río Grande de Loíza was on August 4, 1945 with a discharge of 85,108 cfs. On the Río Gurabo at Gurabo, the largest flood occurred on September 6, 1960, with a discharge of 74,514 cfs. Other notable floods occurred on Río Grande de Loíza on September 6, 1960, August 4, 1961, August 10, 1965, and October 9, 1970, with discharges of 71,512 cfs, 48,381 cfs, 34,962 cfs, and 62, 860 cfs, respectively.

The Río Gurabo experienced a major flood on October 9, 1970 with a discharge of 63,919 cfs (USCE, 1991).

3.4.6 Study Region

The study region selected for this study is the Upper Río Grande of Loíza Watershed (URGLW). The region was defined based on a feasibility study conducted by the United States Corps of Engineers (USCE) in 1991. The report recognized that most of the existing mitigation alternatives implemented or proposed for the watershed were located in the lower region of the watershed. For this study, we are modeling the effects of mitigation alternatives proposed by the USCE report for the Upper Río Grande of Loíza Watershed (URGLW).

Because of the political status of Puerto Rico as a United States territory, Puerto Rico has access to the benefits provided by federal programs and agencies such as the Federal Emergency Management Agency (FEMA). The organizational structures in Puerto Rico for emergency preparedness and management are similar to those in the States.

To perform a Level 1 analysis, HAZUS only requires the input of a DEM. To obtain the DEM, HAZUS provides a built-in feature, which determines the extent of the region and extracts the required data from The National Map Seamless Server Viewer (See Figure 24). The default option is a 1" NED DEM (30 meter), but you can edit the selection and obtain a better resolution DEM. For the study region, the DEM selected was the 1/3" (10 meter) DEM since it was the best resolution available for the entire area. Also, since the study region is extensive, a smaller DEM will require more processing time.

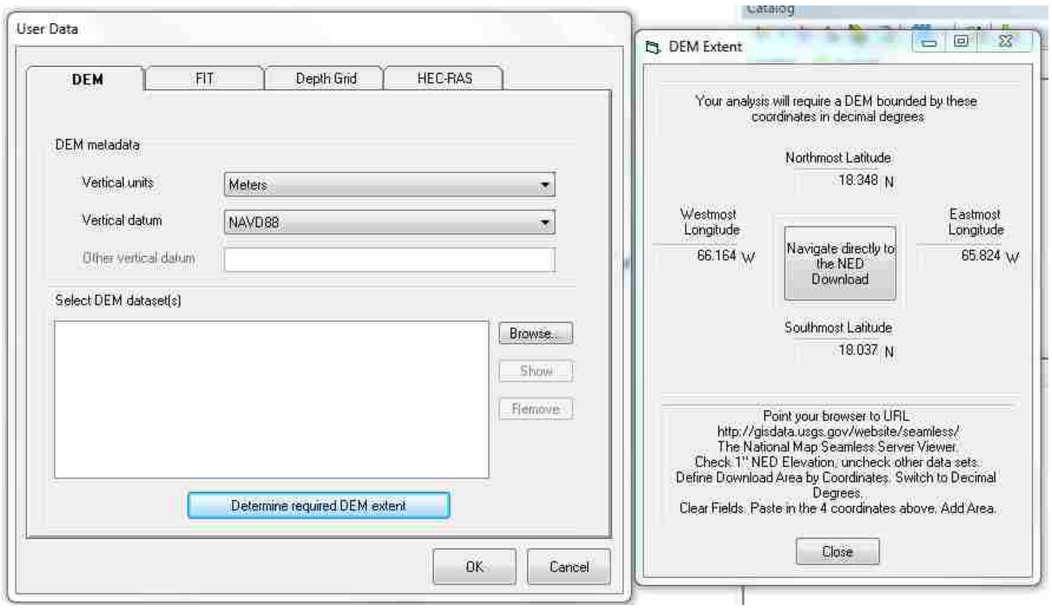


Figure 24. DEM selection of study region.

Once the DEM is added as an input, HAZUS processes the elevation data and create a terrain for the study region as shown in Figure 25.

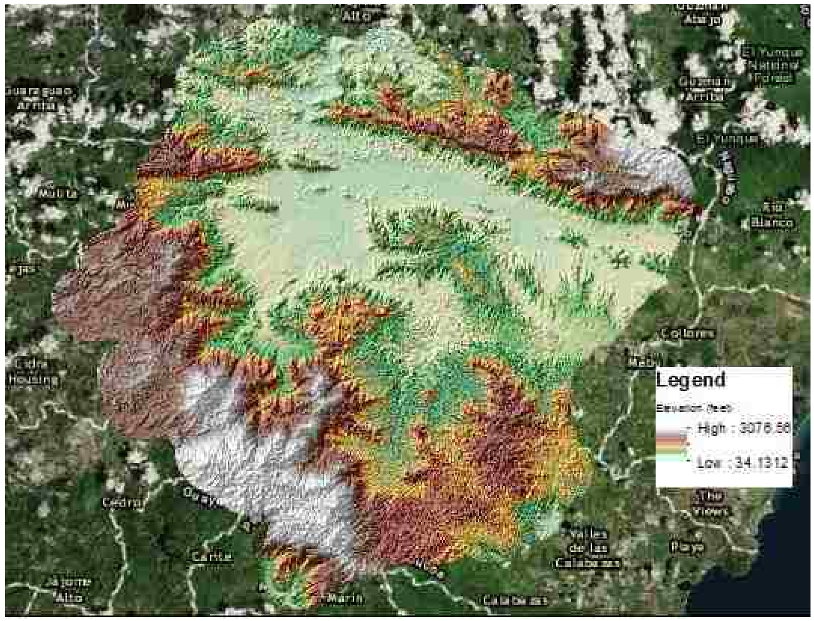


Figure 25. Terrain elevation for study region.

3.4.7 Flood Mitigation Alternatives

Using the tools within the HAZUS software, it is possible to implement a levee, a flow regulation, and a flood warning system. A more advance user is capable of studying the effects of changes in policies such as base flood elevation, land development, among others. As previously mentioned, in this study, three types of mitigation alternatives were studied: (1) no action (2) a combination of levees, and (3) the implementation of a flood warning system.

Within the HAZUS software, the flood model and loss estimation was performed for each return period and each alternative being considered resulting in a total of 15 scenarios developed for the case study. Table 25 presents the list of the defined scenarios and the Scenario ID to be used to identify each scenario.

Table 25: *Case Study Scenarios*

Scenario	FMA	Return period	Scenario ID
1	No action (NA)	010	NA010
2		025	NA025
3		050	NA050
4		100	NA100
5		500	NA500
6	Levee (L)	010	L10
7		025	L25
8		050	L50
9		100	L100
10		500	L500
11	Flood warning system (FWS)	010	FWS10
12		025	FWS25
13		050	FWS50
14		100	FWS100
15		500	FWS500

The "no action" scenario defines the current risks within the study region. Once the risks are identified, the other alternatives are evaluated. The levee is considered a structural mitigation measure and will have an effect on physical impacts (i.e. floodplain and the depth grids) of the flood events. In contrast, the flood warning system (FWS) is a non-structural mitigation measure. FWS provides individuals with an advance warning of a flood event giving them more time to protect their lives and their property. In this study, the benefits of a FWS are assumed to only reduce the building losses (economic category). The other two impacts categories are assumed to be the same as the "no action" alternative. It is significant to clarify that other benefits can be gained from a FWS, the most important one being the protection of human lives.

Using the information from a feasibility study performed by the USCE (USCE 1991) for the URGLW, three levees are proposed. In Figure 26 the spatial location of all three levees is presented. The figure shows the location of the proposed USCE levees and the actual location of the levees that were modeled in the HAZUS software. Levee 1 (Figure 27) protects the community at the south side of the Caguitas River and was given a protection level for the 25-year flood event as proposed by the USCE. Levee 2, shown in Figure 28 delineates the location of the levee proposed by the USCE at the west side of the Río Grande of Loíza river with a protection of a 100-year flood for the adjacent communities at the west of the levee. Levee 3 is located at the south side of the Gurabo River. Given the wrong delineation of the river in the HAZUS software the levee was reconfigured as shown in the Figure 29.

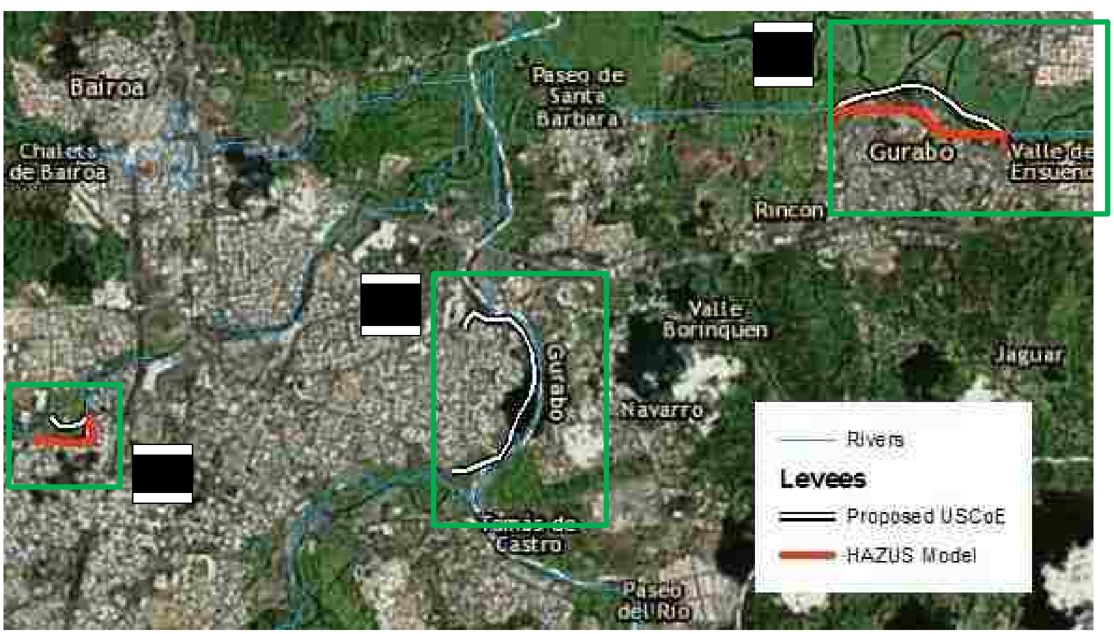


Figure 26. Spatial location of the proposed levees

Figure 27. Proposed levee for Caguitas River (Location 1 in Figure 26)

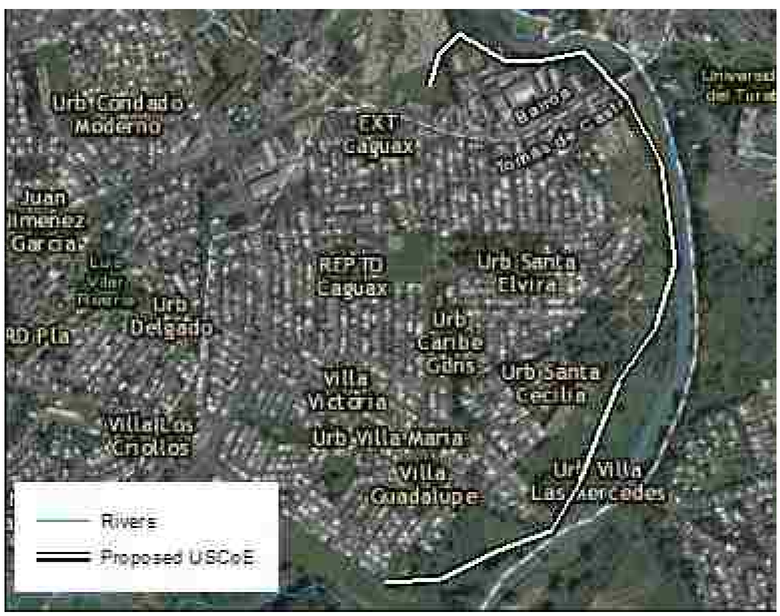


Figure 28. Proposed levee for Río Grande of Loíza River (Location 2 in Figure 26)

Figure 29. Proposed levee for Río Grande of Loíza River (Location 4 in Figure 26**)**

3.4.8 Case Study Surveys

The official languages of the island are Spanish and English, with Spanish being the primary one. In order to accommodate the participants, the survey described in Section 3.3.2 was conducted in Spanish. The survey was translated by the author, who is native of Puerto Rico, has completed college education, and is completely fluent in Spanish. Before deploying the surveys, a Human Subjects Exemption Certification was received from the University of New Mexico Institutional Review Board (IRB) (See Appendix A).

3.6 Chapter Summary

This chapter presented the proposed methodology for a holistic decision-making framework that takes into account economic, social, environmental, and implementation criteria to assess the impact of proposed FMAs. In addition, network analysis, and stakeholder theory was integrated into analysis to account for the stakeholder's roles and opinions. The methodology in Figure 2 consists of four main components: (1) a flood model to assess the extent and force of the floods due to proposed mitigations, (2) the estimation of flood impacts using a spatial flood risk assessment, (3) survey instruments to collect data from the stakeholders, and (4) the use of decision-making model that combines the theory of AHP with Monte-Carlo Simulation. Finally, a description of the case study used to illustrate the methodology was presented. The proposed framework provides a structured methodology that can facilitate the evaluation of multiple FMAs.

CHAPTER 4: RESULTS AND ANALYSIS

4.1 Flood Model Results and Interpretations

The flood model analysis was performed with the HAZUS software from FEMA. HAZUS requires the user to define the drainage area for the stream delineation process. For the study region, the drainage area of the streams was defined as 3 mi^2 (7.77 km^2). The resulting stream network is illustrated in Figure 30.

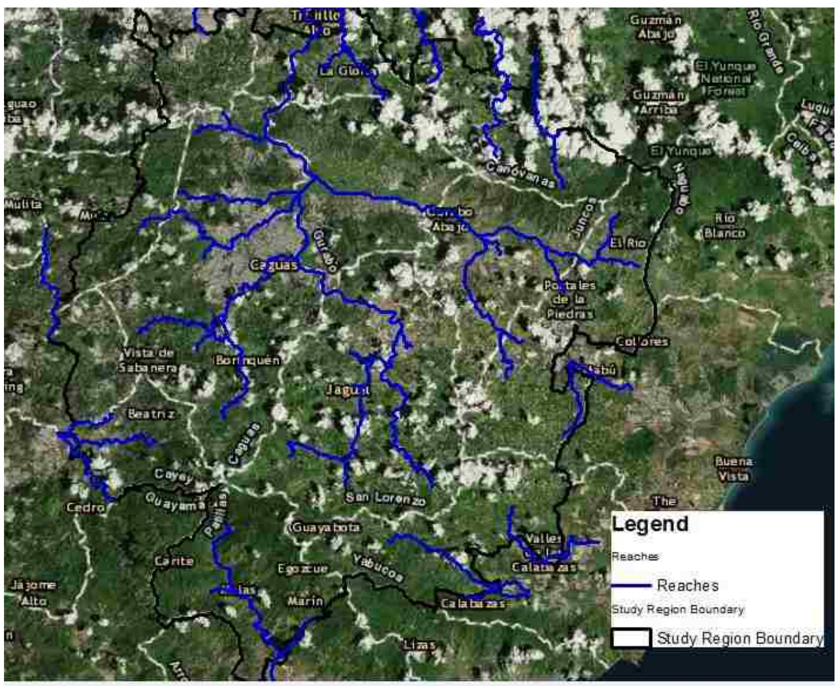


Figure 30. Study region stream network for a 3 square miles drainage area

With the stream network defined, HAZUS performs an H-H analysis in order to delineate the floodplain and calculate the depth grids for each scenario. As an example of the results obtained, Figure 31 shows the results for the "no action" flood mitigation alternative for a 10 year return period (NA010) scenario.

Figure 31. Floodplain and depth grid for the NA010 scenario

4.2 Spatial Flood Risk Assessment (SFRA)

The risk assessment was performed with the results obtained in Section 4.1 and the flood loss estimated calculated by HAZUS. The loss estimation data can be obtained from HAZUS in two formats: written report and GIS data formats (i.e. polygon shapefile). Using these results and the data processed spatially in ArcGIS, the spatial risks for the decision criteria (economic, environmental, social, and implementation-related) were calculated. In the following sections, a summary of the results for each impact category is presented.

4.2.1 Economic Impacts

The criteria used to evaluate the economic impacts were the damage to buildings and infrastructure. Information about the losses as well as data layers were obtained for each scenario defined in Table 25. Figure 32 shows the results obtained for the NA010 scenario. The damage to the infrastructure is presented as point data. The results show that the infrastructure affected by a 10-year flood included two wastewater treatment facilities, one potable water facility, and four bridges. The building damage was obtained as a polygon shapefile aggregated to the census block area.

Figure 32. Economic loss results for the NA010 scenario

A summary of the aggregated results obtained for the building loss estimation is presented in Table 26 for each scenario. Approximately 99% of the losses are associated to residential buildings. The impact to residential buildings affects the recovery process of the community, sometimes requiring temporary or permanent relocation of the residents creating additional social impacts (i.e. anxiety, depression, etc.). The total AAI for building losses is calculated using Equation 3. From the results, FWS presented the lowest AAI of $16,846,800.

Table 26: *Building Loss Estimation Results*

FMA		Total Loss ($1000's)				Total AAI
	Scenario	Residential	Commercial	Industrial	Buildings total	
No Action	NA010	176,170.00	670	30	176,870.00	19,359.01
	NA025	199,800.00	730	70	200,600.00	
	NA050	203,050.00	730	60	203,840.00	
	NA100	217,700.00	750	11	218,461.00	
	NA500	250,270.00	820	200	251,290.00	
Levee	L010	183,000.00	430	50	183,480.00	18,991.99
	L025	189,470.00	720	90	190,280.00	
	L050	197,930.00	720	140	198,790.00	
	L100	210,340.00	760	160	211,260.00	
	L500	247,290.00	810	200	248,300.00	
FWS	FWS010	153,370.00	600	30	153,970.00	16,846.80
	FWS025	173,910.00	660	60	174,630.00	
	FWS050	176,730.00	650	50	177,430.00	
	FWS100	188,750.00	700	120	189,570.00	
	FWS500	217,810.00	740	180	218,730.00	

Figure 33 depicts the total building losses for every alterantive. As expected, the figure shows the losses increasing as the return period increases, with the 500 year return period having the highest loss for all three alterantives. Figure 34 shows the total AAI for each alternative. In this case, considering only the building loss data, the FWS alternative had the lowest AAI of all the options.

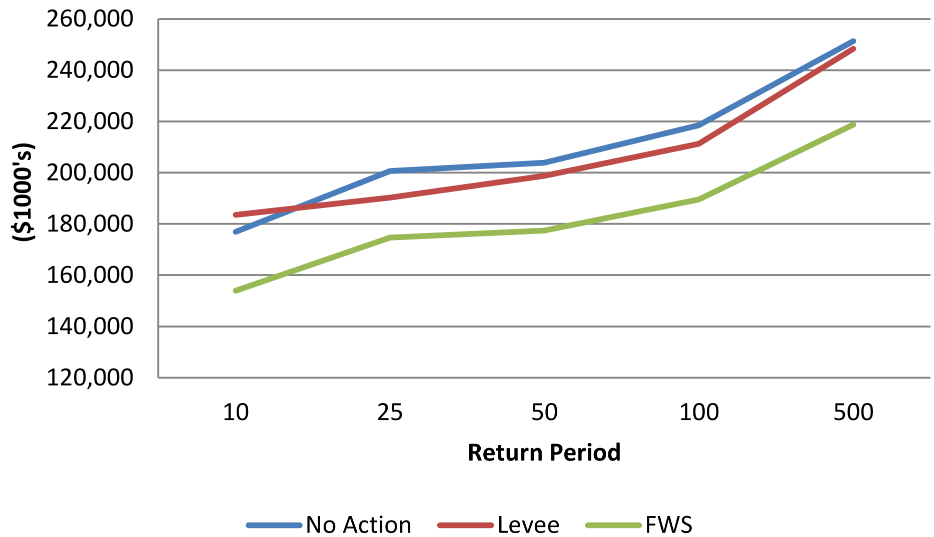


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Figure 33. Building total losses for each alternative

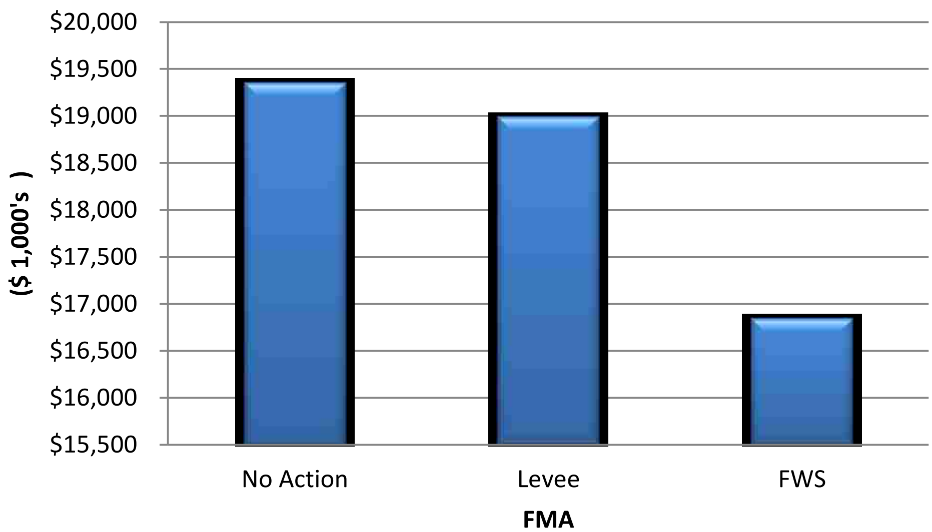

Figure 34. Buildings total AAI for each alternative

The infrastructure loss estimation analysis included the flood impacts to bridges, potable water facilities (PTF) and wastewater treatment facilities (WWTF). The summaries of the results are presented in Table 27. As expected the flood impact increases as the return period of a flood event increases. The impact of the FWS was assumed to be the same as the “no action” scenarios since the FWS does not help reducing the impacts to the infrastructure. The impact of levees to bridges is only reduced for the 25-year return period by 22%. The results may indicate that the implementation of levees can cause the overflow of rivers to have higher impacts on the infrastructure, therefore, as part of the implementation process, various alternatives to protect the infrastructure should be considered (i.e. replacement of bridges, protection of infrastructures, etc.). For purposes of this study, the implementation of the levee will not include the cost of impacts of such protection alternative.

Table 27: *Infrastructure Loss Estimation Results*

FMA	Scenario	Total Loss ($1000's)				
		Bridges	PWF	WWTF	Total Damage	TOTAL AAI
No Action	NA010	9.77	13.32	24.04	47.13	8.80
	NA025	40.92	13.32	26.39	80.63	
	NA050	48.86	13.32	26.45	88.63	
	NA100	97.72	13.32	19.15	130.19	
	NA500	360.71	13.32	40.13	414.16	
Levee	L010	9.77	13.32	26.64	49.73	9.57
	L025	45.09	13.32	33.25	91.65	
	L050	48.86	13.32	33.47	95.65	
	L100	97.73	13.32	35.85	146.9	
	L500	360.71	13.32	40.51	414.54	
FWS	FWS010	9.77	13.32	24.04	47.13	8.80
	FWS025	41.01	13.32	26.39	80.72	
	FWS050	48.86	13.32	26.45	88.63	
	FWS100	97.72	13.32	19.15	130.19	
	FWS500	360.71	13.32	40.13	414.16	

Figure 35 represents the total infratructure losses for each alterantive. Both figures illustrate how the levee alternative generates more losses than the “no action” and FWS alternatives. In Figure 36 the infratructure AAI for each alternative is shown. In this case, considering only the building loss data, the “no action” and FWS alternatives had the lowest AAI from the three alternatives.

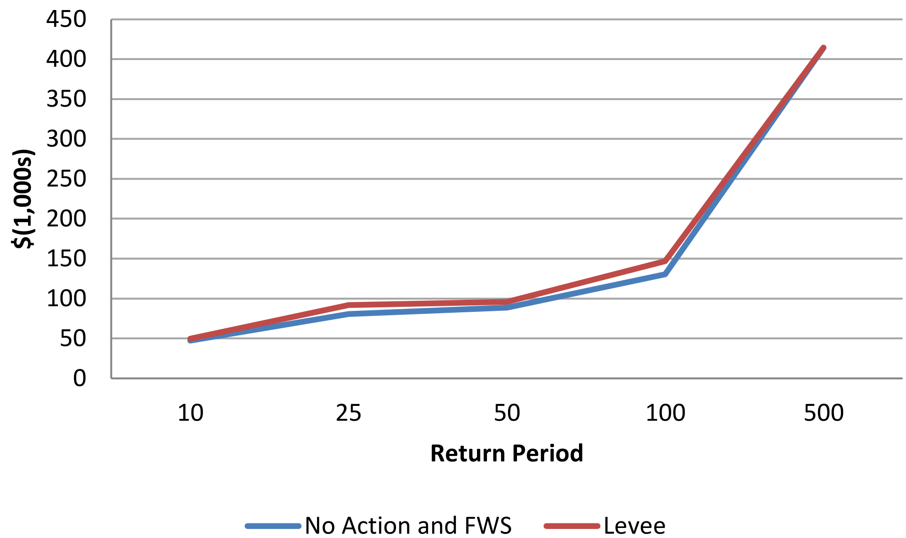

Figure 35. Infrastructure total losses for each alternative

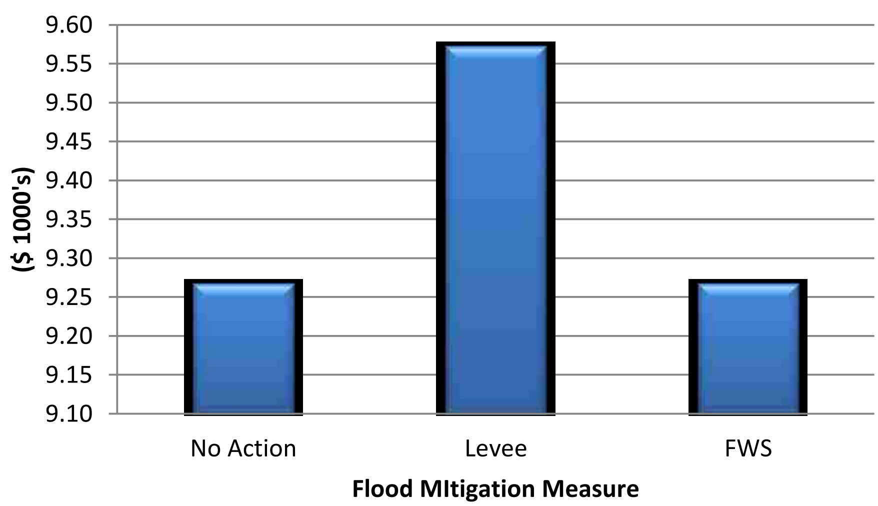

Figure 36. Infrastructure total AAI for each alternative

4.2.2 Social Impacts

The social impacts are evaluated in terms of the following criteria: (1) displaced population, (2) need for short-term shelters, and (3) social hot spots affected. The estimation of the displaced population and the short-term shelters was obtained from the HAZUS model. The analysis for social hot spots can also be performed within HAZUS, but in order to include additional facilities not included in HAZUS inventory data, the estimation was performed outside of the HAZUS model.

HAZUS is able to estimate the number of families that should be displaced from their homes due to the occurrence of a flood event. The software also estimates how many of the displaced families will require temporary shelters. The results collected for the displaced population and shelter needs are presented in Figure 37 to Figure 40. In Figure 37 and Figure 38, the results are shown for the displaced population and shelter requirements respectively. For example, for 100 years return period of the levee alternative, the model estimates 10,823 people will be displaced due to the flood impact. Displacement includes households evacuated from within or from very near the flooded area. Of the people displaced, 9,846 (90%) will seek temporary shelter. Both graphs show an increase on the number of people affected as the return period increases. The levee alternative had less impact on the number of people affected, except for the 500-year return period. Considering that the levees were design for a 100-year return period, the protection will not be enough if a 500-year event were to occur.

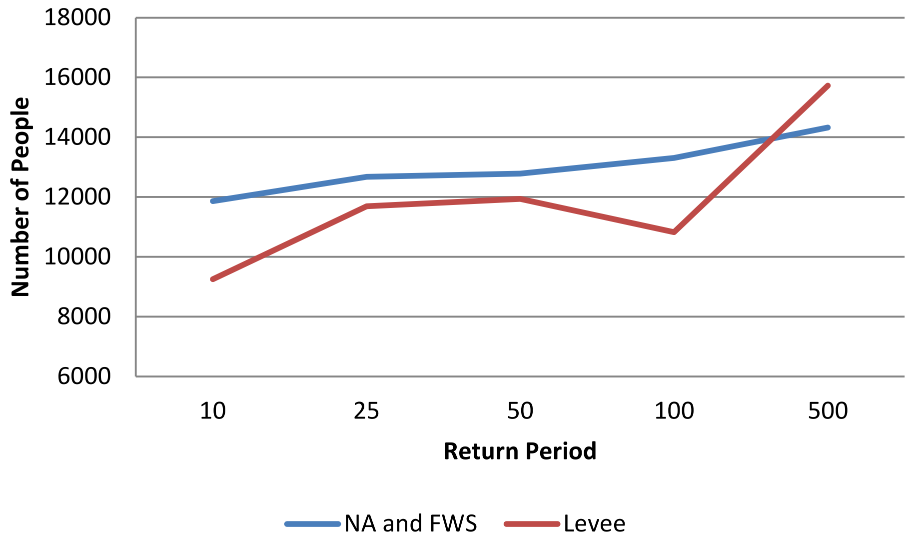

Figure 37: Graph of the # of People Displaced for Each Return Period

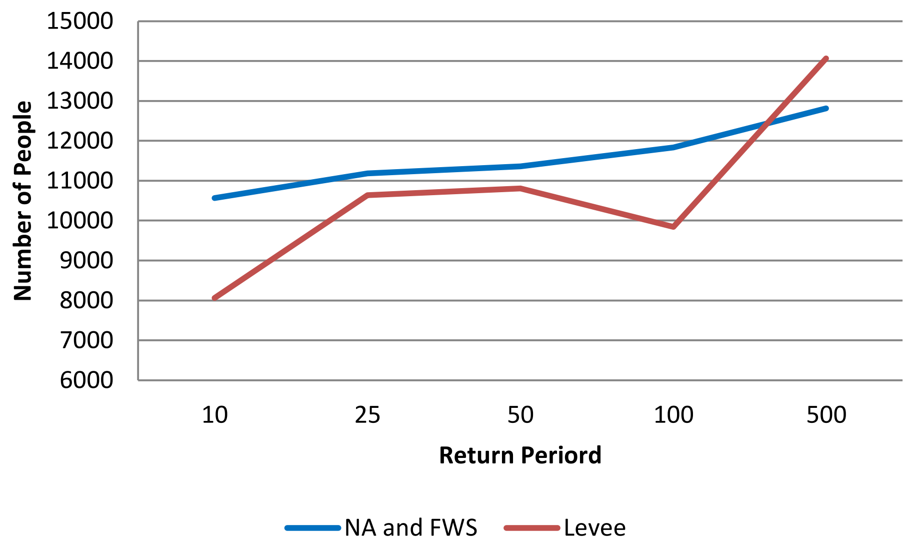

Figure 38. Graph of the number of people in each scenario requiring shelter

In Figure 39 and Figure 40, the total AAI obtained for the displaced population and shelter requirements are shown in a bar graph. The total AAI for the levee alternative is shown to be lower than the other two alternatives by an average of 6%. From the results obtained for the number of people displaced and the number of people requiring short-term shelters, the levee alternative appears to be the best in reducing the impacts of flood.

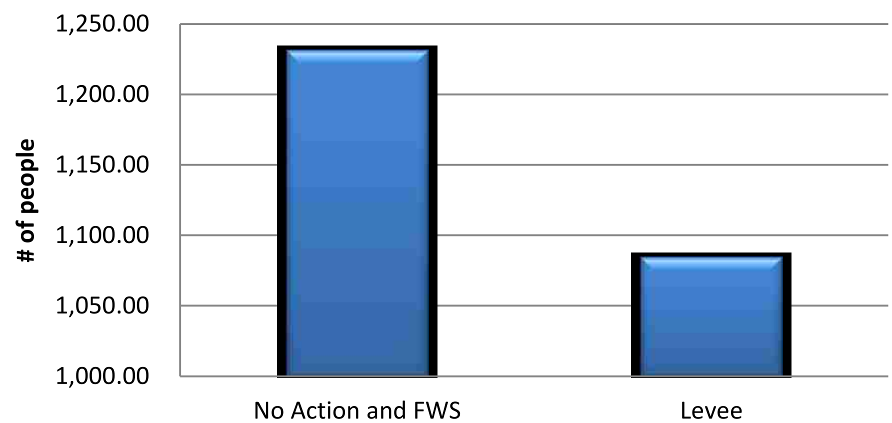

Figure 39. Total AAI for the displaced population criteria

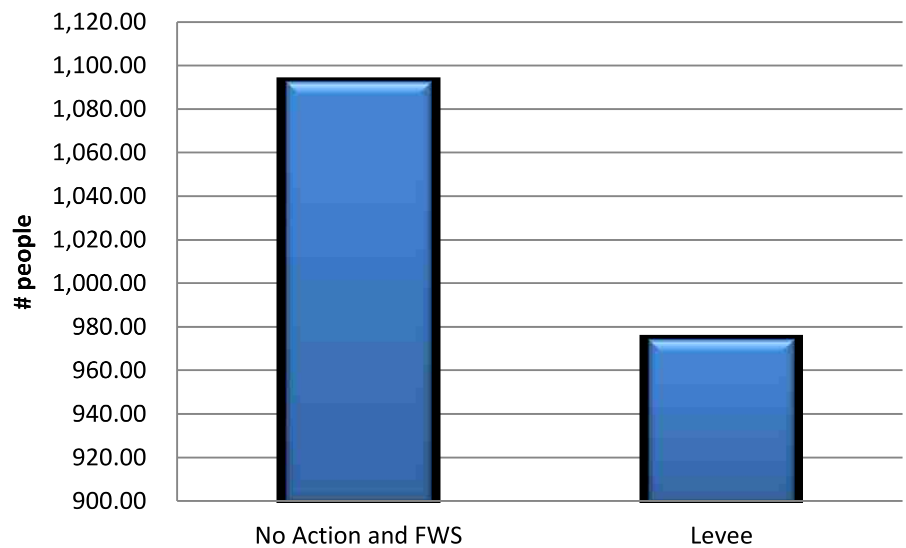

Figure 40. Total AAI for the shelter-requirements criteria

4.2.3 Environmental Impacts (EI)

Three environmental criteria were considered to obtain the EI: (1) debris generation, (2) critical habitats affected, and (3) landslide potential. The datasets were processed using the methodology described in Section 4.2.2.

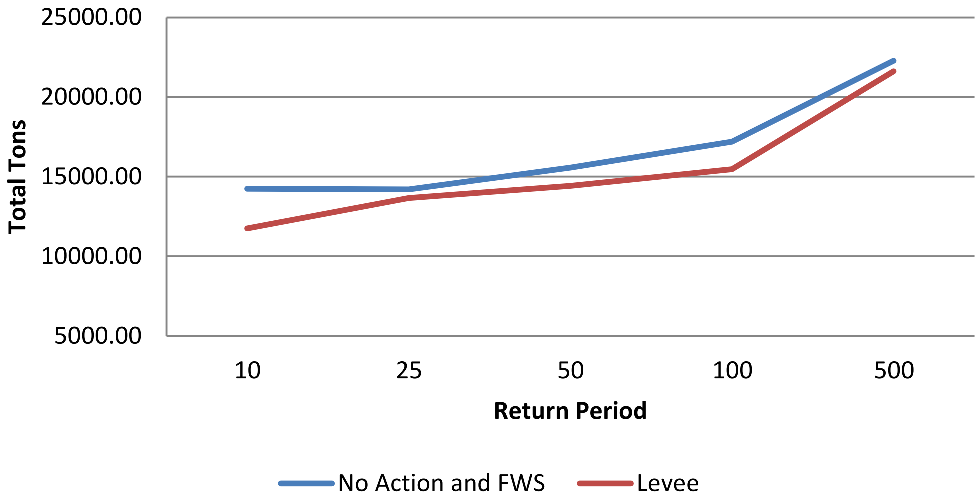

Figure 41. Graph of total debris generated by the alternatives for each return period

The expected debris generated for each return period by each alternative is presented in Figure 41. From the figure, the levee alternative generated less debris for all return periods. For the estimated AAI (see Figure 42) the levee alternative generated 1,341.80 tons of debris, which is 4.61% lower than the other two alternatives. From the results obtained for the debris criteria, the levee alternative is expected to minimize the risks of the amount of debris generated.

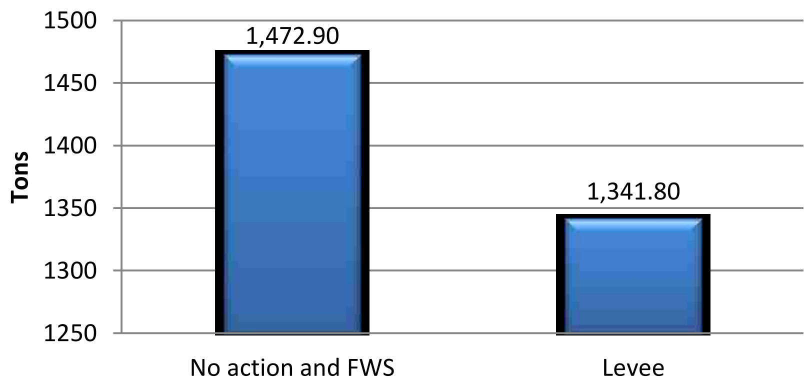

Figure 42. Bar chart of alternatives total AAI for the debris criteria

4.2.4 Spatial Average Annual Impacts (SAAI)

After all the data was processed, the number of cells with a low, moderate, and high ranking was obtained. To get the final impact for each category the following equation was used:

(12) $$I_{k,i} = \sum_{x=1}^{n} IR_x \times CN_x$$

In this equation, I is the total impact for alternative k and return period i, IR is the ranking of the risk category *x* (Refer to Table 15) and CN is the number of cell with ranking *x*. The IR was defined as 1 for low risk, 2 for moderate risk and 3 for high risk. A summary of the impacts results for each alternative within each scenario is presented in Figure 43**.** The results show a consistency of increase in impact for each of the FMAs as the return period is increased. Also, the total AAI for the "levee" alternative showed to be the lowest in all return periods except the 500 year. This result is expected since none of the Levees incorporated in the model were designed for a 500 year event.

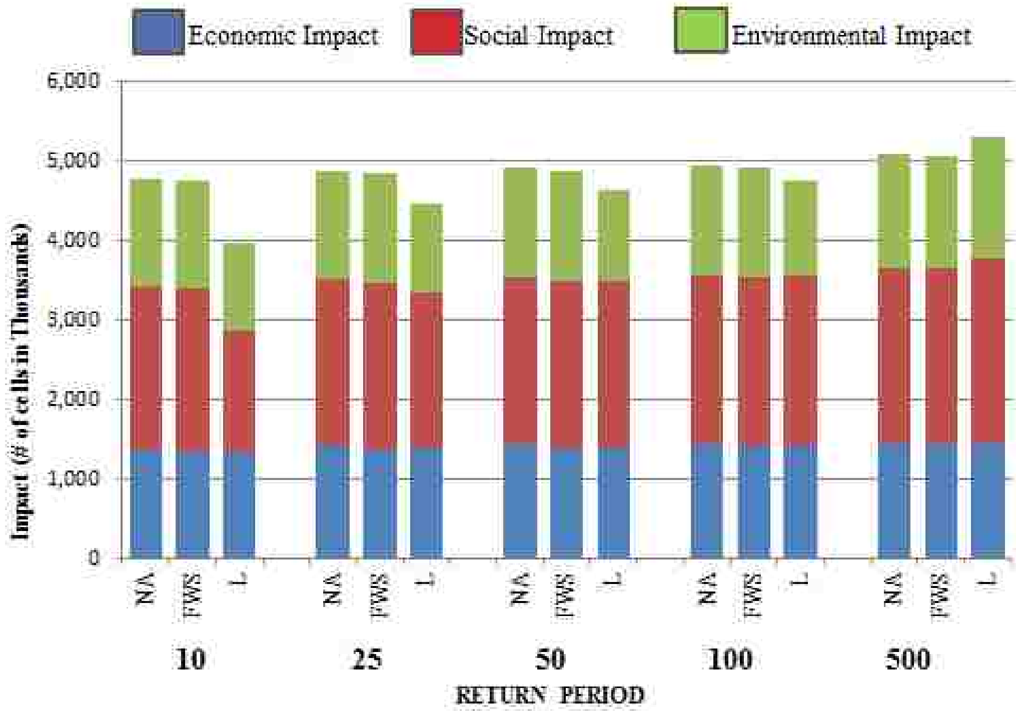

Figure 43. FMA AAI results for each scenario

4.3 Stakeholder Analysis

As described in Chapter 3, the incorporation of the stakeholder's opinion in the decision-making analysis for selecting among flood mitigation alternatives was studied using interviews and questionnaires. The results from the data collected were used to develop the importance weight factors for the risk criteria and define the influence that each stakeholder will have on the final flood mitigation decisions. In this section, the results from the questionnaires are presented. Furthermore, an inter-agency network analysis is conducted in order to understand the interactions between the stakeholders identified for this study (Refer to Table 33). Using Mitchell et. al. (1997) theory of the salience of the stakeholders, it is possible to determine whose opinion will be incorporated in the decision analysis.

4.3.1 Questionnaire Instrument

The opinion and characterization of the stakeholders and agencies interactions was gathered using two web-based surveys, which were deployed using Qualtrics software. As described in Chapter 3, each survey targeted a different population: (1) Survey A targeted residents of the commonwealth of Puerto Rico and (2) Survey B targeted public officials of agencies directly or indirectly responsible for reducing the risk of flooding within the study region. The following sections present a discussion of the results obtained.

4.3.1.1 Survey Deployed to the Community

The survey was completed by a total of eighty-five (85) participants. A summary of the demographics is presented in Figure 44, Figure 45 and Figure 46. In total, 59% of the survey population was in the age group of 26-35 and 54% were males. In terms of education level, most of the respondents have a college education or higher (97%).

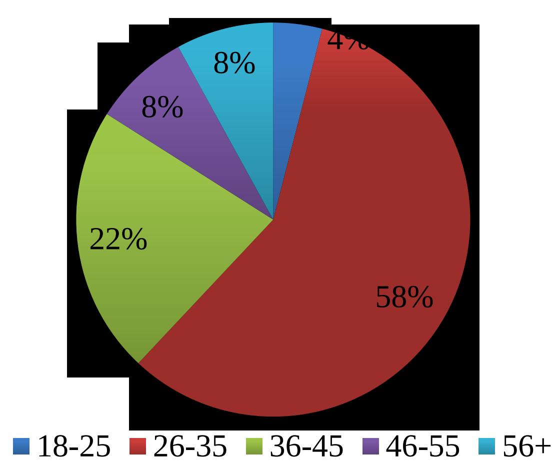

Figure 44. Age Distribution of Participants

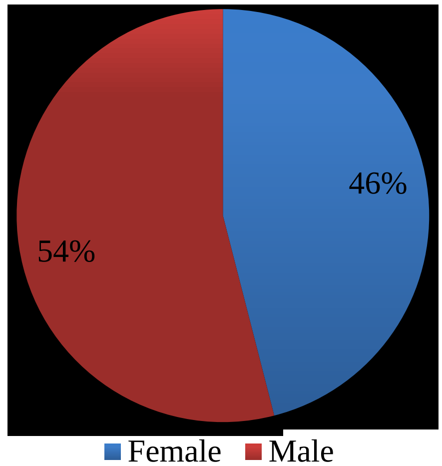

Figure 45. Gender Distribution of the Participants

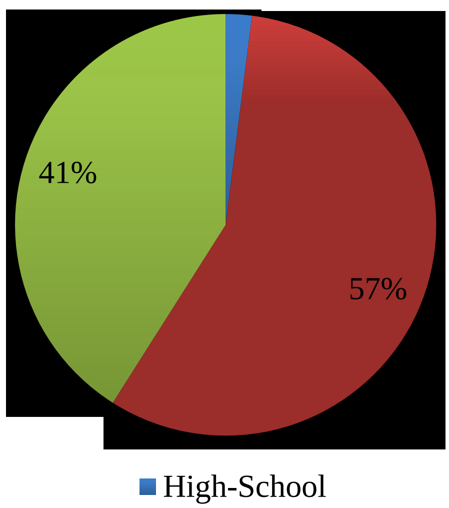

Figure 46. Education level of participants

The questionnaire asked participants about their current flood mitigation features for a maximum of two structures, only if they were the owner or tenant. In total, the respondents provided information on the structures' flood risks and flood protection measures for 94 structures.

The vulnerability of a community is dependent on its residents perception to flood and how well prepared they are *(*Few, 2003*)*. To be prepared, it is important to know and understand the risks to which the community is subjected to, if any. When participants were asked if there was a flood risk to their structure or to their community, 59 (85%) were aware about their exposure to risk. The other 15% were "unsure" about the existence of flood risk to their structures. From those not sure about been exposed to flood risk, 34 are worried about a potential flooding event (Table 28). Government agencies dedicated to education of individuals and communities should target the "unsure" individuals in order to minimize their vulnerability to flood events.

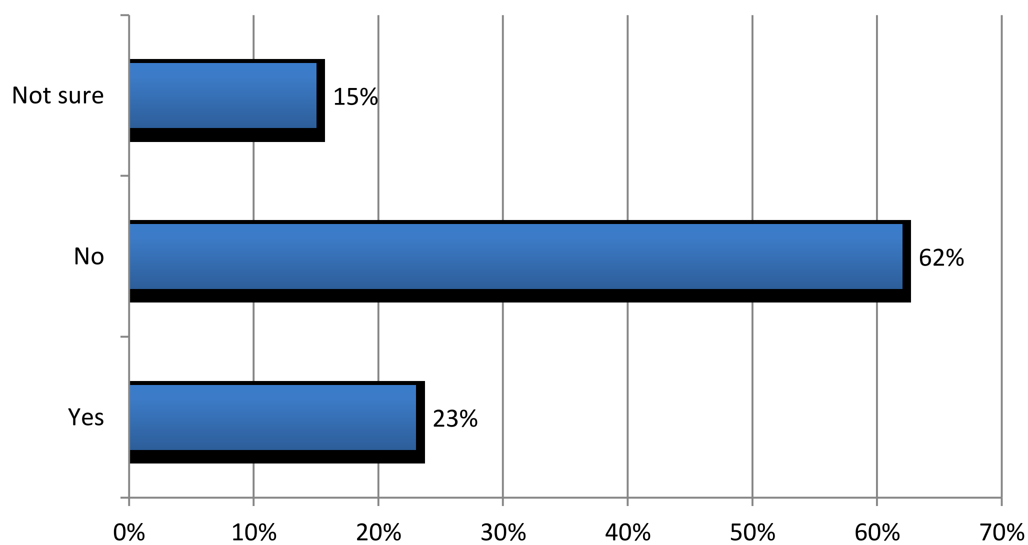

Figure 47. Response from participants indicating existence of risk to their structure

Table 28: *Cross-Tabulation of the Risk (rows) Individuals are Exposed to and Their Worry About the Risk (columns)*

Risk/Worry	Worries Me A Lot	Somewhat Worried	Not Worried
Yes	12	12	6
No	8	14	7
Not sure	2	32	1

Furthermore, the participants were asked to indicate if their structure had some kind of flood mitigation feature, either structural or non-structural. As shown in Figure 47, 34% percent of the respondents have some kind of flood protection and 28% did not know.

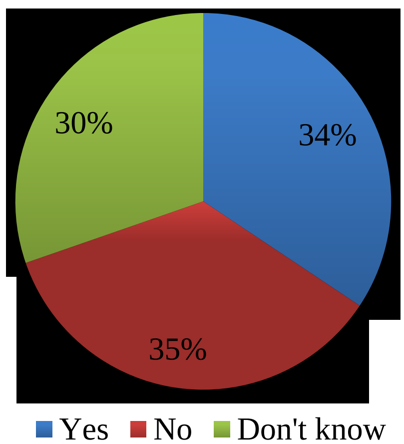

Figure 48. Existence of flood protection to structures

Participants, who indicated to have flood protection or were not sure of having protection, were asked to indicate the type of protection (Figure 49), and the rest were asked why they do not have a protection alternative (Figure 50). From the protection alternative used, flood insurance is the most common followed by the structure been elevated above the base flood level. For 18 of the structures the respondent still was not sure if the structure had some kind of flood protection, which again, increases the vulnerability for those structures if they are in fact subjected to flood risks.

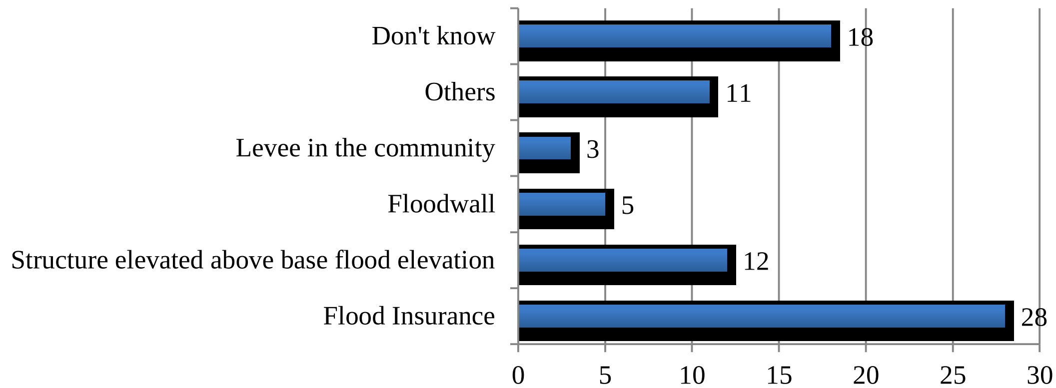

Figure 49. Respondents indicate the type of protection measures implemented in their structures

From the 35% respondents who did not have any kind of flood protection, 36% indicated that they had never thought about it or that it was not their responsibility. This is again indicative of the need of education from the government so that the communities take actions against floods and increase their resilience to a flood risk.

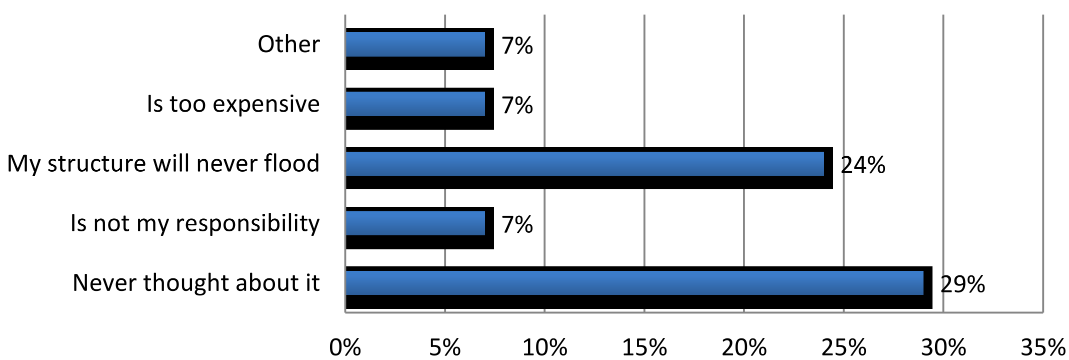

Figure 50. Respondent indicate why the structure does not have any flood protection

In term of past flood events, only 17 out of the 85 participants responded that they had experienced a flood event. Participants, who answered yes to experiencing a flood impact, were asked to rate the severity of the event (Figure 51). From the responses, 35% rated the event as minimal, 47% as moderate, and 18% as a major impact event.

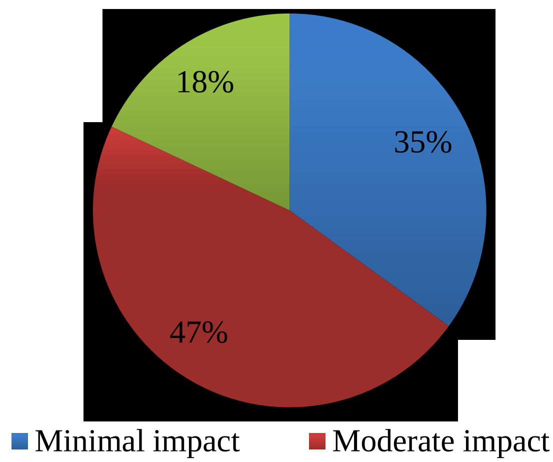

Figure 51. Severity of past flood events experienced by the survey respondents

As discussed earlier, education on the floods plays an important role in minimizing the vulnerability of community. From the survey, a surprising 67% of the respondents stated they have not received any kind of education about flood risk and mitigation alternative (Figure 51). Only 28% percent stated they had some kind of educational information, but when asked who provided the information almost half of the respondents answered that is was supplied by other entities (i.e. University, Puerto Rico Professional College of Engineers and Land Surveyors, etc.).

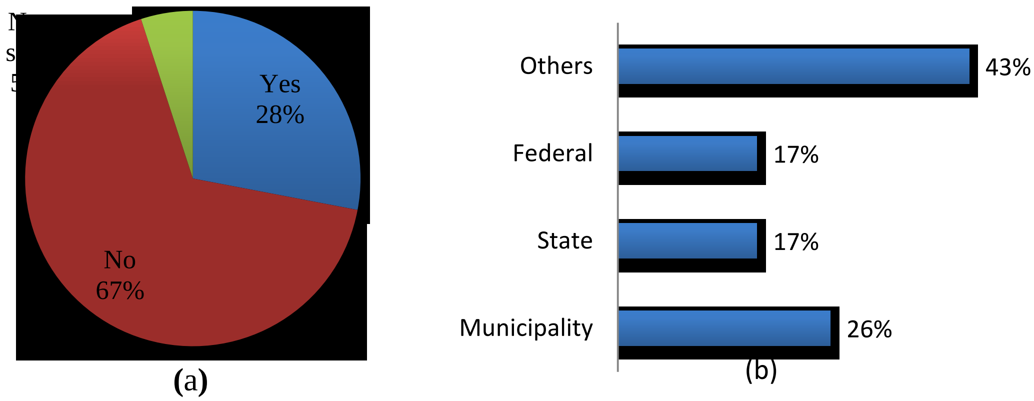

Figure 52. Educational resources (a) Received education (b) Source of education

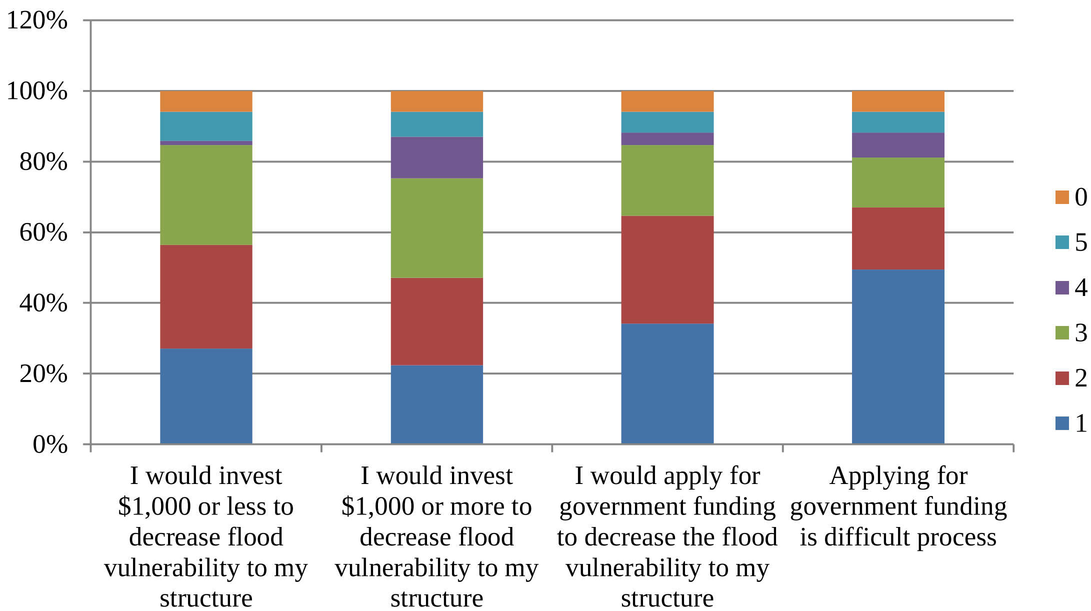

Figure 53. Agreement of participants to the statements in the graph. the scale is defined from 1 (Totally agree) to 5 (Not at all agree), blank responses were given a 0.

Finally, the willingness of the population to reduce the risks of a flood to their property was surveyed.

Figure ***53*** above presents a summary of the results where on average most of the participants are willing to invest in their property to reduce the vulnerability to floods. It is common for agencies, such as FEMA, to give some type of funding in order to reduce the vulnerability of communities. When asked about applying for government funds the majority of the respondents indicated that they are inclined to apply for them, but at the same time, 67% of them agree that the process for obtaining such funds is too difficult, which is indicative of the need to provide easier application process.

4.3.1.2 Agency Officials Survey

The purpose of the agency survey was to get information about the interaction between agencies during decision-making processes related to flood management. The survey consisted of 13 questions, which included general information from the respondent, perception of FMAs, and typology characteristics (see Table 16) of agencies identified as stakeholder in the process of planning and implementing FMAs. Agency officials from different positions were contacted to participate in the survey. The survey was sent by email and the respondents were able to answer using the web-based survey in Qualtrics.

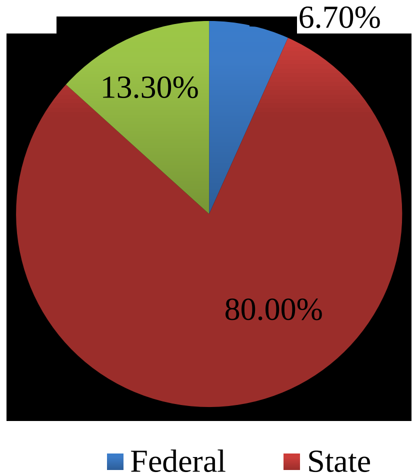

Figure 54. Summary of participants by agency type

The survey was completed by a total of fifteen (15) participants. A summary of respondents' general information is presented from Figure 54 through Figure 56. In total, 80% of the respondents work in a state agency, 13.3% in a municipal agency, and 6.7% in a federal agency. Of the 15 respondents, 53% occupy a management position (i.e. director, manager, etc.). In terms of years of experience, most of the respondents (66%) have 10 or more years of experience working with agency. The responses for flood mitigation preference and agencies characterization are presented in the following section.

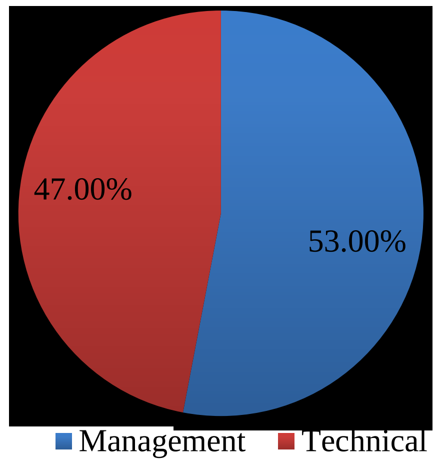

Figure 55. Position of respondents within the agency

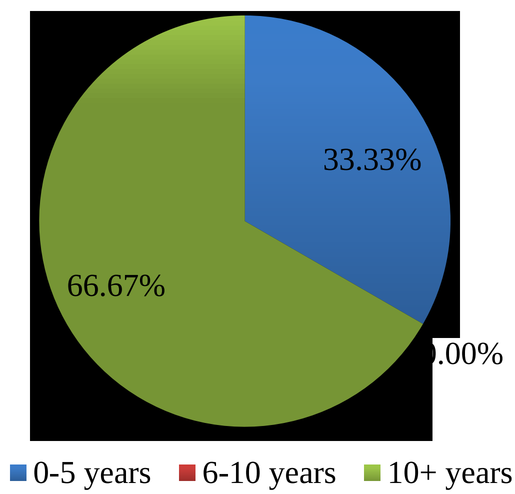

Figure 56. Years of experience

4.3.2 Stakeholder's Perspective of Flood Risk Criteria

Participants of both surveys were asked to use their best judgment for indicating the importance of the sub-criteria identified for the impacts categories (e.g., economic, social, and environmental) evaluated in this study. They were asked to evaluate each sub-criteria using a qualitative scale from (1) Not at all important to (5) Very important.

Table 29: *Community Evaluation of the Risk Criteria*

	Criteria	(1)*	(2)*	(3)*	(4)*	(5)*	Mean**	Median
Implementation	Direct costs of FMA	0	3	19	19	**39**	**4.18**	**4**
	Indirect costs of FMA	0	3	23	20	34	4.06	4
	Creation of employment	1	11	32	16	20	3.54	3
Economic	Damages to structures	0	2	12	25	**41**	**4.31**	**5**
	Damages to the infrastructure	0	1	14	21	**44**	**4.35**	**5**
	Interruption of commercial activity	0	8	31	21	20	3.66	4
Social	Preservation of historical values	0	9	29	18	24	3.71	4
	Loss of life	0	0	2	4	**74**	**4.90**	**5**
	Critical facilities affected	0	0	4	13	**63**	**4.74**	**5**
	Need of shelter	0	1	11	23	45	4.40	5
	Interruption of electrical and water services	0	2	21	21	36	4.14	4
	Required detours due to blocked roadways	2	6	25	21	26	3.79	4
	Displaced population	1	2	21	23	33	4.06	4
Environmental	Enhancing ecosystem services	0	0	19	22	39	4.25	4
	Recreational benefits	2	16	33	11	18	3.34	3
	Accumulation of pollutants	0	0	8	13	**59**	**4.64**	**5**
	Soil erosion potential	0	1	10	15	**54**	**4.53**	**5**
	Habitats affected	0	0	15	21	44	4.36	5

*Scale: (1) Not at all important; (2) Slightly important; (3) Important; (4) Fairly important; (5) Very important
**Highest values presented in bold

The results from the agency survey are presented in Table 30. In the social category, loss of life criteria obtained a 5 from 100% of the respondents. The second highest criteria were the critical facilities affected and the accumulation of pollutants, each obtained a mean value of 4.75. From the results of both surveys, the highest criteria ranked pertain to categories not related to economic factors. This represents the importance of including social and environmental criteria when conducting a risk assessment and making-decisions.

The data collected for each criterion was used to define the weights to be included in the spatial risk assessment impact estimation. The AHP methodology in Section 3.3.4 was used to calculate the weights of importance for each criterion.

Table 30: *Agency's Official Evaluation of the Risk Criteria*

	Criteria	(1)*	(2)*	(3)*	(4)*	(5)*	Mean**	Median
Implementation	Direct costs of FMA	0	0	4	2	6	4.17	4.5
	Indirect costs of FMA	0	0	3	4	5	4.17	4
	Creation of employment	0	1	7	3	1	3.33	3
Economic	Damages to structures	0	0	1	4	**7**	**4.50**	**5**
	Damages to the infrastructure	0	0	1	3	**8**	**4.58**	**5**
	Interruption of commercial activity	0	0	6	1	5	3.92	3.5
Social	Preservation of historical values	0	1	7	4	0	3.25	3
	Loss of life	0	0	0	0	**12**	**5.00**	**5**
	Critical facilities affected	0	0	0	3	**9**	**4.75**	**5**
	Need of shelter	0	0	5	4	3	3.83	4
	Interruption of electrical and water services	0	2	1	5	4	3.92	4
	Displaced population	0	0	5	4	3	3.83	4
Environmental	Enhancing ecosystem services	0	0	3	5	4	4.08	4
	Recreational benefits	0	4	6	1	1	2.92	3
	Accumulation of pollutants	0	0	1	1	**10**	**4.75**	**5**
	Soil erosion potential	0	0	1	3	**8**	**4.58**	**5**
	Habitats affected	0	0	1	4	7	4.50	5

**Highest values presented in bold
*Scale: (1) Not at all important; (2) Slightly important; (3) Important; (4) Fairly important; (5) Very important

The direct and indirect costs of the FMAs were the highest ranked in both surveys for the impact category. For the economic category, the weights from both surveys were equally distributed between the two criteria considered for the case study (i.e. damage to structures and infrastructures). For the social category, the criteria considered in the study (i.e. critical facilities, displaces population, shelter requirements) were equally weighted by the respondents of the community. In contrast, agency officials rated the importance of critical facilities with a 57%, much higher than the other two criteria.

Table 31 and Table 32 present the results for the importance factors for each criterion. Each table contains the results of the importance weights estimated for all the criteria in every impact category. The column labeled "All criteria weight" show the results when all the criteria identified in the literature were considered in the calculations. Given limitation on the availability of data, some of the criteria were not included in the analysis. The column labeled "Case study criteria weights" shows the re-calculated weights to only include the criteria considered in the case study. Table 31 presents the results from the community questionnaire and Table 32 presents the results from the agency questionnaire. The difference in perception from the stakeholders is an important factor to take into consideration. For these reasons, it is crucial to understand the influence that stakeholders can have on the planning and implementation process of FMAs and to include these facts as part of the decision-making process.

Table 31: *AHP Results from Community Survey*

	Criteria	All criteria weights	Case study criteria weights
Implementation	Direct costs of FMA	42%	46%
	Indirect costs of FMA	33%	27%
	Creation of employment	27%	27%
Economic	Damages to structures	**33%**	**50%**
	Damages to the infrastructure	**33%**	**50%**
	Interruption of commercial activity	**33%**	Not included
Social	Preservation of historical values	9%	Not included
	Loss of life	27%	Not included
	Critical facilities affected	19%	33%
	Need of shelter	19%	33%
	Interruption of electrical and water services	13%	Not included
	Displaced population	13%	33%
Environmental	Enhancing ecosystem services	23%	Not included
	Recreational benefits	8%	Not included
	Accumulation of pollutants	23%	33%
	Soil erosion potential	23%	33%
	Habitats affected	23%	33%

Table 32: *AHP Results from Agencies Responses*

	Criteria	Weights	Case study weights
Implementation	Direct costs of FMA	40%	40%
	Indirect costs of FMA	40%	40%
	Creation of employment	19%	19%
Economic	Damages to structures	43%	50%
	Damages to the infrastructure	43%	50%
	Interruption of commercial activity	14%	Not included
Social	Preservation of historical values	6%	Not included
	Loss of life	31%	Not included
	Critical facilities affected	30%	57%
	Need of shelter	11%	17%
	Interruption of electrical and water services	13%	Not included
	Displaced population	8%	25%
Environmental	Enhancing ecosystem services	16%	Not included
	Recreational benefits	6%	Not included
	Accumulation of pollutants	30%	33%
	Soil erosion potential	25%	33%
	Habitats affected	23%	33%

4.3.3 Inter-Agency Social Analysis

As defined in Section 3.3.3, the first step in a network analysis is to identify the stakeholders involved in the planning and implementation process of FMAs. From the research conducted and the opinion of officials contacted, a list of the agencies involved in the process was generated and is summarized in Table 33.

Table 33: *Case Study Stakeholders*

Agency	Acronym	Role in the decision-making process of a flood risk mitigation strategy
Community	COM	Can provide input to decision-makers due to their unique knowledge about the impacts of flooding in their community. Can also affect the implementation project if they oppose to the proposed mitigation strategy.
Mayor's Office	MO	Has the political power to approve budget and projects.
City Planning	CP	Develop the public policy within the municipality.
City's Public Works	CPW	Provide maintenance and operation of the city's FMA and maintenance of creeks.
PR Planning Board	PRPB	Develop public policy for flood prone areas and control land development.
Environmental Quality Board	EQB	The project is revised by the board in order to assure compliance with laws and regulations related to environmental quality control (i.e. water, air, etc.).
Permits Management Office of PR	PMO	Process and approval permits required for the projects implementation.
PR Emergency Management Agency	PREMA	Develop emergency plans for flood disasters and manage the flood warning system.
Department of Natural and Environmental Resources of Puerto Rico	DNER	Provide technical resources for the planning phase as well as manage and control projects proposed within the river floodplain for the conservation of the rivers, the environment and the natural resources.
Puerto Rico Highway and Transportation Authority	PRHTA	Maintain infrastructure within the floodplain and provide assistance during the planning process.
Puerto Rico Office of Management and Budget	OMB	Identify funding available for the proposed mitigations.
PR Aqueduct and Sewer Authority	PRASA	Manage reservoirs and water facilities within the floodplain.
Federal Emergency Management Agency	FEMA	Provide federal guidance for the reduction of risk within the floodplains and provide assistance before, during and after a flood event.
Environmental Protection Agency	EPA	Enforcement of regulations related to the protection of the environment.
USA Corps of Engineers	USCE	Administers construction projects from the planning stage of feasibility studies to the implementation phase.

Agency officials surveyed were requested to characterize the agencies listed in Table 33. For this study, the integration of stakeholders in the decision making process is based on their saliency (Refer to Section3.3.4) which is based on three of the characteristics: power, legitimacy and urgency. A summary of the results is presented in Table 34. The highest value for each category is highlighted in the table with the color green and the lowest with the color red. For instance, for power and legitimacy, the USCE and FEMA were the highest average value.

Table 34: *Stakeholder's Characterization*[1,2]

Entity	Type	Power	Legitimacy	Urgency		Salience
USCE	Federal	4.7	4.6	3.3		12.6
FEMA	Federal	4.7	4.6	3.3		12.6
EPA	Federal	4.3	4.5	3.1		11.9
DNER	State	4.3	4.2	2.5		11.0
PREMA	State	3.8	4.2	2.9		10.9
EQB	State	4	4.1	2.6		10.7
MO	Local	3.6	3.3	3.5		10.4
PRPB	State	3.8	3.8	2.7		10.3
PMO	State	3.6	3.3	2.6		9.5
CP	Local	2.7	3.1	3.2		9.0
PRHTA	State	3.4	3.2	2.2		8.8
PRASA	State	3.3	3.1	2.2		8.6
OMB	State	3.1	2.8	2.3		8.2
CPW	Local	2	2.6	3		7.6
Community	Local	1.3	2.7	2.3		6.3

[1] Refer to Table 16 for a description of the typology and the evaluation scale.
[2] Color scale: High (Green), Yellow (Moderate high), Orange (Moderate Low), and Red (Low)

The saliency results for each stakeholder, it is possible to identify USCE, FEMA, and EPA as the "definitive stakeholders". Therefore, the results from the surveys and interviews of these three agencies are the recommended to be incorporated in the decision models. Nevertheless, of the three agencies, only data from FEMA was collected.

Throughout the rest of this study, FEMA was the "definitive stakeholder" whose opinion was incorporated in the weighting of the criteria and FMA for the DMM.

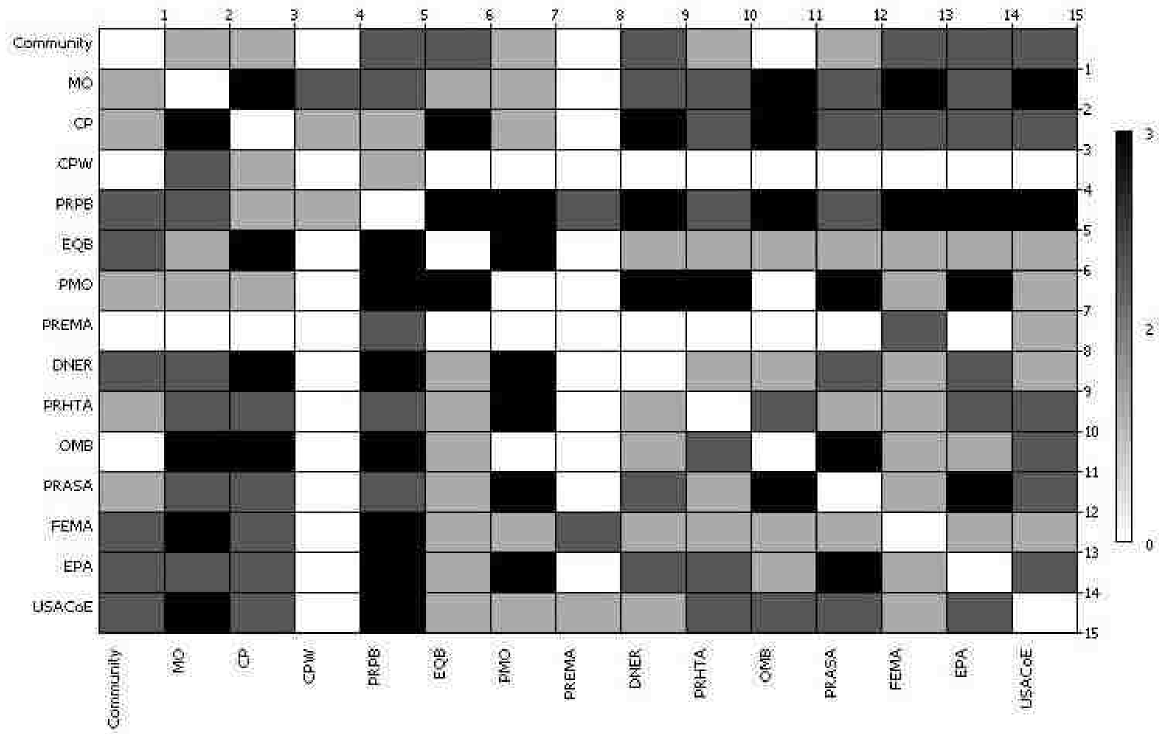

*Figure 57.*Strength of links between agencies

The strength of the links between agencies was defined by interviewing two experts in the planning process. The results are shown in Figure 57 where the square shade ranges from white (0) to black (3). Agencies whose interaction is not expected to affect the planning and implementation process of flooding risk mitigation alternatives were given a value of 0 and is represented in Figure 57 with a white square and agencies whose interaction can greatly affect the process were given a value of 3 represented in Figure 57 with a black square. For example, the interaction between PRPB and EQB was given a strength value of 3 (black square) because this both agencies have the responsibility of establishing regulation and permit requirements that can greatly affect the implementation process of an FMA. Maintaining a strong relationship between both agencies is necessary to avoid inconsistencies between their regulations

To complete the network analysis, the relationships between the stakeholders' typology and characteristics are obtained. For this purpose, a network was depicted using the Netminer software (Figure 58). The network contains all the links defined between agencies. The clusters represent the type of agency (local, state or federal).

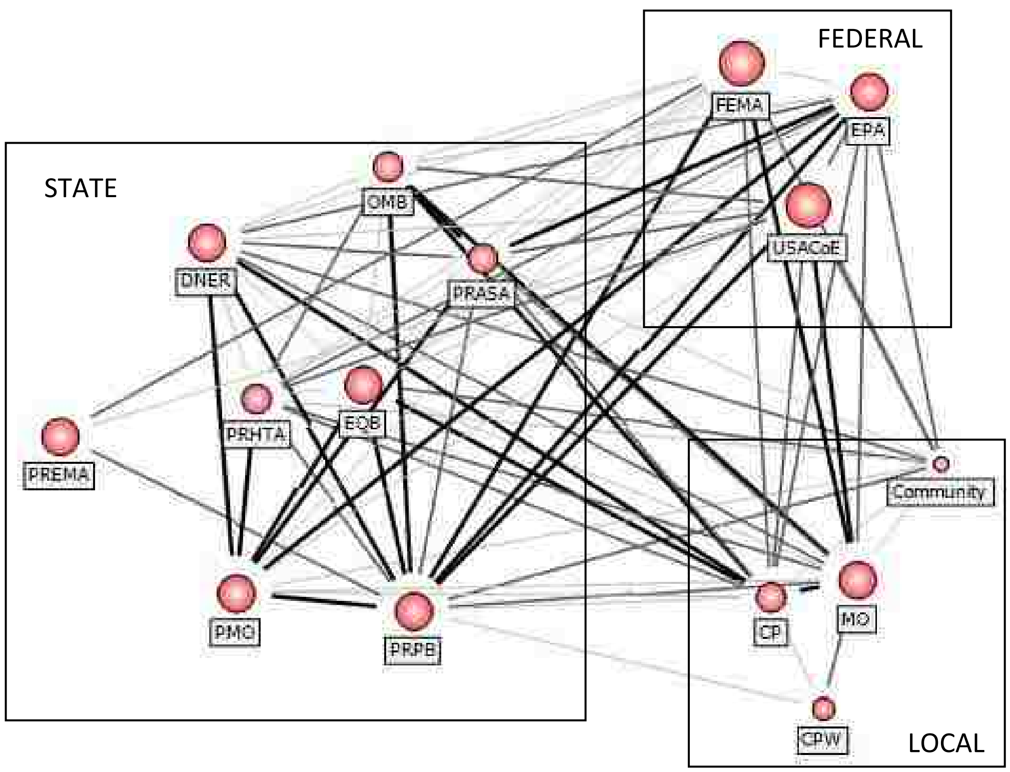

Figure 58. Agencies interaction network

In the network diagram, the agencies are represented with a circle, the larger the circle the higher power during a decision-making process related to flood mitigation alternatives it has. The interactions are represented with line segments between two agencies, the thicker the line the greater the strength of the link. From the results of the network, the power of Federal agencies appear to be similar, all having higher power than agencies in other clusters. At the state level, the PRPB has the higher power and stronger links than all the other agencies. In Puerto Rico, the PRPB regulates the construction within the flood zones. To implement and enforce regulations, the PRPB commonly collaborates with other entities such as the DNER in order to implement and enforce regulations. For this reason, PRPB having a higher degree, relates to the real life situation. Finally, the cluster representing the municipality level defines the MO as the entity with higher power.

Degree refers to the number of connections an entity has with other entities (i.e. with how many agencies it communicates/exchanges with). The pie chart in Figure 59 summarizes the frequency of degree between agencies. Entities with a high degree are expected to communicate with a greater number of entities. Of the 15 agencies considered more than half have a degree of 12 or more. This means that most of the agencies tend to communicate with each other during the process of selecting and implementing a mitigation measure.

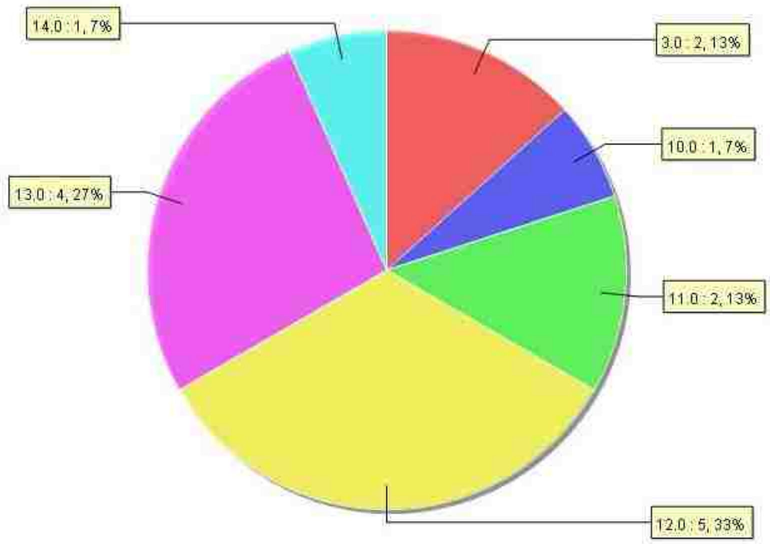

Figure 59. Frequency of degree

Assessing the typology of the stakeholder can assist decision-makers in identifying the impacts that stakeholders could have on the planning and implementation process of FMA. The results obtained for the case study are presented from Figure 60 through Figure 62. Figure 60 shows the relationship between the organizational level of an entity and the weighted degree. The figure shows that entities with a high degree also present a high level of organization. In contrast, entities with low level of organization present a lower median degree and high variability with minimum being 4 and the maximum 17. It can be anticipated that formal agencies such as USCE, FEMA, and DNER, which are more organized, will have a greater impact in DM process since they interact with more entities.

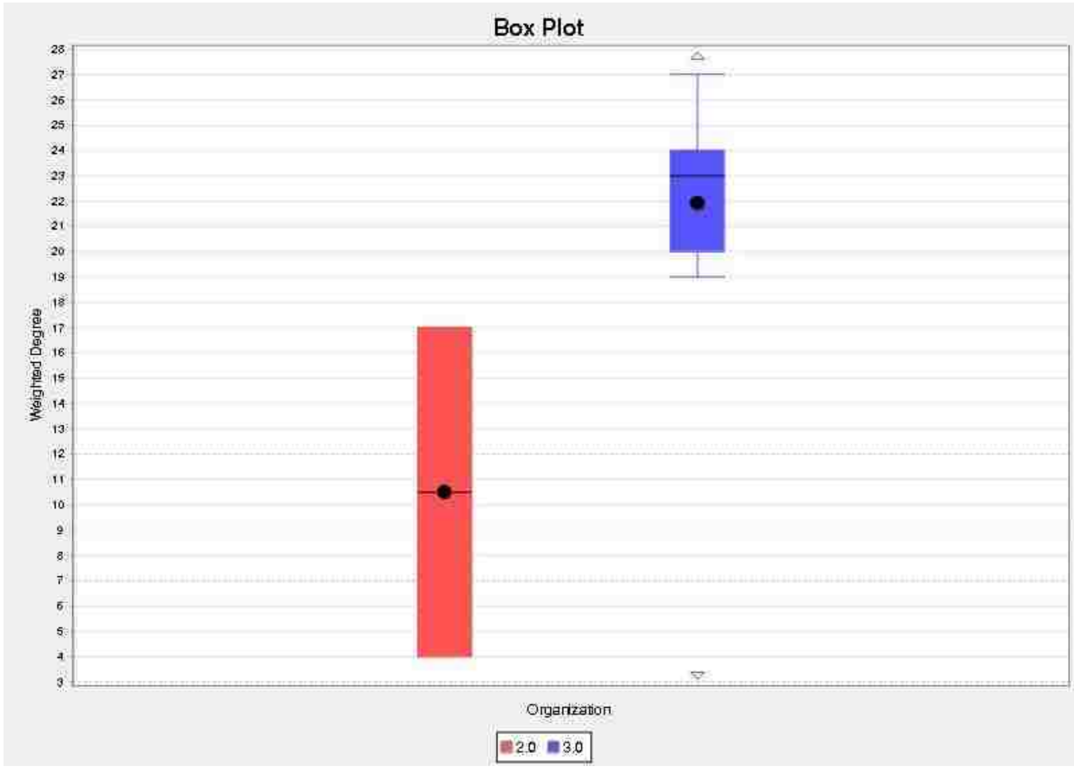

Figure 60. Box-plot of the results between the organization level of the entitiy and the weighted degree.

Figure 61 shows the relationship between the agencies legitimacy and their weighted degree, which is the sum of their number of interactions with other agencies multiplied by the weight of their links. The figure shows that the agencies with the highest degree (5) have a high degree (ranges from 12-13), meaning that they can greatly impact the decision-making process.

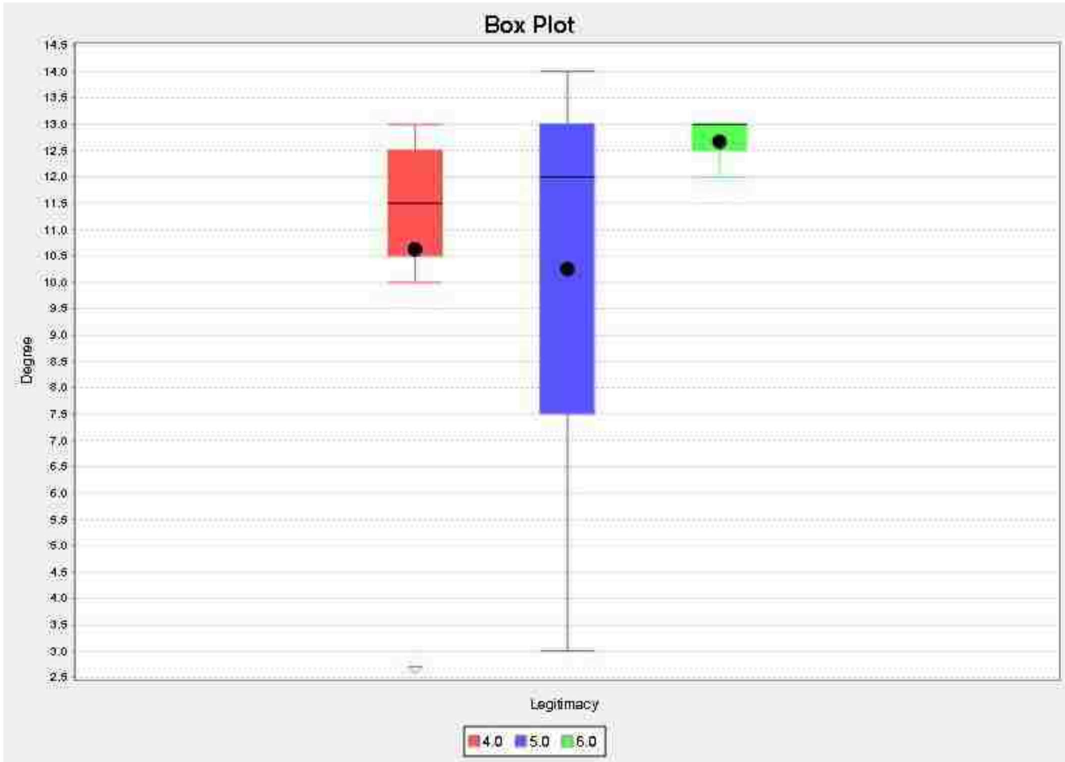

Figure 61. Box-plot of the results between legitimacy of the entitiy and the degree.

Figure 62 shows the relationship between the levels of the agency (i.e., local, state, federal) with their weighted degree. It is shown that even though federal agencies have a higher mean on their weighted degree, local agencies have greater variability, which means that the local agencies may have a low impact or high impact in decision-making process related to flood management alternatives.

Figure 62. Box-plot of the results between the type of agency and the weighted degree.

4.4 Decision-Making Model Results

Two decision frameworks were developed in this study in order to select from multiple FMAs. The MC-DMM considers the risk criteria discussed in Section 3.2.1 (i.e. damage to building and infrastructure, affected population, affected critical facilities, debris generated, landslide potential, and critical habitats affected), while the AHP-MC-DMM integrates the implementation criteria using the AHP methodology. The weight factors for each criterion were defined by considering the opinion of the "definitive stakeholders" identified in Section 3.3.4.

4.4.1 Monte-Carlo Decision-Making Model (MC DMM)

The results obtained in Section 4.2.4 were used as an input to the MC-DMM. Since there is an uncertainty on the estimated loss results given the algorithms, data, and calculation estimates within HAZUS, a distribution was defined for the impact categories AAIs. Since HAZUS does not define a level uncertainty, a margin of error of 10% was assumed. A triangular distribution was defined for each impact category to account for the uncertainty of the results. The probability, which was defined in Table 9 was given a binomial distribution in order to account for the probability of the event occurring during the year in evaluation.

Each impact category was given different importance factors by the decision-maker. The importance factors were defined as a weight. In this study, four sets of weights were defined to observe how the weighting of the impact categories could affect the final decision (Table 35).

Table 35: *Definition of Cases with Different Weight Factors for Each Impact Categories*

Case ID	Case Type	Importance Factor		
		EI	SI	ENI
1	Equal importance to all criteria	33%	33%	33%
2	Economic	80%	10%	10%
3	Social	10%	80%	10%
4	Environmental	10%	10%	80%

With all variables defined and the data added to the model, each case simulation was run for 10,000 iterations using the @Risk software from Palisade. The MC-DM final results for each case are presented in Table 36. In summary the levee resulted with the lowest impact for all cases. The results also illustrate the impact that weights can have in the final decision. A decision-maker needs to understand these effects before defining the weights. For the case where the social category was given the higher weight, the levee presented a considerable higher impact than all the other cases.

Table 36: *MC-DMM results for each case*

	FMA	Goal Cell Statistics (Millions)			
		Mean	Std. Dev.	Min.	Max.
Equally Weighted	No action	157.52	2.04	150.28	166.10
	FWS	156.51	2.03	149.37	163.60
	Levee	**142.31**	**1.83**	**135.51**	**148.33**
Economic	No action	143.81	2.49	135.41	152.95
	FWS	141.36	2.43	133.78	149.57
	Levee	**137.70**	**2.41**	**129.41**	**145.63**
Social	No action	191.55	3.62	179.66	203.09
	FWS	191.24	3.60	179.23	204.85
	Levee	**172.22**	**3.23**	**161.89**	**183.42**
Environmental	No action	141.97	2.43	133.55	150.42
	FWS	141.67	2.45	133.24	149.58
	Levee	**121.34**	**2.01**	**114.73**	**127.91**

4.4.2 AHP Monte-Carlo Aided Decision-Making Model (AHP-MC DMM)

A Benefit-Cost analysis for the DMM was performed by applying the AHP methodology to the MC DMM analysis. The required data input for the AHP-MC DMM was the following:

- Total economic, environmental, and social impact for each mitigation measure (AAI).
- Implementation criteria.
- Pairwise comparison of the criteria and the mitigation options.

The total impact for each mitigation measure is obtained from the MC simulation. In this study, the AAI for the no action scenario was taken as base value. If the alternative's AAI is less than the no action AAI, it means that the alternative reduced the flood risk. In contrast, if the alternative's AAI is greater, it means that it increased the flood risks. In Table 37, the reduced risks results for each FMA and case (Table 35) are shown.

Table 37*: MC-DMM results for each case*

Case	FMA	Grid Cells (Millions)		Rank*
		Mean	Risk Reduction	
Equally Weighted	No action	157.520	0.000	3
	FWS	56.509	1.011	2
	Levee	**142.312**	**15.208**	**1**
Economic	No action	143.811	0.000	3
	FWS	141.361	2.450	2
	Levee	**137.695**	**6.116**	**1**
Social	No action	191.547	0.000	3
	FWS	191.241	0.306	2
	Levee	**172.218**	**19.329**	**1**
Environmental	No action	141.975	0.000	3
	FWS	141.668	0.306	2
	Levee	**121.336**	**20.639**	**1**

*Ranking Scale: (1) Least effective in reducing risk, (2) Moderately effective in reducing risk and (3) Most effective in reducing the risk

The results obtained in the MC-DMM showed that the levee was more efficient in reducing the flood risks. In order to incorporate such results in the AHP, the results were ranked from 1 to 3, 1 been the less effective in reducing the risks. This rank will be used for the pairwise comparison in the AHP analysis.

The implementation criteria defined for this study is presented in Table 38. Two types of implementation criteria were defined: quantitative and qualitative. The quantitative criteria include the costs of investment and maintenance, number of jobs created and the duration of the project. These criteria are estimated during the planning process. The qualitative data refers to the perception of the stakeholder on the efficiency of the FMA. For example, if the stakeholder's perspective is that the measure is easily implementable, very efficient at reducing the risk of floods and less costly, he or she will tend to prefer such alternative.

Table 38: *Implementation criteria for each alternative*

Criteria			Description	UNITS
QUANTITATIVE	1	Cost of maintenance/year	The total cost in of operating and maintaining the FMA.	USD $
	2	Investment	Total cost to evaluate and implement the FMA. (i.e. feasibility studies, permits documentation, construction, etc.	USD $
	3	Job creation	The amount of jobs generated during the construction period	# of jobs
	4	Duration	The duration for implementation.	months
QUALITATIVE	5	Implementation Easiness	Rating of from stakeholders on their perception of the criteria	Pairwise comparis on scale

The data used for the quantitative criteria are shown in Table 39. The estimate of the levee criteria was obtained from a feasibility study from the USCE *(USCoE, 1991)*. The information available for the implementation of FWS was not readily available. Information found in the literature review was used to make an educated estimate. In Puerto Rico, the FWS is operated by PREMA in coordination with the National Weather Services. The FWS is composed of automated river gages requiring minimum effort for the data collection process. The estimate of implementation was obtained from a report by the DNR *(DNR, 1980)*. The estimates include the implementation of the gages, a data management system among other components. For the operation and maintenance (O&M) costs, the rule of thumb is to assume 10%-15% of the initial costs *(National Weather Service, 2012)*; in this study we used 15%. For the no action alternative it was assumed that it would have no impact on the quantitative criteria.

Table 39: *Quantitative criteria values*

FMA	Implementation Cost	Maintenance Costs	Duration	Job Creation
No Action	$ -	$ -	0	0
Levee	$ 7,653,000.00	$ 18,183.00	54	116
FWS	$ 2,500,000.00	$ 375,000.00	24	12
Total	$ 10,153,000.00	$ 393,183.00	78	128

The evaluation of the qualitative criteria for this study was obtained from questionnaire B were agency officials were asked to use their best judgment to rank eight FMAs in a scale from 1-8 for each category. The ranking scale was from 1 to 8 where 1 was the easiest to implement. The survey results obtained for the Levees and FWS is illustrated Figure 63. In summary, FWS was found to be the easiest FMA to implement with an average ranking of 1 while the Levees were mostly ranked with a 6.

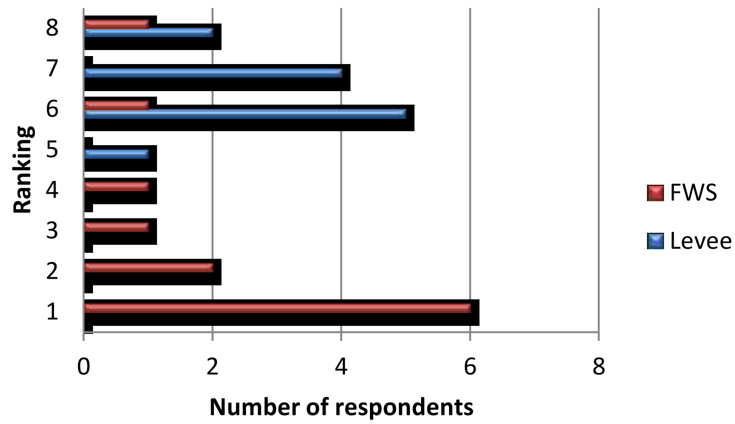

Figure 63. Easiness of the FMA to implement

To evaluate the performance of each FMA within each criterion, two types of AHP categories were defined: benefit (B) criteria and cost (C) criteria. The benefit criteria refer to criterions that provide a benefit such as reducing the risk of flooding. In contrast, cost criteria refer to the ones that represent a cost like the investments required for implementing, operating, and maintaining the proposed FMA. A summary of the data to be considered for each criterion in the AHP-MC DMM is presented in Table 40.

Table 40: *Identification of benefit and cost criteria for case 1 scenario*

	C or B	No Action	LEVEE	FWS	Total
Quantitative					
Implementation Cost	C	0	$ 7,653,000	$ 2,500,000	$ 10,153,000
Maintenance Costs	C	0	$ 18,183	$375,000.00	$ 393,183
Duration	C	0	54	24	78
Job Creation	B	0	116	12	128
Risk Reduction	B	0	-15,207.78	-1,010.56	-16,218.34
Qualitative					
Easiness to implement	B	3	1	2	-

*Benefit (B) criteria and cost (C) criteria

In order to perform the AHP analysis, a pairwise comparison is required between the criteria and the FMAs (Refer to section 3.3.4). The risk reduction and easiness to implement criterions in Table 41 are already in the required scale. In Table 41, the ranked FMAs for the rest of the criteria are shown. For example, in the implementation cost criteria, the "No Action" alternative was considered to be the most efficient, since there is no implementation cost associated to the alternative. Considering this criterion, in a pairwise comparison with the levee, the no action alternative will be 3/1 better than the levee.

Table 41: *Ranking of benefit and cost criteria for case 1 scenario*

	C or B	No Action	Levee	FWS
Implementation Cost	C	3	1	2
Maintenance Costs	C	3	2	1
Duration	C	3	1	2
Job Creation	B	1	3	2
Risk Reduction	B	3	2	1
Easiness to Implement	B	3	1	2

In Table 42, the resulting pairwise comparison matrix for the easiness to implement criteria is shown.

Table 42: *Pairwise comparison of the "easiness to implement" benefit criteria*

	No action	Levee	FWS
No action	1.00	3.00	1.50
Levee	0.33	1.00	0.50
FWS	0.67	2.00	1.00

For the pairwise comparison of each criterion, the same ranking scale from 1 to 3 was used. The input from the "definitive stakeholders" was used to rank the criteria. The resultant matrix is shown in Table 43. The matrix shows that the risk reduction criterion was considered the most important than the job creation criteria and the easiness to implement criteria, with a pairwise comparison of 3/1 and 3/2, respectively.

Table 43: *Pairwise comparison of the benefit criteria*

	Job Creation	Risk Reduction	Easiness to implement
Job Creation	1.00	0.33	0.67
Risk Reduction	3.00	1.00	1.50
Easiness to implement	1.50	0.67	1.00

The resulting AHP diagram for the model is presented in Figure 64, for the Case 1 scenario, were all the impacts categories were weighted equally. In the benefit criteria section, three criterions were considered for each type of AHP category. The model includes the weights obtained for each criteria and each FMA. For instance, in the cost criteria section, the weights show that definitive stakeholders selected the implementation costs as more important than the other two criterions (i.e. maintenance costs, and duration) with an importance factor of 0.48. As well, in the benefit section, the results show that the no action scenario is easier to implement than the other two alternatives with a weight value of 0.50.

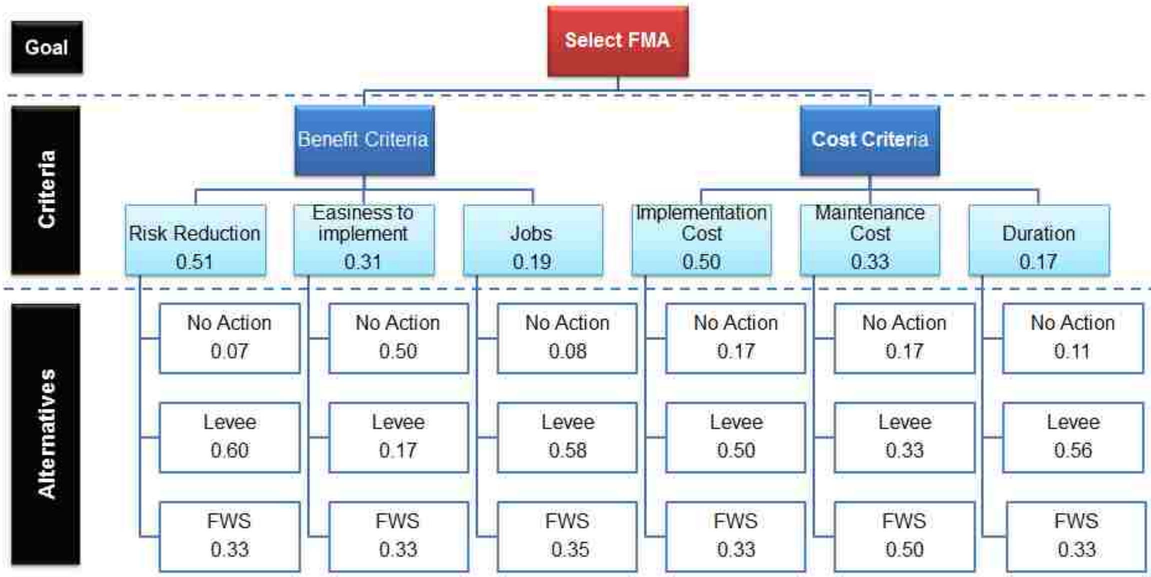

Figure 64. MC-AHP DMM diagram for case 1 (equally importance to all)

In order to obtain the total benefits and costs for the B/C analysis, two other matrices are generated with the results for each AHP Category (i.e. benefit and cost categories). The results from each matrix are the final benefit and cost value for each FMA. Finally the B/C ratio is obtained by dividing the benefit value from the cost value for each FMA. All the required calculations for each case were performed in an Excel spreadsheet. Figure 65 shows a snapshot of one of the spreadsheets developed.

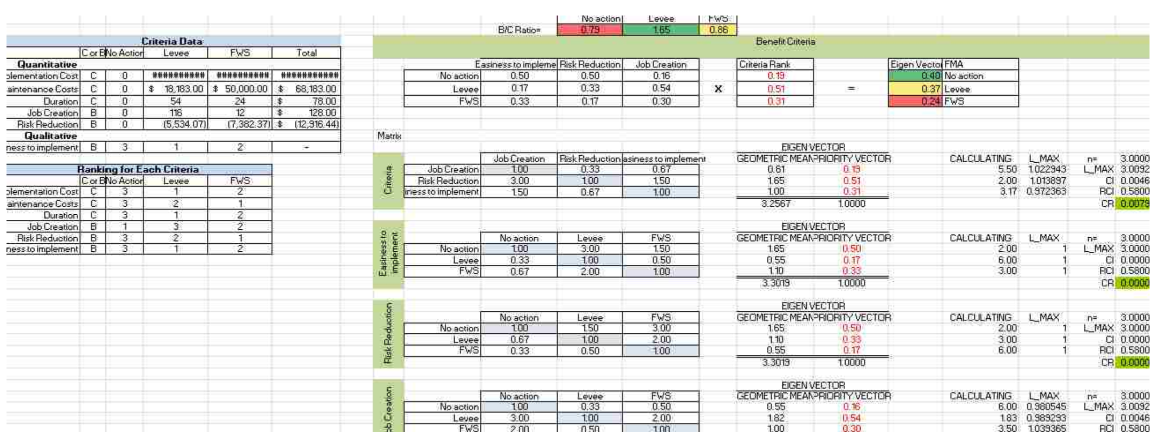

Figure 65. Snapshot of excel spreadsheet for AHP calculations

Finally, once the benefit and cost have been calculated the benefit ratio is calculated. The recommended alternative should be the one with the higher benefits and the lowest costs. The B/C results are presented in Table 44 for all cases. The results maintain a consistency with the ones obtained in the MC-DMM, where the levee resulted as the best alternative in all cases. But, in contrast with the MC-DMM, this model provides even more information to the decision maker. For instance, in the case where the social category was given a higher weight, the no action alternative had a higher B/C ratio than the FWS alternative.

Table 44: *Benefit-Cost (B/C) results*

Case	FMM	COST	BENEFIT	B/C
Equally Weighted	No action	0.16	0.15	0.95
	Levee	**0.45**	**0.51**	**1.13**
	FWS	0.39	0.34	0.87
Economic	No action	0.16	0.15	0.93
	Levee	**0.45**	**0.46**	**1.02**
	FWS	0.39	0.39	1.01
Social	No action	0.16	0.15	0.95
	Levee	**0.45**	**0.51**	**1.13**
	FWS	0.39	0.34	0.87
Environmental	No action	0.16	0.15	0.95
	Levee	**0.45**	**0.51**	**1.13**
	FWS	0.39	0.34	0.87

4.4.3 MC-DMM vs. AHP-MC-DMM

A comparison of the results obtained for each model is presented in Table 45. Although both models resulted in the same recommended alternative for each case scenario, the AHP-MC DMM shows the importance to provide more data to the user by including the implementation criteria and the B/C ratio. As presented in the table, the difference in the results from the MC-DMM represented minimal differences between the alternatives. In contrast, the AHP-MC DMM provided a B/C that clearly demonstrated the benefit of the recommended alternative.

Table 45: *Ranking of alternatives for each case in the AHP-MC-DMM*

	FMA	MC-DMM	AHP-MC DMM
Equally Weighted	No action	157.52	0.95
	FWS	156.51	1.13
	Levee	**142.31**	**0.87**
Economic	No action	143.81	0.93
	FWS	141.36	1.02
	Levee	**137.70**	**1.01**
Social	No action	191.55	0.95
	FWS	191.24	1.13
	Levee	**172.22**	**0.87**
Environmental	No action	141.97	0.95
	FWS	141.67	1.13
	Levee	**121.34**	**0.87**

4.5 Chapter Summary

In this chapter the application of the proposed framework is illustrated for the Case Study. The evaluation of three alternatives (i.e. no action, levee, and FWS) was considered. First, the impacts of floods were obtained using FEMA's HAZUS software. The results from the flood model were included in a risk assessment in order to obtain the economic, social, and environmental impacts of each mitigation alternatives. In total, 15 scenarios (5 for each alternative) were modeled in order to obtain the AAI for each proposed FMA.

In addition, the opinion and the interactions of the stakeholders were evaluated using an AHP, stakeholder theory, and network analysis. The stakeholder analysis allowed identifying the "definitive stakeholders" whose opinion was incorporated in the decision analysis to determine the weight factors for the criteria. The results from the risk assessment and stakeholder's analysis were used to model the MC-DMM. The preliminary results showed that the levee alternative was the most efficient at reducing the impact of floods. The model was then expanded by using the AHP methodology. In the AHP-MC-DMM a fourth impact category was added to the model (i.e. implementation criteria) with the goal to account for the efficiency and easiness to implement the alternative. The criteria were then divided into two AHP categories: benefits and cost with the purpose to get a benefit-cost ratio. The results were consistent with the MC-DMM, but were capable of providing more information to the decision-maker.

CHAPTER 5: SUMMARY AND CONCLUSIONS

Floodplain managers often encounter difficulties when selecting from multiple FMA. This problem is commonly attributed to the complexity of comparing alternatives due to the multiple-criteria and multiple stakeholders involved in the decision-making process. Even more, the problem is exacerbated when some of the criteria tend to conflict with one another. There are numerous alternatives to choose from and each one requires the estimation of the impacts on the economic, social, and environmental criteria. For these reasons, it is essential for decision-makers to have the necessary tools, which help them perform such difficult tasks more efficiently. Of particular interest in this research was the proposal of a holistic approach to the decision-making process for selecting FMA.

5.1 Summary of Research

The objective of this research was to develop a decision-making framework capable of ranking multiple FMA. From the review of previous researches, it was found that studies incorporating all impact categories are limited. Additionally, it was found that the incorporation of stakeholder's opinion and roles in decision-making processes related to FMA is limited in the literature. Of particular interest in this research is to propose a holistic approach to the decision-making process for implementing flood mitigation alternative. An additional contribution is the incorporation of stakeholder's opinion with the use of network analysis.

Three main research questions were formulated and researched throughout the study to achieve this objective. The discussion of the research contributions is based on these questions.

1) *<u>What criteria should be considered when assessing the impacts of flood mitigation alternative?</u>*

In this study, the impact criteria from previous research are categorized in three main groups: economic, environmental, and social. Also, the implementation criteria of FMA are considered. A summary of the criteria is presented in Table 46**.**

Table 46: *Flood Risk Assessment and FMA Implementation Criteria from the Literature*

Implementation	Economic	Social	Environmental
- Investment requirements - Maintenance and operation - Economic opportunities - Cost-benefit	- Damage (buildings, infrastructure, contents, inventories, etc.) - Emergency response costs - Flood relief costs - Land value - Evacuation/Relocati on costs	- Perception of flood risk - Effects on social fabric (i.e. social services, hot spots affected, recreation, - Public health and safety - Perception of landscape changes - Anxiety and physical discomfort - Affected population (i.e. casualties/injuries, displaced population, shelter needs, etc.) - Sense of community	- Water quality - Soil erosion - Suspended matter in rivers and sediments - Effects of the release of toxic chemicals - Spread of polluted sediments - Spread of diseases - Aquatic life affected - Debris - Spill of diesel and other type of oils

Economic and implementation criteria are the most commonly used in FRA and DMM analysis. The estimation of the criteria is easily quantifiable in monetary terms and provides values decision-makers and stakeholders can easily understand. Environmental studies of the implementation of FMA are also very common and for structural alternative it is required for the permits approvals. Nevertheless, quantifying the environmental impacts of flood is a difficult task. Social criteria consider many intangible factors, such as anxiety and depression to the losses that are more difficult to estimate and vary greatly depending on the individual affected. Environmental impacts can be quantified, but its long-term effects on humans and habitats are more complicated to incorporate. Data availability is a constraint when defining which decision criteria to use. This study demonstrated that the input of the stakeholders and implementation criteria could have a significant effect when deciding about FMA.

2) *How can the criteria be efficiently estimated and equally compared in order to assess the impacts of floods and flood mitigation alternative*?

In the proposed research framework, spatial flood risk assessment is incorporated to estimate the impacts a flood occurrence has on a watershed. Being able to spatially represent the impacts provides decision-makers with a visual way of assessing and communicating the risks. For the SFRA, a reclassification of the criteria is required to estimate the impacts in the same scale. In this study, the criteria are reclassified in three categories: low (1), moderate (2), and high (3).

3) *What is the perspective of the stakeholders and how can it be incorporated into the decision-making model?*

The process of planning and implementing FMA can be greatly affected by the perspective of the stakeholders. Stakeholders that are not involved in the planning and implementation process of FMA can oppose the decisions and delay the process. Also, stakeholders can supply relevant information that should be considered in the decision-making process. For example, residents within the floodplain can have years of experience dealing with floods in their community and are able to give historic data about the behavior of flood in the area. For these reasons, it is important to include the opinion of stakeholders capable of affecting the outcome of the decisions.

In this study, two questionnaires were used to gather the perspective of floods and FMA from the stakeholders. With the data collected from the questionnaires, a network was developed. The network, which incorporated the perspective of the respondents on the characteristics of the stakeholders, estimated the level of power, legitimacy, and urgency of each stakeholder. Stakeholders that possessed all three characteristics were defined as the "definitive stakeholders" whose opinions were used in the DMMs and risk assessment.

5.2 Summary of the Results

The application of the proposed framework was illustrated for the URGLW. The proposed mitigation alternatives (i.e. no action, levee, and FWS) were evaluated in accordance to the methodology proposed. First the floodplain and depth grids were obtained within the HAZUS flood model. The impacts of floods were estimated as the total AAI for each alternative using the methodology described in Chapter 3 for the SFRA. To estimate the AAI, the impacts were estimated for each return period i (i.e. 10, 25, 50, 100, and 500). In total, the SFRA was conducted for 15 scenarios.

In addition, the opinion and the interactions of the stakeholders were evaluated using AHP and network analysis. The stakeholder analysis provided the decision-maker the importance factors to be given to each impact category. The results from the risk assessment and stakeholder's analysis were used to model de MC-DMM. The preliminary results showed that the levee alternative had the lowest AAI in all cases. Using the results of the MC-DMM, the AHP-MC-DMM was modeled. A fourth impact category was added to the model (i.e. implementation criteria) to account for the efficiency and easiness of implementing a particular alternative. The criteria were then divided in to AHP categories: benefits and cost to obtain a benefit-cost ratio. The result for each case was a ranking of the alternatives with the levee having the highest rank for all the cases and maintaining consistency with the results collected in the previous model.

5.3 Research Contributions

This research resulted in various contributions. The research framework considered the evaluation of four impact categories in order to assess the effects that FMA are expected to minimize or generate after its implementation.

5.3.1 Contribution to the Body of Knowledge

The main contribution of this research is the development of a decision-making model capable of integrating implementation, economic, social, and environmental criteria. The model integrates stakeholder's opinion and preferences in the evaluation of these impacts. The study proposes a method to quantify implementation criteria while incorporating the role of different stakeholders (i.e., federal, state and local agencies, and community) in the decision-making process. In addition, uncertainties were defined in the model with the incorporation of a MC Simulation. Floodplain manager can use the proposed framework when comparing alternatives for FMA in the watershed.

5.3.2 Contribution to the Body of Practice

The impacts of flood have steadily been increasing over the last decades and many researchers have analyzed their impact. Nevertheless, there is a lack of published work focusing in the implementation of a holistic framework capable of conducting all the components proposed in the framework. Additionally, most of the studies are limited to specific cases.

This study showed the importance of including all aspects of the decision–making process in one single framework. The models are able to spatially estimate the impacts, integrate, and compare quantitative and qualitative information to get an overall impact. The methodology suggested in this research can be used by floodplain managers to assess the impacts of floods within a watershed and compare flood mitigation alternatives.

5.4 Research Limitations

Data availability and data quality is one of the main limitations of this study. For example, to model a flood event, the H-H analysis was performed with the information provided by a DEM. The DEM obtained for the study region had a resolution of 10 meters. This elevation data is collected for only one point within the cell and the entire cell (10m x 10m) is given the same elevation value. Detailed information like river delineation and bathymetry cannot be obtained with the DEM.

Another example of the limitation of this study is the estimation of the losses. The total expected damages of a flood event are obtained from HAZUS software. In this study, a Level 1 analysis was conducted within HAZUS. This type of analysis only considers the inventory data provided by HAZUS and the impacts are estimated based on aggregated data from the census. For example, HAZUS only supplied for the loss estimation of bridges and water facilities, infrastructure such as roads and electric lines were not considered. In addition, the final criteria were selected based on the data available. A more complete analysis could be performed if data is collected for additional criteria.

5.5 Recommendation for Future Research

Given the limitations of this study, there are multiple opportunities to expand on the research. For instance, the main contribution of the research framework is the comparison of multiple alternatives. In addition to the “no action” alternative, only the consideration of levees and FWS were evaluated in this study. For future research, studies can focus on developing a methodology capable of spatially implementing numerous combinations of structural and non-structural mitigation alternative. This will provide decision-makers the opportunity of evaluating all the alternatives in the same environment and under the same considerations.

Another opportunity for future research is the development of a computerized decision support system (DSS) that incorporates all the components of the framework (i.e. flood model, stakeholder characterization, risk assessment, and decision-making models). The DSS can able to integrate all the data and processes in a single computer-based program with a graphical user interface (GUI).

The input of experts from multiple disciplines (i.e. economist, psychologist, environmentalist, etc.) can also be considered for future research. From the criteria identified in the study, an inter-disciplinary methodology can be developed with the goal of integrating the analysis from experts.

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APPENDIX A: IRB APPROVAL

UNM | Office of the Institutional Review Board

DATE:	October 27, 2014
REFERENCE #:	17314
PROJECT TITLE:	[663845-1] Stakeholder's perception on flood Risk and the impacts associated with the Implementation of Flood Mitigation Measures
PI OF RECORD:	Vanessa Valentin, PhD
SUBMISSION TYPE:	New Project
BOARD DECISION:	APPROVED
EFFECTIVE DATE:	October 24, 2014
EXPIRATION DATE:	October 23, 2015
REVIEW TYPE:	Expedited Review
REVIEW CATEGORY:	Expedited review category 7
SUBPART DECISION:	Not Applicable
PROJECT STATUS:	Active - Open to Enrollment

DOCUMENTS:

- Advertisement - Recruitment Scripts for Target Population B (English and Spanish) (UPDATED: 09/29/2014)
- Advertisement - Recruitment Scripts for Target Population A (English and Spanish) (UPDATED: 10/7/2014)
- Application Form - Project Information (UPDATED: 10/7/2014)
- Consent Form - Consent Form- Target Population B (English and Spanish) (UPDATED: 10/7/2014)
- Consent Form - Consent Form- Target Population A (English and Spanish) (UPDATED: 10/7/2014)
- Other - Confirmation of translations (UPDATED: 10/1/2014)
- Other - Department Review (UPDATED: 10/1/2014)
- Other - Project Team (UPDATED: 09/30/2014)
- Other - Document Translation Certification by Qualified Translator (UPDATED: 09/29/2014)
- Protocol - Protocol (UPDATED: 10/7/2014)
- Questionnaire/Survey - Questionnaire_Target Population B (Spanish) (UPDATED: 10/6/2014)
- Questionnaire/Survey - Questionnaire_Target Population B (English) (UPDATED: 10/6/2014)
- Questionnaire/Survey - Questionnaire_Target Population A (Spanish) (UPDATED: 10/7/2014)
- Questionnaire/Survey - Questionnaire_Target Population A (English) (UPDATED: 10/7/2014)

Thank you for your submission of New Project materials for this project. The University of New Mexico (UNM) IRB Main Campus has APPROVED your submission. This approval is based on an appropriate risk/benefit ratio and a project design wherein the risks have been minimized. This determination applies only to the activities described in the submission and does not apply should any changes be made to these documents. If changes are being considered, it is the responsibility of the Principal Investigator to submit an amendment to this project for IRB review and receive IRB approval prior to implementing the changes. A change in the research may disqualify this research from the current review category.

The University of New Mexico (UNM) IRB Main Campus has determined the following:

Informed consent has been altered and documentation of informed consent has been waived for this project. To obtain consent, use only approved consent document(s).

All reportable events must be promptly reported to the UNM IRB, including: UNANTICIPATED PROBLEMS involving risks to participants or others, SERIOUS adverse events, UNEXPECTED adverse events, NON-COMPLIANCE issues, and COMPLAINTS. All FDA and sponsor reporting requirements should also be followed.

The UNM IRB approved the project using Expedited procedures from October 24, 2014 to October 23, 2015 inclusive. A continuing review or closure submission is due no later than September 23, 2015. It is the responsibility of the Principal Investigator to apply for continuing review and receive continuing approval for the duration of this project. If this project lapses past the expiration date, all research related activities must stop and further action may be required by the IRB.

Please use the appropriate reporting forms and procedures to request amendments, continuing review, closure, and reporting of events for this project.

Please note that all IRB records must be retained for a minimum of three years after the closure of this project.

The Office of the IRB can be contacted through: mail at MSC02 1665, 1 University of New Mexico, Albuquerque, NM 87131-0001; phone at 505.277.2644; email at irbmaincampus@unm.edu; or in-person at 1805 Sigma Chi Rd. NE, Albuquerque, NM 87106. You can also visit our website at irb.unm.edu.

Sincerely,

J. Scott Tonigan, PhD
IRB Chair

APPENDIX B: SURVEY INSTRUMENTS

Stakeholder's perception on flood Risk and the impacts associated with the implementation of Flood Mitigation Measures

SURVEY
(Time: 10 mins.)

I. **Subject's Information**

This section inquires about the participant's general demographic information and the structure(s) that will be references throughout the survey.

1. Age:
   - ☐ 18-25
   - ☐ 26-35
   - ☐ 36-45
   - ☐ 46-55
   - ☐ 56-65
   - ☐ 66–

2. Gender:
   - ☐ Male
   - ☐ Female

3. Level of education:
   - ☐ Less than high-school
   - ☐ High-school
   - ☐ College
   - ☐ Graduate
   - ☐ Other:__________________

4. It is possible to provide information for a maximum of two structures. In addition to your residence, you can include an additional structure for which you're either the owner or tenant. Please indicate how many structures you will include as part of the survey.
   - ☐ 1 (Residence only)
   - ☐ 2 (Residence and additional structure)

5. Please indicate the 5 digit Zip-code of your residence: _ _ _ _ _

6. Are you the owner or the tenant of your residence?
   - ☐ Owner
   - ☐ Tenant
   - ☐ Other:______________

7. Please indicate the 5 digit Zip-code of the additional structure: _ _ _ _ _

8. Are you the owner or the tenant of the additional structure?
   - ☐ Owner
   - ☐ Tenant
   - ☐ Other:______________

9. Is the additional structure:
   - ☐ Residential
   - ☐ Commercial
   - ☐ Industrial
   - ☐ Other: _______________

8. If you answered "Yes" to question #7, how is your household prepared? (Select all that apply)
   - ☐ Bought flood insurance
   - ☐ Have an emergency plan
   - ☐ Modification of the elevation of structure
   - ☐ Floodwall
   - ☐ Levee in the community
   - ☐ Waterproof membranes
   - ☐ Other type of flood proofing. Which ones? ___________________

9. If you answered "No" to question #7, why isn't your household prepared?
   - ☐ I do not live in a flood prone area
   - ☐ It is not my responsibility
   - ☐ The structure will never flood
   - ☐ It is too costly
   - ☐ Never thought about it
   - ☐ Other: _________________________

10. Is your additional structure prepared for future flood event?
    - ☐ Yes
    - ☐ No
    - ☐ I don't know

11. If you answered "Yes" to question #10, how is the additional structure prepared? (Select all that apply)
    - ☐ Bought flood insurance
    - ☐ Have an emergency plan
    - ☐ Modification of the elevation of structure
    - ☐ Floodwall
    - ☐ Levee in the community
    - ☐ Waterproof membranes
    - ☐ Other type of flood proofing. Which ones? ___________________

12. If you answered "No" to question #10, why isn't the additional structure prepared?
    - ☐ I do not live in a flood prone area
    - ☐ It is not my responsibility
    - ☐ The structure will never flood
    - ☐ It is too costly
    - ☐ Never thought about it
    - ☐ Other: _________________________

III. Flood Mitigation Measures and Protocols

In this section, your perception on flood mitigation measures and flood management strategies will be evaluated. Before proceeding to the questions please review the following definitions: - Flood mitigation measures- are strategies implemented in flood prone areas in order to reduce the risk of flooding. Mitigation measures are divided in two main groups: structural and non-structural. - Structural mitigations- mitigations that tend to modify the characteristics of a flood (i.e. dams, levees, retention ponds, etc.). - Non-structural measures- help reduce the hazard from unavoidable damages (i.e. warning systems, flood zoning regulations, relocation, etc.).

1. Which type of government agency do you believe to be the **most** responsible for implementing **structural** mitigation measures?
   - ☐ Municipality
   - ☐ State
   - ☐ Federal Agency

2. Which type of government agency do you believe to be the **most** responsible for implementing **non-structural** mitigation measures?
   - ☐ Municipality
   - ☐ State
   - ☐ Federal Agency

3. For quality control purposes please select the number "2" from the list.
   - ☐ 1
   - ☐ 2
   - ☐ 3

4. Have you received any type of educational information (workshops, seminars, literature, etc.) regarding flood risks and mitigation measures within the past year?
   - ☐ Yes
   - ☐ No
   - ☐ Not sure

5. If you answered yes to question #4, who offered the educational information? (Select all that apply)
   - ☐ Municipality
   - ☐ State Agency
   - ☐ Federal Agency
   - ☐ Other: _______________

6. Rate how much do you prefer the following educational material for 1 to 5 (1 being "Preferred less" preferable and 5 being "Preferred the most")

Educational Material	1- Prefer less	2	3	4	5- Prefer the most
Workshops/Community Meetings	☐	☐	☐	☐	☐
Literature/Brochures/Newsletters	☐	☐	☐	☐	☐
Websites	☐	☐	☐	☐	☐
Television/Radio	☐	☐	☐	☐	☐
Other:________________	☐	☐	☐	☐	☐

7. Rate the importance the following **Economic Criteria** should be given when defining flood risk management objectives and prioritizing measures.

Criteria	Not at all important	Slightly important	Important	Fairly important	Very important
Direct costs of measures (Planning /Implementation)	☐	☐	☐	☐	☐
Indirect costs of measures (Operation/Maintenance)	☐	☐	☐	☐	☐
Creation of employment	☐	☐	☐	☐	☐
Damages to structures	☐	☐	☐	☐	☐
Damages to the infrastructure	☐	☐	☐	☐	☐
Interruption of commercial activity	☐	☐	☐	☐	☐

8. Rate the importance the following **Social Criteria** should be given when defining flood risk management objectives and prioritizing measures.

Criteria	Not at all important	Slightly important	Important	Fairly important	Very important
Preservation of historical values	☐	☐	☐	☐	☐
Loss of life	☐	☐	☐	☐	☐
Critical facilities affected	☐	☐	☐	☐	☐
Need of shelter	☐	☐	☐	☐	☐
Interruption of electrical and water services	☐	☐	☐	☐	☐
Required detours due to blocked roadways	☐	☐	☐	☐	☐
Displaced population	☐	☐	☐	☐	☐

9. Rate the importance the following **Environmental Criteria** should be given when defining flood risk management objectives and prioritizing measures.

Criteria	Not at all important	Slightly important	Important	Fairly important	Very important
Enhancing ecosystem services	☐	☐	☐	☐	☐
Recreational benefits	☐	☐	☐	☐	☐
Accumulation of pollutants	☐	☐	☐	☐	☐
Soil erosion potential	☐	☐	☐	☐	☐
Habitats affected	☐	☐	☐	☐	☐

10. Please indicate how much to you agree or disagree with the following statements:

Mitigation Measure	I totally agree	I agree	Neutral	I disagree	I totally disagree
a. I would invest $1,000 or less to decrease flood vulnerability to my structure	☐	☐	☐	☐	☐
b. I would invest $1,000 or more to decrease flood vulnerability to my structure	☐	☐	☐	☐	☐
c. I would apply for government funding to decrease the flood vulnerability to my structure	☐	☐	☐	☐	☐
d. Applying for government funding is difficult process	☐	☐	☐	☐	☐

11. Please use the following space to add any other information you would like to share about you perception of floods and mitigation measures. (Optional)

END OF SURVEY

Stakeholder's perception on flood Risk and the impacts associated with the implementation of Flood Mitigation Measures

SURVEY
(Time: 15-20 mins.)

I. General Information

1. To what type of entity do you belong?
   - ☐ Municipal agency
   - ☐ State agency
   - ☐ Federal agency
   - ☐ Private entity
2. Please indicate the name of your agency or private entity:
   - ☐ Agency/Entity: ______________________________
   - ☐ Prefer not to answer
3. Job Position within the agency:
   - ☐ Management (i.e. Director, manager, supervisor, etc.)
   - ☐ Technical (i.e. inspector, data collection, technical analyst, permit technician, etc.)
4. Years of experience with the agency:
   - ☐ 0-5 years
   - ☐ 6-10 years
   - ☐ 10+ years
5. Are you familiar with Flood Management practices (i.e. flood risks, flood vulnerability, mitigation measures, implementation process, maintenance process, outreach, etc.)?
   - ☐ Yes
   - ☐ No

II. Mitigation Measures

In this section, your perception on flood mitigation measures and flood management strategies will be evaluated. Before proceeding to the questions please review the following definitions:

- Flood mitigation measures- are strategies implemented in flood prone areas in order to reduce the risk of flooding. Mitigation measures are divided in two main groups: structural and non-structural.
- Structural mitigations- mitigations that tend to modify the characteristics of a flood (i.e. dams, levees, retention ponds, etc.).
- Non-structural measures- help reduce the hazard from unavoidable damages (i.e. warning systems, flood zoning regulations, relocation, etc.).

1. In what processes is your agency involved during flood management? (Please select all that apply)
   - ☐ Surveying and/or data collection
   - ☐ Planning
   - ☐ Regulation
   - ☐ Feasibility Study
   - ☐ Construction/Implementation
   - ☐ Inspection
   - ☐ Maintenance
   - ☐ Other: ________________

2. To your best knowledge, what is the main source of funding for flood mitigation measures?
   - ☐ State
   - ☐ Federal
   - ☐ Municipality
   - ☐ Taxes
   - ☐ Private developers
   - ☐ Others:________

3. For quality control purposes please select "No"
   - ☐ Yes
   - ☐ No

4. Who decides which mitigation strategy will be implemented?
   - ☐ Municipality
   - ☐ State Authority
   - ☐ Federal Authority

5. Rate the importance the following **Economic Impacts** should be given when defining flood risk management objectives and prioritizing measures.

Criteria	Not at all important	Slightly important	Important	Fairly important	Very important
Direct costs of measures (Planning /Implementation)	☐	☐	☐	☐	☐
Indirect costs of measures (Operation/Maintenance)	☐	☐	☐	☐	☐
Creation of employment	☐	☐	☐	☐	☐
Reduction of damages to structures	☐	☐	☐	☐	☐
Reduction of damages to the infrastructure	☐	☐	☐	☐	☐
Reduction of interruption of commercial activity	☐	☐	☐	☐	☐

6. Rate the importance the following **Social Impacts** should be given when defining flood risk management objectives and prioritizing measures.

Criteria	Not at all important	Slightly important	Important	Fairly important	Very important
Preservation of historical values	☐	☐	☐	☐	☐
Minimize loss of life	☐	☐	☐	☐	☐
Minimize critical facilities affected	☐	☐	☐	☐	☐
Minimize the need of shelter	☐	☐	☐	☐	☐
Reduction of possible interruption of electrical and water services	☐	☐	☐	☐	☐
Reduction of displaced population	☐	☐	☐	☐	☐

7. Rate the importance the following **Environmental Impacts** should be given when defining flood risk management objectives and prioritizing measures.

Criteria	Not at all important	Slightly important	Important	Fairly important	Very important
Enhancing ecosystem services	☐	☐	☐	☐	☐
Recreational benefits	☐	☐	☐	☐	☐
Reduction of accumulation of pollutants	☐	☐	☐	☐	☐
Reduce soil erosion potential	☐	☐	☐	☐	☐
Reduce the habitats affected	☐	☐	☐	☐	☐

As part of the study, we are evaluating the implementation of various alternatives for the mitigation of floods. The following questions will ask you to rank the alternatives from 1 to 7 considering the following criteria:

- Effectiveness reducing the risks of floods
- Cost of implementation
- Easiness of implementation

8. Please rank the following alternative from 1 to 7, 1 been to the alternative that you understand is the **most effective in minimizing the risks of flooding**.
   ______ Channels
   ______ Reservoir
   ______ Levees and Floodwalls
   ______ Debris basins
   ______ National Flood Insurance Program (NFIP)
   ______ Stream clean-out program
   ______ Flood warning systems

9. Please rank the following alternative from 1 to 7, 1 been to the alternative that you understand is the most costly alternative to implement. By cost, we are referring to feasibility studies, design, construction/implementation, etc.
   ______ Channels
   ______ Reservoir
   ______ Levees and Floodwalls
   ______ Debris basins
   ______ National Flood Insurance Program (NFIP)
   ______ Stream clean-out program
   ______ Flood warning systems

10. Please rank the following alternative from 1 to 7, 1 been to the alternative that you understand is the **easiest to implement**. When we talk about implementation, we refer to planning process, financing, implementation/construction process, public approval, etc.
   ______ Channels
   ______ Reservoir
   ______ Levees and Floodwalls
   ______ Debris basins
   ______ National Flood Insurance Program (NFIP)
   ______ Stream clean-out program
   ______ Flood warning systems

11. If the measure were to be implemented, it will have positive or negative impacts on the economy, the environment and society. For example, channelization of a river can change the existing habitats, of the area, having a negative impact on the environment. For the following alternatives, please indicate if you expect the measure to have positive (+), neutral (0) or negative impact on each category.

Mitigation Alternatives	Economic Impacts			Environmental Impacts			Social Impacts		
	Positive (+)	Neutral (0)	Negative (-)	Positive (+)	Neutral (0)	Negative (-)	Positive (+)	Neutral (0)	Negative (-)
1. Channels	☐	☐	☐	☐	☐	☐	☐	☐	☐
2. Reservoir	☐	☐	☐	☐	☐	☐	☐	☐	☐
3. Levees and Floodwalls	☐	☐	☐	☐	☐	☐	☐	☐	☐
4. Debris basins	☐	☐	☐	☐	☐	☐	☐	☐	☐
5. National Flood Insurance Program (NFIP)	☐	☐	☐	☐	☐	☐	☐	☐	☐
6. Stream clean-out program	☐	☐	☐	☐	☐	☐	☐	☐	☐
7. Flood warning systems	☐	☐	☐	☐	☐	☐	☐	☐	☐

12. Please use the following space to add any other information you would like to share about you perception of floods and mitigation measures. (Optional)

III. Entities Typology and Attributes

In this section, we will identify the inter-organizational process of evaluating and implementing flood mitigation measures. Before identifying the attributes of each agency, please review the concepts that will be evaluated.

- **Level of involvement-** Degree of involvement of entity during evaluation and implementation of the mitigation.
- **Level of Interest-** Degree of interest the stakeholder has during the project phase being evaluated
- **Power-** Linked to the use of coercive, utilitarian, or normative means to obtain their goals in the context of a specific type of conflict during the process of evaluating and implementing a mitigation measure
- **Legitimacy-** associated with appropriate actions according to socially established norms in the context of a specific type of conflict
- **Time sensitivity-** the degree to which managerial delay in attending to the claim or relationship is unacceptable for the entity
- **Criticality-** the importance of the claim or the relationship to the entity
- **Level of organization-** Refers to the degree of organization of the entity during the phase of planning and implementation of the mitigation measure
    - Not organized
    - Informal
    - Formal
- **Level of representation-** Refers to the degree of representation of the entity
    - **Individual-** Only one person representing the entity during the planning and implementation of the mitigation measure
    - **Aggregated-** A small group of individuals representing the entity during planning and implementation of the mitigation measure
    - **Highly aggregated-** A committee or larger group of individuals, duly assign to represent the entity during the planning and implementation of the mitigation measure.

13. **Flood Management Agencies:** Rate the attributes of the following entities involved in the process of decision-making process of flood mitigation strategies using the following scales:

*0-None; 1-Very Low; 2-Low; 3-Medium; 4-Large; 5-Very Large

**Level of organization: 1- not organized; 2- informal; 3- formal

***Level of representation: 1- individual; 2- aggregate; 3- highly aggregate

ID	Organization	Typology and attributes							
		Involvement*	Influence*	Power*	Urgency*: Time sensitivity	Urgency*: Criticality	Legitimacy*	Level of organization**	Level of representation***
1	Community								
2	Mayor's Office								
3	Municipal Planning and Permits Office								
4	Municipal Department of Transportation and Public Works								
5	Municipal Emergency Management Agency/ Municipal Police								
6	State Planning Board								
7	Department of Education								
8	State's Permits and Management Office								
9	State's Environmental Quality Board								
11	State's Transportation and Public Works Department								
12	Aqueduct and Sewer Authority								
13	Fire Department/ State Police Department								
15	Department of Environment and Natural Resources								
17	Puerto Rico Emergency Management Agency (PREMA)								
19	State's Health Department								
23	Federal Emergency Management Agency (FEMA)								
24	Environment Protection Agency (EPA)								
25	US Corps of Engineers (USCoE)								

END OF SURVEY