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16. Abstract

The need to accelerated bridge construction (ABC) activities due to flooding (e.g., accelerated bridge upgrade prior to flood events and accelerated bridge repair after flood events) has complex interdependencies with physical, social, and environmental factors in urban areas. The interdependencies get exacerbated in coastal areas because of the pronounced effects of climate change such as extreme weather events and sea level rise impacts on surface and ground waters. Flood related factors can also contribute to bridge scour, the biggest cause of bridge failure in the United States. Due to the limited available budget for accelerated upgrade/repair processes, a comprehensive decision support tool is needed to prioritize bridges in terms of the vulnerability of bridge location and risk level of each bridge to support state Departments of Transportation (DOTs) in project selection. This project presents a spatial, risk-based, multi-criterion decision analysis framework to assign a risk factor to each bridge in the study area based on the vulnerability of urban areas against flood-related, social, and environmental issues, and structural and traffic condition of bridges. The framework is applicable as a decision support tool for prioritizing accelerated rehabilitation projects. As a case study, the developed framework was used for risk-based prioritization of existing bridges in urban areas of the Miami-Dade County, Florida. The proposed decision support tool is simple enough to be used in real projects, yet systematic and structured to be adjusted and implemented in various geographic locations. The tool incorporates social equity and environmental justice into bridge rehabilitation planning process.

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Integrated Flood and Socio-Environmental Risk Analysis for Prioritizing ABC Activities

Final Report

October 2023

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CHAPTER 1. INTRODUCTION

1.1. Project Motivation

The need to Accelerated Bridge Construction (ABC) activities due to flooding (e.g., accelerated bridge upgrade prior to flood events and accelerated bridge repair after flood events) has complex interdependencies with many physical, social, and environmental factors in urban areas. The interdependencies get exacerbated in coastal areas, such as southeast Florida, because of the pronounced effects of climate change such as extreme rainfall events and Sea Level Rise (SLR) impacts on surface and ground waters. According to the National Oceanic and Atmospheric Administration (NOAA, 2014) reports, 612% increase in flooding in the United States has been reported from 1960s. Flood-related factors can contribute to bridge scour, the biggest cause of bridge failure in the United States (52% of all failure cases- Cook et al., 2015). Besides, depending on bridge location, rainfall patterns are highly functional in hydraulic failure of bridges (Khandel and Soliman, 2019). Because of the limited available budget for accelerated upgrade/repair processes, a comprehensive decision support tool is needed to prioritize existing bridges in terms of the vulnerability of bridge location and risk level of each bridge to support decision makers from state Departments of Transportation (DOTs) in project selection. To refine funds allocation for the ABC, there is a need for a simplified, yet accurate, methodology to estimate bridge vulnerability to several interdisciplinary factors. The methodology should practice existing data and display important variables to assess the vulnerability of urban areas and risk of bridges against urban flooding considering various flood-related and socio-environmental factors. Considering factors such as extreme rainfall events, storm surges, and SLR mostly in coastal areas, flooding is not only a natural hazard with the distinguished impact on bridge failures and the amount of damage and costs resulting from that, but it is difficult to model and accordingly plan for as well. Furthermore, given population growth rates, urbanization, and poor land use practices in flood-prone areas, flood risk has increased significantly recently. Floods and associated hazards will become more persistent, extreme, and regular along with climate change and socio-environmental effects, notably in already vulnerable areas. The project first performs a vulnerability/risk assessment considering urban flooding, structural and traffic condition of bridges, and socio-environmental factors, and then develops a multi-criteria decision analysis framework in Geographic Information Systems (GIS) environment to assign a risk factor to each bridge in the study area. The risk-factor can then be used as the prioritization basis for selecting accelerated bridge upgrade or accelerated bridge repair projects by decision makers (e.g., state DOTs). As a case study, the developed framework will be used for risk-based prioritization of existing bridges in urban areas of the Miami-Dade County, Florida (FL), with the purpose of selecting projects for accelerated bridge upgrade or repair.

1.2. Problem Statement

The success of ABC projects depends on several factors which result in improving safety, reducing traffic load, costs, and yielding better overall travelling experience (Wang et al., 2011). Decision-makers need to ensure that the ABC techniques are thoughtfully viewed since many of the projects will have only access to the limited budgets and time (Chaphalkar and Shirke, 2013). ABC projects in urban areas interacted with traffic potentially have complex interdependencies with several natural hazards (e.g., flood), environmental, and social factors (Jia et al., 2018). Past studies have asserted that flooding has been the most common natural disaster, accounting for 43% of all disasters during 1995 to 2015 in the world (CRED, 2015). A study by Wardhana &

Hadipriono (2003) found that 53% of bridge failures in the United States during 1989 to 2000 were because of the scour due to floods.

Scour typically occurs in areas where water flows rapidly around the structural support elements (Prendergast and Gavin, 2014). Over time, due to the formation of eddies or vortices, it erodes and displaces the soil around the columns and the footing/pile cap, initially at their base and gradually progressing forward (Khandel and Solimen, 2019; Prendergast and Gavin, 2014). The failure mechanism resulting from scour is primarily linked to the undermining of the foundation soil beneath the footing (for direct foundations) or the pile cap (for deep or indirect foundations) supporting the columns, rather than the direct impact of debris on the structure's columns, though the latter can contribute to the issue (Deng et al., 2016). This process is influenced by factors such as the neutral pressure from water in the soil and the subterranean water flow within the soil mass. These factors alleviate soil compaction, making it easier for the current vortices to remove soil (Lin et al., 2014). This soil removal can persist for years and becomes particularly critical during flooding events when there is a significant increase in water volume and velocity (Khandel and Solimen, 2019; Hung and Yau, 2017; Lee et al., 2017)

In point of fact, the rapid water flow generated by flood often gives rise to accumulated debris, which yields a compounded loading impact on bridges and may cause structural damage or failure (Kalantari et al., 2017). Meanwhile, the structural integrity of a bridge may be degraded by the corrosion of steel reinforcements. In this case the failure risk of bridges under flood hazards magnifies and their failure can become more severe (AASHTO, 2008). Therefore, reducing the construction time through ABC methods can potentially minimize the risk of flooding due to temporary flood diversions during the construction phase. Moreover, in the event of flood damage, ABC bridges can be restored more rapidly. The use of prefabricated components allows for quicker replacement or repair, minimizing the downtime for transportation routes.

High temperatures as an environmental risk factor can cause health issues for humans, impacting ABC progress, and may affect flooding conditions due to the effects on soil hydraulic properties. Social and demographic factors in adjacent areas of bridges (e.g., population, residents' age, race, and income, and age of the buildings) have implications in the need to an ABC process and can impact the construction speed. For example, ABC can help faster revitalization of a high crime rate neighborhood based on urban master plans while ABC activities may also be negatively impacted in those neighborhoods. To obtain a more realistic and accurate vulnerability assessment of bridge failure against floods, flood-related and other interdependent socio-environmental factors should be included in the risk analysis (Arenson, 2013). Complexity, multidimensionality, and inherent uncertainties of urban systems require the risk analysis to be comprehensive and able to address different criteria, multiple stakeholders, and spatial aspects of the problem (Glas et al., 2019). The proposed study addresses the need for a comprehensive risk-based multi-criteria decision analysis framework that can be used as a decision support tool for prioritizing ABC activities in the presence of limited budgets.

1.3. Research Objectives

The primary objective of this research project is to develop a multi-criteria decision analysis framework in GIS environment to assess the vulnerability of urban areas and risk of bridges against flooding and socio-environmental factors. The framework can be used as a decision support tool for selecting accelerated bridge upgrade or accelerated bridge repair projects by decision makers. As a case study, the developed framework will be used for risk-based prioritization of existing bridges in urban areas of Miami-Dade County, FL, with the purpose of selecting projects for accelerated bridge upgrade or repair.

1.4. Description of Research Project Tasks

The objective of the project was accomplished through the following research tasks.

- *Task 1 – Literature Review*: The objective of literature review is to identify the existing state of the knowledge and practice about socio-techno-environmental risk analysis approaches for flooding problems in urban areas. Also, another literature review is performed to identify the existing studies on the interdependencies of climate factors, land factors, bridge characteristics, and bridge scour to be leveraged in the study.
- *Task 2 – Study Area Overview*: As a case study, the developed framework will be used for a risk-based prioritization of existing bridges in Miami-Dade County with the purpose of selecting projects for accelerated bridge upgrade or repair.
- *Task 3 – Data Identification, Collection, and Analysis:* To understand the interactions between flood and socio-environmental factors with the need to ABC activities in urban areas, a GIS-based multi-criteria decision analysis framework will be developed in this study. According to The United Nations Office for Disaster Risk Reduction (UNDRR), vulnerability is defined as a set of conditions and processes resulting from different factors that increase the susceptibility of a community to the impact of a hazard. This study will consider three types of vulnerability: physical, social, and environmental vulnerability. Examples of GIS data that will be used for determining vulnerability in each category are environmental, physical, social, traffic and bridge data. Sources of physical, social, and environmental data with appropriate resolution as well as traffic and bridge data are identified. Data will be collected from national, state, or local databases for the study area (urban areas of Miami-Dade County, FL).
- *Task 4 – Framework Development:* An effective, multi-criteria decision analysis (MCDA) technique that is compatible with the problem in hand and is capable of handling group decision making will be used in GIS environment to develop the decision support framework. The details and interrelationship between the elements in the framework will be determined.
- *Task 5 – Final Report:* The results and findings of the study will be reported in a manner consistent with existing protocols. A final report will be prepared meeting the RITA requirements for UTC funded projects. The content of the report will contain a detailed summary of the results from the preceding tasks and a recommendation for future phases of the project, if necessary.

1.5. Research Advisory Panel (RAP)

The project work was done in collaboration with the Research Advisory Panel (RAP). The following people participated in the RAP:

- Jose DaSilva (Chief Engineer, WGI, Florida)
- Vahid Moshtagh (Senior Project Manager, Virginia Department of Transportation)

1.6. Report Overview

The research is organized as follows. In Section 2, a literature review to identify the existing state of the knowledge and practice about socio-physical-environmental risk analysis approaches for natural hazard problems in urban and coastal areas are presented. Section 3 includes the developed MCDA framework as well as vulnerability and risk maps. Section 4 presents the results and discussion, and section 5 includes the conclusions and future research recommendations.

CHAPTER 2. LITERATURE REVIEW

2.1. Literature Review

The objective of literature review is to identify the state of knowledge and practice about socio-techno-environmental risk analysis approaches for natural hazard (especially flood) problems in urban areas, the interdependencies between climate factors, land factors, bridge characteristics, and bridge scour, and their application in bridge infrastructure planning. Urban infrastructures, namely bridges, as the result of urbanization, are increasing in demand. However, due to natural hazards and climate change effects, such as floods, SLR in coastal areas, high temperature, and severe storms, their construction might be at risk of failure. According to the UNDRR risk is the combination of the probability of a hazardous event and its negative consequences which develop out of interactions between natural or man-made hazard(s), vulnerability, exposure, and capacity (Birkmann et al., 2010). Vulnerability can be the combination of multi criteria categories, including physical, social, economic, environmental, psychological, structural, and institutional problems (Pescaroli and Alexander, 2019; Ebrahimian Ghajari et al., 2017). The Intergovernmental Panel on Climate Change (IPCC) considered the risk concept, as a function of hazard, exposure, and vulnerability, instead of the vulnerability definition (IPCC, 2012). This concept determines that the damaging effects of a hazard depend on the local vulnerability of an exposed society. Considering vulnerability as one element of the hazard risk, it has a multidimensional nature which is varying across temporal and spatial scales. It is required to decrease the vulnerability before and after the hazard’s occurrence in the context of coping and adaptation. While coping is referred to ex post actions, adaptation is normally associated with ex ante actions (IPCC, 2014) that boost resilience (Golz et al., 2015), yet in many applications, vulnerability still is considered only as the impacts of a hazard (Yang et al., 2018; Weis et al., 2016). In recent years, a better representation of hazard and vulnerability along with spatial science (e.g., GIS) has been challenging. Recent studies used ‘integrated’ (Weis et al., 2016), ‘hybrid’ (Roodposhti et al., 2016), ‘MCDA’ and ‘system-thinking’ terms (Martin et al., 2020). However, most definitions are not fitting to different areas of hazards because of geographical differences, human interactions, and inadequate data (Robinson et al., 2019), governance ordering (Driessen et al., 2018), the involvement of stakeholders and dynamism of cities (Ciullo et al., 2017). The vulnerability also varies over different time periods and due to different causes, which provide challenges for the assessment in different areas (Pescaroli & Alexander, 2019). Yet, bridge failures are highly interdisciplinary, a mixture of various factors that might not result in a significant bridge failure if they occur individually. For instance, in coastal areas, such as southeast Florida, the pronounced effects of climate change such as extreme storm events and SLR impacts on surface and ground waters may cause bridges failure if they happen along with high traffic loads. Regarding the multidisciplinary nature of risk assessment, MCDA has been considered as a popular, common, and real-world-based challenge way focusing on the risk assessment problems. For massive computational efforts on data collection and analysis, GIS technology including various spatial and temporal dimensions has been commonly applied to multi-dimensional problems (Tehrany et al., 2014; Termeh et al., 2018). Integrated analysis is feasible using GIS in both technical and socioeconomic features (Chen et al., 2021). GIS can integrate and analyze data from various sources and report the results, which makes it a valuable tool in the management process (Eastman, 1987). GIS is applicable for damage assessment due to its ability to combine results from the hydraulic model and socio-environmental information. Complex decision-making situation like flood risk assessment that consists of several spatial criteria can be developed through Geographic Information Systems' capability of visualization, analysis, and management of spatial data (Meyer et al., 2009; Papaioannou et al., 2015; Tang et al., 2018). GIS is an important tool in analyzing and assessing the effects of natural hazards (Haq et al., 2012; Kanani Sadat and Karimipour, 2014; Karimipour and Kanani-Sadat, 2016); therefore, many studies have investigated flood analysis and developing flood risk assessment map using the capabilities of GIS (Khosravi et al., 2018; White et al., 2010; Tehrany et al., 2014; Termeh et al., 2018; Strobl et al., 2012; Sanyal and Lu, 2009). Considering mapping approaches, the discussion of selecting an appropriate indicator is a challenge (Malczewski and Rinner, 2015). Indicator's assignment and the quality of available data require a deep conception of the complex system. Another challenge is the criteria weights allotment as the complexity of systems is limiting the criteria to have equal influence in a hazard (Jung et al., 2011). For vulnerability and exposure mapping assessments, studies mostly assess equal weighting or either subjective or objective (Tahmasebi Birgani and Yazdandoost, 2018) methods for weights calculation. Furthermore, data collection/preparation is the most important step and can be the most time-consuming part of an analysis. Generally, study of natural hazards requires multiple datasets to distinguish the spatial changes and the processes of hazards (Martinez and Le Toan, 2007). Natural hazards could be under the effects of several factors, namely geomorphology, vegetation, geologic and hydrologic parameters, and patterns that must be considered in providing flood risk assessment maps. Therefore, risk assessment mapping is an MCDA process (Malczewski, 2006). MCDA has been recognized as an essential tool for analyzing complex decision problems that often concern incomparable data or criteria (Hwang et al., 1981; Malczewski, 2006). To evaluate natural disaster risks, there are various MCDA methods, e.g., Analytical Hierarchy Process (AHP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and Multi Attributive Border Approximation Area Comparison (MABAC). Fernandez & Lutz (2010) have estimated the efficiency of AHP and GIS for mapping any area adjacent to a river, lagoon, or lake likely to have floods anytime the water level rises in Tucuman Province, Argentina. Ozturk and Batuk (2011) applied AHP to identify flood vulnerability, and then, use GIS to generate the flood risk map. TOPSIS has been used in flood hazard management due to its ability to cope with multiple attributes (de Brito and Evers, 2016). Mojtahedi & Oo (2016) presented an integrated non-parameter resampling bootstrap technique and TOPSIS to assess the flood risk of Australia's states. Luu et al. (2019) developed the brand-new multiple linear regression TOPSIS for Vietnam's evaluation flood risk. Several studies also have used the fuzzy-TOPSIS technique (Tehrany et al., 2014; Shariat et al., 2019). In general, MCDA methods are approaches that have been most popular in flood hazard assessment applied by many researchers in recent studies (Rahmati et al., 2016; Rahman et al., 2019; Ogato et al., 2020). Improving the accuracy of these models has always been a major concern for researchers and decision makers. While the existing literature provides no universal guideline in finding the best model in a region due to the models' limitations, some studies (e.g., Tehrany et al., 2018; Hong et al., 2018; Costache and Bui, 2020; Rahman et al., 2019) showed that combining several methods may lead to higher accuracy in flood susceptibility assessment. Table 1 lists some of the GIS-based, MCDA, and combined GIS-MCDA studies regarding the flood risk assessment in urban areas. Some studies have been assessing flood risk integrated with socio-economic and environmental factors. Gain & Giupponi (2015), and Dewan, A. & Dewan, A. M. (2013) introduced the random economic changes, population growth, urbanization, poor policies, and land-use changes as the flood risk assessment factors. Bubeck et al. (2012) related the anthropogenic activities such as land-use changes to flooding risk. Khosravi et al. (2016) considered geo-morphological and geo-environmental factors (e.g., slope, plan curvature, elevation and land use) as the effective factors on the flood risk. Furthermore, MCDA can apply combining process to spatial data and information layers for the decision-making process (Malczewski, 2006). Chen et al. (2011); Shariat et al. (2019) combined GIS and MCDA to come up with a powerful spatial decision support system.

Table 1 Examples of GIS-based, MCDA, and MCDA-GIS studies for flood risk assessment in urban areas

Authors	Indicator			Method
	Environmental	Physical	Social	
Ullah & Zhang, 2020	NDVI	DEM Slope Drainage density Rainfall intensity	Land use	GIS
Cai et al., 2019		DEM Slope Impermeability Water (flood) depth Flood duration	Land use Building density Population density	GIS
Kabenge et al., 2017		Slope Drainage network Distance from channel Rainfall intensity Flow accumulation	Land Use	GIS
Toosi et al., 2019		DEM Rainfall intensity Drainage network Soil erosion Soil map Historical flood	Land use	MCDA
Meyer et al., 2009	Areas with accumulation potential of pollutants	Erosion	Annual average damage Number of people affected at their home. Hot spots (hospitals, schools, daycares)	MCDA
Vignesh et al. 2021	NDVI	DEM Slope River network Distance from channel	Population density Hot spots (hospitals, schools, daycares)	MCDA-GIS

		Rainfall intensity Flood frequency		
Hadipour et al., 2020	Tidal range Storm surge Wind speed	SLR	Population density Age Gender	MCDA-GIS
Rincón et al., 2018		Slope Distance to stream Curve number Rainfall intensity Flood frequency	Age Family structure Language proficiency Income Education Population density	MCDA-GIS
Fernández & Lutz, 2010		DEM Slope Distance from channel Depth to groundwater table Land cover	Land use	MCDA-GIS

Researchers have used different metrics or indicators in flood risk analysis studies. Singh et al. (2020) considered six physical factors that have significant impact on flooding in India: rainfall intensity, curve number, time of travel, surface slope, Manning's coefficient, and drainage density. Kia et al. (2012) introduced rainfall, slope, and flow as the effective natural hazard factors in urban areas. Sun et al. (2020) selected five primary and nineteen secondary flood risk assessment indicators, including annual precipitation, frequency of rainstorm, vegetation coverage, drainage density, topography, regional circulation, urbanization rate, land use, population density, unemployment rate, old and young population density, building density and economic density, namely general budget expenditure of local finance and economic loss. They considered two vulnerability indicators including the old and young population per unit area and the proportion of crops per area; two secondary indicators including economic and crop loss were considered as the disaster loss criteria. Gain and Giupponi (2015) indicated that flood risk is the result of extreme hydrological events in addition to physical and social indicators. They introduced building age and types, building materials, land-use map, number of cars and population density as vulnerability indicators. Wang et al. (2021) addressed fourteen flood risk assessment indicators including physical geography and socio-economic factors, out of which there are seven hazard indicators and seven vulnerability indicators. Digital elevation model (DEM), soil texture, rainfall intensity, the normalized difference vegetation index (NDVI), rainstorm frequency, drainage density, and slope data were defined as the hazard indicators by Wang et al. (2021) while they used gross domestic product, road network density, average schooling years, population density, grain output, and per capita disposable income as the vulnerability indicators. Glas et al. (2020) developed flood risk maps integrated with social, economic, and physical vulnerability maps for the catchments of the river Moustiques, Haiti, a data poor region. They used rainfall depth, DEM, soil texture, land-use/cover, and channel characteristics in the hydrological model. Only material damage to buildings and roads is considered as physical vulnerability, whereas economic vulnerability also considers the economic damage to farmlands.

In addition to the studies previously discussed, there are further research efforts that have delved into the complexities surrounding bridges and their susceptibility to various factors, particularly in the context of flood risk. For example, Karatzetzou et al. (2021) presented homogenizing methodology to combine the single flood risk indicators and derive a combined flood risk assessment scenario for roadways, bridges, and tunnels in Greece. Andric and Lu (2016) classified the potential hazards based on the collapse reason into six groups, including windstorm, hydraulic, traffic, construction, and human-made hazards. They introduced fifteen risk indicators contributed to bridge failure, including earthquakes, tsunamis, hurricanes, floods, debris, scour, ice, soil, the age of the bridge, collision, overloading, deterioration, construction and design, fire, and terrorist attack. Connecting these studies creates a more holistic view that goes beyond general aspects of flood risk to include specific considerations related to bridges. This comprehensive understanding is crucial for developing effective strategies and frameworks to enhance the resilience of bridge infrastructure in the face of natural hazards.

In response to historical incidents, such as the collapse of the Interstate Highway Bridge over Schoharie Creek in 1987, attributed to scour caused by flooding, regulatory measures have been implemented. The Federal Highway Administration mandated the identification of highway bridges at risk of scour-related issues in each state. Recent studies, such as those by Cantero-Chinchilla et al. (2021), Barankin et al. (2020), and Mondoro et al. (2018), delve into factors impacting local scour formation, analyze vulnerability of transportation assets to socio-economic and flooding events, and propose optimal risk-based methods for coastal region bridges, respectively. These endeavors collectively contribute valuable insights for informed decision-making and improved infrastructure resilience. Mondoro et al. (2018) specifically proposed an optimal risk-based method for coastal region bridges, addressing natural hazards like hurricanes, updated flood maps by FEMA, and economic and social indicators such as detour length, duration, average daily traffic, vehicle occupancy, and detour speed. This approach ensures a comprehensive evaluation of risk factors, integrating both environmental and socio-economic considerations.

In the context of socio-economic vulnerability in risk analysis of highway bridges, literature has been using various combinations of factors. Schmidt-Thome (2006) presented land management/development and disaster mitigation plans as social vulnerability factors. Tables 2 to 6 list some of the risk assessment indicators due to socio-economic, environmental, and physical factors.

Table 2 Environmental factors affecting disaster risk assessment

Reference	**Indicator**			
	NDVI	**Water quality**	**Air quality**	**Wind speed**
Vignesh et al. 2020	*			
Ullah and Zhang, 2020	*			
Hadipour et al., 2020				*

Ronco et al., 2015		*	*	
Turner et al., 2003	*			
Chen et al., 2011	*			
Yamin et al., 2013				*
Andric et al., 2016				*
Mortazavi, 2020		*	*	

Table 3 Physical factors affecting disaster risk assessment, part 1

Reference	**Indicator**				
	DEM	**Slope**	**Road network**[1]	**Bridge network**[2]	**Land cover**
Turner et al., 2003		*			
Chen et al., 2021	*	*			
Dewan et al., 2007	*				
Meyer et al., 2009					
Fernandez & Lutz, 2010	*	*			
Te Linde et al., 2011	*	*			*
Cheng-Hsien et al., 2011		*			
Bloetscher et al., 2021			*	*	*
Kia et al., 2012		*			
Zou et al., 2013	*	*			*
Yamin et al., 2013			*		
Ballesteros-Ca et al., 2013	*				
Gain et al., 2015	*		*		
Ronco et al., 2015			*		
Andric et al., 2016	*			*	
Mondoro et al., 2018	*			*	
Lee at al., 2017		*			

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[1] Road network refers to all types of roads, including international roads, national highways, district roads, feeder roads and urban roads.

[2] Bride network refers to all type of bridges with any size, shape and material.

Kabenge et al., 2017		*			
Rincon et al., 2018		*			
Toosi et al., 2019	*	*			

Table 4 Physical factors affecting disaster risk assessment, part 2

Reference	**Indicator**				
	Canal network	**Soil type**	**Permeability**	**Distance from drainage system**	**River network**[1]
Turner et al., 2003			*		
Meyer et al., 2009		*			
Fernandez & Lutz, 2010			*	*	
Te Linde et al., 2011				*	*
Bloetscher et al., 2021				*	*
Zou et al., 2013				*	*
Dewan A. & Dewan A. M. 2013		*		*	
Gain et al., 2015					*
Andric et al., 2016		*			
Lee et al., 2017				*	
Kabenge et al., 2017	*			*	
Rincon et al., 2018				*	
Toosi et al., 2019	*	*		*	
Chen et al., 2021	*			*	*

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[1] River network refers to any river located in the study area.

Table 5 Social factors affecting disaster risk assessment.

Reference	**Land use**	**Population density**	**Gender**	**People age**	**Employment rate**[4]	**Income rate**[5]	**Building type**[6]	**Building density**[7]
Tobin, 1997			*	*		*		
Turner et al., 2003	*	*						
Zou et al., 2013	*	*						
Quan, 2014	*							
Yamin et al., 2013		*						
Te Linde et al., 2011	*							
Dewan A. & Dewan A. M. 2013	*							
Rincon et al., 2018	*			*				
Glas et al., 2020	*							
Singh et al., 2020	*							
Chen et al., 2021	*	*						
Cardona et al., 2005		*			*	*	*	
Messner & Meyer, 2006		*	*	*				
Lee et al., 2017			*			*		
Hadipour et al., 2020		*	*	*	*			
Rygel et al., 2006		*						
Meyer et al., 2009		*						
Gain et al., 2015		*						
Ronco et al., 2015		*						
Mondoro et al., 2018		*						

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[4] Ratio of the employed to the working age population
[5] Average annual income per capita
[6] Building types based on their services offered and functionality, e.g., hospitals, clinics, schools
[7] The concentration of buildings in a given geographic area

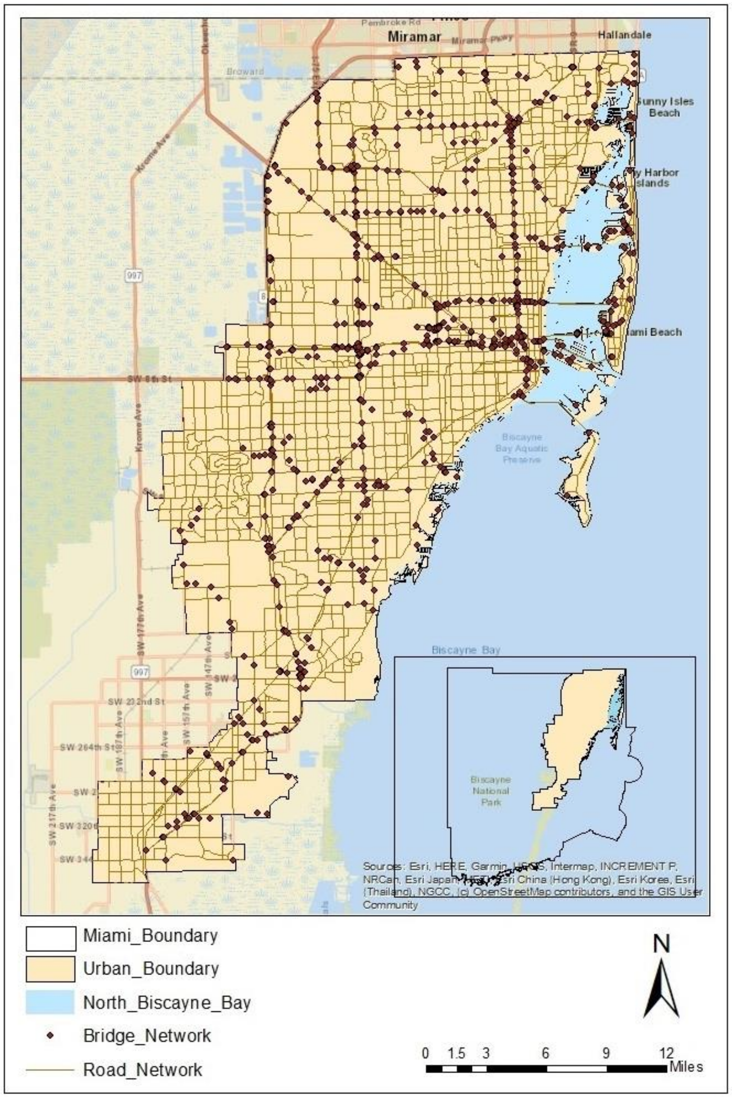
Yang et al., 2018		*						
Barankin et al., 2020		*						
Sun et al., 2020	*	*			*			*
Wang et al., 2021		*						
Hsieh et al., 2011				*	*	*		*

CHAPTER 3. METHODOLOGY

3.1. Study Area

Miami-Dade County, in southeast Florida, Figure 1, one of the low-lying areas on the southeast coast of the United States exposed to the risk of flood and storm surge (Chen, H. et al., 2015), is used as the case study. Social factors of a society, namely age, is important to determine its limitation and capacity to face the natural hazards effects on the society. In fact, to evaluate each society's capacities for facing natural hazards, the more factors on that society we use, the more detailed and accurate evaluation of that society we can extract. An interaction of multi hazardous factors and the combination of environmental and human elements exposed to the risk are important to get realistic risk analysis result. Therefore, these terms are considered by applying a specific combination of socioeconomic and environmental conditions present at the Miami-Dade County. Miami-Dade County is the ninth in population exposure to climate extremes among world port cities and has a population of 2,6 million in 2021, one of the largest counties in the US and has the largest amount of exposed assets and the population vulnerable to sea-level rise in the world. For instance, drivers' age that causes different social vulnerability is diverse within the county and neighborhoods. Miami-Dade's estimated beachfront property value is more than $14.7 billion, not including infrastructure (Tompkins & DeConcini, 2014). King tides, flood events with high tide conditions, have been causing serious damage to the constructions including bridges and transportation systems. This damage due to coastal flooding will become even worse with the rising sea level.

As a case study, the developed framework will be used for the risk-based prioritization of existing bridges in urban areas of Miami-Dade County with the purpose of selecting projects for accelerated bridge upgrade or repair. The bridge inspections summary in Miami-Dade County reported in 2018 for a total of 1046 bridges (968 in urban development areas) is presented in Figure 1. More detailed information is presented in Table 6.



Sources: Esri, HERE, Garmin, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri (Thailand), NGCC, (c) OpenStreetMap contributors, and the GIS User Community

Figure 1 Bridge and road network in the study area (urban areas of Miami-Dade County, FL)

Table 6 Bridge status summary, Miami-Dade County, FL (Source: National Bridge Inventory)

summary	**Number**	**Percent**	**Number**	**Percent**
	Miami-Dade County		Urban Development Area	
Total number of bridges	1046	-	986	-
Bridges need repair or corrective action	156	14.91	151	15.31
Closed	7	0.67	2	0.20
Reported poor by USDOT	58	5.54	39	3.96
Structurally deficient	61	5.83	61	6.19

3.2. Data Identification, Collection, and Analysis

The geographic information system (GIS) is a system which uses data referenced by spatial coordinates. Observation and collection of data as well as storage, analysis, and use of the information derived are crucial parts of a decision-making process. No solid guideline concerning which data to choose and how to analyze exists in the literature. Flood risk is a common bridges' failure reason, which leads to an increase in the probability of failure besides the structural characteristics of bridges due to scouring (Cook et al. 2015). Scouring happens directly not only because of the structural characteristics of bridges, but from the impacts of extreme natural events like flood on the bridges. Besides, considering bridge construction timelines, alternative routes for road users usually have higher flood risk, highlighting the importance of ABC activities in flood risk and asset management strategies. For example, bridges in Miami-Dade County are at risk due to scour, which is worsened by tidal changes and becomes even more critical during tropical storms or hurricanes because of significant water level differences between the ocean and intra-coastal water (Orcesi et al., 2022). The collapse of these critical infrastructure elements can obstruct water flow, disrupt transportation routes, and contribute to localized flooding in urban areas, particularly during tidal changes and severe weather events like tropical storms and hurricanes (Hughes & Zhang, 2023; Orcesi et al., 2022). Additionally, Miami-Dade County experiences occasional heavy rainfall, tropical storms, and hurricanes, which can lead to urban flooding (McAlpine & Porter, 2018). The frequency and intensity of these events can increase the likelihood of scour-related issues for bridges.

In terms of social factors, social and cultural heterogeneity changes in different urban communities and then, various methodologies can be applied to assess social vulnerability. Vulnerable or marginalized groups require special attention to secure their human rights for being equal in status. ABC activities accelerate bridge rehabilitation or construction and improve mobility and accessibility in society. Regarding environmental justice, ABC can reduce the impact of construction activities on the environment and work force by having less disruptions to the surrounding. Extreme heat is also a threat to public health. ABC activities reduce the number of working days to protect workforce from high temperature, whereas the lack of rapid construction activities can cause long deviations and traffic congestions and the air quality impacts. On the other hand, since elements of bridges in ABC activities are prefabricated, they are less vulnerable to the weather condition, which means ABC decreases the chance of delays by weather in the construction process. The data used in this study was collected from readily available sources (national and regional datasets). We developed a new data selection set which is comprehensive and aligned with the present research's goals. Some researchers combined rainfall intensity with population density for risk analysis (Vignesh et al. 2021 & Lin et al. 2020). Other studies added more social indicators to their methodology, however, there is still a limited number of studies that explored the integration of social equity and environmental justice in ABC activities. Therefore, based on the performed literature review (looking at the data used by other researchers in similar studies) and specific conditions of the current research and study area, we ended up with using the data presented in Tables 7 to 12 and Figure 2 under three categories, physical, social, and environmental, each with multiple subcategories. Every category introduced in this study includes factors causing impacts in the context of prioritizing ABC activities. This understanding of data collection improves the accuracy of the final risk map. This research attempts to frame an approach to omit/combine data often have overlapped to provide meaningful and specific assessments rather than introducing new data. It is noted that any expected damage to bridges is always integrated with their intrinsic conditions, namely age, and structural status. Therefore, vulnerability is considered as the susceptibility of a bridge to the impact of physical, social, and environmental factors integrated with bridges' structural conditions and traffic data.

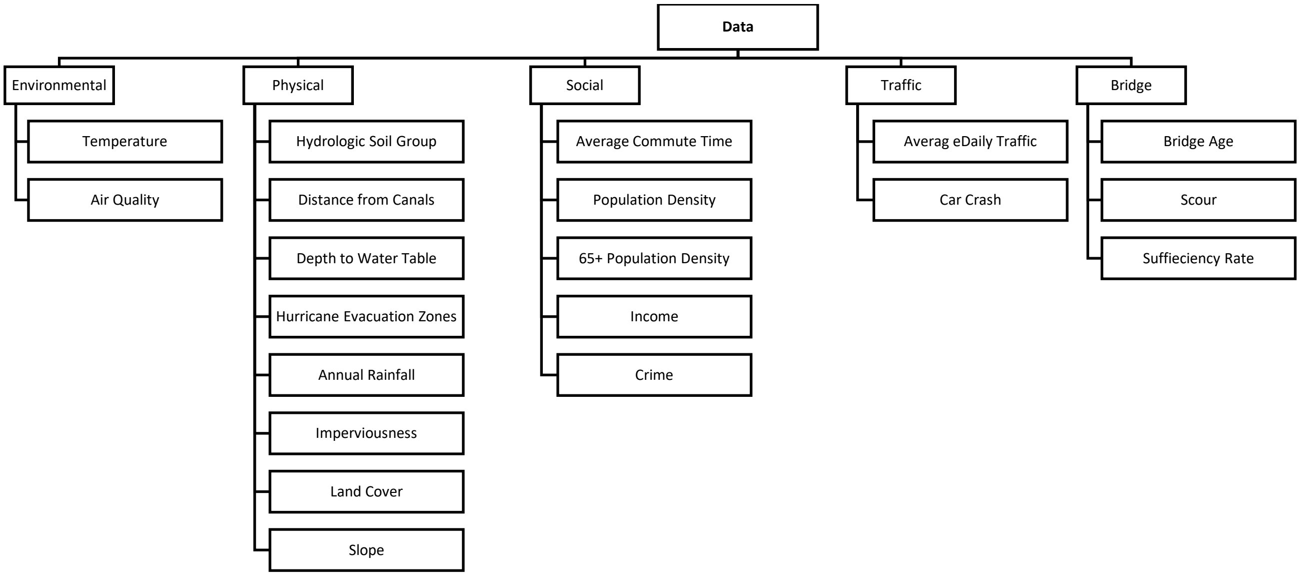


Figure 2 Data used in the study.

Table 7 Data description and sources

Environmental Indicators	
Temperature	
Definition	August average temperature, °F
Date	2000 to 2021
Source	National Centers for Environmental Information, NOAA https://www.noaa.gov/weather https://www.weather.gov/wrh/climate?wfo=mfl
Air Quality	
Definition	Air Quality Index
Date	2000 to 2022
Source	EPA, Florida Department of Environmental Protection https://www.epa.gov/outdoor-air-quality-data/air-quality-index-report
Physical Indicators	
Imperviousness	
Definition	NLCD imperviousness products represent urban impervious surfaces as a percentage of developed surface over every 30-meter pixel in the United States
Date	2019
Source	USGS, The Multi-Resolution Land Characteristics (MRLC) consortium https://www.mrlc.gov/data/type/urban-imperviousness
Land Cover	
Definition	Land Cover

Date	2019
Source	National land cover database (NLCD) https://www.usgs.gov/centers/eros/science/national-land-cover-database
Hydrologic Soil Group	
Definition	Hydrologic Soil Group
Date	2000
Source	Web Soil Survey https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx
Depth to Water Table	
Definition	Depth to water table measured from the surface, ft
Date	2012 to 2021
Source	USGS https://waterdata.usgs.gov/nwis/gw
Slope	
Definition	The surface ratio of change in height to change in horizontal distance, percentage
Date	2021
Source	DEM 5ft, Miami-Dade County Open Data Hub https://gis-mdc.opendata.arcgis.com/
Distance from Canals	
Definition	Horizontal distance from canals, ft
Date	2018
Source	Canal network, Miami-Dade County Data Hub https://gis-mdc.opendata.arcgis.com/datasets/MDC::canal/about
Hurricane Evacuation Zones	
Definition	Evacuation zones during a hurricane or storm surge of 1.5 feet or higher for a hurricane due to risk of storm surge
Date	2022
Source	Miami-Dade County Open Data Hub provided by National Hurricane Center https://gis-mdc.opendata.arcgis.com/datasets/cb44c8fd35474a9d8b8ec35eda9ee40f_0/explore
Rainfall	
Definition	Average rainfall per year for 10 years, inch
Date	2011 to 2021
Source	NASA
Social Indicators	
Income	
Definition	Average annual income per capita, $
Date	2018/2022
Source	Miami-Dade County Open Data Hub, Department of Housing and Urban Development for FY2022
Crime	
Definition	Number of crimes per 1000 residents per year
Date	2020
Source	Open Data Hub www.miamidade.gov/police/library
Population density	
Definition	Population per square mile

Date	2020
Source	www.census.gov
65+ population density	
Definition	Population of people above 65 years old per square mile
Date	2020
Source	Open Data Hub
Land Use	
Definition	Human use of land
Date	2018
Source	Open Data Hub
Average Commute Time	
Definition	The total number of minutes that it usually takes a person to get from home to work each day during the working week. (Workers 16 years old and over who do not work at home)
Date	2016 to 2021
Source	The American Community Survey (ACS) conducted annually by the U.S. Census Bureau.
Traffic Indicators	
ADT	
Definition	Annual Average Daily Traffic
Date	2017
Source	Florida Department of Transportation (FDOT) https://www.fdot.gov/
Car Crash	
Definition	The number of crashes for the total number of cars driving over 1000 miles of a road per day
Date	2008 to 2010
Source	National Highway Traffic and Safety Administration https://www.nhtsa.gov/press-releases/2020-traffic-crash-data
Bridge Indicators	
Bridge Age	
Definition	Bridge year-built
Date	2018/2021
Source	National Bridge Inventory; Federal Highway Administration https://bridgereports.com/
Scour	
Definition	Erosion of stream bed or bank material due to flowing water, elevation, in this case: National Bridge Inventory (NBI) a single-digit code to identify the status of the bridge regarding. its vulnerability to scour
Date	2016, Last Update: 2020
Source	National Bridge Inventory; Federal Highway Administration: National Bridge Data Dictionary FHWA https://bridgereports.com/ https://catalog.data.gov/dataset/national-bridge-inventory-national-geospatial-data-asset-ngda-bridges

Sufficiency Rate	
Definition	Determines whether a bridge that is structurally deficient or functionally obsolete should be repaired or just replaced. The sufficiency ratings for bridges are part of a formula used by the Federal Highway Administration (FHWA) when it allocates federal funds to the states for bridge replacement. Structural Adequacy and Safety 55%, Serviceability 30%, Essentiality for Public Use 15%, and an undefined category of Special Reductions (up to 13%), percentage
Date	2018, Last update: 2021
Source	National Bridge Inventory data https://bridgereports.com/

Table 8 Environmental indicators classification

Indicator	**Classification**	
	Numerical Value	**Vulnerability**
Temperature, °F	<75	Very Low
	75 - 85	Low
	85 - 90	Medium
	90 - 100	High
	>100	Very High
Air quality, AQI	<50	Very Low
	50 – 100	Low
	100 - 150	Medium
	150 - 200	High
	>200	Very High

Table 9 Physical indicators classification

Indicator	**Classification**	
	Numerical Value	**Vulnerability**
Hydrologic soil group	A	Very Low
	B	Low
	BD	Medium
	C	High

	D	Very High
Distance from canals, feet	<100	Very Low
	100 - 150	Low
	150 - 200	Medium
	200 - 250	High
	>250	Very High
Depth to water table, feet	>12	Very Low
	9 - 12	Low
	5 - 9	Medium
	2 - 5	High
	<2	Very High
Hurricane Evacuation Zone, Zone ID	E	Very Low
	D	Low
	C	Medium
	B	High
	A	Very High
Annual rainfall, inches	<54	Very Low
	54 - 56	Low
	56 - 58	Medium
	58 - 60	High
	>60	Very High
Imperviousness, percentage	<20	Very Low
	20 - 40	Low
	40 - 60	Medium
	60 - 80	High
	>80	Very High
Land cover	Green/barren land Open Water Low density residential	Very Low Low Medium High Very High

	Medium density residential High density residential	
Slope, percentage	<0.5 0.5 - 2 2 - 4 4 - 7 >7	Very Low Low Medium High Very High

Table 10 Social indicators classification

Indicator	Classification	
	Numerical Value	**Vulnerability**
Per capita income, $	>60,000 50,000 - 60,000 40,000 - 50,000 30,000 - 40,000 <30,000	Very Low Low Medium High Very High
Population density per square mile	<1000 1000 - 1500 1500 - 2000 2000 - 2500 >2500	Very Low Low Medium High Very High
65+ year-old population per square mile	<250 250 - 500 500 - 750 750 - 1000 >1000	Very Low Low Medium High Very High
Crime, number of crimes per 1000	<0.1 0.1 - 0.4 0.4 - 0.7 0.7 - 1	Very Low Low Medium High

residents per year	>1	Very High
Average daily commute time, minute	<25 25 - 30 30 - 35 35 - 40 >40	Very Low Low Medium High Very High
Land use	Vacant/Institutional Low density residential/Industrial Medium density residential High density residential Hospital	Very Low Low Medium High Very High

Table 11 Traffic indicators classification

Indicator	**Classification**	
	Numerical Value	**Vulnerability**
Average Daily Traffic, ADT	<18000 18000 - 45000 45000 - 90000 90000 - 165000 >165000	Very Low Low Medium High Very High
car crash density	<0.5 0.5 - 1 1 - 1.5 1.5 - 2 >2	Very Low Low Medium High Very High

Table 12 Bridge indicators classification

Indicator	**Classification**	
	Numerical Value	**Vulnerability**
Year-built	<1940 1940 - 1960 1960 - 1980 1980 - 2000 >2000	Very High High Medium Low Very Low
Scour, NBI index	0 - 3 4 - 5 6 - 7 8 - 9 N	Very High High Medium Low Very Low
Sufficiency rate, Percentage	<50 50 - 60 60 - 70 70 - 80 >80	Very High High Medium Low Very Low

3.3. Framework Development

3.3.1. Spatial Multi-Criteria Decision Analysis

This study developed a spatial (GIS-based) Multi-Criteria Decision Analysis (MCDA) tool for a risk-based prioritization of bridges against floods using multiple integrated indices (e.g., structural, traffic, and socio-environmental- Figure 3). The risk map is the output of a set of maps with spatial display of each defined criteria, which have, for each grid cell, a pixel value based on the MCDA and given weight. Simple Additive Weighting (SAW) with equal weights of criteria was used for the development of the MCDA method. As the proposed problem has a geospatial nature, integrating GIS with MCDA is consequential. Using GIS, geographical data sets are combining, and values are added to solve spatial problems. Integrating MCDA with GIS can cover a suitable number of alternatives due to the computational extensions. Once the data is defined, GIS-based analysis could be conducted. Figure 3 shows a simple example of overlying two data sets, flood risk and census data, to create newly formed areas. This is a simple example of a topological analysis with a spatial relationship between two features. GIS overlying could include more than two layers or criteria to develop a multi spatial overlay process.

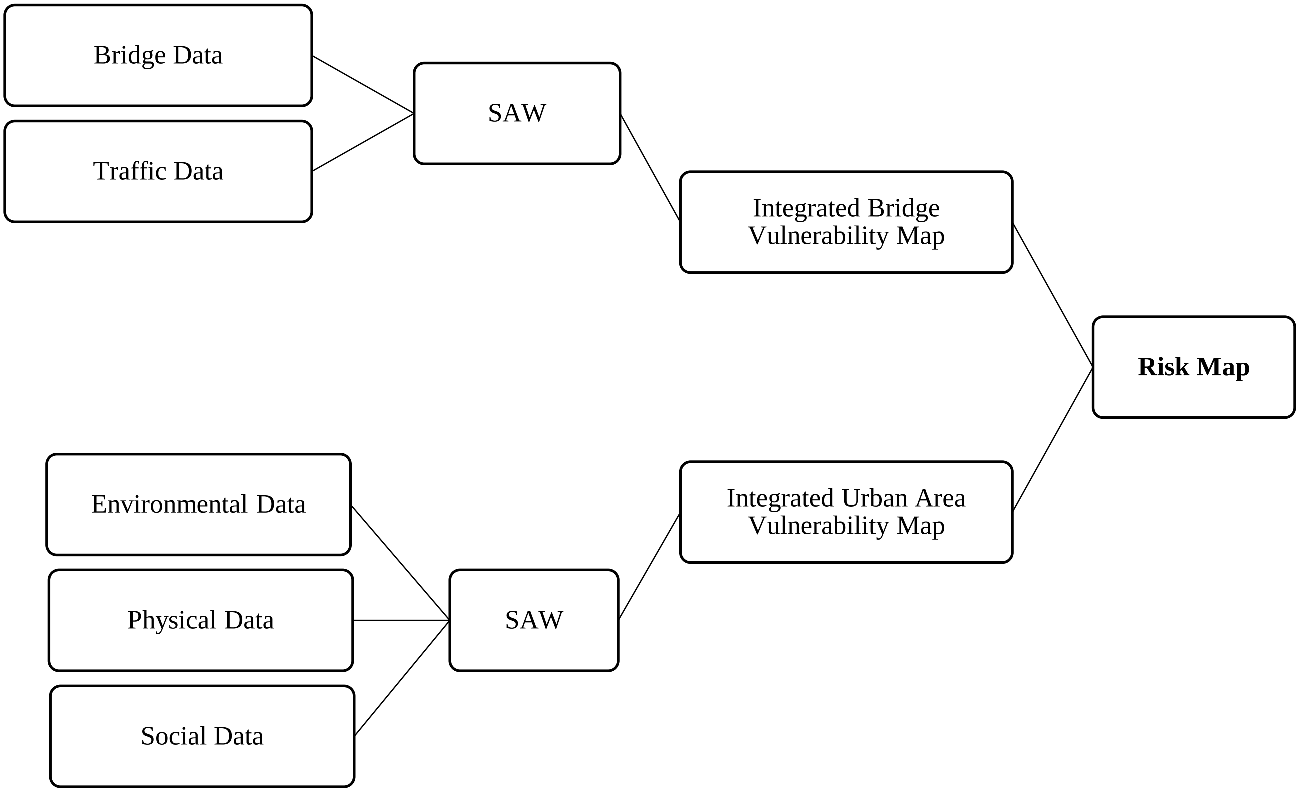


Figure 3 Data integration flowchart based on MCDA.

Scenarios of relative weights as represented in Table 13 were applied to discover and address various risk levels. The scenarios present how the different evaluations are combined to generate the final risk map to develop and evaluate the risks of bridges. Therefore, they enable rapid analysis of possibilities and concerns among many decision makers.

Scenario 1 reflects the traditional prioritization approach (existing practice) that only considers bridge structural and traffic conditions of bridges. Scenario 2 adds flood vulnerability (physical criteria) to the existing practice. Scenario 3 is the most comprehensive scenario that incorporates all the five main criteria into the MCDA framework. The weights of the main criteria in each scenario were determined in consultation with the RAP members in this study comprised of a senior bridge engineer from industry and a senior traffic planner from a state DOT. It should be noted that the utilized weights in the scenarios are only for demonstrating the impact of different factors on the final prioritization and the relative importance (weights) of criteria in each problem should be determined by the decision maker(s) or based on the preferences of decision maker(s).

Table 13 Weights of criteria in different scenarios

Scenarios	**Main Criteria Weights**				
	Traffic	**Bridge**	**Environmental**	**Physical**	**Social**
Scenario 1	0.30	0.70	0.00	0.00	0.00
Scenario 2	0.35	0.35	0.00	0.30	0.00
Scenario 3	0.30	0.30	0.10	0.20	0.10

3.3.2. Spatial Preprocessing

The preprocessing flowchart is shown in Figure 4. For generating the risk map, first the input layers should be defined. Then, input layers are preprocessed to reclassify layers as a function of their initial thematic values as shown in Figures 5 to 9.

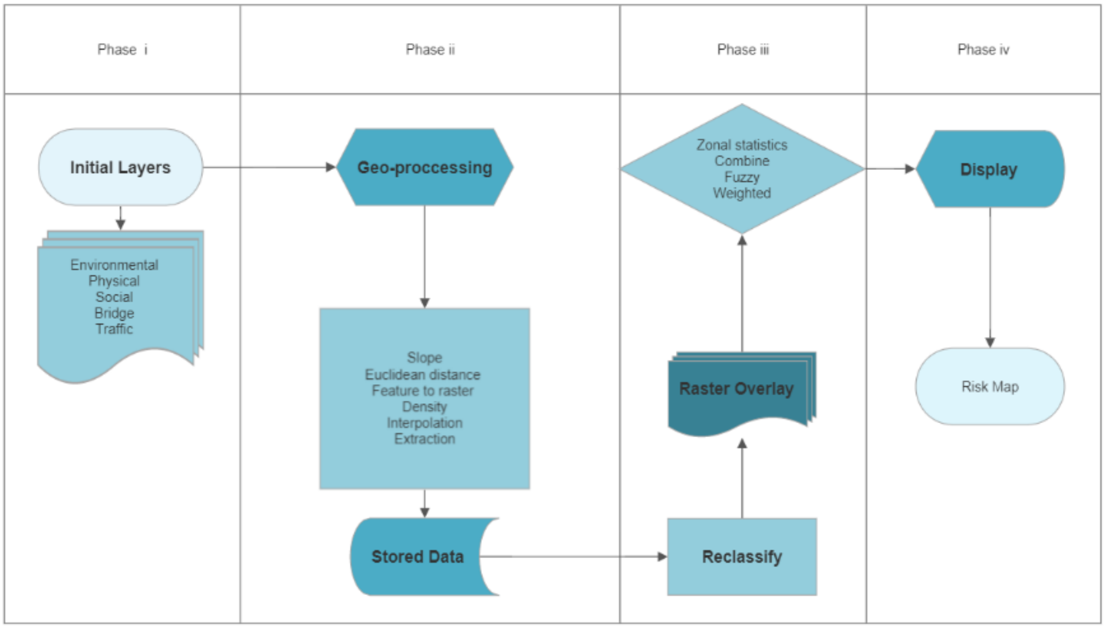


Figure 4 flowchart of data preprocessing in GIS

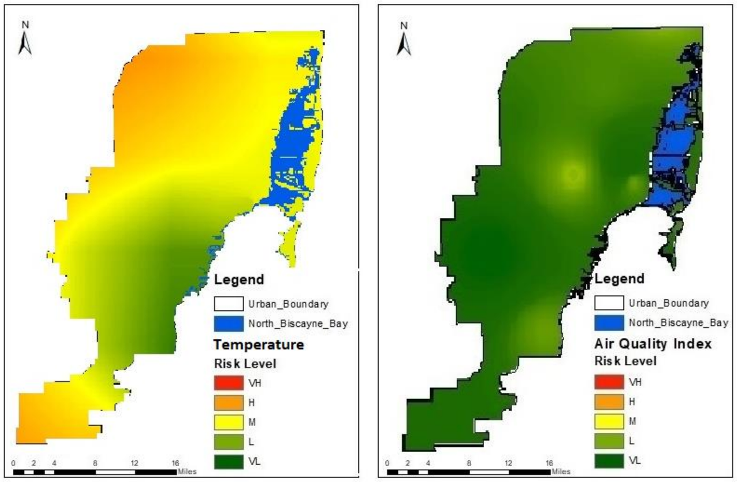


Figure 5 Risk maps for environmental indicators in the study area

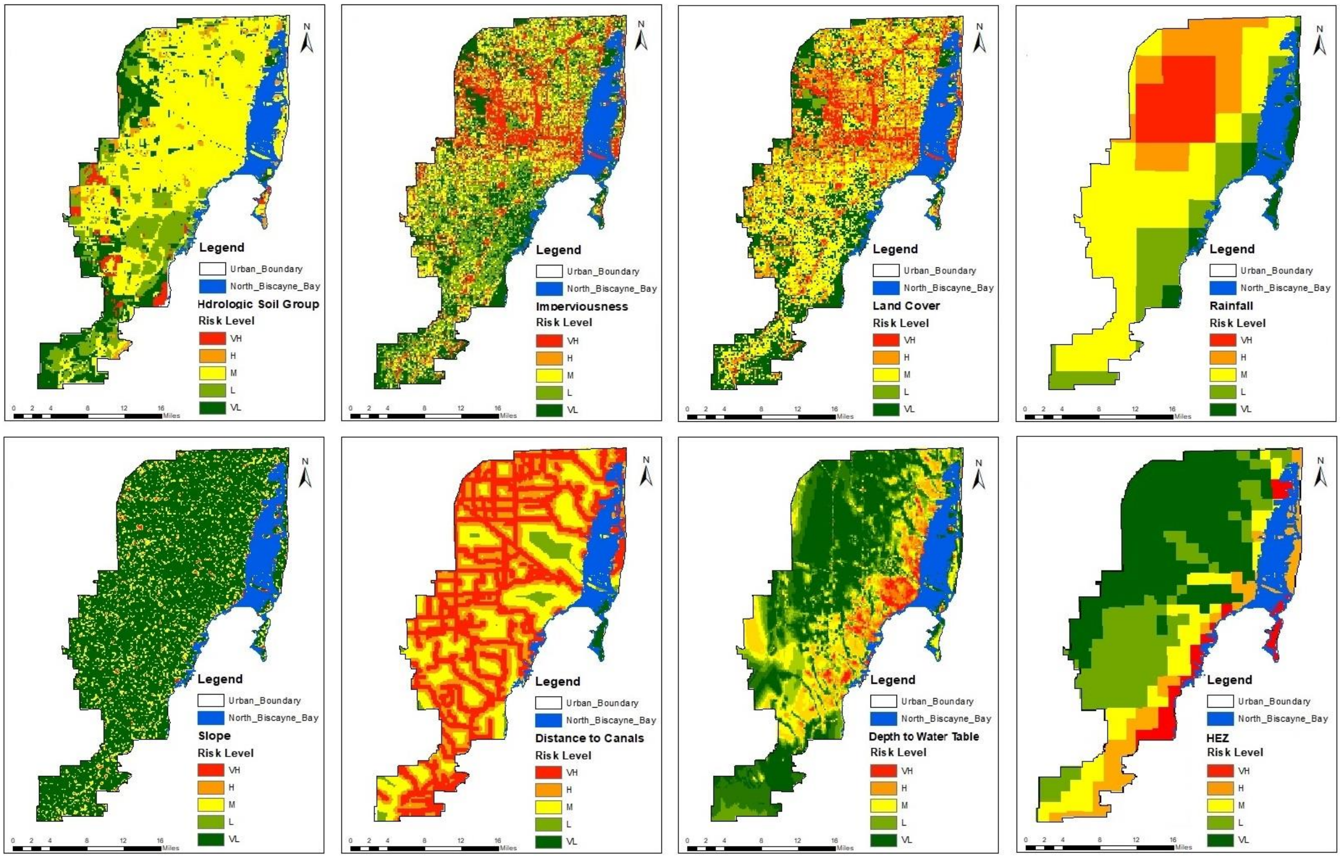


Figure 6 Risk maps for physical (flood) indicators in the study area

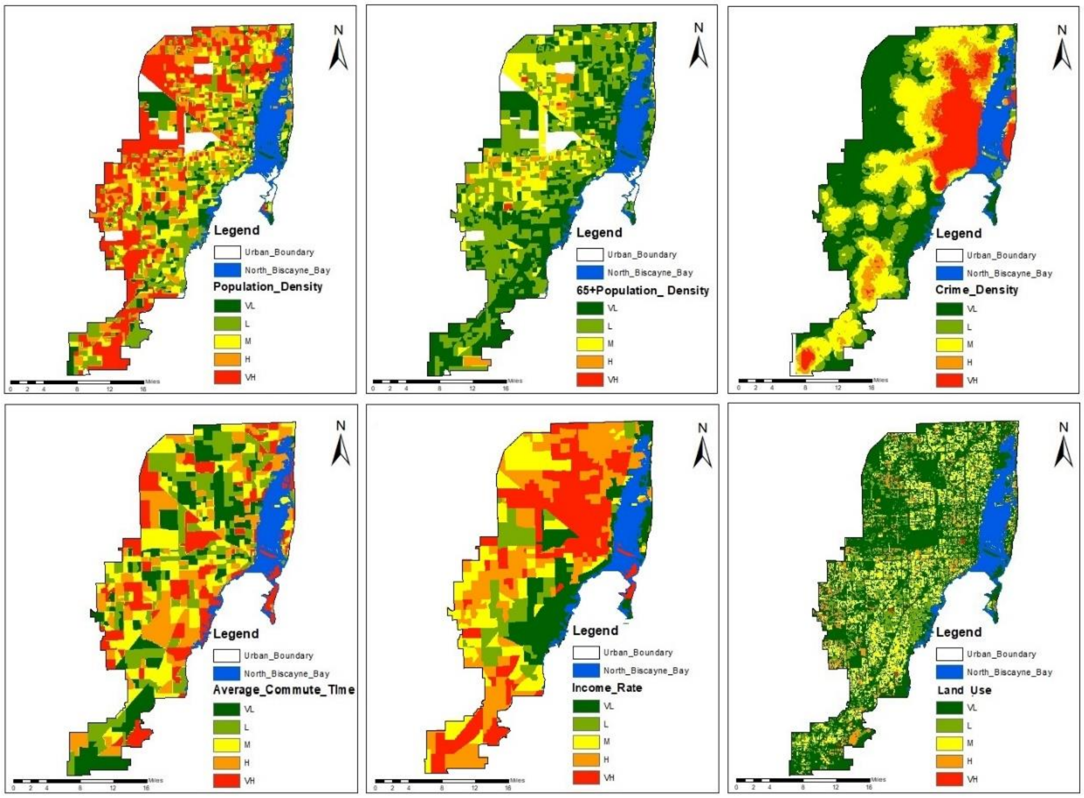


Figure 7 Risk maps for social indicators in the study area

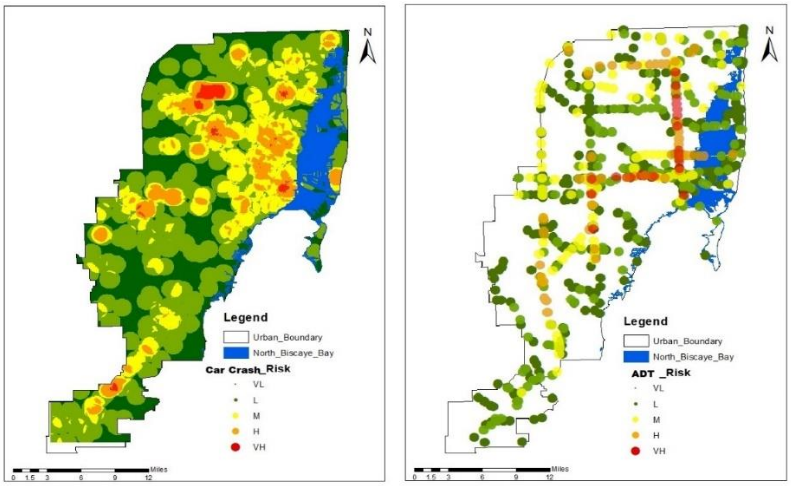


Figure 8 Risk maps for traffic indicators in the study area

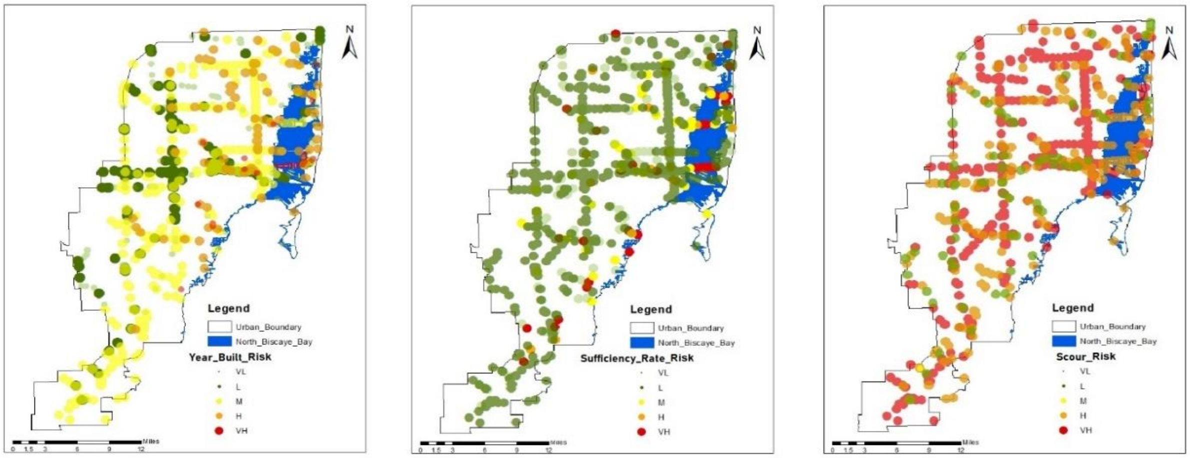


Figure 9 Risk maps for bridge structural indicators in the study area

3.3.3. Assessment of Vulnerability and Risk

In this research, not only vulnerability is defined for all environmental, physical, and social dimensions, but any expected damage to bridges is integrated with their intrinsic conditions, namely age and structural condition. Therefore, vulnerability of bridges was considered as the susceptibility of a bridge to the impact of environmental, physical, and social factors integrated with traffic and bridge related data. For extracting the bridges risk level in the study area, the data layers were integrated as demonstrated in Figures 10 and 11.

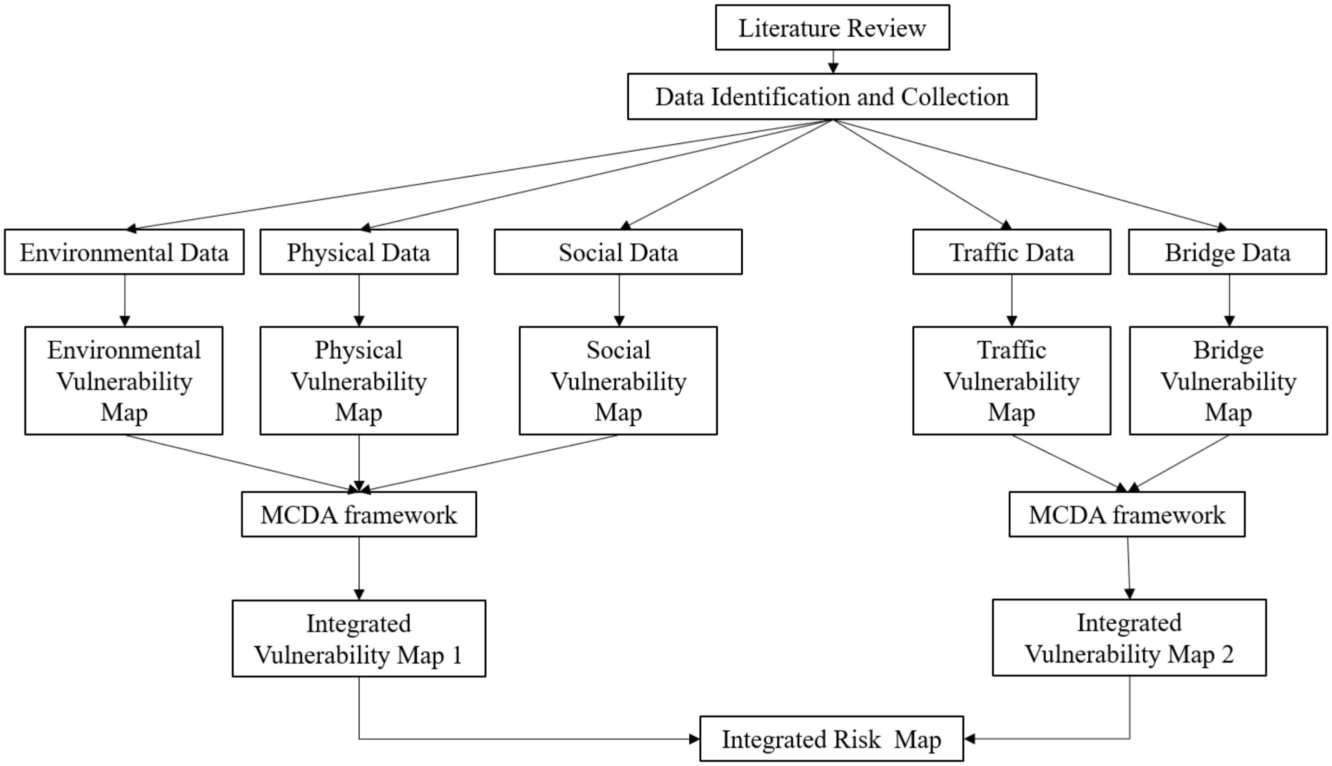


Figure 10 Flowchart of the proposed methodology.

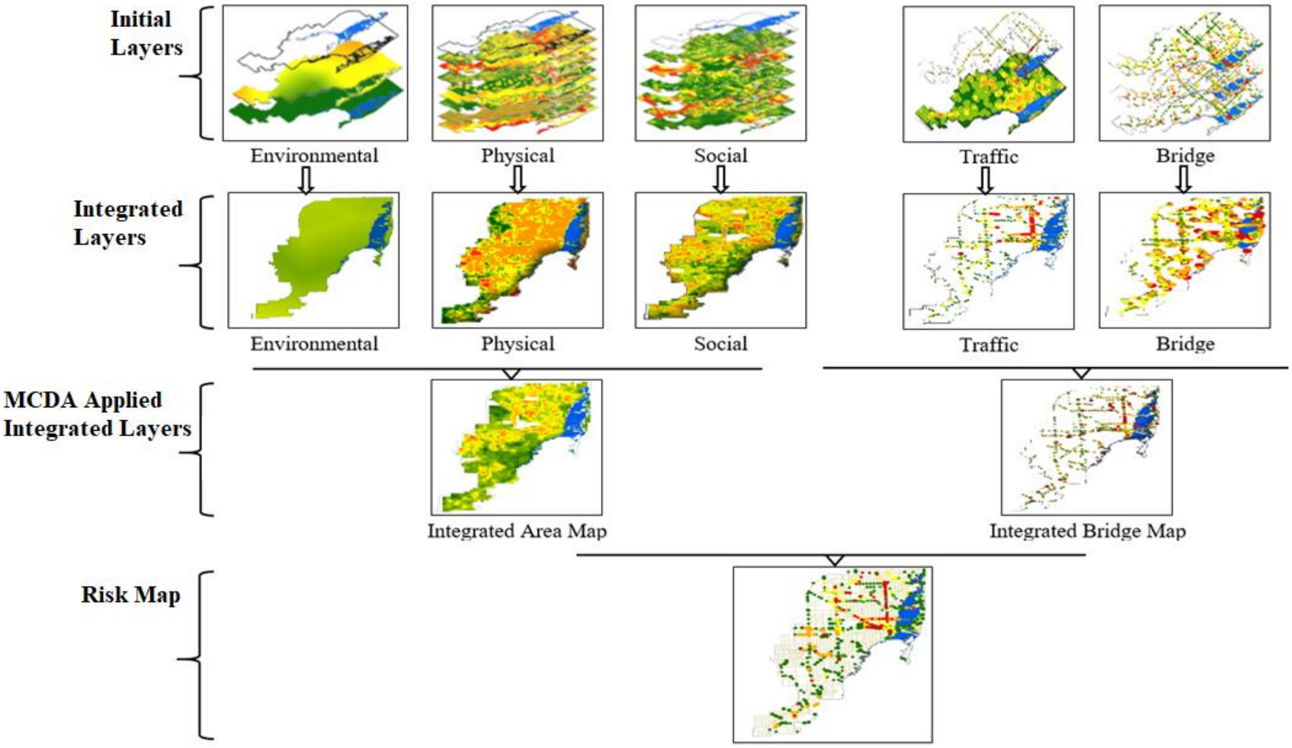


Figure 11 Visual demonstration of the methodology for creating the integrated risk map.

CHAPTER 4. RESULTS AND DISCUSSION

4.1. Influencing Factors

The spatial MCDA model proposed in this study was operated with physical and socio-environmental data sets integrated with traffic and bridge structural data to create a risk map that assigns a risk factor (Very Low to Very High) to each bridge in the study area. The results were compared with another risk map that is based on traffic and bridge structural conditions of bridges to demonstrate the effects of considering socio-environmental data in the decision-making process.

4.2. Integrated Flood and Socio-Environmental Risk Map

The GIS-based MCDA framework proposed in this study is operated with physical and socio-environmental data sets integrated with traffic and bridge structural data. The final vulnerability-based prioritization of bridges in the study area for Scenarios 1, 2, and 3 are presented in Figures 12-a, 12-b, and 12-c, respectively, where the priority levels of VL to VH correspond to the same vulnerability level (VL to VH) considering the integrated impact of all the contributing factors in each scenario.

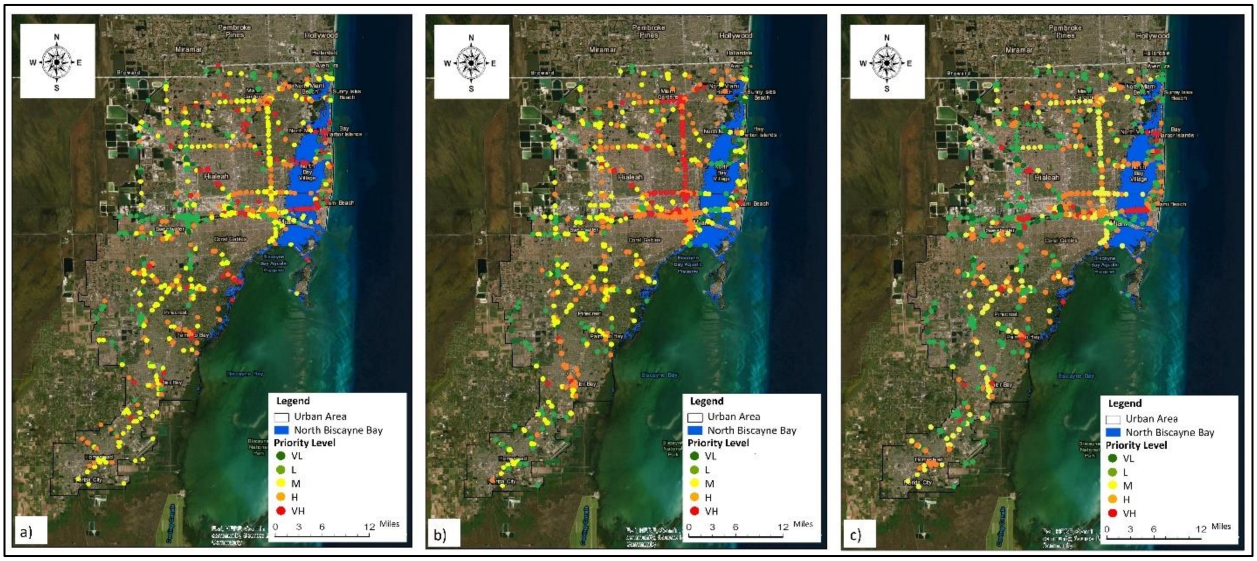


Figure 12 Bridge rehabilitation priorities a) Scenario 1 b) Scenario 2, and c) Scenario 3.

Scenario 1 (Figure 12-a) is a representation of the traditional prioritization approach, focusing solely on the traffic and structural conditions of bridges as decision criteria. The results revealed that the west side of the study area had fewer dominant high-vulnerability bridges than the east sites. About 61% of the bridges were identified as having M to VH vulnerability when considering only structural and traffic conditions with the assumed weights in Table 13.

Scenarios 2 and 3 expanded upon the traditional approach by incorporating additional criteria including those considering flood vulnerability, social equity, and environmental justice in the prioritization process. These scenarios provide a more comprehensive and equitable prioritization approach, considering not only the bridge structural and traffic conditions of the bridges but also their interaction with the surrounding communities.

In Scenario 2 (Figure 12-b), where flood vulnerability was incorporated alongside traffic and bridge structural conditions, bridges along the east coast of the study area displayed the highest vulnerability (priority), similar to Scenario 1. However, the priority of the bridges in the central north of the study area mostly increased, compared to Scenario 1, due to the flood vulnerability in the latter region. This agrees with the flood vulnerability map where the central north region shows higher vulnerabilities. The distribution of vulnerability levels experienced a change in Scenario 2 when compared to Scenario 1. In Scenario 2, 25% of bridges were classified as "M," 31% as "H," and 16% as "VH." In this scenario, 72% of the bridges in the study area fell within the "M" to "VH" vulnerability range, reflecting how the inclusion of flood vulnerability considerations influenced the prioritization of bridges. Although individual data sets may not happen during the flooding event all together, the fully or partially inundated bridges or transportation segments could be damaged under extreme flooding events. Furthermore, increasing travel time during the flooding event could exacerbate the vulnerability of both traffic and bridges.

In Scenario 3, the other two social and environmental data were integrated with flood, traffic, and bridge structural criteria, as depicted in Figure 12-c. This integration resulted in notable changes in the priority levels of some bridges compared to Scenarios 1 and 2. Nevertheless, bridges in the eastern and southern parts of the study area, which were highly vulnerable, continued to exhibit the highest vulnerability levels. In other words, while the very high (VH) and high (H) vulnerability bridges in the previous scenarios often shifted to high (H) and medium (M) vulnerability in Scenario 3 due to the reduced emphasis on structural, traffic, and flood weights, they still remained among the bridges with the highest vulnerability levels in this scenario.

Approximately 31% of the bridges were classified as medium (M) vulnerability, 24% as high (H), and 10% as very high (VH) vulnerability in Scenario 3. Collectively, these categories made up 65% of the bridges, indicating a substantial portion of bridges with various levels of vulnerability overall. This highlights how the inclusion of social equity and environmental justice concerns in the prioritization process can lead to altered results and a more equitable prioritization. The flexibility to incorporate new criteria into the established MCDA framework is a significant advantage of this approach. Therefore, by departing from the conventional prioritization approach and integrating new criteria related to flood vulnerability and social equity and environmental justice, decision-makers (e.g., state DOTs) can effectively address the complex challenges associated with bridge vulnerability assessment and prioritize them in a more equitable and effective manner.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

The objective of this study is to develop a comprehensive decision-making framework to support state DOT decision makers in the process of selecting accelerated bridge upgrade or repair projects. This aim was addressed using a spatial (GIS based) MCDA approach. First, vulnerability maps for every individual factor in five categories [i.e., environmental, physical (flood), social, traffic, and bridge structural data] were developed. Then, integrated vulnerability maps for the study area (based on physical, environmental, and social data) and the bridges in the study area (based on traffic and structural data) were created using the SAW method. Finally, the integrated vulnerability maps were combined using the SAW method to develop an integrated risk map that presents an integrated risk factor (VL to VH) for each bridge in the study area. High risk bridges can be considered for ABC processes. This study showed that the proposed integrated flood and socio-environmental risk analysis framework is highly compatible to a high number of alternatives (bridges) under multi-criteria risk assessment. One limitation of the study was the identification of weights for the decision criteria in the SAW method. It should be noted that the identification of weights for decision criteria in the SAW method. Although considering the relative importance of criteria is crucial in MCDA methods, this study used three representative scenarios with hypothetical weights, including one with structural and bridge criteria only, and two scenarios expanding the approach to include additional factors such as flood vulnerability, social equity, and environmental justice in the prioritization process. The selection of criteria and their weights should be tailored to the specific study area. Extracting relative weights from decision makers' opinions using MCDA methods is a potential avenue for future research.

The transferability of the presented MCDA framework to other regions and its adaptation by other State DOTs or government bodies is a valid and important consideration. Here are key points addressing adaptability and potential challenges. The MCDA framework should be customizable to allow the adjustment of criteria and their associated weights, aligning with the specific needs and conditions of each region. DOTs should have the flexibility to add, remove, or modify criteria based on local priorities and data availability. Besides, this MCDA framework is a user-friendly interface that allows users to easily add, remove, or modify criteria and their associated weights. In this regard, experts or consultants’ engagement when the framework is being customized is valuable. Their input and insights can be valuable in ensuring that the customization aligns with local priorities and conditions. For example, in coastal areas, experts emphasize the significance of coastal flooding and the need to account for specific topographical features. The DOTs can add a new criterion named "Coastal Vulnerability Index" that takes into account proximity to the coast, elevation, and historical storm data. In contrast, another region where experiences arid and dry conditions, which are distinct from the coastal and riverine flood risks. The DOT might include a criterion called "Extreme Temperature Resilience" to account for the impact of high temperatures on bridge materials and structures. Or soil moisture and historical drought data to assess the vulnerability of bridges to drought-related stresses could be considered.

While this project considered readily available data (in most cases national data resources) for developing the MCDA framework, the transferability of this MCDA framework to other regions is feasible with careful consideration of data availability and customization. This might involve field surveys, remote sensing, or collaboration with local agencies to gather relevant information. In situations where historical data are limited, spatial and temporal interpolation or modeling techniques can be applied to estimate missing values. This may involve using statistical methods or geographic information systems (GIS) to fill data gaps.

While most risk assessment methods for planning purposes are designed at large scales (e.g., regional or state scales), this research proposed a fine-scale risk analysis where each bridge is analyzed individually and assigned a risk factor. Such a detailed approach leads to a practical risk evaluation tool which assists state DOT decision makers in prioritizing existing bridges for ABC activities using an integrated flood and socio-environmental risk assessment. The proposed method can also be used as an appropriate large-scale management tool for long-term planning strategies. The utilized integration framework highlights understanding of the relationship between all influencing factors in the risk assessment process, improving the effectiveness and efficiency of the proposed framework.

For the future work, further elaboration on decision-makers' preferences and determining the weights of criteria will be needed. Performing sensitivity analysis on the weights assigned to subcategory risk factors in the MCDA framework is indeed a valuable aspect of future work. This analysis involves systematically varying the weights assigned to subcategory risk factors to understand their impact on final bridge vulnerability rankings. It is important to explore potential interactions among risk factors and how variations in the weights of one subcategory may affect the importance of others. For example, if there is a high correlation between Imperviousness and Land Cover, sensitivity analysis can help determine the optimal weight distribution to account for this correlation effectively. Also, different regions may have varying risk factor priorities, and sensitivity analysis can provide insights into how to best adjust weights to suit local conditions. Data uncertainty and its effect on the final risk map can also be investigated. Another area for future research is to consider economic factors in the decision-making process (e.g., life-cycle cost analysis and quantifying the economic benefits for surrounding communities. Future studies may further investigate the impacts of adaptation strategies in coastal areas using spatial MCDA for multi-criteria risk-based prioritization of ABC upgrade/repair planning. For example, corrosion rates could be controlled under environmental factors, including climate change and SLR).

This study had a comprehensive look at the social and environmental aspects of risk assessment integrated with flood risk factors for existing bridges; yet, workforce technical skill level, workforce shortage impact, robotic and artificial intelligence in the construction field, workforce/community safety and health level, and construction noise pollution may be implemented as other potential risk factors that jeopardize construction and community safety.

All in all, this research will facilitate the selection of existing bridges for ABC upgrade/repair projects and support decision makers in the appropriate allocation of funds to these projects. Infrastructure monitoring followed by risk evaluation/prediction using the proposed spatial MCDA tool can be used to mitigate or eliminate sever damages from flood events and provide cost-saving due to optimized budget allocation while improving social equity and environmental justice in vulnerable communities. Finally, ongoing risk assessment helps maintain structural standards against integrated risk factors within budget and time limitations.

CHAPTER 6. REFERENCES

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