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ABC-UTC GUIDE FOR:

INTEGRATED FLOOD AND SOCIO-ENVIRONMENTAL RISK ANALYSIS FOR PRIORITIZING ABC ACTIVITIES

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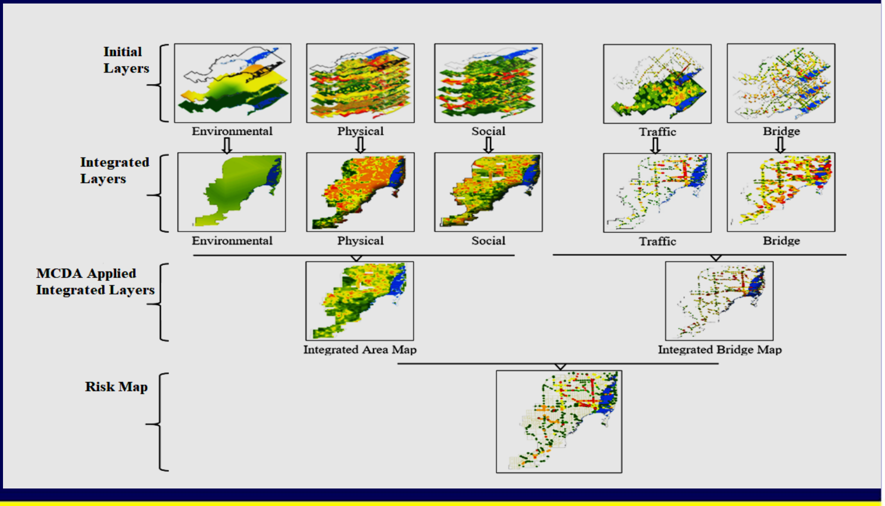
Performing Institutions:

Department of Civil and Environmental Engineering
Florida International University
10555 West Flagler Street, EC 3740
Miami, FL 33174

Name of PI:
Dr. Ali Ebrahimian

Research Assistant:
Nasim Mohamadiazar, PhD Candidate



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University of Nevada, Reno

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ABSTRACT

This ABC-UTC Guide offers a systematic, step-by-step methodology for conducting a spatial, risk-based, multi-criterion decision analysis aimed at assessing and assigning priorities for bridge rehabilitation within a designated study area. This comprehensive assessment takes into account the vulnerability of urban areas to flood-related factors while considering social equity and environmental justice. Moreover, it evaluates the traffic and bridge structural data under consideration.

This framework serves as a valuable decision support tool for prioritizing accelerated bridge rehabilitation projects. In a compelling case study, the developed framework was successfully applied to prioritize existing bridges in the urban areas of Miami-Dade County, Florida. Notably, the proposed decision support tool strikes a balance between simplicity, making it accessible for real-world projects, and a systematic, structured approach that can be adapted and implemented across diverse geographic locations.

An innovative aspect of this framework lies in its incorporation of social equity and environmental justice considerations into the ABC bridge rehabilitation planning process. By addressing these critical dimensions, the ABC-UTC Guide ensures a holistic approach that goes beyond technical aspects, making it a robust and inclusive solution for decision-makers in infrastructure planning and management.

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1. INTRODUCTION

The need for ABC activities, particularly in flood-prone areas like southeast Florida, presents complex challenges due to climate change impacts such as extreme rainfall events and Sea Level Rise (SLR). Flood-related factors contribute significantly to bridge scour, the leading cause of bridge failure in the U.S. (52% of cases - Cook et al., 2015). With a 612% increase in U.S. flooding since the 1960s (NOAA, 2014), there's a critical need for a decision support tool to prioritize existing bridges based on vulnerability and risk. Population growth, urbanization, and inadequate land use practices in flood-prone regions compound the existing complexity. The challenges intensify with the additional impact of climate change and socio-environmental effects, especially in areas already vulnerable to such hazards.

Limited budgets for accelerated upgrade/repair processes necessitate a simplified yet accurate methodology. This project initiates with a comprehensive vulnerability assessment, considering urban flooding, bridge conditions, and socio-environmental factors. Subsequently, it develops a Geographic Information Systems (GIS)-based multi-criteria decision analysis framework. This framework assigns a vulnerability factor to each bridge in the study area. The derived risk factor serves as the basis for prioritizing accelerated bridge upgrade or repair projects. Decision-makers, including state Departments of Transportation (DOTs), can utilize this prioritization approach. The case study focuses on Miami-Dade County, Florida (FL), aiming to select projects for accelerated bridge upgrade or repair based on the developed risk-based prioritization framework.

1.1. BACKGROUND

The background aims to review the current state of knowledge and practices in socio-techno-environmental risk analysis approaches for natural hazards, particularly floods, in urban areas. It explores the intricate interdependencies among environmental, physical, and social data, traffic, and bridge structure conditions (e.g., bridge scour), with a focus on their application in ABC rehabilitation planning.

Urban infrastructures, specifically bridges, face increasing demand due to urbanization. However, natural hazards and climate change effects, such as floods, SLR in coastal areas, high temperatures, and severe storms, pose risks to their construction and resilience. The United Nations Office of Disaster Risk Reduction (UNDRR) defines risk as the combination of the probability of a hazardous event and its negative consequences, influenced by interactions between natural or man-made hazards, vulnerability, exposure, and capacity (Birkmann et al., 2010). Vulnerability encompasses diverse criteria categories, spanning physical, social, economic, environmental, psychological, structural, and institutional aspects (Pescaroli & Alexander, 2019; Ghajari et al., 2017). Recognizing vulnerability as a multidimensional factor with temporal and spatial variations, efforts are needed to reduce vulnerability both before and after the occurrence of a hazard for effective coping and adaptation.

In the realm of risk assessment, Multi-Criteria Decision Analysis (MCDA) emerges as a widely acknowledged and practical approach. Given the computational challenges in data collection and analysis, Geographic Information Systems (GIS) technology, with its spatial and temporal dimensions, proves invaluable for tackling multi-dimensional problems (Tehrany et al., 2014; Termeh et al., 2018;). GIS facilitates integrated analysis of technical and socioeconomic features by collecting and analyzing data from various sources (Chen et al., 2021). The combined use of GIS and MCDA in decision-making processes enhances the spatial decision support system (Chen et al., 2011; Shariat et al., 2019).

Several studies have integrated flood risk assessment with socio-economic and environmental factors. One study conducted by Gain et l. (2015) identified random economic changes, population growth, urbanization, poor policies, and land-use changes as key factors influencing flood risk. In another study Bubek et al. (2012) recognized activities like land-use changes influencing flooding risk.

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 instance, researchers like Karatzetzou et al. (2021) have developed methodologies that harmonize flood risk indicators, providing a comprehensive assessment scenario specifically tailored for roadways, bridges, and tunnels. This approach aligns with the broader exploration of flood risk analysis on critical infrastructure elements. Additionally, Andrić et al. (2016) have classified potential hazards contributing to bridge failure into distinct categories, shedding light on various risks such as windstorms, hydraulic issues, traffic-related challenges, and more. Their identification of fifteen risk indicators provides a nuanced perspective on the multifaceted nature of risks faced by bridges. By connecting these studies, a more holistic view emerges, encompassing not only the general aspects of flood risk but also specific considerations related to bridges. The collective findings contribute valuable insights into developing strategies and frameworks for enhancing the resilience of bridge infrastructure in the face of natural hazards.

In response to the collapse of the Interstate Highway Bridge over Schoharie Creek in 1987, attributed to scour caused by flooding, the Federal Highway Administration mandated the identification of highway bridges at risk of scour-related issues in each state (Chen, 2015; Nasr et al., 2023). Studies evaluate factors impacting local scour formation, including flow intensity, blockage area ratio, and depth ratio (Cantero-Chinchilla et al., 2021). FEMA data is utilized to analyze the vulnerability of transportation assets to socio-economic and flooding events in coastal Massachusetts regions (Barankin et al., 2020). Optimal risk-based methods for coastal region bridges address natural hazards and incorporate economic and social indicators (Mondoro et al., 2018). 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.

1.2. SCOPE OF THE GUIDE

This guide is organized as follows. In Section 2, includes the developed MCDA framework as well as vulnerability and risk maps. Section 3 presents the results and discussion, and section 4 includes the conclusions and future research recommendations.

1.3. INTENDED USERS

Stakeholders, ranging from infrastructure decision makers and construction professionals to risk assessment experts and community representatives, will find valuable insights in this research. Specifically, state DOTs decision-makers will benefit greatly as they navigate the selection process for accelerated bridge upgrades or repair projects.

2. MATERIALS AND METHODS

The Materials and Methods section provides a detailed account of the procedures and data utilized in the research, offering transparency and reproducibility to the study. In this section, we outline the framework employed for data collection, analysis, and interpretation. By detailing the materials and methodologies employed, this section serves as a comprehensive guide for readers and researchers to understand the study's approach and rigor.

2.1. 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 et al., 2015), is used as the case study. Social factors of a society, namely age, are 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 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 more detailed in Table 1.

Table 1. 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

2.2. DATA IDENTIFICATION AND COLLECTION

Data availability is key for the development of the proposed MCDA framework. To address this issue and ensure the applicability of the framework to various geographic regions in the country, this study utilized the most recent readily available data from national databases and regional/state datasets, where national data were not available.

To organize the data and facilitate the spatial MCDA, five major groups were developed: environmental, physical (flood-related), and social data related to the study area and traffic and bridge structural data related to roadways and bridges in the study area. Each of these groups was further categorized into subcategories (Figure 1), based on the existing literature and specific conditions of the study area.

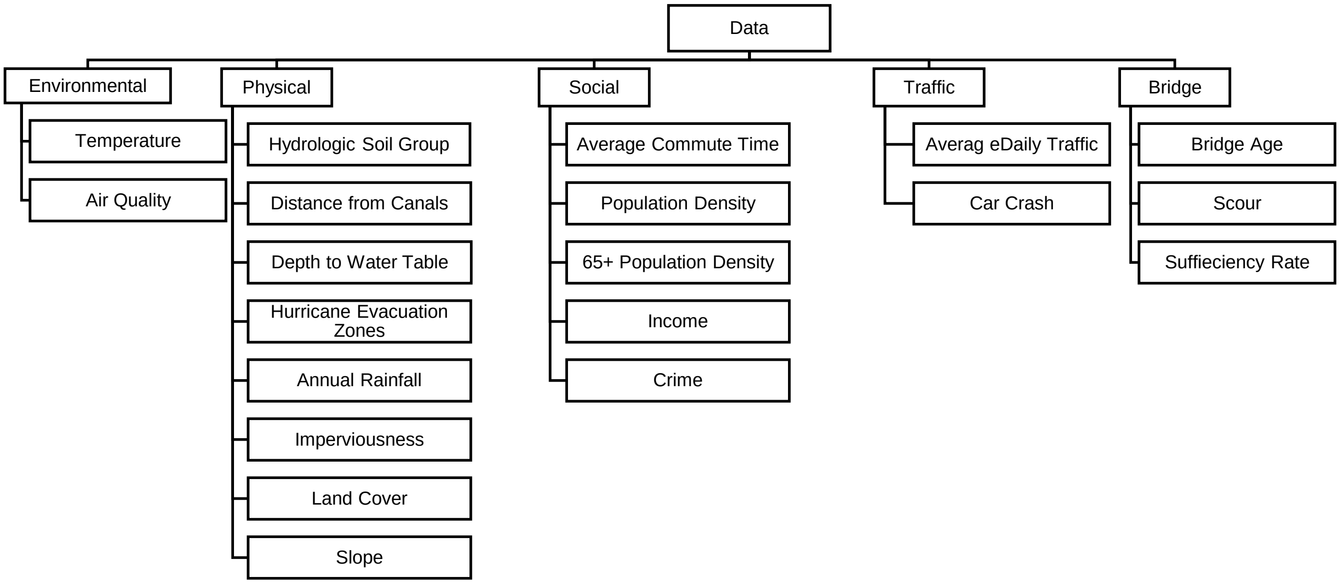

Figure 1. Organization of the data used in the study.

2.3. METHODOLOGY

The methodology of this study developed in Figure 2. 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.

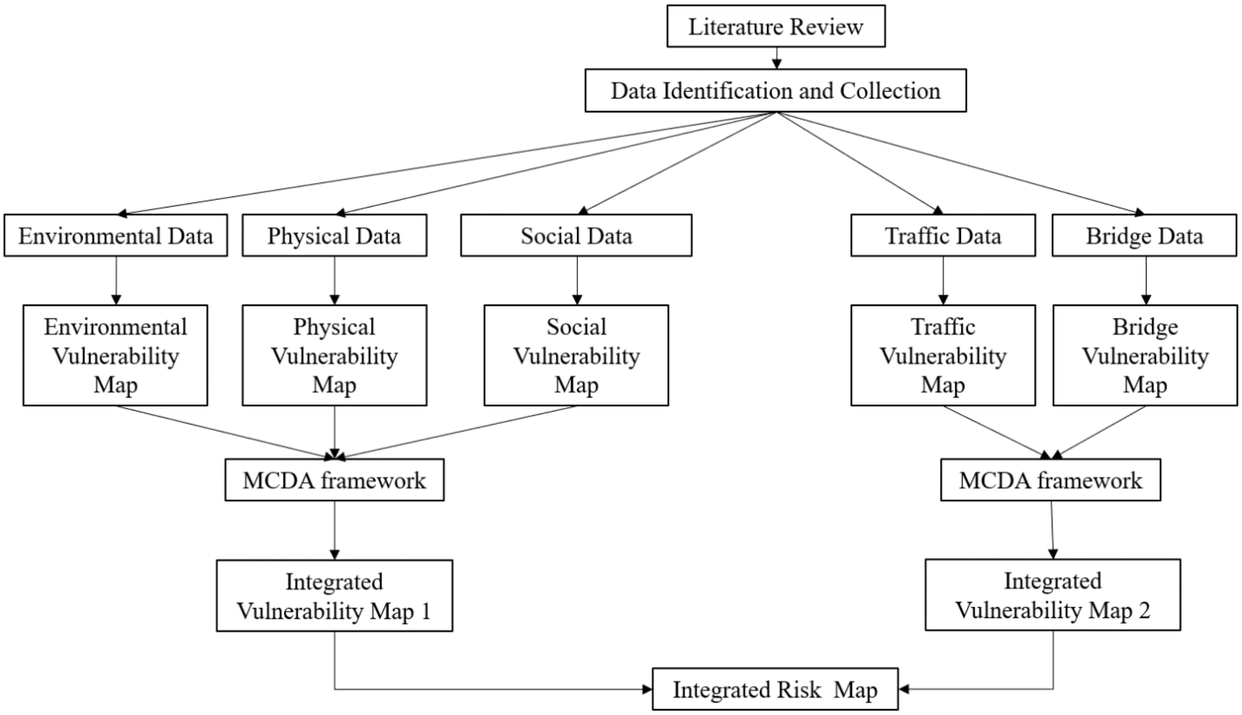

Figure 2. Flowchart of the proposed methodology.

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.

To develop the decision support framework, scenarios of relative weights as represented in Table 2 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 2. Weights of criteria in different scenarios

Scenarios	**Main Criteria Weights**				
	Bridge	**Traffic**	**Environmental**	**Physical**	**Social**
Scenario 1	0.70	0.30	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. RESULTS AND DISCUSSION

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 3-a, 3-b, and 3-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.

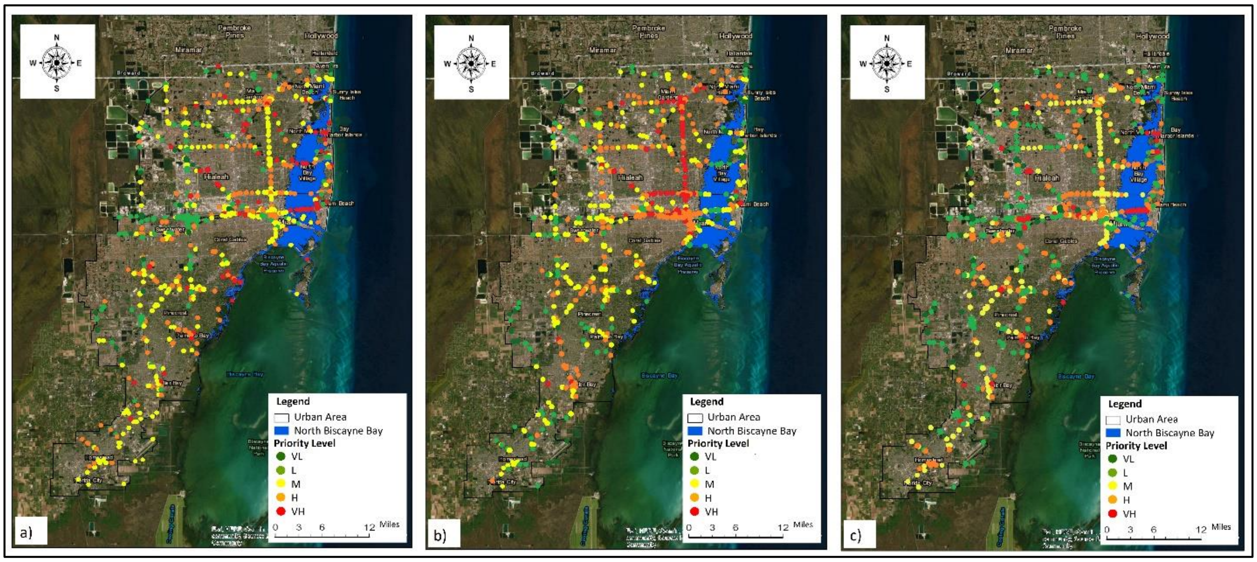

Figure 3. Bridge rehabilitation priorities a) Scenario 1 b) Scenario 2, and c) Scenario 3.

Scenario 1 (Figure 3-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 2.

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 3-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 3-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.

4. 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.

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