Methods for Flood Vulnerability Assessment: An Analytical Review

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ABSTRACT

Vulnerability is a central concept in flood risk management, serving as a crucial link between theoretical frameworks and practical applications in administrative processes. It enables decision-makers to understand and address the factors that make certain areas or populations more susceptible to flood impacts. Over time, various approaches have been developed to assess vulnerability, making it essential for decision-makers to select the most suitable methodology based on their specific needs and contexts. The main methods of vulnerability assessment are generally grouped into four categories: the curve method, which estimates potential losses based on historical data; the disaster loss data method, which analyzes past flood impacts to forecast future vulnerabilities; computer modeling techniques, which simulate flood scenarios to predict vulnerabilities; and indicator-based approaches, which use a set of socio-economic, environmental, and physical indicators to evaluate vulnerability. This study undertakes a comprehensive review and comparison of these methods, analyzing their strengths and weaknesses to guide more informed choices in flood risk management. Findings indicate that the indicator-based approach, by providing a more holistic view of vulnerability factors across different regions, offers a clearer, more accurate depiction of overall flood vulnerability. This makes it particularly useful for planners and policymakers focused on targeted mitigation and resilience strategies.

Keyword: *Flood Vulnerability, Flood Risk, Flood Management, Disaster Loss Method, Modeling*

1. INTRODUCTION

Flood vulnerability assessment is a crucial component of flood risk management, focusing on identifying and analyzing the susceptibility of specific regions or populations to flood impacts. It plays a central role in bridging scientific research and practical implementation, helping policymakers, planners, and local authorities to understand where and why certain areas or groups are more vulnerable to floods. Vulnerability assessment considers not only the physical and environmental aspects but also social, economic, and infrastructural factors that may exacerbate flood risks. This multi-dimensional approach is essential because floods do not impact all communities equally; the degree of vulnerability often depends on a region's unique characteristics, including land use, population density, infrastructure resilience, and socioeconomic conditions.

Various methods have been developed to assess flood vulnerability, each offering distinct perspectives and tools. Common approaches include indicator-based methods, disaster loss data, computer modeling, and empirical methods such as damage or fragility curves. Indicator-based methods, widely used for their flexibility and adaptability, involve selecting key variables to create a composite index that reflects flood vulnerability spatially. Meanwhile, disaster loss data methods rely on historical records to provide insights into patterns of vulnerability based on past flood impacts, although they may lack predictive power for unprecedented events. Computer models simulate flood scenarios and evaluate vulnerability by integrating topographic, hydrological, and socioeconomic data, allowing for dynamic and scenario-based assessments. Despite the varied approaches, each method comes with its limitations, such as data requirements, transferability, or the challenge of integrating social and environmental factors.

In light of increasing flood risks due to climate change and urban expansion, advancing flood vulnerability assessment techniques is more critical than ever. Such assessments not only enhance our understanding of where vulnerabilities exist but also support decision-making in disaster risk reduction, mitigation planning, and resource allocation, ultimately contributing to more resilient communities in flood-prone areas. This study aims to examine these approaches, comparing their strengths and limitations, to support more effective flood vulnerability assessments and better preparedness strategies.

2. LITERATURE REVIEW ON CONTEMPORARY KEY GENERATION METHODS

The aim of this paper is to assess the current understanding of flood vulnerability assessment approaches. With the increasing impacts of climate change, unplanned rapid urbanization, changes in land use, poor watershed management, and the reduced groundwater recharge due to the expansion of impermeable surfaces in urban areas, floods are expected to become more frequent and severe in the future. Ensuring the safety and well-being of people and protecting the environment are key responsibilities of city authorities in flood-prone areas. To achieve this, reducing vulnerability and enhancing resilience are critical strategies. A crucial step in this process is assessing vulnerability to identify at-risk areas and implement effective measures [1]. Urban flood vulnerability varies over time and across different locations due to changing environmental conditions, human activities, and societal attitudes toward potential threats. Advancing assessment methods and deepening our understanding of flood risk vulnerability can aid decision-makers in reducing damage and fatalities. Over the past few decades, various approaches for assessing flood vulnerability have been developed [2]. This paper aims to examine four of the most commonly used methods.

In most cases, the term 'risk' has been defined based on the objectives of different scientific disciplines that require disaster management strategies. Despite the numerous definitions in the literature, the concept of risk in relation to 'hazard' and 'vulnerability' is the most widely accepted in flood risk management. It is important to recognize that 'risk' is entirely a human construct. While floods are a natural part of the hydrological cycle, human activities—particularly those that disrupt the natural functions of river floodplains in transporting water and sediment—have significantly increased the risk [3]. So many definitions of vulnerability appear in the literature. Some most important definition of vulnerability are explained in the following paragraphs.

According Alexander [4], the vulnerability of individuals and assets to losses is linked to a specific level of danger and the likelihood of its occurrence under particular conditions and to a certain extent. UNDP defined, Vulnerability is a condition shaped by physical, social, economic, and environmental factors that increase people's susceptibility to the impacts of hazards [5]. Also defined by Wisner, vulnerability is the traits of an individual or group, along with their circumstances, influence their ability to anticipate, address, cope with, and recover from the impacts of environmental threats [6]. Adger [7] defined that, Vulnerability to harm arises from exposure to pressures associated with environmental and social changes, compounded by a lack of adaptive capacity. Naess [8] stated about vulnerability is a function of exposure, sensitivity, and adaptive capacity, generated by multiple factors and processes. Borden et al. [9] described about that, the distinct vulnerability means potential or sensitivity to losses or harm. Social vulnerability contains the susceptibility of society or social groups to potential losses from hazards. Vulnerability is defined with interaction between Exposure, susceptibility and resilience of each community in risk condition [10].

Mileti [11] defined about the vulnerability is the degree of capacity to withstand or recover from the impacts of a hazard over time refers to an individual's or community's ability to absorb shocks, minimize damage, and bounce back from adverse effects. This capacity is influenced by factors such as resources, preparedness, and the effectiveness of response and recovery efforts. Vulnerability term is damage goods, people, buildings, infrastructures and activities in hazard condition [12]. Canon [13] defined that the People's conditions and their social, political and economic behaviors in the face of risks provide different degrees of vulnerability. United Nations [14] defined, Vulnerability refers to the extent of potential damage to specific objects at flood risk, quantified on a scale from 0 to 1, where 0 represents no damage and 1 indicates total destruction.

Researchers have developed numerous methods to assess flood vulnerability, aiming to better understand and mitigate the risks associated with flooding. Despite these advancements and the increasing awareness of the factors that contribute to vulnerability, the threat of flooding continues to be widespread. This is due to ongoing challenges such as climate change, rapid urbanization, and inadequate flood management practices [15]. Vulnerability measurement is a complex process because it influenced by several environmental, economic, and social or even political elements in local scale [16]. This raises concerns about the effectiveness of current

vulnerability assessment methods and their actual impact on flood mitigation and adaptation strategies. Doubts persist regarding whether these evaluations are accurately informing decision-makers and leading to meaningful improvements in reducing flood risks and enhancing community resilience. As flood threats intensify, the need for reliable and actionable vulnerability assessments becomes even more critical for guiding effective mitigation and adaptation efforts [17]. In other words, vulnerability is influenced by various factors, including settlement conditions, infrastructure, government policies and capacities, social inequalities, and economic patterns. As a result, flood vulnerability differs significantly for people in varying circumstances [18].

Instance the vulnerability of urban areas is reflection of the exposure and susceptibility of the city to flood risk and the resilience of that region to cope and recover from the flood effects [19]. Human systems are vulnerable to floods due to three key factors: exposure, susceptibility, and resilience. Exposure encompasses people, their surroundings, and all elements located within flood-prone areas that are subject to potential losses from flood impacts [20]. This paper is grounded in an extensive review of literature on flood vulnerability, focusing on studies that address various assessment methods. The current study organizes these methodologies into four distinct groups and provides a comparative analysis to evaluate the strengths and weaknesses of each approach. By highlighting the advantages and limitations of these methods, the paper aims to support decision-makers in flood-prone areas, offering insights that can guide the selection of the most effective strategies for assessing and managing flood vulnerability.

3.   FLOOD VULNERABILITY ASSESSMENT

A wide range of vulnerability assessment methods exists, each differing in its conceptualization of vulnerability, theoretical framework, variables, and methodology. Based on prior research, these assessment methods can be classified into four distinct categories, which are examined in this paper [21].

3.1 Vulnerability Indicators Method:

The vulnerability indicators method is designed to utilize available data to provide a logical representation of an area's vulnerability. This approach is widely employed in flood vulnerability studies and is favored by policymakers for its clear spatial visualization of vulnerability, helping prioritize actions and plan effective risk responses within specific regions. This category of methods relies on complex indices, sometimes using weighting and sometimes not. However, it also encounters significant challenges related to standardization, weighting, and data aggregation. Additionally, uncertainty is a key issue, as each added layer introduces diverse variables, requiring resolution of interdependencies between variables. A common solution to address this challenge is applying weights to variables, thus minimizing their influence in the final assessment [22]. Another weakness of model is the difficulties that the quantification of a number of social indicators poses to the calculation [17].

Regards to [23] there are two approaches are commonly used for selecting indicators: a theory-based (deductive) approach and a data-based (inductive) approach. Although these approaches differ in methodology, they work together to provide a clearer understanding of local vulnerability. The deductive approach relies on a theoretical framework to select relevant indicators and analyze their interrelationships. In contrast, the inductive approach selects indicators based on their statistical association with observed vulnerability outcomes, such as flood-related mortality. Since vulnerability outcomes are not clearly defined for the development of aggregated indices, the data-based approach tends to be effective primarily within specific flood exposure systems. In fact development and testing an index in the circumstance where deal with short term instability is the significant limitation of all data-based indexes [24].

3.2 Vulnerability Curve Method:

The relationship between flood risk and the assets exposed to this risk, such as buildings and infrastructure, can be examined through empirical damage or fragility curves. These curves are developed primarily from data collected in well-documented flood case studies and are typically focused on residential properties within a defined area. The process begins by selecting a representative sample of assets from each category (e.g., different types of buildings or infrastructure) and compiling relevant data. This data is then averaged across all samples within each category to create stage-damage curves, which depict the potential extent of damage at

varying flood levels. Additionally, similar methods can be applied to measure real-time damage immediately after a flood event, offering a snapshot of actual losses and damages sustained.

While empirical damage curves offer valuable insights based on actual damage surveys, they are both time- and resource-intensive to produce. Furthermore, the reliability of these curves is somewhat limited, as they often lack transferability to different regions due to unique local variables such as building standards, environmental conditions, and economic factors. This specificity can restrict the broader applicability of empirical damage curves, making them less versatile compared to other flood risk assessment methods that may provide more generalizable insights across diverse areas.

3.3 Disaster Loss Method:

This method relies on empirical data from actual flood events, drawing from historical records to project future flood impacts and vulnerabilities. By examining past flood occurrences, this approach offers a straightforward means to assess flood risk and identify potential vulnerable zones based on observed outcomes. However, a significant limitation is the potential inconsistency and incompleteness in recorded data, which may lead to inaccuracies and variability in the assessment results. Discrepancies in data collection practices, gaps in documentation, and regional differences in reporting standards can all contribute to an uneven dataset, making predictions less reliable. Thus, while this method can provide valuable baseline insights, especially in regions where advanced modeling tools are unavailable, it should be applied with caution.

Despite its simplicity and accessibility, this method is best utilized as a supplementary tool alongside more sophisticated assessment techniques, particularly in areas where detailed, high-accuracy vulnerability data are essential for effective flood risk management. By combining historical flood data with modern methods like computer modeling and indicator-based assessments, practitioners can enhance the robustness of vulnerability assessments. Integrating different methods allows for a more comprehensive understanding of flood risk, supporting better-informed decision-making and targeted interventions to improve community resilience against future flood events.

3.4 Modelling Methods:

Computer models are powerful tools for assessing flood characteristics, including depth, elevation, and flow velocity, by utilizing key flood parameters such as frequency, magnitude, and hydrograph shape. To simulate flood inundation, both one-dimensional (1D) and two-dimensional (2D) models are commonly used. These models are based on solving either the complete or simplified forms of surface water flow equations. The choice of model dimension influences the detail and accuracy of the results, with 2D models generally providing more detailed spatial representations of flooding dynamics.

For accurate flood assessments, these models rely heavily on detailed data about the region's topography, hydrography, and economic conditions. This data enables the models to produce realistic representations of potential economic losses, making the information accessible and understandable to both decision-makers and the public. However, in cases where detailed data is lacking, models may produce significant irregularities, compromising the accuracy of their predictions. Such data gaps can lead to questions about the validity of the assessment and may complicate decision-making processes, highlighting the importance of reliable and comprehensive data for effective flood modeling [25]. In Geographic information system-based vulnerability modeling (GIS) variables used as an input data those should geo-referenced and converted to raster format for the tangible analysis. This method of modeling can assess vulnerability in local scale more sensitive than other ones because considers specific local factors however cannot describe a clear link between predicted map and the level of real flood damage [22].

The indicator-based method, curve method, disaster loss data analysis, and modeling approaches represent a variety of techniques for assessing flood risk and vulnerability. Each of these four distinct approaches offers unique advantages and challenges that can significantly impact policy decisions. The indicator-based method provides a clear and comprehensive picture of vulnerability across different regions, helping policymakers prioritize areas in need of intervention. However, it may also involve complexities related to standardization and weighting of indicators. The curve method allows for a straightforward estimation of potential damage based on historical data but can be limited by the availability and reliability of that data. Disaster loss data analysis provides valuable insights into past flood impacts, aiding in the development of more effective future strategies.

Nonetheless, this method may not fully capture future risks, particularly in changing environmental conditions. Modeling approaches, whether 1D or 2D, can simulate flood scenarios and assess their potential impacts in detail. While these models offer a scientific basis for decision-making, they are highly dependent on accurate and comprehensive data, and any deficiencies can lead to significant uncertainties. Given these factors, it is crucial for policymakers to carefully consider the benefits and limitations of each approach. This understanding can help them choose the most appropriate methods for their specific context, ultimately leading to more effective flood risk management and resilience-building strategies. Table 1 summarized main strengths and weaknesses of these methods.

Table 1: Vulnerability Assessment Methods

Methods	Vulnerability Index System	Vulnerability Curve Method	Disaster Loss Data	Models
Characteristics	Commonly used in flood vulnerability studies Pertain to complex indices and weighting of their subjective	Is founded on real damage Investigation Should be fairly precise Takes a lot of time and Resource Not valid for other areas	Simple Imprecise	Intelligible for public Low validity in data shortage condition

The objective of this study is to compare various existing assessment approaches to determine the most effective method for evaluating flood vulnerability. In this context, the indicator-based assessment approach emerges as a powerful tool for policymakers. It not only enhances public awareness about flood risks but also aids governments in prioritizing budget allocations and guiding international organizations in fostering participation and collaboration. However, it is essential to acknowledge that the indicators and outcomes of this approach are often based on assumptions that cannot be fully validated with observed data. As a result, this methodology relies on expert evaluation to interpret vulnerability results, taking into account the specific characteristics of the system being assessed. This reliance on expert judgment emphasizes the need for a well-defined framework that incorporates local context and conditions to improve the accuracy and relevance of the assessment. By critically evaluating the strengths and limitations of various assessment methods, this study aims to provide valuable insights that can inform more effective flood risk management strategies and enhance overall community resilience. Ultimately, the findings will contribute to a more nuanced understanding of how different approaches can be integrated into policymaking processes, ensuring that decisions are grounded in robust evidence and expert analysis.

4. FLOOD RISK MANAGEMENT

Flood vulnerability is one of the significant components in risk management and flood damage assessment. Since vulnerability is found to be the main reason of disasters, it seems necessary to develop our perception of the vulnerability [26].

In many disciplines, the term "risk" is defined according to specific goals and needs within disaster management. Despite numerous definitions in the literature, the concept of risk, particularly as it relates to "hazard" and "vulnerability," is the most widely accepted in flood risk management. It's important to recognize that "risk" is fundamentally a human-centered concept; floods are natural components of the hydrological cycle. However, human activities—especially land use changes that disrupt the natural function of river floodplains in transporting water and sediment—have amplified this risk, intensifying flood impacts [27].

In studying flood risk, it is useful to classify floods to:
- coastal floods which can occur on the coast and along the banks of large lakes;
- river floods that occur seasonally when spring rains water fills river basins too quickly, and the river will overflow its banks;
- flash floods are short-term floods in small region such as part of the city which kill and damage the most [28].

The primary goal of flood risk management is to reduce human losses and economic costs to an acceptable level. While it's impossible to completely eliminate flood risk, managing it effectively is essential. In essence, flood management focuses not on removing risk entirely but on mitigating it. This is achieved by minimizing, reducing, or redirecting flood impacts through comprehensive mitigation and adaptation strategies, all aimed at reducing risk to more manageable levels [20].

The main steps of risk management are:

- Flood planning mitigation measures in other words preparedness before disaster.
- Response measures during disaster.
- Recovery after disaster [29]. Fig.1
- In flood management subject there are two approaches for flood mitigation and protection:
- Structural and non-structural; structural measures consist of infrastructure development like levees, dams or river dike that modifies the river flow [30].

A comprehensive Flood Management Approach organized into three main phases: Flood Planning, Flood Preparedness, and Flood Fighting & Post-Flood Operations. Each phase comprises several key components critical for managing flood risk effectively.

1. Flood Planning: This phase emphasizes proactive steps to mitigate flood impacts before they occur. It includes:
    o Infrastructure: Developing and reinforcing flood-resistant infrastructure.
    o Land Use Planning: Strategically planning land use to minimize flood-prone development and enhance natural water absorption.
    o Flood Forecasting & Early Warning: Implementing systems for timely flood prediction and alerts to inform communities in advance.
    o Vulnerability, Exposure & Risk Assessment: Identifying areas and populations at risk to prioritize resources and mitigation efforts.
2. Flood Preparedness: This stage focuses on ensuring readiness to respond to floods, with activities such as:
    o Conditions & Responsibilities: Defining roles and responsibilities for all stakeholders involved in flood response.
    o Inspection: Regularly checking flood protection measures and systems.
    o Materials, Equipment & Supplies: Stockpiling essential materials, equipment, and supplies needed for flood response.
    o Identification of Safe Havens: Designating safe locations for evacuation and shelter in case of flooding.
3. Flood Fighting & Post-Flood Operations: This phase involves actions taken during and after a flood to mitigate damage and aid recovery. Key components include:
    o Flood Flow Regulation & Protection: Managing water flow through structural measures to protect critical areas.
    o Rescue & Relief Operations: Conducting rescue missions and providing immediate relief to affected populations.
    o Resettlement: Assisting displaced people in relocating or returning to safe locations.
    o Damage Restoration & Recovery: Repairing and restoring damaged infrastructure, homes, and facilities to support long-term recovery.
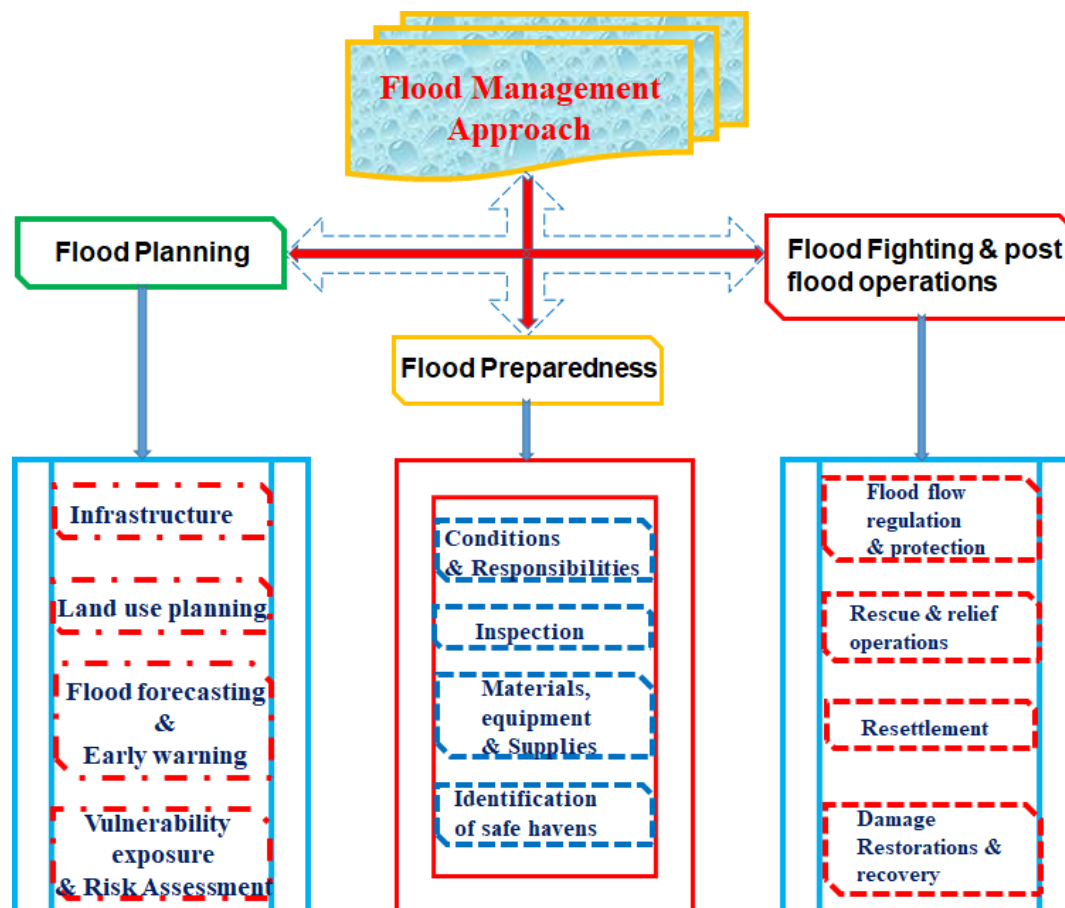
Fig. 1: Flood Risk Management Process

The figure 1 demonstrates how these phases are interrelated, highlighting the need for a holistic and collaborative approach across multiple disciplines and planning stages to reduce flood impacts and enhance community resilience

The basic principles consist of storing; diverting and confinement of floods. Non-structural measures involve several mitigation measures not modifying the river flow. They include educating, reporting, warning and forecasting, assessing measures, emergency services, land use planning, flood insurance, Building codes, Health and social measures, public participation, etc.

Some studies declare that flood risk management (includes structural and non-structural measures) needs a complete ordered set of activities before and after hazard;

Samuels [31] suggests these activities as follows:

Pre-flood activities include:
- Distinguish vulnerable areas
- Disaster planning to found discharge paths, public service and infrastructure supplies for emergency actions
- Construction of flood related infrastructure (physical structure and forecasting system)
- Land-use planning and preventing unsuitable development in the flood plains
- Awareness among the people exposed to flood

The post flood activities:
- Injuries relief
- Reconstruction of damaged places
- Recovery of the environment and the economic
- Review of the flood management measures to advance the planning for future hazards

Flood risk management is a collaborative effort involving diverse professionals including hydrologists, hydraulic engineers, economists, social scientists, ecologists, and urban planners all working to reduce the

impacts of flood hazards. Each field brings specific methods to assess flood risk and vulnerability. Regular re-evaluation of risks after implementing flood mitigation measures, both structural and non-structural, allows for an accurate assessment of each measure's effectiveness. This ongoing assessment also helps identify any remaining risk components that may require additional mitigation efforts [32].

5.   CONCLUSIONS AND PERSPECTIVES

Enhancing vulnerability measurement is a critical first step toward identifying its root causes and developing more precise frameworks that can effectively reduce the loss of lives and property. A thorough analysis of flood vulnerability assessment methods leads to the following key conclusions: Indicator-based vulnerability assessments are widely used for evaluating flood vulnerability, yet they face several challenges, particularly with standardization, weighting, and data aggregation. While these assessments do not directly measure flood risk, they contribute valuable insights that aid in assessing overall flood risk. These methods capture diverse risk characteristics, including social, environmental, physical, and economic factors, providing a broad, efficient, and reliable overview of flood vulnerability within a specific region.

However, the approach is complicated by the limited availability of high-quality data and the difficulty in quantifying a large number of indicators, especially social ones. A primary limitation of this method is that vulnerability assessments must go beyond measuring tangible impacts to reflect underlying social processes and complex interconnections. This complexity makes it challenging to develop precise, comprehensive indicators that accurately capture the nuanced and interconnected nature of vulnerability in communities. Vulnerability is, therefore, not easily decreased to a solitary metric and is not easily calculable [7]. On the other hand, computer based modeling can assess vulnerability in local scale more sensitive than other ones because considers specific local factors, however, it has little validity in data scarcity situation.

Future research on flood vulnerability increasingly focuses on the integration of Remote Sensing (RS) and Geographic Information Systems (GIS) tools to enhance predictive accuracy and spatial understanding. Remote sensing technologies, with their ability to capture real-time and multi-temporal data, allow researchers to monitor land-use changes, assess flood-prone areas, and track alterations in hydrological patterns at multiple scales. When combined with GIS, these tools enable the development of highly detailed flood vulnerability maps that incorporate diverse data layers, including topography, soil types, vegetation cover, and socio-economic indicators. This integration supports more dynamic modeling of flood exposure and vulnerability by visualizing complex relationships between environmental factors and human settlements. Additionally, advancements in machine learning and data processing algorithms within these systems allow for the efficient analysis of large datasets, paving the way for near real-time flood forecasting and risk assessment. By continuing to develop and refine these Remote Sensing and GIS approaches, future research can help provide decision-makers with precise, actionable insights to improve flood preparedness, prioritize areas for mitigation, and ultimately enhance resilience in vulnerable communities.

6.   REFERENCES

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