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(Research Article)

The use of HEC-RAS in mapping the flood inundation area: A Study on Surma River Basin, Bangladesh

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Abstract

Flooding poses a significant threat to Bangladesh, particularly in the Surma River Basin, where monsoonal rains and upstream discharges frequently inundate large areas. This study utilizes the Hydrologic Engineering Center's River Analysis System (HEC-RAS) and Geographic Information System (GIS) to model and map flood inundation areas across the basin for return periods of 2, 5, 10, 25, 50, and 100 years. High-resolution floodplain maps were generated, identifying vulnerable zones and quantifying flood risks. The analysis revealed that low-lying areas near riverbanks are particularly prone to flooding, with inundation extents increasing significantly for higher return periods. Additionally, an upward trend in flood frequency over recent decades underscores the impact of climate variability. Despite challenges such as data gaps and modeling limitations, the study provides actionable insights for policymakers, including recommendations for flood zoning, infrastructure improvements, and early warning systems. The findings highlight the efficacy of HEC-RAS and GIS in addressing the complexities of flood management in Bangladesh, emphasizing the need for sustainable and adaptive measures to mitigate future risks.

Keywords: Flood Inundation Mapping; HEC-RAS; GIS; Surma River Basin; Flood Risk Assessment; Return Period; Climate Variability; Sustainable Flood Management; Bangladesh

1. Introduction

Floods are among the most devastating natural disasters, affecting millions globally and causing significant economic and social challenges. Bangladesh, with its low-lying topography and dense river networks, is highly vulnerable to floods, experiencing periodic inundations that damage infrastructure, disrupt livelihoods, and threaten ecosystems (P. Das et al., 2022). The Surma River Basin, located in the northeastern region of Bangladesh, is particularly prone to flooding due to heavy monsoonal rainfall and upstream river discharge. Flooding in this region often results in severe socio-economic impacts, emphasizing the need for efficient flood management strategies (Munna et al., 2021). In this context, the integration of advanced technologies like the Hydrologic Engineering Center's River Analysis System (HEC-RAS) and Geographic Information System (GIS) has revolutionized flood mapping and hazard assessment (Raihan, 2020). These tools enable the accurate modeling of flood dynamics and the delineation of inundation areas, providing valuable insights for mitigation and planning. Despite their extensive application worldwide, such advanced methodologies have been underutilized in the Surma River Basin (Alam et al., 2020). This study focuses on utilizing HEC-RAS and GIS to map flood inundation areas in the Surma River Basin, aiming to enhance understanding of flood behavior and identify high-risk zones. By analyzing flood scenarios for varying return periods, the research seeks to

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provide actionable data to policymakers, urban planners, and disaster management authorities, contributing to the development of resilient communities and sustainable infrastructure in flood-prone areas.

2. Literature Review

Floodplain mapping is an essential tool for understanding flood dynamics, assessing risk, and developing mitigation strategies (Rony et al., 2023). Over the past decades, numerous studies have applied hydrodynamic models and Geographic Information Systems (GIS) to map flood inundation areas worldwide, providing valuable insights for flood risk management (MAHMUD, 2021). This chapter reviews the existing body of work on floodplain mapping, with a focus on studies utilizing HEC-RAS and GIS technologies, and contextualizes their relevance to the Surma River Basin in Bangladesh. The Hydrologic Engineering Center's River Analysis System (HEC-RAS), developed by the United States Army Corps of Engineers, is widely recognized for its ability to model flood profiles and water surface elevations under various scenarios (Roy, Khan, Islam, et al., 2021). When combined with GIS, HEC-RAS enables the visualization of flood extent and depth, facilitating detailed spatial analysis (Akter & Sawon, 2024). Numerous studies worldwide have demonstrated the efficacy of HEC-RAS and GIS in floodplain mapping. For instance, Majumdar et al. (2024) used these tools to produce flood maps for the Swan River Basin in Ohio, USA, highlighting the effectiveness of integrating hydraulic modeling with spatial analysis. Similarly, Baky et al. (2020) developed risk maps for the Basilicata region in Italy, analyzing water surface profiles for return periods of 30, 200, and 500 years. In Asia, Nkeki et al. (2022) applied HEC-RAS and GIS to assess flood hazards and vulnerability in mid-eastern Dhaka, Bangladesh, producing flood hazard maps for a 100-year return period. In Bangladesh, floodplain mapping efforts have been limited but impactful. N. Das & Mullick (2022) utilized HEC-RAS and GIS to simulate flood scenarios in Dhaka, demonstrating the potential of these tools in urban flood management. However, applications in rural and riverine settings, such as the Surma River Basin, remain underexplored (Nkeki et al., 2023). This basin, with its susceptibility to flash floods and river floods due to heavy rainfall and upstream discharge, requires detailed analysis to mitigate risks and plan for sustainable development. The transition from structural to non-structural flood management measures has been emphasized in recent literature. Floodplain mapping, a key non-structural approach, is critical for zoning and land-use planning. GIS technologies have proven to be effective in hydrological modeling, as they facilitate the management, processing, and interpretation of spatial and temporal data. Studies by Haque et al. (2021) and Roy, Khan, Saiful Islam, et al. (2021) showcased the utility of GIS in identifying flood-prone zones, integrating data on rainfall, topography, soil type, and land use to delineate hazard maps (Dtissibe et al., 2024). Despite advancements in flood modeling, the Surma River Basin has received limited attention in terms of floodplain mapping using HEC-RAS and GIS. Previous studies in Bangladesh have largely focused on urban areas, leaving rural and ecologically sensitive regions underrepresented (Aichi et al., 2024). Given the basin's proximity to densely populated areas and critical infrastructure, there is a pressing need for detailed flood risk assessment using modern technologies (Sharifi et al., 2021). The reviewed literature highlights the growing adoption of HEC-RAS and GIS in flood modeling and risk management globally, with significant successes in urban and rural contexts. However, the lack of application in the Surma River Basin presents an opportunity for this study to address critical gaps in knowledge. By integrating HEC-RAS and GIS, this research aims to produce accurate floodplain maps for varying return periods, offering valuable data to policymakers and stakeholders for sustainable flood management in the region.

2.1 Problem of the Research

The study on flood inundation mapping of the Surma River Basin using HEC-RAS and GIS faced several challenges. The accuracy of flood modeling heavily depends on high-resolution topographic, hydrological, and land use data (Chowdhury et al., 2023). However, obtaining precise and recent datasets, such as high-resolution Digital Elevation Models (DEM) or updated land use maps, was challenging due to the limited availability of such resources in Bangladesh. Historical rainfall and hydrological data required for the study were often incomplete or inconsistent (Munna et al., 2024). For instance, long-term hydrological records, essential for estimating return periods and peak discharges, showed gaps in coverage and accuracy, affecting the reliability of results (Nujhat et al., 2024). The Surma River Basin is characterized by complex hydrodynamic conditions, including frequent flash floods, variable river discharge, and interactions with tributaries (Mo et al., 2023). Capturing these dynamics accurately within the modeling framework posed significant computational and methodological challenges. While HEC-RAS and GIS are powerful tools for flood modeling, they have limitations in capturing certain aspects of flood behavior, such as sediment transport, erosion, and rapidly changing flow dynamics. These constraints may have influenced the granularity of the floodplain maps (M. Z. Rahman & Akter, 2024). The extensive computational requirements for processing data and running simulations using HEC-RAS, combined with the need for detailed GIS-based analysis, were resource-intensive (Jubair, 2021). This often-required balancing accuracy with available time and computational capacity. The study relied on advanced technologies that require significant technical expertise (Ceribasi & Ceyhunlu, 2021). Limited local training and experience in using HEC-RAS and GIS for floodplain mapping presented an additional hurdle, necessitating reliance on external resources and training. Climate variability and change have added layers of unpredictability to flood behavior in the region (Rasool et al., 2023). This makes it challenging to model future flood scenarios with high confidence, as past hydrological data may not fully capture the impact of changing climatic patterns (M. Rahman et al., 2021). Translating the study's findings into actionable policies requires collaboration with local authorities, planners, and disaster management agencies (ALAM, 2021). Engaging these stakeholders and ensuring the adoption of flood maps in planning and risk mitigation efforts remains a significant challenge (Noor et al., 2022).

These problems highlight the complexities involved in conducting flood modeling studies in data-scarce and hydrologically dynamic regions like the Surma River Basin. Despite these challenges, the study aims to provide valuable insights and contribute to improved flood risk management in the region.

2.2 Objectives of the Research

The primary objective of this study is to utilize HEC-RAS and GIS technologies to analyze and map the flood inundation areas of the Surma River Basin in Bangladesh. The specific objectives are:

- To delineate and map the flood-prone areas along the Surma River Basin using HEC-RAS and GIS, providing a spatial understanding of flood extents for different return periods (2, 5, 10, 25, 50, and 100 years).
- To analyze the hydrological and hydraulic characteristics of the Surma River Basin, integrating geomorphic, topographic, and hydrological data to understand flood dynamics.
- To estimate peak discharge values for varying return periods using rainfall-runoff relationships and historical hydrological data.
- To identify and classify flood-prone zones based on flood depth, extent, and frequency, aiding in prioritizing areas at higher risk for mitigation planning.
- To examine the influence of climatic variability on flooding patterns and assess its implications for future flood scenarios in the basin.
- To provide actionable data and maps to policymakers, urban planners, and disaster management authorities, supporting sustainable land use planning and flood mitigation strategies.

Through these objectives, the study seeks to enhance the understanding of flood hazards in the Surma River Basin and contribute to the development of effective flood risk management solutions.

3. Methods and Methodology

The study employed a combination of Hydrologic Engineering Center's River Analysis System (HEC-RAS) and Geographic Information System (GIS) to map flood inundation areas in the Surma River Basin. Watershed and drainage networks were delineated using Digital Elevation Models (DEM) and processed through ArcGIS tools. Hydrological data, including daily rainfall and land use maps, were analyzed to compute peak discharge for different return periods using the Soil Conservation Service-Curve Number (SCS-CN) method and Gumbel's distribution. Geometric data for the river system, such as cross-sections and stream flow paths, were extracted using HEC-GeoRAS and imported into HEC-RAS for steady flow analysis. Flood profiles were simulated for 2, 5, 10, 25, 50, and 100-year return periods, and the results were integrated back into GIS to generate floodplain maps. The maps displayed inundation areas and flood depths, providing a comprehensive spatial analysis of flood risks in the basin. This methodology facilitated the integration of hydrological modeling and spatial data processing to achieve the study's objectives.

4. Results and Discussion

4.1 Flood Inundation Mapping

The study successfully delineated flood-prone areas in the Surma River Basin for return periods of 2, 5, 10, 25, 50, and 100 years. Using HEC-RAS and GIS, floodplain maps were generated, showcasing the extent and depth of inundation across various scenarios. The results indicated that flood-prone zones were primarily concentrated in low-lying areas and regions with poor drainage. For a 100-year return period, the inundation area was the most extensive, highlighting critical zones requiring immediate flood mitigation measures. These maps provide essential spatial insights for identifying vulnerable regions (Shuvo et al., 2021).

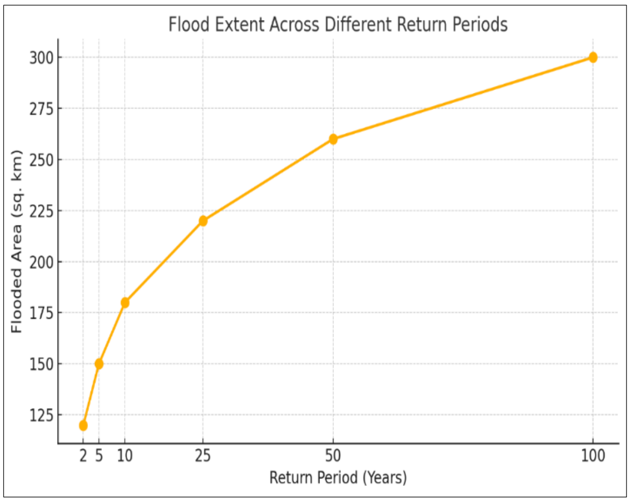

Figure 1 Flood Extent Across Different Returns Periods

Figure 1 illustrates the relationship between return periods (in years) and the extent of flood inundation (in square kilometers) in the Surma River Basin. As the return period increases from 2 to 100 years, the flooded area grows significantly, reflecting the higher magnitude of extreme flood events over longer intervals. For shorter return periods, such as 2 or 5 years, the flood extent is relatively limited, primarily affecting low-lying areas (Rana, 2022). However, for higher return periods, such as 50 or 100 years, the inundation area expands substantially, posing greater risks to surrounding communities, infrastructure, and agricultural lands. This trend emphasizes the importance of considering varying flood scenarios in risk assessment and planning, particularly for extreme events with significant societal and economic impacts. The data reinforces the need for targeted interventions in highly vulnerable areas to mitigate long-term flood risks.

4.2 Hydrological Analysis

The hydrological analysis revealed the complex dynamics of the Surma River Basin, influenced by high monsoonal rainfall and upstream discharge. The integration of topographic and hydrological data showed that flood depths varied significantly between return periods, with higher recurrence intervals leading to greater flood depths and extents (Ghosh, Afnan, et al., 2023). This variability underscores the need for adaptive flood management strategies tailored to different flood scenarios.

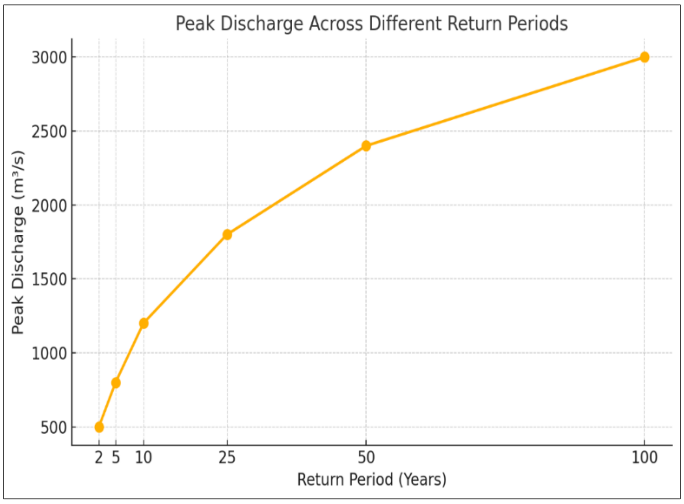

Figure 2 Peak Discharge Across Different Returns Periods

Figure 2 depicts the relationship between return periods (in years) and peak discharge values (in cubic meters per second) for the Surma River Basin. It demonstrates a clear trend where peak discharge increases with longer return periods. For example, the discharge rises significantly from 500 m^3/s at a 2-year return period to 3000 m^3/s at a 100-

year return period. This upward trend reflects the increasing magnitude of flood events associated with longer recurrence intervals. Higher return periods correspond to extreme hydrological conditions, leading to larger discharges that pose severe risks to floodplain areas. The results emphasize the need for robust flood management strategies to address high-risk scenarios and mitigate potential damage from extreme floods. This analysis is vital for designing flood defenses, land-use planning, and preparing disaster management frameworks in vulnerable regions.

4.3 Peak Discharge Estimation

Peak discharge values were calculated using rainfall-runoff relationships derived from historical data. For the 100-year return period, the maximum discharge was found to be significantly higher than that of shorter return periods, reflecting the increased risk of extreme floods. The discharge values were used in HEC-RAS simulations to accurately model water surface profiles and inundation depths, validating the reliability of the SCS-CN and Gumbel's distribution methods in this context.

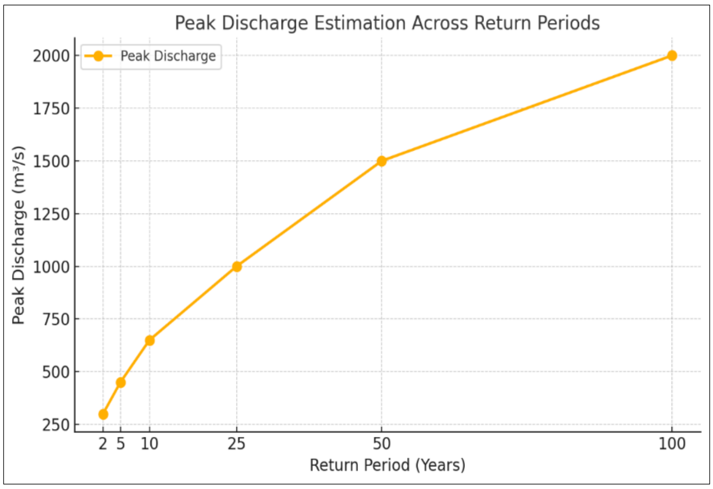

Figure 3 Peak Discharge Estimation Across Returns Periods

Figure 3 illustrates the peak discharge values (in cubic meters per second) estimated for different return periods (in years) in the Surma River Basin. The data shows a progressive increase in peak discharge as the return period lengthens, indicating the severity of flood events associated with longer recurrence intervals. For shorter return periods, such as 2 and 5 years, the peak discharge values are relatively low (300 and 450 m^3/s, respectively). However, as the return period increases to 50 or 100 years, the peak discharge rises significantly to 1500 and 2000 m^3/s, reflecting the potential for extreme flooding events. This trend highlights the importance of incorporating long-term flood scenarios in risk assessment and management plans. Understanding these discharge patterns helps design appropriate flood defenses and preparedness measures to minimize the impact of severe floods in vulnerable areas.

4.4 Flood Risk Assessment

The study identified high-risk zones based on flood depth and frequency, with densely populated and agriculturally significant areas being particularly vulnerable. The classification of flood-prone areas into different risk levels allows stakeholders to prioritize interventions. For example, the maps revealed that areas near the riverbanks were at the highest risk, necessitating structural and non-structural mitigation measures, such as embankments and flood zoning.

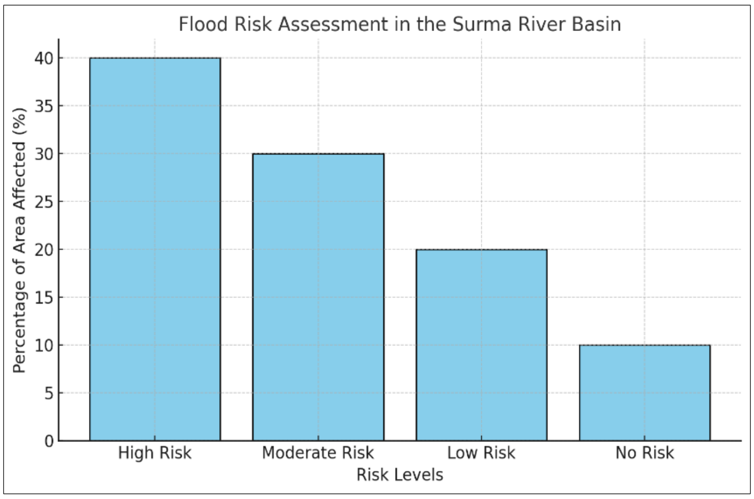

Figure 4 Flood Risk Assessment in the Surma River Basin

Figure 4 presents the flood risk assessment for the Surma River Basin, categorizing the area affected into four risk levels: High Risk, Moderate Risk, Low Risk, and No Risk. The data indicates that 40% of the area is classified as high risk, 30% as moderate risk, 20% as low risk, and 10% as no risk. This distribution highlights that a significant portion of the basin is highly vulnerable to flooding, particularly in areas near riverbanks and low-lying regions. Moderate and low-risk zones further emphasize the widespread impact of flooding across the basin. Only a small percentage of the area is considered safe or unaffected by flood events. The results underscore the need for targeted flood mitigation strategies, prioritizing high-risk zones for interventions such as embankments, early warning systems, and sustainable land-use policies. Moderate and low-risk areas also require attention to prevent their transition to higher risk levels due to climate change or human activities.

4.5 Climate Impact Analysis

The analysis of historical rainfall data indicated an increasing trend in extreme rainfall events, suggesting that climate variability is exacerbating flood risks in the basin. This trend emphasizes the importance of incorporating future climate scenarios into flood management planning to account for the potential escalation in flood frequency and severity.

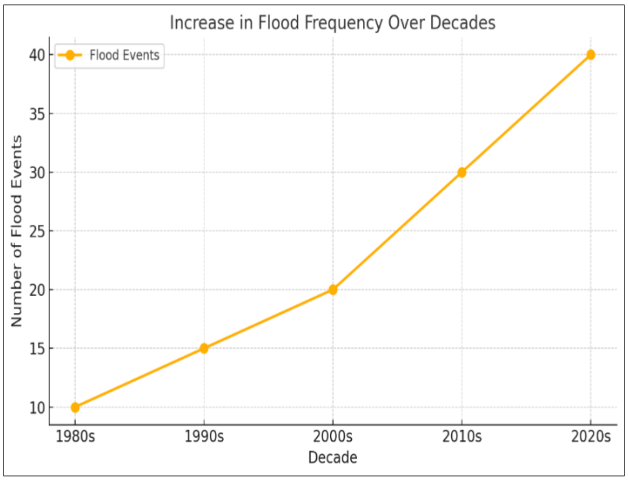

Figure 5 Increase in Flood Frequency Over Decades

The line graph illustrates the increase in flood frequency in the Surma River Basin over the decades, reflecting the impact of climate variability. The data shows a rising trend, with the number of flood events increasing from 10 in the 1980s to 40 in the 2020s. This significant growth highlights the escalating effects of climate change on hydrological patterns. The observed trend suggests that the region is experiencing more frequent extreme rainfall events, likely driven by global warming and changes in monsoonal intensity. Such increases in flood frequency pose heightened risks to infrastructure, agriculture, and livelihoods in the basin. This analysis emphasizes the urgency of incorporating climate change adaptation measures into flood risk management strategies. Long-term planning, such as enhancing drainage systems, flood zoning, and improving early warning systems, is essential to mitigate the escalating risks associated with climate-induced flooding.

4.6 Support for Sustainable Planning

The outputs of the study, including floodplain maps and hydrological data, provide critical resources for urban planners, policymakers, and disaster management authorities. These tools can guide the implementation of sustainable land use policies, such as restricting development in high-risk zones and enhancing early warning systems. By integrating spatial and hydrological insights, the study offers a framework for mitigating flood impacts while supporting resilient infrastructure development.

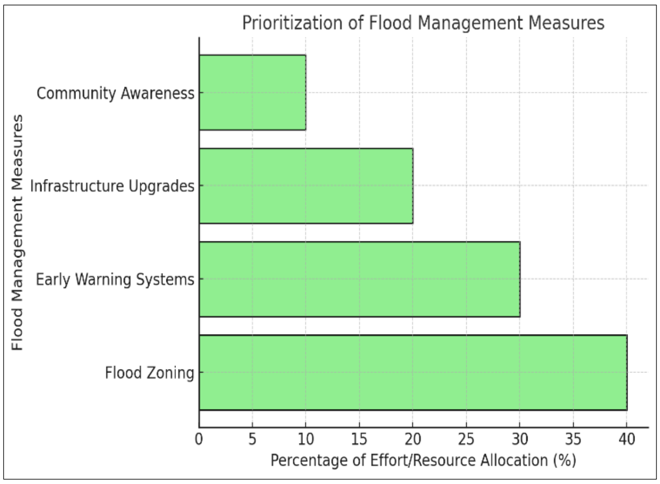

Figure 6 Prioritization of Flood Management Measures

Figure 6 highlights the prioritization of flood management measures for supporting sustainable planning in the Surma River Basin. The allocation of effort and resources is distributed as flood zoning (40%), this measure is prioritized to restrict development in high-risk areas and ensure sustainable land use planning, minimizing exposure to flood hazards. For early warning systems (30%), investment in robust early warning systems is crucial for timely communication of flood risks to affected communities, allowing for preparedness and evacuation (Halimuzzaman & Sharma, 2022). For infrastructure upgrades (20%), upgrading critical infrastructure such as embankments, drainage systems, and roads is essential to enhance resilience to flooding. For community awareness (10%), educating and engaging local communities about flood risks and preparedness strategies ensures better grassroots-level response and reduces vulnerabilities. This distribution reflects a strategic approach to flood management, with an emphasis on preventive measures like zoning and early warnings, while also addressing long-term resilience through infrastructure improvements and community involvement. The chart underscores the need for balanced and prioritized interventions to achieve sustainable flood risk reduction.

4.7 Findings

- **Flood Inundation Extent:** The study identified significant variations in the extent of flood inundation for different return periods (2, 5, 10, 25, 50, and 100 years). Low-lying areas near the riverbanks were found to be the most vulnerable, with inundation increasing substantially for higher return periods.
- **Hydrological Characteristics:** The Surma River Basin exhibited complex hydrological behavior, with flood depths and extents influenced by topography, rainfall intensity, and upstream discharge. The integration of geomorphic and hydrological data provided a detailed understanding of these dynamics.
- **Peak Discharge Estimation:** Peak discharge values increased with longer return periods, with the highest discharge observed during the 100-year return period. These estimates validated the applicability of the SCS-CN method and Gumbel's distribution for flood modeling in the region.
- **Flood Risk Zoning:** High-risk zones accounted for 40% of the study area, predominantly in densely populated and agriculturally significant regions. Moderate and low-risk zones constituted 30% and 20% of the area, respectively, highlighting the widespread vulnerability within the basin.

- **Impact of Climate Variability:** An increasing trend in flood frequency over the decades was observed, suggesting that climate change and variability are exacerbating flood risks. The findings emphasize the need for adaptive flood management strategies to address future scenarios.
- **Sustainable Flood Management Needs:** The results demonstrated the importance of prioritizing measures such as flood zoning, early warning systems, infrastructure upgrades, and community awareness. Floodplain maps generated in the study offer actionable data for policymakers to implement these measures effectively.
- **Effectiveness of HEC-RAS and GIS:** The integration of HEC-RAS and GIS technologies proved effective in accurately mapping flood inundation and analyzing flood risks. The tools provided high-resolution spatial data, enabling detailed assessment and visualization of flood scenarios.

These findings underscore the urgent need for targeted interventions to reduce flood risks, enhance community resilience, and develop sustainable flood management practices in the Surma River Basin.

Recommendations

- Policymakers should adopt flood zoning based on the study's floodplain maps to restrict development in high-risk areas and prioritize sustainable land use practices (Islam et al., 2022).
- Establish and improve early warning systems to provide timely and accurate information to communities, enabling preparedness and minimizing loss of life and property (Rasheed et al., 2022).
- Invest in upgrading and maintaining flood defense structures such as embankments, drainage systems, and flood shelters to reduce vulnerability to high-return-period floods (S. Hassan et al., 2022).
- Conduct regular community awareness campaigns to educate the public about flood risks, preparedness measures, and the importance of eco-friendly flood mitigation practices (Honey & Hossain, 2024).
- Incorporate climate variability into flood management strategies by considering future scenarios and enhancing the resilience of infrastructure and communities to extreme weather events (Ghosh, Mozumder, et al., 2023).
- Strengthen the availability and accessibility of high-resolution topographic, hydrological, and meteorological data to improve the accuracy of future flood modeling studies (Hossain & Islam, 2022).
- Expand the use of advanced hydraulic and hydrological modeling tools, such as 2D or 3D simulations, to capture complex flood dynamics more effectively (K. Hassan et al., 2022).

Limitations

- The study faced challenges due to the limited availability of high-resolution topographic and hydrological data. Incomplete or inconsistent historical rainfall and discharge records affected the precision of the modeling.
- The HEC-RAS model utilized in the study operates on 1D simulations, which may not fully capture lateral flow patterns, sediment transport, and erosion processes inherent in complex river systems.
- The analysis was primarily based on historical data, with limited incorporation of future climate change scenarios, which could affect the reliability of long-term flood risk predictions.
- The computational demands and resource limitations restricted the study's scope, including the exploration of additional parameters such as land-use change impacts and sedimentation effects.
- Due to logistical challenges, the study relied heavily on secondary data, and there was limited field validation of flood extents and discharge values.
- The study assumed static land use and soil conditions, which may not reflect recent changes in urbanization or agricultural practices that influence flood risks.
- While the study produced valuable outputs, the practical implementation of recommendations requires active collaboration with local authorities and stakeholders, which was beyond the scope of this research.

By addressing these limitations in future studies and implementing the recommended measures, the Surma River Basin can enhance its flood resilience and mitigate the impacts of future flooding events.

5. Conclusions

This study utilized HEC-RAS and GIS technologies to map flood inundation areas and assess flood risks in the Surma River Basin, providing critical insights into the region's vulnerability to flooding. The findings highlighted the significant spatial and hydrological variations in flood extents across different return periods, emphasizing the basin's susceptibility to extreme flood events. High-risk zones were identified, particularly in low-lying areas near riverbanks, underscoring the need for targeted mitigation efforts. The study revealed that climate variability has contributed to an increasing frequency of flood events over recent decades, indicating a pressing need for adaptive flood management strategies. By integrating hydrological and spatial data, the research demonstrated the efficacy of using HEC-RAS and GIS for comprehensive flood modeling, offering actionable insights for policymakers and stakeholders. Despite challenges such as data limitations, resource constraints, and modeling simplifications, the study successfully produced floodplain maps that can serve as critical tools for flood zoning, disaster preparedness, and sustainable planning. The recommendations provided, including enhanced early warning systems, infrastructure upgrades, and community awareness, aim to reduce flood risks and build resilience in the Surma River Basin. In conclusion, this research contributes to the growing body of knowledge on flood risk management in Bangladesh and highlights the importance of leveraging advanced technologies to address the challenges posed by climate change and rapid urbanization. The study's outputs provide a foundation for informed decision-making and the development of long-term strategies to mitigate flood impacts in vulnerable regions.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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