A Review of Flood Risk Assessment Due to Probable Maximum Precipitation in the West Rapti River Basin, Nepal

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Abstract

Floods driven by extreme precipitation events pose significant risks to communities, infrastructure, and ecosystems, particularly in regions with complex topography, such as Nepal. Probable Maximum Precipitation (PMP) is a critical parameter for assessing flood risk and designing resilient infrastructure. This review examines the methodologies and findings of a study focused on flood risk assessment in the West Rapti River Basin, Nepal, with emphasis on PMP and Probable Maximum Flood (PMF). This study employs hydrometeorological and statistical methods to estimate PMP, utilizes Snyder's unit hydrograph for PMF calculation, and applies HEC-RAS 2D modeling to map flood hazards, vulnerabilities, and risks. Key findings include PMP estimates of 507 mm and 575 mm, a PMF of 11,211.1 m³/s, and detailed flood risk maps highlighting significant inundation risks in Deukhuri Valley. This review synthesizes the contributions of this study, compares its approaches to global practices, and discusses its implications for flood risk management in Nepal.The study on flood risk assessment in the West Rapti River Basin, Nepal, employs a comprehensive approach to evaluate and map flood hazards, vulnerabilities, and risks. By combining hydrometeorological and statistical methods to estimate Probable Maximum Precipitation (PMP), the research provides crucial insights into extreme precipitation events in the region. The use of Snyder's unit hydrograph for Probable Maximum Flood (PMF) calculation and HEC-RAS 2D modeling for flood hazard mapping demonstrates a robust methodology for assessing flood risks in complex topographical areas.

The findings of this study have significant implications for flood risk management in Nepal and similar regions. The PMP estimates of 507 mm and 575 mm, along with the calculated PMF of 11,211.1 m³/s, provide valuable data for designing resilient infrastructure and implementing effective flood mitigation strategies. The detailed flood risk maps highlighting substantial inundation risks in Deukhuri Valley offer critical information for local authorities, urban planners, and policymakers to develop targeted interventions and improve community preparedness. This research contributes to the broader understanding of flood risk assessment methodologies and their application in regions with challenging topography, potentially informing similar studies in other flood-prone areas worldwide.

Keywords:

Flood risk assessment, West Rapti River Basin, Nepal, Probable Maximum Precipitation (PMP), Snyder's unit hydrograph, Probable Maximum Flood (PMF), HEC-RAS 2D modeling, Flood hazard mapping, Deukhuri Valley, Flood mitigation strategies, Hydrometeorological methods, Statistical analysis, Extreme precipitation events, Flood risk management, Inundation risks

Introduction

Floods are among the most devastating natural disasters, impacting millions of people globally through loss of life, property damage, and disruption of socio-economic activities. In Nepal, the interplay of monsoon-dominated precipitation, diverse topography, and rapid urbanization amplifies flood risks, particularly in low-lying regions, such as the Deukhuri Valley, the headquarters of Lumbini Province. The West Rapti River flows through this valley and is a significant flood hazard owing to its susceptibility to extreme rainfall events. Probable Maximum Precipitation (PMP), defined as the theoretical maximum precipitation possible for a given duration and area, is the cornerstone for estimating the Probable Maximum Flood (PMF) and designing hydraulic infrastructure. This review article presents a comprehensive study on flood risk assessment in the West Rapti River Basin, focusing on PMP-driven flood risks. The objectives of this study include estimating PMP and PMF, modeling flood inundation using HEC-RAS 2D, and mapping flood hazards, vulnerabilities, and risks. This review contextualizes the study within the broader literature, critiques its methodologies, and highlights its relevance to flood risk mitigation.

Floods in Nepal, particularly in the Deukhuri Valley and the West Rapti River Basin, present significant challenges due to the region's unique geographical and climatic characteristics. The combination of monsoon-driven precipitation, varied topography, and increasing urbanization exacerbates flood risks, making it crucial to develop robust flood risk assessment methodologies. The study's focus on Probable Maximum Precipitation (PMP) and Probable Maximum Flood (PMF) provides a theoretical framework for understanding the worst-case scenarios in terms of precipitation and flooding events. This approach is essential for designing resilient hydraulic infrastructure and implementing effective flood mitigation strategies.

The comprehensive nature of the study, encompassing PMP and PMF estimation, flood inundation modeling using HEC-RAS 2D, and the mapping of flood hazards, vulnerabilities, and risks, offers a holistic view of flood risk assessment in the region. By integrating these various components, the research provides valuable insights for policymakers, urban planners, and disaster management authorities. The use of advanced modeling techniques, such as HEC-RAS 2D, enhances the accuracy of flood inundation predictions, enabling more precise risk mapping and targeted mitigation efforts. This multifaceted approach to flood risk assessment in the West Rapti River Basin serves as a model for similar studies in other flood-prone regions, contributing to the broader field of disaster risk reduction and management.

Literature Review

Probable Maximum Precipitation (PMP) Estimation

PMP estimation is a critical step in flood risk assessment, as it provides the upper limit of precipitation for a specific region. The World Meteorological Organization (WMO, 2009) outlines six methods for PMP estimation: local, transposition, combination, inferential, generalized, and statistical. The reviewed study employs hydrometeorological and statistical methods, aligning with practices in regions with limited meteorological data. The hydro-meteorological method uses historical storm data and depth-area-duration (DAD) curves, whereas the statistical method, based on Hershfield's approach, leverages long-term rainfall records. Globally, studies like those in the United States (Hershfield, 1965) and India (Rakhecha & Kennedy, 1985) have refined PMP estimation, emphasizing the importance of regional calibration. The study's PMP estimates (507 mm and 575 mm) are consistent with Nepal's monsoon-dominated climate, where annual precipitation can exceed 5,000 mm in some areas. Some of the highest world rainfalls that has been recorded are listed in

Table **Error! No text of specified style in document.**-1.

Table **Error! No text of specified style in document.**-1: World highest point Rainfall (IWMI, 2003)

Durations	**Depths (mm)**	**Location**	**Date**
1 minute	38	Barot, Guadeloupe	26.11.1970
15 minutes	198	Jamaica	12.5.1916
42 minutes	305	Holt	22.6.1947
45 hours	782	Smethport, PA	18.7.1942
9 hours	1087	Belouve la Reunion	28.2.1964
12 hours	1340	Belouve la Reunion	28.2.1964
18.5 hours	1689	Belouve la Reunion	28.2.1964
24 hours	1825	Foe la Reunion	15-16.3.1952
2 days	2259	Hsin, Taiwan .	17-18.10.1967
3 days	2759	Cherrapunji, India	12-14.9.1974
4 days	3721	Cherrapunji, India	12-15.9.1974

Probable Maximum Flood (PMF) Calculation

PMF, derived from PMP, represents the theoretical maximum flood under extreme conditions. The study uses Snyder’s unit hydrograph method, a widely adopted approach for ungauged or data-scarce basins. This method correlates basin morphology with hydrograph characteristics, producing a PMF of 11,211.1 m³/s, comparable to a 10,000-year return period flood. Similar approaches are used in studies of Himalayan rivers (e.g., Bhattarai et al., 2019), where synthetic hydrographs compensate for sparse gauging data. However, the reliance on Snyder’s method assumes uniform rainfall distribution, which may oversimplify complex monsoon dynamics.The Probable Maximum Flood (PMF) concept, an extension of the Probable Maximum Precipitation (PMP), serves as a critical tool in hydrological engineering for estimating the most severe flood scenario possible in a given watershed. Snyder's unit hydrograph method, employed in this study, is particularly valuable for regions with limited hydrological data, as it correlates basin characteristics with hydrograph parameters. The resulting PMF estimate of 11,211.1 m³/s, equivalent to a 10,000-year return period flood, provides a crucial benchmark for flood risk assessment and infrastructure design in the study area.

While the application of Snyder's method aligns with practices in other Himalayan river studies, it is important to acknowledge its limitations. The assumption of uniform rainfall distribution inherent in this approach may not fully capture the complex spatial and temporal variability of monsoon precipitation patterns. This simplification could potentially lead to under- or overestimation of flood magnitudes in certain scenarios. Future research could benefit from incorporating more sophisticated rainfall distribution models or exploring alternative methods that better account for the nuanced dynamics of monsoon-driven flooding in mountainous regions.

Hydraulic Modeling and Flood Risk Mapping

HEC-RAS 2D modeling is a robust tool for simulating unsteady flow and mapping flood inundation. The study's use of HEC-RAS 2D, with a 50 m x 50 m mesh and Diffusion Wave equations, aligns with global standards for floodplain modeling (Rincón et al., 2022). The resulting flood hazard map categorizes 44.0% of the inundated area as extreme hazard, reflecting the severe flood risk in Deukhuri Valley. Vulnerability assessments, incorporating land use and road networks, highlight the socio-economic impacts of flooding, consistent with studies in Nepal (Awal et al., 2005) and globally (Su et al., 2005). The integration of hazard and vulnerability into a risk matrix using ArcGIS is a standard practice, though the study's reliance on outdated Open Street Map (OSM) data may limit accuracy.HEC-RAS 2D modeling, employed in this study with a 50 m x 50 m mesh and Diffusion Wave equations, demonstrates its effectiveness in simulating unsteady flow and mapping flood inundation in the Deukhuri Valley. The resulting flood hazard map, which categorizes 44.0% of the inundated area as extreme hazard, provides a clear visualization of the severe flood risk in the region. This approach aligns with global standards for floodplain modeling and offers valuable insights for flood risk management and mitigation strategies.

The study's comprehensive approach extends beyond hazard mapping to include vulnerability assessments that incorporate land use and road networks. This holistic perspective allows for a more nuanced understanding of the socio-economic impacts of flooding, consistent with similar studies conducted in Nepal and other parts of the world. The integration of hazard and vulnerability data into a risk matrix using ArcGIS further enhances the study's utility for decision-makers and stakeholders. However, the reliance on outdated Open Street Map (OSM) data may introduce some limitations to the accuracy of the vulnerability assessment, highlighting the importance of using up-to-date geospatial information in flood risk analysis.

Gaps in Existing Research

While significant research exists on flood modeling in Nepal, studies often focus on major river basins like the Koshi or Bagmati, leaving smaller basins like the West Rapti understudied. The reviewed study addresses this gap by providing a detailed assessment of a less-researched region. However, limitations such as coarse 30 m DEM resolution and sparse meteorological stations underscore the need for improved data infrastructure in Nepal.

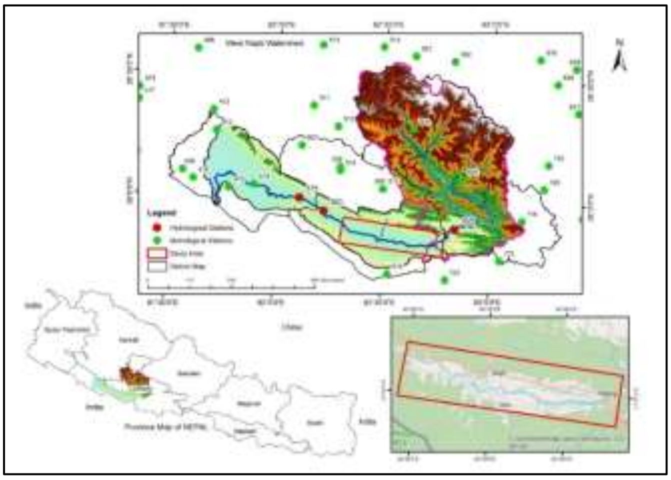

Figure **Error! No text of specified style in document.**-1: Study area with West Rapti Basin

Methodological Critique

The study's methodology is robust but faces challenges common to data-scarce regions. The hydro-meteorological PMP estimation, using DAD curves and Inverse Distance Weighting (IDW), is appropriate for Nepal's variable topography but sensitive to the quality of historical storm data. The statistical method, while simpler, may overestimate PMP due to its reliance on extreme value distributions. Snyder's unit hydrograph method is effective for PMF estimation but assumes linearity in rainfall-runoff processes, potentially underestimating peak flows in flashy monsoon events. The HEC-RAS 2D model is well-calibrated, but the 30 m DEM resolution limits its ability to capture micro-topographic features in flat terrains. The exclusion of structures like bridges and canals in the model simplifies the analysis but may underestimate localized flooding. Finally, the use of OSM data, which is not regularly updated, introduces uncertainties in vulnerability and risk mapping.The study's methodology demonstrates a comprehensive approach to flood risk assessment in Nepal, leveraging various techniques to overcome data limitations. The hydro-meteorological Probable Maximum Precipitation (PMP) estimation, utilizing Depth-Area-Duration (DAD) curves and Inverse Distance Weighting (IDW), is particularly well-suited for Nepal's complex topography. This method allows for a nuanced understanding of spatial rainfall patterns, crucial in a region with significant elevation changes. However, the accuracy of this approach heavily depends on the quality and quantity of historical storm data, which can be sparse in developing regions. The statistical method offers a simpler alternative but may lead to overestimation of PMP due to its reliance on extreme value distributions, potentially skewing risk assessments.

The Probable Maximum Flood (PMF) estimation using Snyder's unit hydrograph method provides a practical solution for translating rainfall into runoff. While this approach is widely accepted, its assumption of linearity in rainfall-runoff processes may not fully capture the complexity of flashy monsoon events characteristic of Nepal. The HEC-RAS 2D model employed for flood simulation offers a robust platform for analysis, benefiting from proper calibration. However, the 30 m Digital Elevation Model (DEM) resolution limits the model's ability to represent fine-scale topographic features, particularly in flat terrains where small elevation changes can significantly influence flood patterns. The deliberate exclusion of structures like bridges and canals from the model, while simplifying the analysis, may lead to underestimation of localized flooding effects. Additionally, the reliance on OpenStreetMap (OSM) data for vulnerability and risk mapping introduces a level of uncertainty due to potential outdated information, highlighting the ongoing challenges in data acquisition and management for comprehensive flood risk assessment in data-scarce regions.

Key Findings and Implications

The study's PMP estimates (507 mm and 575 mm) highlight the extreme precipitation potential in the West Rapti River Basin, driven by monsoon dynamics. The PMF of 11,211.1 m³/s, validated against flood frequency analyses, underscores the basin's vulnerability to catastrophic flooding. The flood hazard map reveals that 44.0% of the inundated area faces extreme risk, with 240.5 km of roads and diverse land cover types (e.g., farmland, residential areas) affected. The risk map, categorizing areas into low (6,624.0 ha), medium (5,599.5 ha), and high (362.4 ha) risk zones, provides actionable insights for urban planning and disaster preparedness. These findings have significant implications for Lumbini Province, where rapid urbanization in Deukhuri Valley necessitates flood-resilient infrastructure and land use policies.The study's findings on Probable Maximum Precipitation (PMP) and Probable Maximum Flood (PMF) in the West Rapti River Basin reveal the region's susceptibility to extreme weather events and catastrophic flooding. The PMP estimates of 507 mm and 575 mm indicate the potential for intense rainfall, primarily driven by monsoon patterns. This precipitation potential, when combined with the basin's characteristics, results in a calculated PMF of 11,211.1 m³/s. The validation of this PMF value against flood frequency analyses strengthens its reliability as a benchmark for assessing flood risks in the area.

The flood hazard and risk maps generated from this study provide crucial information for urban planning and disaster management. With 44.0% of the inundated area classified as facing extreme risk and 240.5 km of roads potentially affected, the maps highlight the vulnerability of critical infrastructure and various land cover types, including farmland and residential areas. The categorization of risk zones into low (6,624.0 ha), medium (5,599.5 ha), and high (362.4 ha) risk areas offers a nuanced understanding of flood vulnerability across the basin. These insights are particularly relevant for Lumbini Province, where rapid urbanization in Deukhuri Valley necessitates the implementation of flood-resilient infrastructure and land use policies to mitigate potential disaster impacts and ensure sustainable development.

Comparison with Global Practices

Globally, flood risk assessments integrate advanced remote sensing, high-resolution DEMs, and real-time data to improve accuracy. For example, studies in the Greater Toronto Area (Rincón et al., 2022) use LiDAR-based DEMs and multi-criteria decision analysis, offering finer resolution than the 30 m SRTM DEM used in the study. In data-scarce regions like Nepal, however, the study's reliance on SRTM and OSM is pragmatic, though it highlights the need for investment in geospatial technologies. The use of HEC-RAS 2D is consistent with global standards, but incorporating velocity and duration in hazard assessments, as done in some European studies (Islam et al., 2002), could enhance the analysis.Globally, flood risk assessments have evolved to incorporate a diverse array of advanced technologies and methodologies. The integration of high-resolution remote sensing data, LiDAR-based Digital Elevation Models (DEMs), and real-time hydrological information has significantly enhanced the accuracy and granularity of flood risk analyses. Studies conducted in urban areas like the Greater Toronto Area (Rincón et al., 2022) exemplify this trend, utilizing LiDAR-derived DEMs and sophisticated multi-criteria decision analysis techniques. These approaches offer substantially finer resolution compared to the 30 m Shuttle Radar Topography Mission (SRTM) DEM employed in the Nepal study, enabling more precise delineation of flood-prone areas and improved risk assessment in complex urban environments.

However, the application of advanced geospatial technologies in flood risk assessment is not uniform across the globe. In data-scarce regions such as Nepal, the reliance on freely available SRTM data and OpenStreetMap (OSM) information represents a pragmatic approach to flood risk assessment. While this method allows for meaningful analysis in resource-constrained settings, it also underscores the pressing need for investment in geospatial infrastructure and data collection in developing nations. The use of HEC-RAS 2D for hydraulic modeling aligns with global best practices, but there is potential for further refinement. Incorporating additional parameters such as flow velocity and flood duration into hazard assessments, as demonstrated in some European studies (Islam et al., 2002), could provide a more comprehensive understanding of flood dynamics and their potential impacts, thereby enhancing the overall robustness of the analysis.

Recommendations for Future Research

1. **Improved Data Resolution**: Utilize high-resolution DEMs (e.g., LiDAR) and updated land use data to enhance modeling accuracy.
2. **Incorporation of Structures**: Include bridges, canals, and other infrastructure in HEC-RAS models to capture localized flooding effects.
3. **Multi-Parameter Hazard Assessment**: Integrate flood velocity and duration alongside depth for a comprehensive hazard analysis.
4. **Real-Time Monitoring**: Establish denser meteorological and hydrological networks to improve PMP and PMF estimations.
5. **Community Engagement**: Incorporate local knowledge and socio-economic data to refine vulnerability and risk assessments.

Conclusion

The study on flood risk assessment in the West Rapti River Basin provides a comprehensive framework for understanding PMP-driven flood risks in a rapidly urbanizing region of Nepal. Its use of hydro-meteorological and statistical PMP estimation, Snyder’s unit hydrograph for PMF, and HEC-RAS 2D modeling aligns with global practices, though data limitations highlight areas for improvement. The findings underscore the urgent need for flood-resilient infrastructure and land use planning in Deukhuri Valley. By addressing methodological gaps and leveraging emerging technologies, future research can further enhance flood risk management in Nepal, contributing to safer and more resilient communities.The study's comprehensive approach to flood risk assessment in the West Rapti River Basin integrates multiple methodologies to provide a holistic understanding of PMP-driven flood risks. By combining hydro-meteorological and statistical PMP estimation techniques with Snyder's unit hydrograph for PMF calculation and HEC-RAS 2D modeling, the research aligns with global best practices in flood risk analysis. This multi-faceted approach allows for a more accurate representation of potential flood scenarios, taking into account the complex interplay of meteorological, hydrological, and topographical factors that influence flooding in the region. The study's focus on a rapidly urbanizing area of Nepal adds particular relevance to its findings, as it addresses the pressing need for flood risk management strategies in areas experiencing significant land use changes.

While the study provides valuable insights, it also highlights areas for improvement, particularly regarding data limitations. These constraints underscore the importance of continued investment in data collection and monitoring infrastructure to enhance the accuracy and reliability of flood risk assessments. The findings emphasize the critical need for flood-resilient infrastructure and informed land use planning in the Deukhuri Valley, suggesting that proactive measures are essential to mitigate potential flood impacts. Future research in this field could benefit from addressing methodological gaps and incorporating emerging technologies, such as advanced remote sensing techniques or machine learning algorithms for improved flood prediction. By building upon this study and addressing its limitations, future work can contribute to more robust flood risk management strategies in Nepal, ultimately leading to safer and more resilient communities in flood-prone areas.

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