# Evaluating Flood Risk Associated with Probable Maximum Precipitation in the West Rapti River Basin, Nepal

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## Abstract

Floods, driven by extreme precipitation, pose significant risks to Nepal's Deukhuri Valley, the headquarters of Lumbini Province, located in the West Rapti River Basin. This study assesses flood risk due to Probable Maximum Precipitation (PMP) using hydro-meteorological and statistical methods to estimate PMP, Snyder's unit hydrograph for Probable Maximum Flood (PMF), and HEC-RAS 2D modeling for flood inundation mapping. PMP values of 507 mm (hydro-meteorological) and 575 mm (statistical) were derived, with the latter used to estimate a PMF of 11,211.1 m³/s, comparable to a 10,000-year return period flood. The flood hazard map indicates 44.0% of the inundated area as extreme hazard, with 240.5 km of roads and diverse land cover types affected. Risk mapping categorizes areas into high (362.4 ha), medium (5,599.5 ha), and low (6,624.0 ha) risk zones. These findings provide critical insights for flood risk mitigation and infrastructure planning in the study area.The study expands on flood risk assessment in Nepal's Deukhuri Valley, focusing on the impact of Probable Maximum Precipitation (PMP) in the West Rapti River Basin. Using a combination of hydro-meteorological and statistical methods, the research establishes PMP values of 507 mm and 575 mm, respectively. The higher statistical value is then utilized to calculate a Probable Maximum Flood (PMF) of 11,211.1 m³/s, which is comparable to a flood event with a 10,000-year return period. This comprehensive approach provides a robust foundation for understanding the potential magnitude of extreme flooding events in the region.

The study's findings have significant implications for flood risk management and urban planning in the Deukhuri Valley. The flood hazard map reveals that 44.0% of the inundated area falls under the extreme hazard category, with 240.5 km of roads at risk. Furthermore, the research categorizes the affected areas into high (362.4 ha), medium (5,599.5 ha), and low (6,624.0 ha) risk zones. This detailed risk assessment, combined with the analysis of impacted land cover types, offers valuable insights for local authorities and planners. The information can be used to develop targeted flood mitigation strategies, improve infrastructure resilience, and inform land-use policies to minimize the potential impact of extreme flooding events on the region's population and economy.

Keywords:

1. Flood risk assessment, Nepal, Deukhuri Valley, Probable Maximum Precipitation (PMP), West Rapti River Basin, Hydro-meteorological methods, Statistical methods, Probable Maximum Flood (PMF), Flood hazard mapping, Extreme flooding events, Urban planning, Infrastructure resilience, Land-use policies, Flood mitigation strategies, Risk zonation

## Introduction

Nepal's diverse topography and monsoon-dominated climate make it highly susceptible to floods, particularly in low-lying areas like Deukhuri Valley, traversed by the West Rapti River. Probable Maximum Precipitation (PMP), the theoretical maximum precipitation for a given duration and area, is a key parameter for estimating Probable Maximum Flood (PMF) and designing hydraulic infrastructure. Despite the significant flood risk in Deukhuri Valley, research on PMP-driven flooding in the West Rapti River Basin is limited. This study aims to assess flood risk in the region by estimating PMP and PMF, modeling flood inundation using HEC-RAS 2D, analyzing flood hazard, vulnerability, and risk, and developing a flood risk map. The study addresses a critical gap in flood risk assessment for a rapidly urbanizing region, providing data-driven insights for disaster preparedness and infrastructure resilience.Nepal's topography and climate create a complex environment prone to flooding, particularly in areas like Deukhuri Valley. The West Rapti River, which flows through this region, poses a significant flood risk due to its location and the monsoon-driven precipitation patterns. Probable Maximum Precipitation (PMP) plays a crucial role in understanding and predicting extreme rainfall events, which in turn inform estimates of Probable Maximum Flood (PMF). These parameters are essential for designing robust hydraulic infrastructure and implementing effective flood management strategies. However, the lack of comprehensive research on PMP-driven flooding in the West Rapti River Basin has left a critical knowledge gap, potentially hindering the development of adequate flood protection measures.

This study aims to address this research gap by conducting a thorough flood risk assessment in the Deukhuri Valley region. By estimating PMP and PMF, the research will provide valuable insights into the maximum potential flood scenarios. The use of HEC-RAS 2D for flood inundation modeling will offer detailed simulations of flood extent and depth under various conditions. Furthermore, the analysis of flood hazard, vulnerability, and risk factors will contribute to a comprehensive understanding of the region's flood dynamics. The development of a flood risk map will serve as a crucial tool for urban planners, policymakers, and emergency responders, enabling them to make informed decisions about land use, infrastructure development, and disaster preparedness in this rapidly urbanizing area.

## Materials and Methods

### Study Area

Deukhuri Valley, located in Lumbini Province, Nepal, spans approximately 600 km² within the 6,100 km² West Rapti River Basin. The valley, drained by the West Rapti River, experiences monsoon-dominated rainfall (80% of annual 1,500 mm) and varied climatic conditions, transitioning from temperate to subtropical. The basin's average slope is 16.8%, with runoff driven by monsoon rainfall and groundwater.

The methodology of the study follows the sequential process as shown in Figure 1. The detail of each methods and process are described below.The Deukhuri Valley, nestled within the larger West Rapti River Basin in Nepal's Lumbini Province, presents a diverse and dynamic ecological landscape. This 600 km² area is characterized by its varied topography and climate, transitioning from temperate to subtropical conditions. The valley's hydrology is primarily influenced by the monsoon season, which contributes a significant 80% of the annual 1,500 mm rainfall. This concentrated precipitation pattern plays a crucial role in shaping the region's water resources and agricultural practices.

The West Rapti River, the primary drainage system of the valley, is fed by both monsoon rainfall and groundwater sources. The basin's average slope of 16.8% contributes to the complex hydrological processes in the area, affecting water flow patterns and soil erosion rates. This interplay between topography, climate, and hydrology creates a unique environment that supports diverse ecosystems and agricultural activities. Understanding these intricate relationships is essential for effective water resource management and sustainable development in the Deukhuri Valley, particularly in the context of climate change and increasing human pressures on natural resources.

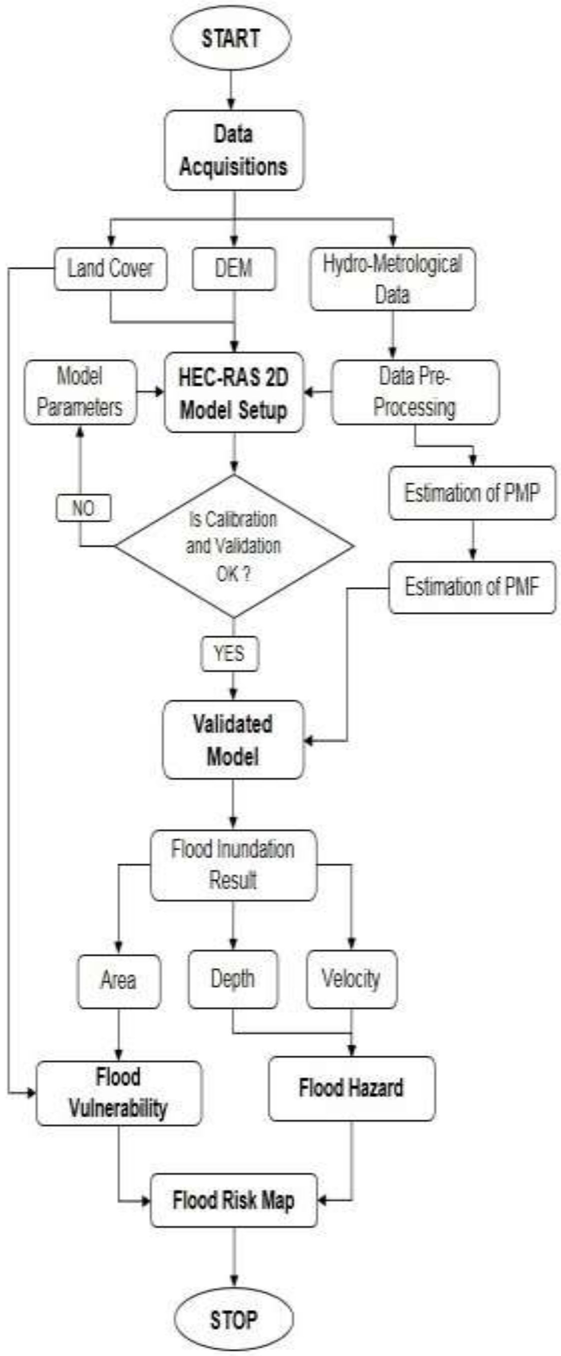


Figure 1: Methodology adopted for the study

**Data Collection**

Data included:

- **Digital Elevation Model (DEM)**: 30 m resolution SRTM data.
- **Land Cover**: 2020 ICIMOD dataset.
- **Open Street Map (OSM)**: Road and land use data.
- **Rainfall**: 1949–2014 data from the Department of Hydrology and Meteorology (DHM).
- **Discharge**: 1964–2019 DHM data from three hydrological stations.
- Table 1: Data Collection

| S.N. | Data | Source | Remark |
|---|---|---|---|
| 1 | DEM | SRTM | 30 m Resolution |
| 2 | Land Cover | ICIMOD | 2020 AD |
| 3 | OSM | Open Street Map | |
| 4 | Rainfal | DHM | 1949- 2014 |
| 5 | Discharge | DHM | 1964-2019 |

**PMP Estimation**

PMP was estimated using:

1. **Hydro-Meteorological Method**: Historical storm data were maximized using Depth-Area-Duration (DAD) curves and Inverse Distance Weighting (IDW) in ArcGIS, yielding a basin-average PMP of 507 mm.

2. **Statistical Method**: Hershfield’s method, using long-term rainfall records, produced a PMP of 575 mm, adjusted by a factor of 1.13 for extreme values.

**PMF Estimation**

The statistical PMP (575 mm) was used to calculate PMF via Snyder's unit hydrograph method. Key parameters included a catchment area of 4,049.4 km², a longest flow path of 151.18 km, and a base flow of 12.5 m³/s. The resulting PMF was 11,211.1 m³/s, with a flood hydrograph peaking at 26 hours and ending at 145 hours.

Table 2: PMP of hydrological stations of Nepal

| Station ID | Name | Latitude (N) | Longitude (E.) | Elevation (amsl) | PMP (mm) |
|---|---|---|---|---|---|
| 104 | Dadeldhura | 29.3 | 80.58 | 1848 | 559.14 |
| 105 | Mahendra Nagar | 29.03 | 80.21 | 176 | 601.74 |
| 202 | Chainpur (West) | 29.55 | 81.21 | 1304 | 601.74 |
| 209 | Dhangadi | 28.68 | 80.6 | 170 | 644.34 |
| 303 | Jumla | 29.28 | 82.16 | 2300 | 559.14 |
| 405 | Chisapani (Karnali) | 28.65 | 81.26 | 225 | 625.17 |
| 406 | Surkhet (Birendra Nagar) | 28.6 | 81.61 | 720 | 625.17 |
| 601 | Jomsom | 28.78 | 83.71 | 2744 | 580.44 |
| 609 | Beni Bazar | 28.35 | 83.56 | 835 | 618.78 |
| 703 | Butwal | 27.7 | 83.46 | 205 | 631.56 |
| 705 | Bhairawa Airport | 27.51 | 83.43 | 109 | 621.98 |
| 706 | Dumkauli | 27.68 | 83.21 | 154 | 644.34 |
| 804 | Pokhara Airport | 28.21 | 84 | 827 | 618.78 |
| 809 | Gorkha | 28 | 84.61 | 1097 | 618.78 |
| 816 | Chame | 28.55 | 84.23 | 2680 | 468.61 |
| 906 | Hetauda N.F.I. | 27.41 | 85.05 | 474 | 637.95 |
| 1004 | Nuwakot | 27.91 | 85.16 | 1003 | 591.09 |
| 1043 | Nagarkot | 27.7 | 85.51 | 2163 | 580.44 |
| 1103 | Jiri | 27.63 | 86.23 | 2003 | 559.14 |
| 1111 | Janakpur Airport | 26.71 | 85.96 | 90 | 535.18 |
| 1206 | Okhaldhunga | 27.31 | 86.5 | 1720 | 580.44 |
| 1307 | Dhankuta | 26.98 | 87.35 | 1210 | 549.55 |
| 1319 | Biratnagar Airport | 26.48 | 87.26 | 72 | 618.78 |
| 1416 | Kanyam Tea Estate | 26.86 | 88.06 | 1678 | 520.8 |

| Station ID | Name | Latitude (N) | Longitude (E.) | Elevation (amsl) | PMP (mm) |
|---|---|---|---|---|---|
| 1421 | Gaida (Kankai) | 26.58 | 87.9 | 143 | 564.46 |

**Flood Frequency Analysis**

Flood frequency analysis used Gumbel, Log-Pearson Type III, and Log Normal distributions, with discharge data from the Jalkundi gauging station (5,150 km² catchment) correlated to the study area using a Catchment Area Ratio (CAR) of 0.79. The 10,000-year return period floods were 10,922.24 m³/s (Gumbel), 11,459.2 m³/s (Log-Pearson), and 15,029.0 m³/s (Log Normal).

Table 3: Flood frequency analysis using different methods

| Return period | Log-Pearson Type III Distribution | Log Normal Distribution | Gumbel Distribution |
|---|---|---|---|
| 2 | 2113.6 | 2157.3 | 2207.18 |
| 5 | 3124.6 | 3147.7 | 3324.11 |
| 10 | 3879.7 | 3835.7 | 4063.61 |
| 20 | 4668.1 | 4515.7 | 4772.96 |
| 30 | 5151.5 | 4916.0 | 5181.04 |
| 50 | 5788.3 | 5426.0 | 5691.15 |
| 100 | 6708.4 | 6132.6 | 6379.20 |
| 200 | 7700.5 | 6859.4 | 7064.73 |
| 500 | 9136.0 | 7856.5 | 7969.17 |
| 1000 | 10325.7 | 8641.2 | 8652.72 |
| 2000 | 11613.6 | 9454.2 | 9336.03 |
| 5000 | 13480.8 | 10574.8 | 10239.13 |
| **10000** | **15029.0** | **11459.2** | **10922.24** |

**HEC-RAS 2D Modeling**

A HEC-RAS 2D model was set up with:

- **Terrain**: 30 m SRTM DEM.
- **Mesh**: 50 m x 50 m computational grid.

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- **Equations**: Diffusion Wave for hydraulic routing.
- **Boundary Conditions**: Upstream flood hydrograph from Snyder's method; downstream normal depth based on river slope.
- **Parameters**: 10-second time step, default error tolerances.

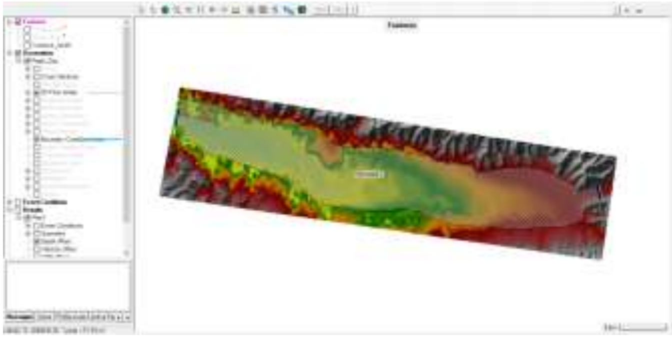

Figure 2: 2D flow area and mesh created in HEC-RAS 2D

**Flood Hazard, Vulnerability, and Risk Mapping**

- **Hazard**: Based on flood depth (<1 m: low; 1–2 m: moderate; 2–3 m: high; >3 m: extreme).
- **Vulnerability**: Assessed for roads (polyline) and land cover (polygons) using OSM data, with vulnerability levels (low, medium, high) assigned based on land use.
- **Risk**: Derived from a hazard-vulnerability matrix using ArcGIS weighted overlay, categorized into low, medium, and high risk zones.
- Flood risk is expressed as a function of hazard, vulnerability which is illustrated by the following equation.

$$Risk = f(hazard, vulnerability)$$

Initially, hazard and vulnerability maps were created in raster format. Subsequently, they were combined using the weighted overlay tool in ArcGIS. Specific weights were assigned to each criterion using the Analytical Hierarchy Process (AHP) method, as described in the following sub-section. The output raster obtained from the overlay analysis was then reclassified into three equal intervals, each representing different levels of risk. Lower numbers indicated low levels of risk, while higher numbers represented very high levels of risk, resulting in four distinct risk levels: low, medium, high, and very high.The process of creating hazard and vulnerability maps in raster format serves as the foundation for comprehensive risk assessment. These initial maps capture spatial data representing various hazards and vulnerabilities across the study area. The weighted overlay tool in ArcGIS is then employed to combine these maps, integrating multiple criteria into a single analysis. This step is crucial as it allows for the consideration of diverse factors that contribute to overall risk.

The Analytical Hierarchy Process (AHP) method plays a pivotal role in assigning specific weights to each criterion. This systematic approach ensures that the relative importance of different factors is accurately reflected in the final risk assessment. Once the weighted overlay is complete, the resulting output raster undergoes reclassification into three equal intervals. This reclassification step transforms the continuous risk data into discrete categories, facilitating easier interpretation and decision-making. The final product is a risk map with four distinct levels: low, medium, high, and very high. This categorization provides a clear visual representation of risk distribution across the area, enabling stakeholders to identify priority zones for risk mitigation and management strategies.

Table 4: Risk Matrix based on hazard and vulnerability level

| | | **Land Cover** | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | **River** | **Quarry** | **Forest** | **Scrub** | **Farmland** | **Residential** | **Industrial** |
| **Hazard** | | **L** | **L** | **M** | **M** | **M** | **H** | **H** |
| **Low** | **L** | L | L | L | L | L | M | M |
| **Moderate** | **M** | L | L | L | L | L | H | H |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **High** | **M** | L | L | M | M | M | H | H |
| **Extreme** | **H** | M | M | H | H | H | H | H |

**Results**

**PMP and PMF**

The hydro-meteorological method yielded a PMP of 507 mm, while the statistical method produced 575 mm. The latter was used to estimate a PMF of 11,211.1 m³/s, closely aligning with 10,000-year return period floods (10,922.24–15,029.0 m³/s).

**Flood Inundation**

The total inundated area was 12,585.3 ha, with a maximum depth of 18 m. The flood hazard map showed:

- Low hazard: 2,443.9 ha (19.4%).
- Moderate hazard: 1,886.1 ha (15.0%).
- High hazard: 2,719.5 ha (21.6%).
- Extreme hazard: 5,535.7 ha (44.0%).
- The inundation extent, obtained from HEC-RAS modeling, was exported to ArcGIS for further analysis to calculate the area of inundation. In the Deukhuri Valley, the total inundation area resulting from the overflow of the West Rapti River is determined to be 12,585.3 hectares. Additionally, the highest depth of inundation recorded in the affected area is approximately 18 meters. The flood inundation map overlaid in Open Street Map is shown in Figure.

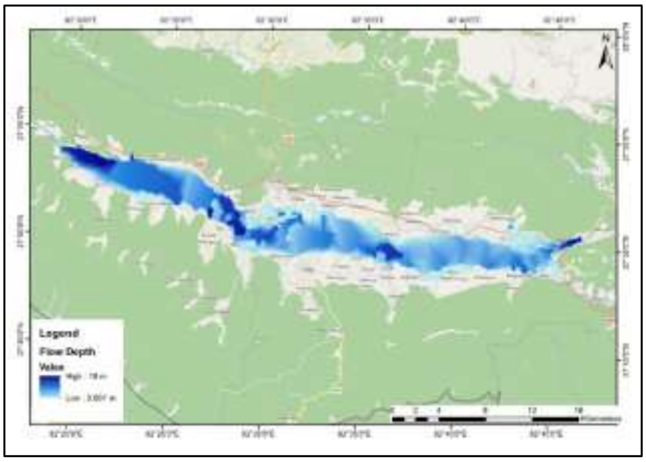


Figure 3: Flood Inundation Map overlaid on Open Street Map

**Vulnerability**

- **Roads**: 240.5 km inundated, including 89.9 km of tracks and 61.3 km of paths.
- **Land Cover**: Affected areas included farmland (316.7 ha), residential (363.4 ha), and quarry (9,347.9 ha).
- Flood vulnerability maps were created separately for road networks and land covers, as roads are represented as polyline features, while land cover is depicted as polygons. The road categories included in the analysis are Path, Residential, Secondary, Service, Tertiary, Track, Trunk, and Unclassified. Table presents the length of each road category that is inundated due to flooding in the study area, with a total inundated length across all categories amounting to 240.5 kilometers.
- These vulnerability maps provide valuable insights into the susceptibility of road networks to flooding, helping to identify vulnerable segments and prioritize mitigation measures. The Flood Vulnerability Map for roads is presented in Figure, employing different colors to represent the various road categories. This visualization facilitates the assessment of flood vulnerability across different road types, aiding in the planning and implementation of measures to enhance resilience and mitigate flood-related risks in the study area.

- Table 5: Flood Vulnerability of road

| Road Class | Length (m) |
|---|---|
| Path | 61295 |
| Residential | 26633 |
| Secondary | 855 |
| Service | 451 |
| Tertiary | 16785 |
| Track | 89887 |
| Trunk | 4422 |
| Unclassified | 40130 |
| Total | 240458 |

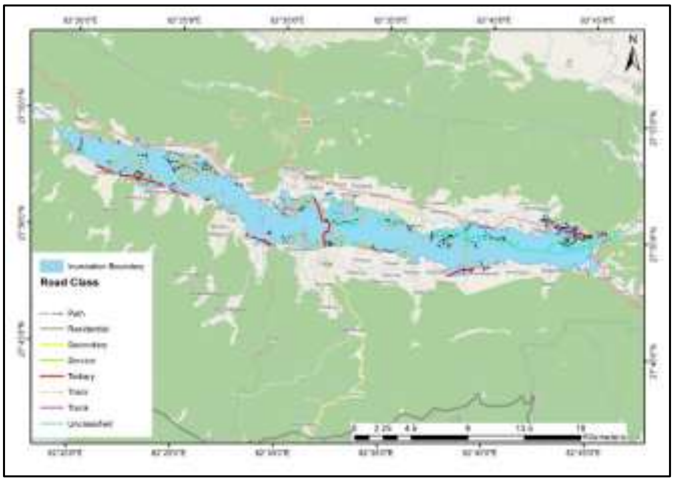


Figure 0: Flood Vulnerability Map of different road categories

**Flood Risk**

The risk map categorized:

- Low risk: 6,624.0 ha.
- Medium risk: 5,599.5 ha.
- High risk: 362.4 ha.
- The Flood Risk Map was derived from a matrix analysis of Hazard and Vulnerability, integrating information on the susceptibility of different land cover categories to flooding. Notably, road vulnerability was excluded from the risk analysis due to the inherent limitations of polyline data representation in OSM, which cannot be analyzed as polygon data.
- The risk assessment categorized the study area into three distinct classes: high, medium, and low risk. The analysis revealed that the high-risk area encompasses 362.4 hectares, while the medium-risk area covers 5599.5 hectares, and the low-risk area spans 6624.0 hectares.
- The Flood Risk Map, presented in figure, employs a color scheme to visually represent the different risk classes. Green color signifies low risk, yellow indicates medium risk, and red denotes high risk. This visualization enables stakeholders and decision-makers to easily identify areas with varying levels of flood risk within the study area, facilitating informed decision-making and the prioritization of mitigation and adaptation measures to enhance community resilience and reduce vulnerability to flooding hazards.

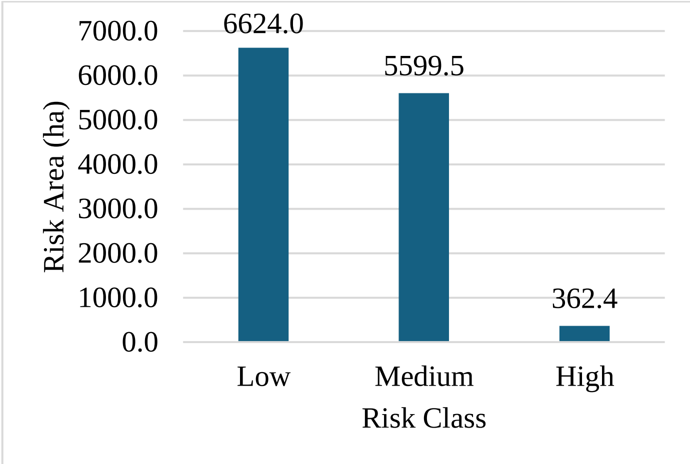


Figure 5: Risk Class Vs Inundation Area

Table 6: Flood risk class and its inundation area

| Risk Class | Area (ha) |
|---|---|
| Low | 6624.0 |
| Medium | 5599.5 |
| High | 362.4 |
| Total | 12586.0 |

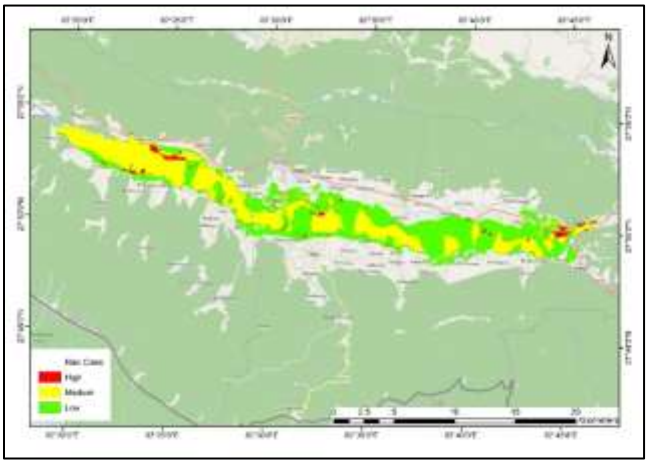

Figure 6 Flood Risk Map of the Study Area

**Discussion**

The higher PMP from the statistical method (575 mm) reflects its sensitivity to extreme rainfall records, suitable for Nepal's monsoon climate. The PMF of 11,211.1 m³/s, validated against flood frequency analyses, highlights the basin's extreme flood potential. The HEC-RAS 2D model effectively captured inundation patterns, though the 30 m DEM resolution limited topographic detail. The significant extreme hazard area (44.0%) underscores the need for robust flood defenses in Deukhuri Valley. Vulnerability analysis revealed critical impacts on farmland and residential areas, necessitating land use regulations. The risk map provides a clear framework for prioritizing mitigation in high-risk zones. Limitations include coarse DEM resolution, outdated OSM data, and exclusion of infrastructure like bridges, which may affect localized flooding.The statistical method's higher Probable Maximum Precipitation (PMP) of 575 mm demonstrates its effectiveness in capturing extreme rainfall events characteristic of Nepal's monsoon climate. This approach, which is particularly sensitive to outlier precipitation records, provides a more conservative estimate suitable for flood risk assessment in regions prone to intense seasonal rainfall. The method's ability to account for historical extremes and potential future climate variability makes it a robust tool for long-term flood planning and infrastructure design in areas with complex meteorological patterns.

The resulting Probable Maximum Flood (PMF) of 11,211.1 m³/s, validated through flood frequency analyses, underscores the significant flood potential of the basin. This extreme flow value serves as a crucial input for designing flood protection measures and assessing the vulnerability of infrastructure in the region. The magnitude of the PMF highlights the need for comprehensive flood management strategies that consider both structural and non-structural measures to mitigate potential impacts on communities, agriculture, and critical infrastructure.

The application of the HEC-RAS 2D model proved effective in simulating inundation patterns, offering valuable insights into flood behavior across the study area. The model's ability to represent complex flow dynamics and floodplain interactions provides decision-makers with a powerful tool for visualizing potential flood scenarios and identifying areas of high risk. This information is essential for developing targeted flood mitigation strategies and improving emergency response planning.

However, the use of a 30 m Digital Elevation Model (DEM) imposed limitations on the model's ability to capture fine-scale topographic features, potentially affecting the accuracy of local flood predictions. This resolution constraint may lead to oversimplification of terrain characteristics, particularly in areas with subtle elevation changes or small-scale drainage features that can significantly influence local flood behavior. Future studies could benefit from the use of higher-resolution DEMs, such as those derived from LiDAR data, to enhance the precision of flood simulations and improve the reliability of risk assessments at smaller spatial scales.

The analysis revealed that a substantial portion (44.0%) of the area falls within the extreme hazard category, emphasizing the critical need for comprehensive flood defense strategies in Deukhuri Valley. This high percentage of land at extreme risk underscores the urgency of implementing both immediate and long-term flood mitigation measures. Such measures may include the construction of flood control structures, improvement of drainage systems, and the development of early warning systems to enhance community resilience.

The vulnerability assessment highlighted the particular susceptibility of farmland and residential areas to flood impacts, underscoring the importance of implementing stringent land use regulations to mitigate future risks. This finding emphasizes the need for integrated flood risk management approaches that combine physical interventions with policy measures. Strategies such as flood-resistant building codes, relocation of critical facilities from high-risk areas, and the creation of flood buffer zones could significantly reduce the potential for damage and loss of life during extreme flood events.

While the generated risk map provides a valuable tool for prioritizing flood mitigation efforts in high-risk zones, it is important to acknowledge the study's limitations. The coarse DEM resolution may lead to uncertainties in flood extent and depth predictions, particularly in areas with complex topography. Reliance on potentially outdated OpenStreetMap data could result in inaccuracies in land use classification and infrastructure representation, affecting the assessment of vulnerability and exposure.

The omission of key infrastructure elements like bridges, which may influence localized flooding patterns, represents another significant limitation. Bridges and other hydraulic structures can alter flow dynamics, potentially exacerbating or mitigating flood impacts in specific areas. Future studies should aim to incorporate these elements to improve the accuracy of flood simulations and risk assessments.

To enhance the robustness of future flood risk analyses in the region, several improvements could be considered. These include the use of higher-resolution topographic data, incorporation of up-to-date land use information, and the integration of climate change projections to account for potential shifts in precipitation patterns and flood frequency. Additionally, the inclusion of socio-economic data in vulnerability assessments could provide a more comprehensive understanding of flood risk, enabling the development of targeted and equitable flood management strategies.

In conclusion, while the study provides valuable insights into flood risk in Deukhuri Valley, it also highlights the complexities and challenges associated with flood modeling and risk assessment in mountainous regions. Continuous refinement of methodologies, data sources, and modeling techniques is essential to improve the accuracy and reliability of flood risk assessments, ultimately supporting more effective flood management and resilience-building efforts in vulnerable communities.

## Conclusion

This study provides a comprehensive flood risk assessment for the West Rapti River Basin, estimating PMP (507–575 mm) and PMF (11,211.1 $m^3/s$), and mapping inundation, hazard, vulnerability, and risk. The findings highlight significant flood risks in Deukhuri Valley, with 44.0% of the inundated area at extreme hazard and 362.4 ha at high risk. These results inform flood-resilient urban planning and infrastructure design, addressing a critical gap in flood research for the region. Future studies should leverage higher-resolution data and incorporate infrastructure to enhance modeling accuracy.This study offers a thorough flood risk assessment for the West Rapti River Basin, employing advanced methodologies to estimate Probable Maximum Precipitation (PMP) and Probable Maximum Flood (PMF). The analysis reveals substantial PMP values ranging from 507 to 575 mm and a significant PMF of 11,211.1 $m^3/s$. Through detailed mapping of inundation, hazard, vulnerability, and risk, the research identifies critical areas of concern, particularly in the Deukhuri Valley. The findings indicate that 44.0% of the inundated area faces extreme hazard conditions, while 362.4 hectares are classified as high-risk zones. These results provide crucial insights for developing flood-resilient urban planning strategies and designing robust infrastructure in the region.

The comprehensive nature of this assessment addresses a significant gap in flood research for the West Rapti River Basin, offering valuable data for decision-makers and planners. By quantifying the extent and severity of potential flood impacts, the study enables more informed and targeted interventions to mitigate flood risks. However, the authors acknowledge the potential for further refinement of their approach, suggesting that future research should utilize higher-resolution data and incorporate existing infrastructure into the modeling process. These enhancements would likely improve the accuracy and granularity of flood risk predictions, allowing for even more precise and effective flood management strategies in the region.

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