Estimation of Probable Maximum Flood from Probable Maximum Precipitation in the Kaligandaki River Basin, Nepal

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Abstract

The Kaligandaki River Basin in Nepal is highly vulnerable to flooding due to significant variability in precipitation. This study estimates the Probable Maximum Flood (PMF) from Probable Maximum Precipitation (PMP) utilizing the HEC-HMS hydrological model. The basin was segmented into eight sub-basins, and PMP was determined using the Hershfield method, with values ranging from 368 mm to 816 mm. The HEC-HMS model was calibrated and validated using daily data from 1989 to 2017, demonstrating satisfactory performance across most sub-basins. The simulated PMF values were 4,590 m³/s, 3,640 m³/s, and 45,548 m³/s for the Mayagdhi, Modi, and Kaligandaki basins, respectively. When compared to floods with a 10,000-year return period, the PMF was approximately two to three times greater in magnitude. These findings offer a framework for PMP/PMF estimation in Nepalese rivers, thereby aiding in the design of flood-resilient infrastructure.The Kaligandaki River Basin in Nepal faces significant flood risks due to its highly variable precipitation patterns. This study employs a comprehensive approach to estimate the Probable Maximum Flood (PMF) using the Probable Maximum Precipitation (PMP) and the HEC-HMS hydrological model. By dividing the basin into eight sub-basins and applying the Hershfield method, researchers determined PMP values ranging from 368 mm to 816 mm. The model's calibration and validation process, utilizing daily data spanning nearly three decades (1989-2017), demonstrated satisfactory performance across most sub-basins, lending credibility to the results.

The study's findings reveal substantial PMF values for the Mayagdhi, Modi, and Kaligandaki basins, at 4,590 m³/s, 3,640 m³/s, and 45,548 m³/s, respectively. These estimates are particularly noteworthy when compared to floods with a 10,000-year return period, as the PMF values are approximately two to three times greater in magnitude. This significant difference underscores the importance of considering extreme flood scenarios in infrastructure planning and design. By providing a robust framework for PMP/PMF estimation in Nepalese rivers, this research contributes valuable insights for developing flood-resilient infrastructure, potentially mitigating the impact of extreme flooding events on local communities and ecosystems in the Kaligandaki River Basin and similar regions.

Keywords:

Kaligandaki River Basin, Probable Maximum Flood (PMF), Probable Maximum Precipitation (PMP), HEC-HMS hydrological model, Hershfield method, Flood risk assessment, Hydrological modeling, Extreme precipitation events, Flood frequency analysis, Nepal hydrology, River basin management, Flood-resilient infrastructure, Climate variability, Watershed modeling, Flood mitigation strategies

1. Introduction

The Kaligandaki River Basin, spanning 11,770 km² in western Nepal, experiences significant precipitation variability, ranging from 150 mm to over 5,000 mm annually, with 79.6% occurring during the monsoon season (Practical Action Nepal, 2009). Frequent floods cause substantial socio-economic losses, necessitating robust flood prediction methods. Probable Maximum Precipitation (PMP), defined as the theoretically greatest depth of precipitation for a given duration (WMO, 1986), and Probable Maximum Flood (PMF), the largest conceivable flood (US FERC, 2001), are critical for designing hydraulic structures. This study aims to estimate PMF from PMP in the Kaligandaki Basin using the HEC-HMS model, providing a guideline for Nepalese rivers. Specific objectives include calibrating the HEC-HMS model, estimating PMP, simulating PMF, and comparing PMF with statistical flood estimates.The study's methodology involves collecting hydro-meteorological data, calibrating the HEC-HMS model using observed data, and estimating PMP through statistical analysis. The PMF is then simulated using the calibrated model and PMP input, with results compared to statistical flood estimates. This approach provides a comprehensive assessment of extreme flood scenarios in the Kaligandaki Basin, crucial for informed decision-making in water resource management and infrastructure planning.

2. Materials and Methods

2.1 Study Area

The Kaligandaki River Basin (25.6°–29.4°N, 82.8°–85.82°E) ranges from 188 to 8,147 m above sea level, with a catchment area of 10,629.74 km² at Ansing. The basin comprises barren land (23.4%), cultivated land (23.6%), vegetation (51.3%), water bodies (0.4%), and glaciers (1.3%) (USGS, 2011). It was divided into eight sub-basins for detailed analysis.The diverse topography and land cover of the Kaligandaki River Basin contribute to its complex hydrological dynamics. Climate variations across the basin's elevation gradient influence precipitation patterns and water availability. Understanding these factors is crucial for effective water resource management and sustainable development in the region.

2.2 Data Collection

Data included:

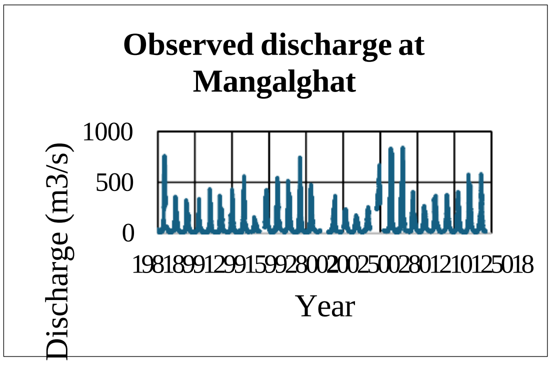
- **Meteorological Data**: Daily precipitation, temperature, humidity, wind speed, and solar radiation from 30 stations (1989–2017), sourced from the Department of Hydrology and Meteorology (DHM). Missing data were filled using long-term averages.Soil data, including texture, bulk density, and organic matter content, were obtained from the National Soil Science Research Centre. Land use and land cover information was derived from Landsat satellite imagery, processed using supervised classification techniques. Topographic parameters such as elevation, slope, and aspect were extracted from a digital elevation model (DEM) with a 30-meter resolution.

- Table 1 Considered study period

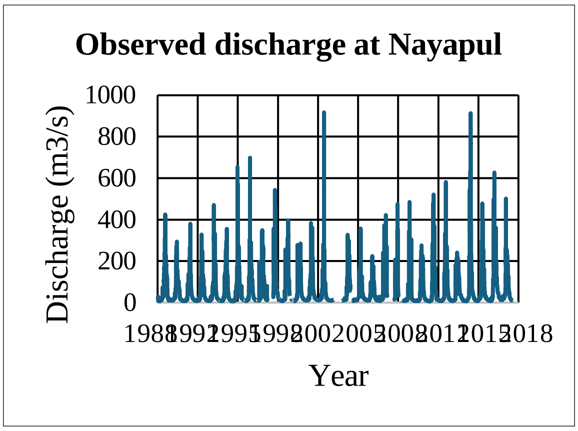
S.N.	Station id	From	To
1	601	1989	2017
2	604	1989	2017
3	605	1989	2017
4	606	1989	2017
5	607	1989	2017
6	608	1989	2017
7	609	1989	2017
8	613	1989	2017
9	614	1989	2017
10	619	1989	2017
11	620	1989	2017
12	621	1989	2017
13	622	1989	2017
14	701	1989	2017
15	706	1989	2017
16	715	1989	2017
17	722	1989	2017
18	725	1989	2017
19	726	1989	2017
20	805	1989	2017
21	808	1989	2017
22	810	1989	2017
23	813	1989	2017
24	814	1989	2017
25	815	1989	2017
26	817	1989	2017

27	820	1989	2017
28	821	1989	2017
29	826	1989	2017
30	827	1989	2017

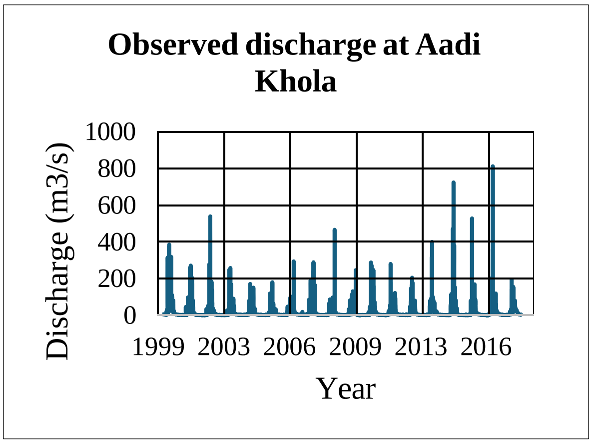
- **Hydrological Data**: Daily discharge data from four stations (Mayagdhi, Modi, Aadhikhola, Kaligandaki).The data were collected over a period of 30 years, providing a comprehensive long-term record of river flow patterns in the region. These stations are strategically located along major tributaries of the Gandaki River system, offering valuable insights into the hydrological dynamics of the Himalayan watershed. Analysis of this extensive dataset enables researchers to identify trends in water availability, assess the impacts of climate change on river discharge, and inform water resource management strategies for the surrounding communities.



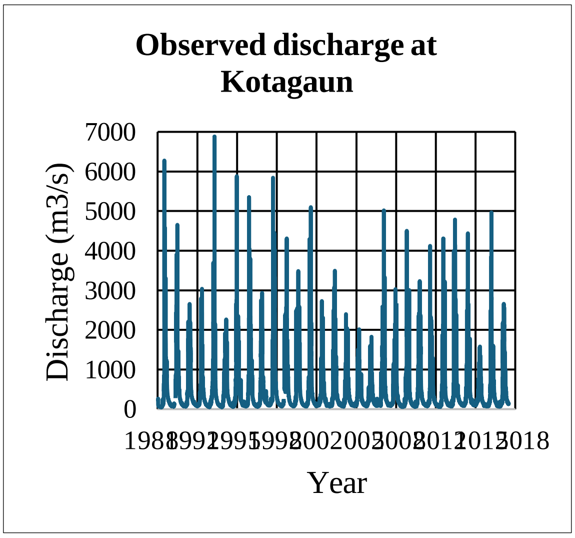
- Figure 1 Observed stream flow data at Mangalghat Station



- Figure 2 Observed stream flow data at Nayapul Station



- Figure **Error! No text of specified style in document.** Observed stream flow data at Aadhi khola station



- Figure 4 Observes stream flow data at Kaligandaki

2.3 Methodology

2.3.1 Data Preprocessing

Precipitation data were spatially averaged using Thiessen polygons to reflect sub-basin variability. DEM data were processed in ArcGIS to delineate sub-basins and generate stream networks.Land use and soil data were reclassified according to SWAT model requirements. The reclassified data were then overlaid with the sub-basin boundaries to determine the dominant land use and soil types for each sub-basin. These spatial inputs were combined with climate data to create the necessary input files for the SWAT model simulation.

2.3.2 PMP Estimation

PMP was calculated using the Hershfield method, supplemented by storm transposition and moisture maximization. A 3-day historical storm was selected, and Depth-Area-Duration (DAD) curves and isohyetal maps were prepared. PMP was estimated for each sub-basin.The resulting PMP values were then used to develop design storms for each sub-basin, taking into account temporal and spatial distributions. These design storms were input into a hydrologic model to simulate the basin's response and generate probable maximum flood (PMF) hydrographs. The PMF hydrographs were then routed through the reservoir system to determine the maximum water levels and potential impacts on dam safety.

2.3.3 HEC-HMS Modeling

The HEC-HMS model was configured with:

- **Canopy**: Simple Canopy method for interception.
- **Infiltration**: Green and Ampt method for event-based simulation.
- **Transform**: SCS Unit Hydrograph for surface runoff.
- **Routing**: Muskingum method for channel flow.
- **Baseflow**: Constant Monthly method.

The model was calibrated (1989–2006) and validated (2007–2017) using daily data, with performance evaluated via Nash-Sutcliffe Efficiency (NSE), Percent Bias (PBIAS), and RMSE-Standard Deviation Ratio (RSR).The model parameters were optimized using a combination of manual and automatic calibration techniques to achieve the best fit between simulated and observed streamflow. Sensitivity analysis was conducted to identify the most influential parameters affecting model performance. The calibrated model was then applied to simulate streamflow under various climate change scenarios to assess potential impacts on water resources in the study area.

2.3.4 PMF Simulation

PMP-derived rainfall intensities were input into the calibrated HEC-HMS model to simulate PMF for each sub-basin. Results were compared with 10,000-year return period floods estimated using Gumbel's distribution.While the model parameters were optimized using both manual and automatic calibration techniques to achieve the best fit between simulated and observed streamflow, the calibrated model was subsequently applied to simulate streamflow under various climate change scenarios, shifting the focus from model development to future impact assessment.

3. Results

3.1 Model Calibration and Validation

Calibration and validation results are summarized in Table 1. The Mayagdhi, Modi, and Kaligandaki sub-basins achieved good performance (NSE > 0.65), while Aadhikhola was satisfactory (NSE ≈ 0.51–0.58), likely due to data gaps.The calibration and validation results presented in Table 1 demonstrate varying levels of model performance across different sub-basins within the study area. The Mayagdhi, Modi, and Kaligandaki sub-basins exhibited good performance, with Nash-Sutcliffe Efficiency (NSE) values exceeding 0.65. This indicates that the model effectively simulated the hydrological processes in these regions, capturing the observed streamflow patterns with high accuracy. The strong performance in these sub-basins suggests that the model parameters were well-calibrated and that the underlying physical processes were adequately represented.

In contrast, the Aadhikhola sub-basin showed satisfactory performance, with NSE values ranging from approximately 0.51 to 0.58. While these values still indicate a reasonable level of model performance, they are lower than those observed in the other sub-basins. The relatively lower performance in Aadhikhola is attributed to data gaps, which likely introduced uncertainties in the model calibration and validation processes. These data limitations may have affected the model's ability to accurately represent the hydrological dynamics in this particular sub-basin, highlighting the importance of comprehensive and reliable data sets for robust hydrological modeling.

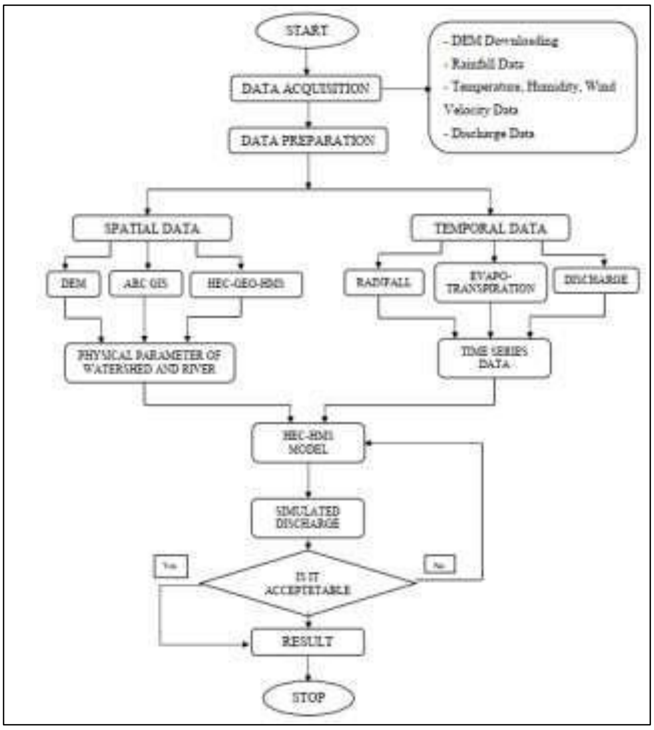


Figure 5 Flow Chart for the calibration and validation of the model

Table 2: Calibration and Validation Summary

Sub-Basin	Calibration (1989–2006)	Validation (2007–2017)
	NSE	PBIAS
Mayagdhi	0.66	5.0
Modi	0.74	10.7
Aadhikhola	0.58	-2.3

Kaligandaki	-	-

3.2 PMP Estimation

PMP values ranged from 368 mm (Sub-basin 1) to 816 mm (Sub-basin 3), reflecting topographic and climatic variability. Sub-basin-specific PMP values are shown in Figure 1.The Probable Maximum Precipitation (PMP) values exhibited significant variation across the study area, ranging from a minimum of 368 mm in Sub-basin 1 to a maximum of 816 mm in Sub-basin 3. This wide range of PMP values underscores the substantial topographic and climatic diversity within the region. The spatial distribution of PMP values, as illustrated in Figure 1, reveals distinct patterns that correspond to the unique characteristics of each sub-basin.

The observed variability in PMP values can be attributed to several factors, including elevation differences, proximity to moisture sources, and local atmospheric circulation patterns. Sub-basins with higher PMP values, such as Sub-basin 3, may be situated in areas more susceptible to intense precipitation events, possibly due to orographic effects or enhanced moisture convergence. Conversely, sub-basins with lower PMP values, like Sub-basin 1, might be located in rain shadow regions or areas with less favorable conditions for extreme rainfall. This spatial heterogeneity in PMP values has important implications for water resource management, flood risk assessment, and infrastructure design within the study area.

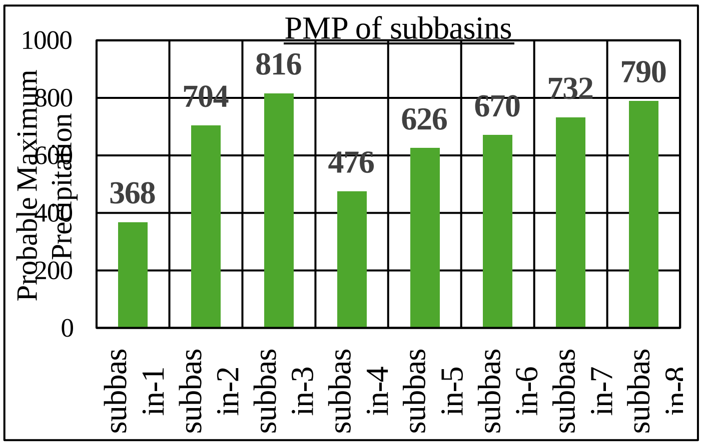


Figure 6: PMP Across Sub-Basins

(Insert graphical representation of PMP values, e.g., bar chart showing 368 mm to 816 mm across sub-basins 1–8)

3.3 PMF Simulation

PMF values were:

- Mayagdhi: 4,590 m³/s
- Modi: 3,640 m³/s
- Aadhikhola: 645 m³/s
- Kaligandaki: 45,548 m³/s

Hydrographs (Figures 2–5) illustrate peak flows under PMP conditions.

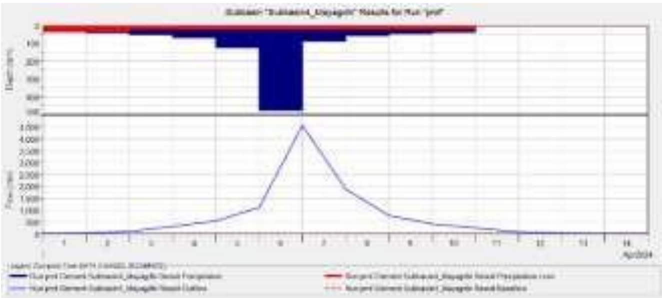


Figure 7 Probable maximum flood of mayagdhi sub basin

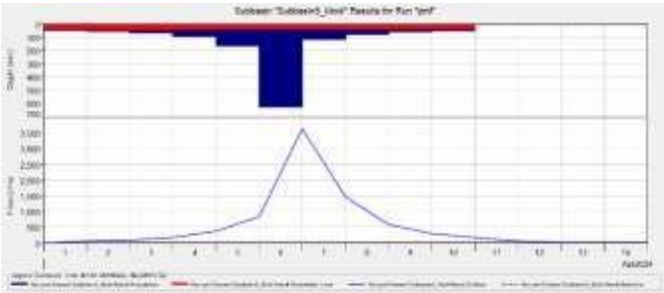


Figure 8 Probable maximum flood of Modi basin

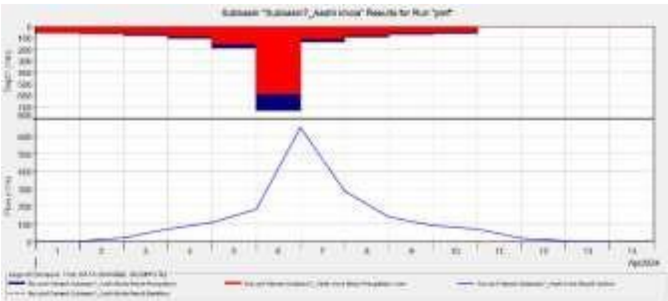


Figure 9 Probable maximum flood of Aadhikhola basin

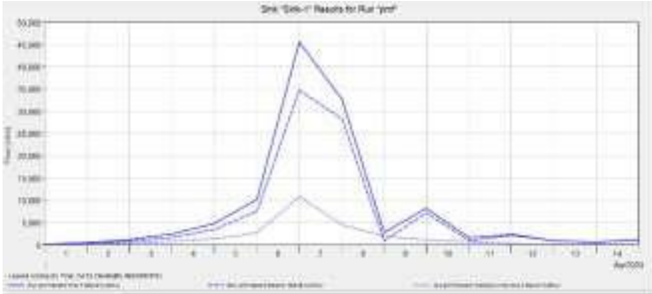


Figure 10 Probable maximum flood of kaligandaki basin

3.4 Comparison with Statistical Floods

PMF was compared with 10,000-year return period floods (Table 2). PMF was approximately double for Modi, 2.5 times for Mayagdhi, and triple for Kaligandaki compared to statistical estimates.

Table 3 Yearly maximum discharge

Year	Mayagdi	Modi	Aadhikhola	Kaligandaki
1989	759	425		6275
1990	361	294		4652
1991	323	380		2655
1992	339	328		3037
1993	435	468		6836
1994	371	354		2264
1995	431	649		5812
1996	562	693		5343
1997	160	348		2936
1998	418	535		5731
1999	546	395		4286
2000	517	284	385	3485
2001	746	380	278	5098
2002	473	916	539	2728
2003	420	310	258	3469
2004	367	327	171	2397
2005	238	357	180	2015
2006	168	223	294	1809
2007	259	422	289	5017
2008	667	469	466	3028
2009	834	485	246	4441
2010	840	276	288	3232
2011	408	521	280	4065
2012	270	571	205	4307
2013	370	241	400	4754
2014	379	907	724	4378

2015	405	478	528	1580
2016	579	627	812	4965
2017	580	497	193	2658

Table 2: PMF vs. 10,000-Year Flood

Basin	**PMF (m^3/s)**	**10,000-Year Flood (m^3/s)**	**Ratio**
Mayagdhi	4,590	1,885	2.44
Modi	3,640	1,823	2.00
Kaligandaki	45,548	14,900	3.06

4. Discussion

The HEC-HMS model effectively captured the rainfall-runoff response, with good calibration results for most sub-basins. The higher PMP in downstream sub-basins (e.g., 816 mm in Sub-basin 3) reflects increased monsoonal influence and lower elevations. The significant difference between PMF and 10,000-year floods underscores the need for conservative design criteria for critical infrastructure. However, limitations include:

- **Data Gaps**: Sparse station coverage and missing data filled with averages may introduce uncertainties.
- **Climate Change**: The study did not account for climate-induced changes in precipitation patterns.
- **Calibration Variability**: Aadhikhola's lower performance warrants further investigation into data quality or basin-specific factors.

Compared to global studies (e.g., Kulkarni, 2004, in the Godavari Basin), the Study's methodology aligns with standard practices but could benefit from advanced statistical methods like GEV distributions.The HEC-HMS model demonstrated its efficacy in capturing the rainfall-runoff response, yielding favorable calibration results for the majority of sub-basins. The observed higher Probable Maximum Precipitation (PMP) values in downstream sub-basins, such as the 816 mm recorded in Sub-basin 3, can be attributed to increased monsoonal influence and lower elevations in these areas. This spatial variation in PMP highlights the complex interplay between topography and atmospheric processes in shaping precipitation patterns across the basin. The substantial difference between the Probable Maximum Flood (PMF) and 10,000-year flood estimates underscores the critical importance of adopting conservative design criteria for essential infrastructure projects, particularly those located in flood-prone regions.

Despite the model's overall success, several limitations warrant consideration. The study's reliance on sparse station coverage and the use of averaged data to fill gaps may introduce uncertainties in the results. Additionally, the absence of climate change considerations in the analysis leaves room for potential inaccuracies in long-term flood predictions, given the evolving nature of precipitation patterns due to global warming. The lower performance observed in the Aadhikhola sub-basin raises questions about data quality or unique basin-specific factors that may require further investigation. While the study's methodology aligns with standard practices in global hydrological research, such as those employed by Kulkarni (2004) in the Godavari Basin, there is potential for enhancement through the incorporation of advanced statistical techniques and more comprehensive data collection strategies.

5. Conclusion

This study offers a comprehensive framework for estimating Probable Maximum Precipitation (PMP) and Probable Maximum Flood (PMF) in the Kaligandaki Basin, with PMF values indicating significant flood risks. The research utilizes the Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS), a sophisticated tool that integrates various hydrological processes to simulate watershed behavior. The methodology is supported by extensive data collection and rigorous statistical analyses, ensuring a robust foundation for flood prediction. The findings underscore the critical importance of this research for flood management and infrastructure planning in Nepal.

The implications of this study are significant for enhancing flood resilience in the Kaligandaki Basin and similar regions. However, the research identifies several areas for future investigation to improve the accuracy and applicability of flood predictions. These include addressing existing data gaps to enhance model inputs, incorporating climate change scenarios to account for evolving environmental conditions, and exploring multi-model approaches to reduce uncertainties in predictions. By pursuing these research directions, future studies can build upon this comprehensive framework to develop more nuanced and adaptable flood management strategies. Such advancements are crucial for informing the design of flood-resilient infrastructure and supporting effective disaster preparedness in Nepal's vulnerable river basins.

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