A Review of Advances in Probable Maximum Precipitation and Flood Estimation in the Kaligandaki Basin, Nepal

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Abstract

The Kaligandaki River Basin in Nepal, a region characterized by extreme precipitation variability and frequent flooding, has been the focus of recent hydrological studies to estimate Probable Maximum Precipitation (PMP) and Probable Maximum Flood (PMF). This review synthesizes the methodologies, findings, and challenges of a pivotal study that employed the HEC-HMS model to estimate PMF from PMP in the Kaligandaki Basin. The study's approach, which integrates hydro-meteorological data, statistical methods, and hydrological modeling, is evaluated in the context of global PMP/PMF estimation practices. Key strengths include robust data utilization and sub-basin-specific analysis, while limitations, such as sparse data networks and the omission of climate change impacts, are highlighted. Recommendations for advancing PMP/PMF research in data-scarce, topographically complex regions, such as Nepal, are provided, emphasizing the need for enhanced data collection, multi-model approaches, and climate-resilient methodologies.The Kaligandaki River Basin study represents a significant advancement in hydrological research for Nepal's complex terrain. By employing the HEC-HMS model to estimate Probable Maximum Flood (PMF) from Probable Maximum Precipitation (PMP), the research provides crucial insights into extreme flood scenarios in a region prone to hydrological extremes. The methodology's strength lies in its comprehensive approach, integrating diverse hydro-meteorological data and statistical methods to produce sub-basin-specific analyses. This granular approach allows for a more nuanced understanding of flood risks across the basin's varied topography.

However, the study faces notable challenges inherent to its geographical context. The sparse data networks in Nepal limit the accuracy and spatial resolution of the analysis, potentially affecting the reliability of PMP and PMF estimates. Additionally, the omission of climate change impacts in the modeling process represents a significant gap, given the increasing influence of global warming on precipitation patterns and flood frequencies. To address these limitations and enhance future research, there is a pressing need for improved data collection infrastructure, the adoption of multi-model approaches to reduce uncertainty, and the integration of climate change projections into PMP/PMF estimations. These advancements would not only improve the accuracy of flood risk assessments but also contribute to more effective flood management and climate adaptation strategies in the Kaligandaki Basin and similar data-scarce, topographically complex regions worldwide.

Keywords:

Kaligandaki River Basin, Probable Maximum Precipitation (PMP), Probable Maximum Flood (PMF), HEC-HMS model, Hydrological modeling, Flood risk assessment, Nepal hydrology, Extreme precipitation, Data-scarce regions, Climate change impacts, Topographically complex terrain

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1. Introduction

Floods pose significant risks to human life, infrastructure, and economies in Nepal, particularly in the Kaligandaki River Basin, where the annual precipitation varies from less than 150 mm to over 5,000 mm. The estimation of Probable Maximum Flood (PMF), derived from Probable Maximum Precipitation (PMP), is critical for designing resilient hydraulic structures such as dams and spillways. PMP is defined as the theoretically greatest depth of precipitation possible for a given duration and area (WMO, 1986), while PMF represents the largest conceivable flood under extreme meteorological and hydrological conditions (US FERC, 2001). A recent study (referred to hereafter as "the Study") investigated PMP and PMF in the Kaligandaki Basin using the HEC-HMS model, providing guidelines for Nepalese rivers. This review article evaluates the study's methodologies, results, and implications, situating it within the broader context of PMP/PMF estimation, and offers insights for future research.The Study's findings have significant implications for flood risk management and infrastructure planning in Nepal. By providing a comprehensive analysis of PMP and PMF in the Kaligandaki Basin, it offers valuable insights for policymakers and engineers working on flood mitigation strategies. However, the study's limitations, such as data scarcity and potential uncertainties in climate change projections, highlight the need for continued research and refinement of PMP/PMF estimation techniques in the region.

2. Overview of the Study

The Study focused on the Kaligandaki River Basin, which spans 11,770 km² and ranges from 188 to 8,147 m above sea level. The basin was divided into eight sub-basins to capture spatial variability in precipitation and runoff. The main objectives of this study were as follows.

- Calibrate and validate the HEC-HMS model using hydrological and meteorological data.
- Estimating PMP using statistical and hydrometeorological methods.
- Simulate the PMF through rainfall-runoff modeling.
- Comparison of PMF with floods derived from statistical return periods.

The Study utilized data from 30 meteorological stations (1989–2017), a 90m-resolution Digital Elevation Model (DEM), and discharge data from four stations. The HEC-HMS model was employed for hydrological simulations, with the PMP calculated using the Hershfield method and validated using storm transposition techniques.

Methodology

The general methodology of the project is illustrated in Figure Error! **No text of specified style in document.**-1.

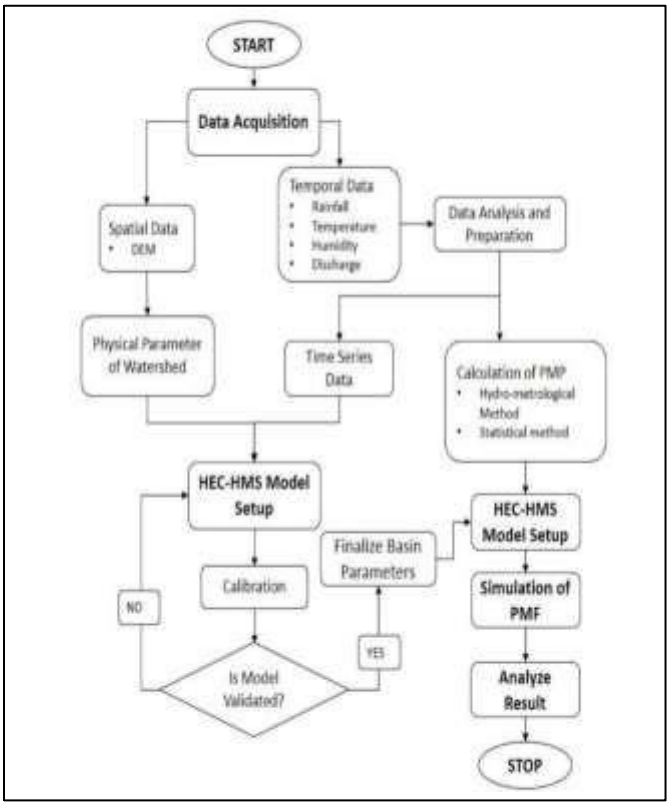

Figure **Error! No text of specified style in document.**-1General Methodological Flow Chart

The hydrological, meteorological, and climatic data required were collected from the Department of Hydrology and Meteorology. Thus, the obtained data contained some missing data. These missing precipitation data were filled using the average of the nearest stations, whereas hydrological data were not filled. The required Digital Elevation Module (DEM) is downloaded from the Alaska Satellite Facility.

Processed data from the Department of Hydrology and Meteorology were obtained from 30 different stations. The precipitation data for each sub-basin were prepared using the Thiesson polygon method. The next important step was the preparation of the geometric file for Arc-Gis and HEC-HMS. The prepared terrain data in the Arc-Gis are fed to the HEC-HMS and then used in the HEC-HMS, which is characterized by eight different sub-basins. The HEC-HMS model was then calibrated using observed streamflow data to ensure accurate representation of the basin's hydrological processes. Sensitivity analysis was performed to identify the most influential parameters affecting the model's performance. Finally, the calibrated model was validated using an independent set of data to assess its predictive capabilities and reliability for future hydrological simulations in the study area.

3. Methodological Advances

3.1 Data Collection and Preprocessing

This Study's use of extensive meteorological data, including daily precipitation, temperature, humidity, wind speed, and solar radiation, is significant. The application of Thiessen polygons to spatially averaged precipitation data across sub-basins ensured a robust input for the HEC-HMS model. The DEM, sourced from the USGS, facilitates accurate catchment delineation and stream network generation, which is critical for modeling complex topographies.

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

S.N.	Data	Description	Sources
1.	Precipitation	Daily precipitation data of different hydrological stations	DHM
2.	Climatic data	Temperature, Humidity, Sunshine hours, Wind speed	DHM
3.	Discharge data	Daily discharge data of Kaligandaki	DHM
4.	DEM	12.5m X 12.5m resolution	Alaska Satellite Facility

3.2 Hydrological Modeling with HEC-HMS

The HEC-HMS model, a widely used tool for precipitation-runoff simulation, was effectively employed to simulate rainfall-runoff responses. The model parameters, including canopy storage, infiltration (Green and Ampt), and unit hydrograph (SCS), were calibrated and validated using daily data from 1989 to 2017. The Study's multi-site calibration at four stations (Mayagdhi, Modi, Aadhikhola, and Kaligandaki) enhanced the model's reliability, with performance metrics (Nash-Sutcliffe Efficiency, Percent Bias) indicating good to satisfactory results.

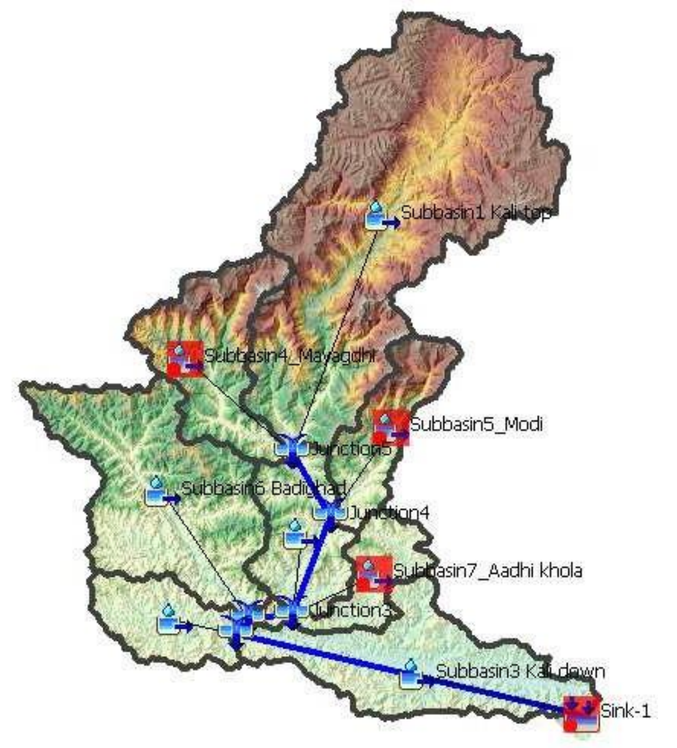

Figure **Error! No text of specified style in document.**-2
Subbasin of kaligandaki basin

Table **Error! No text of specified style in document.**-2 Considered stations and station id

Station Name	**Stati on id**	**latitude**	**longitude**	**Elevation**	**Annual Rain**	**Monsoon Rain**
JOMSOM	601	28.78333	83.71667	2744	263	136
THAKMARPHA	604	28.75	83.7	2566	387	223
BAGLUNG	605	28.26667	83.6	984	1842	1494
TATOPANI	606	28.48333	83.65	1243	1523	1126
LETE	607	28.63333	83.6	2384	1213	744
RANIPAUWA	608	28.81667	83.88333	3609	336	248
BENI BAZAR	609	28.35	83.56667	835	1503	1205
KARKI NETA	613	28.18333	83.75	1720	2474	2031
KUSHMA	614	28.21667	83.7	891	2382	1964
GHOREPANI	619	28.4	83.73333	2742	2772	2289
TRIBENI	620	28.03333	83.65	700	2125	1788
DARBANG	621	28.38333	83.4	1160	1630	1295
RANGKHANI	622	28.15	83.56667	1740	3443	2886
RIDI BAZAR	701	27.95	83.43333	442	1422	1146
DUMKAULI	706	27.68333	84.21667	154	2268	1896
KHANCHIKOT	715	27.93333	83.15	1760	1810	1469
MUSIKOT	722	28.16667	83.26667	1280	1891	1528
TAMGHAS	725	28.06667	83.25	1530	1889	1523
GARAKOT	726	27.86667	83.8	500	1891	1503
SYANGJA	805	28.1	83.88333	868	2850	2250
BANDIPUR	808	27.93333	84.41666	965	1853	1404
CHAPKOT	810	27.88333	83.81667	460	1828	1459

BHADAURE DEURALI	813	28.26667	83.81667	1600	3949	3250
LUMLE	814	28.3	83.8	1740	5284	4493
KHAIRINI TAR	815	28.03333	84.1	500	2286	1692
DAMAULI	817	27.96667	84.28333	358	1718	1241
MANANG BHOT	820	28.66667	84.01667	3420	441	238
GHANDRUK	821	28.38333	83.8	1960	3281	2673
WALLING	826	27.98333	83.76667	750	2120	1736
RUMJAKOT	827	27.86667	84.13333	660	1573	1197

3.3 PMP Estimation

The PMP was estimated using the Hershfield statistical method, complemented by storm transposition and moisture maximization techniques. The Study calculated PMP values ranging from 368 mm to 816 mm across the sub-basins, reflecting the basin's climatic heterogeneity. The use of depth-area-duration (DAD) curves and isohyetal maps aligned with the WMO guidelines ensures methodological consistency with global standards.

3.4 PMF Simulation and Comparison

The HEC-HMS model simulated PMF values of 4,590 m^3/s, 3,640 m^3/s, and 45,548 m^3/s for the Mayagdhi, Modi, and Kaligandaki basins, respectively. A comparative analysis of 10,000-year return period floods (derived using Gumbel's distribution) revealed that the PMF was approximately double to triple the statistical flood estimates, underscoring the severity of extreme events.

4. Strengths and Contributions

The strengths of this Study are its comprehensive data utilization, rigorous calibration, and sub-basin-specific analysis. Integrating statistical and hydrometeorological approaches provides a robust framework for PMP/PMF estimation in data-scarce regions. A comparison with statistical flood estimates offers practical insights into infrastructure design, particularly for sizing spillways and reservoirs. The Study guidelines for Nepalese rivers address a critical gap in regional flood management, where sparse data and rugged terrain pose significant challenges.The findings of this Study have significant implications for flood risk management and infrastructure planning in Nepal. By providing a reliable methodology for estimating extreme flood events, it enables policymakers and engineers to make more informed decisions about flood protection measures and dam safety. Furthermore, the Study's approach could potentially be adapted and applied to other mountainous regions with similar data limitations, contributing to improved flood risk assessment on a broader scale.

5. Limitations and Challenges

5.1 Data Constraints

The dependence on a limited number of meteorological stations and the utilization of long-term averages to compensate for missing data introduce uncertainties. The sparse coverage of stations in high-altitude sub-basins may lead to an underestimation of precipitation extremes.

5.2 Exclusion of Climate Change

The omission of climate change impacts in the study represents a significant limitation, particularly given the increasing intensity of monsoonal rainfall in the Himalayas. Climate models project heightened flood risks, which could influence the estimates of Probable Maximum Precipitation (PMP) and Probable Maximum Flood (PMF).

5.3 Calibration Variability

The satisfactory calibration performance of the Aadhikhola sub-basin, in contrast to the good performance of other sub-basins, suggests potential issues with data quality or model parameterization. This study did not thoroughly investigate these discrepancies.

5.4 Limited Statistical Methods

While the reliance on the Hershfield method and Gumbel's distribution is effective, it could be complemented by other distributions, such as the Generalized Extreme Value distribution, to enhance robustness.

5.5 Uncertainty Quantification

The study lacks a comprehensive uncertainty analysis, which is critical for PMP/PMF estimates given the inherent variability in hydrological models and data inputs.

6. Comparison with Global Practices

Globally, PMP/PMF estimation employs a range of methods, including local storm maximization, storm transposition, and generalized approaches (WMO, 2009). The Study's use of the Hershfield method aligns with practices in regions like the United States and Malaysia, where statistical methods are favored for their simplicity. However, advanced techniques, such as ensemble modeling or machine learning for precipitation forecasting, are increasingly adopted in data-rich regions. The Study's hydro-meteorological approach, while robust, could benefit from these emerging methodologies.

7. Recommendations for Future Research

1. **Enhanced Data Networks**: Deploying additional meteorological stations or leveraging satellite-based precipitation data (e.g., TRMM, GPM) could improve data coverage and reduce reliance on interpolation.
2. **Climate Change Integration**: Incorporating regional climate model projections (e.g., CORDEX-South Asia) would enhance the Study's relevance in a warming climate.
3. **Multi-Model Approaches**: Comparing HEC-HMS with other models (e.g., SWAT, VIC) could validate results and highlight model-specific biases.
4. **Advanced Statistical Methods**: Employing distributions like GEV or Generalized Gamma for frequency analysis could provide a more comprehensive assessment of extreme events.
5. **Uncertainty Analysis**: Sensitivity analysis or Monte Carlo simulations should be used to quantify uncertainties in model parameters and PMP/PMF estimates.
6. **Stakeholder Engagement**: Collaborating with local authorities and communities could ensure that the guideline is practical and implementable for flood management.

8. Conclusion

The Study on PMP and PMF estimation in the Kaligandaki Basin represents a significant advancement in flood hydrology for Nepal. Its robust methodology and practical guideline address critical needs in a flood-prone region. However, limitations such as data constraints and the exclusion of climate change necessitate further research. By integrating advanced data sources, multi-model approaches, and climate-resilient methodologies, future studies can build on this foundation to enhance flood prediction and infrastructure resilience in Nepal and similar regions.The Study on PMP and PMF estimation in the Kaligandaki Basin marks a crucial step forward in Nepal's flood hydrology research. By employing a comprehensive methodology and providing practical guidelines, it addresses the pressing need for accurate flood prediction in a region highly susceptible to such events. The study's significance lies not only in its immediate applications for flood management but also in establishing a foundation for future research and policy-making in Nepal's water resource sector. The robust approach used in this study can potentially inform similar efforts in other flood-prone regions, contributing to a broader understanding of extreme precipitation events and their hydrological impacts.

Despite its notable contributions, the study acknowledges certain limitations that open avenues for further research. The constraints in data availability and the exclusion of climate change considerations highlight the need for more comprehensive approaches in future studies. To build upon this foundation, subsequent research could focus on integrating advanced data sources such as high-resolution satellite imagery and radar data to improve spatial and temporal coverage. Additionally, incorporating multi-model approaches and ensemble forecasting techniques could enhance the reliability of predictions. Future studies should also prioritize the inclusion of climate change scenarios to ensure that flood estimation methodologies remain relevant and effective in the face of evolving environmental conditions. By addressing these aspects, researchers can further refine flood prediction capabilities and contribute to the development of more resilient infrastructure and effective flood management strategies in Nepal and similar regions.

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