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Applicability of CHIRPS Satellite Precipitation in Hydrological Modeling of the Poorly Gauged Himalayan Basin: A Case Study of Sunkoshi Basin, Nepal

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Abstract

This study evaluates the applicability of the CHIRPS Satellite Precipitation Products (SPPs) for runoff simulation in the ungauged Sunkoshi Basin, Nepal. Limited studies have assessed the performance of CHIRPS SPPs in this region, leaving their potential largely underexplored. Given that most of Nepal's river basins remain ungauged due to extreme terrain and climatic conditions, hydrological modeling plays a crucial role in water resources management. A HEC-HMS model was calibrated (1997-2010) and validated (2014-2018) at the Hampachuwar outlet using observed DHM precipitation and discharge data. Runoff simulations using CHIRPS as input achieved good performance, with NSE score of 0.753 and R^2 of 0.771 during calibration, and NSE score of 0.814 and R^2 of 0.798 during validation, while PBIAS score of 4.3% and -10.5% for calibration and validation respectively. These results demonstrate that CHIRPS precipitation provides reliable estimates for hydrological modeling, indicating its suitability for application in ungauged or poorly gauged basins of Nepal for improved water resources management and flood risk assessment.

Keywords: HEC-HMS, Satellite Precipitation Products (SPPs), CHIRPS, Himalayan Basin, Sunkoshi Basin

1. Introduction

1.1 Background

The diverse physiography of Nepal, spanning from the soaring Himalayan ranges to the flat Terai plains, strongly governs the nation's water resources (Nepal et al. 2021). The steep Himalayan River basins provide substantial hydropower opportunities, driven by their elevation yet constrained by marked spatio-temporal rainfall variability and complex geological conditions (Tuladhar et al. 2020). The combination of rugged landscapes, challenging geology, and remote locations limits the development of dense and representative rainfall monitoring networks (Diodato et al., 2010). Under these circumstances, rainfall-runoff modeling becomes an essential approach for efficient water resource planning, hydropower development, and flood hazard mitigation (Gautam 2025).

Precipitation is a key driver of the hydrological cycle, supporting both ecosystems and human needs, while extreme or high-intensity rainfall often triggers floods, landslides, debris flows, and soil erosion(Hamal et al., 2020). Continuous monitoring of precipitation with high spatial and temporal resolution is essential for accurate forecasting and early warning (Fuentes, Reich, and Lee 2008). Yet, addressing the spatial and temporal variations of precipitation in mountainous areas is highly challenging because of the complex terrain, further compounded by technological constraints and economic limitations (Nakagawa, et al., 2021). Given these challenges, rainfall-runoff modeling plays a crucial role in converting rainfall data into streamflow estimates, supporting better water management, hydropower development, and flood risk reduction in mountainous regions with limited data (Shrestha and Tamrakar 2013).

Accurate rainfall-runoff modeling is crucial for managing water resources, hydropower planning, and mitigating flood risks (Ceola et al. 2016). However, the effectiveness of hydrological simulations, such as those using the Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) model, is heavily dependent on the

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availability of high-quality precipitation and discharge data. Hydrological models, such as HEC-HMS, simulate rainfall-runoff processes and provide decision-makers with tools for sustainable planning and infrastructure design (Vaze et al., 2011). The planning and design of bridges, dams, and hydropower projects require a robust understanding of basin hydrology, specifically the magnitude and variability of water availability across seasons and extremes, to ensure safety, efficiency, and sustainability (Paudel, Basnet, and Sherchan 2019). In remote, high-relief regions like the Mountainous River Basin, where ground-based rainfall observations are often sparse, inconsistent, or absent due to difficult terrain and inaccessibility, this lack of data introduces significant uncertainties in runoff estimation and model calibration (Duwal et al. 2023). To overcome these limitations, satellite-based precipitation products offer a valuable alternative by providing spatially continuous rainfall estimates across remote and ungauged regions, thereby improving runoff simulation and hydrological model performance (Aryal et al. 2023).

Satellite Based Precipitation Products (SPPs) such as Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) provide long-term, spatially continuous, high-resolution rainfall estimates, making them valuable where gauges are limited (Funk et al. 2015). In Nepal, Tropical Rainfall Measuring Mission (TRMM) has been identified as a comparatively reliable source in the mountainous basin like Karnali Basin (Khatakho, Talchabhadel, and Thapa 2021). In the West Rapti River Basin, TRMM demonstrated superior performance compared to Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN) and Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks-Cloud Classification System (PERSIANN-CCS) in capturing the magnitude of extreme precipitation events (Talchabhadel, Aryal, et al. 2021). CHIRPS has been reported to outperform European Centre for Medium-Range Weather Forecasts Reanalysis v5 (ERA5) and Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks–Climate Data Record (PERSIANN-CDR) in capturing rainfall events in eastern Nepal (Subba et al. 2024). CHIRPS has a spatial resolution of 5 Km, and it would be helpful to evaluate the use of CHIRPS products in hydrologic modeling and water resources planning, management, and decisions. Satisfactory monthly performance of CHIRPS over three decades in the Koshi Basin (Shrestha et al. 2017). While CHIRPS has been used successfully in various parts of the world, its performance in mountainous and data-scarce basins remains underexplored, especially for operational use in flood modeling and hydropower planning.

Nepal's abundant water resources remain largely underutilized for critical purposes such as hydropower generation, irrigation expansion, and drinking water supply (Subedi, Karki, and Panday 2020). Reliable estimation of water resource potential is therefore essential, as the performance and safety of hydraulic infrastructure depend heavily on accurate basin-scale hydrological assessment and parameterization (Bhattarai et al. 2024). Hydrological modeling has become an indispensable tool for simulating runoff, assessing water availability, and guiding planning and design (Dutta and Sarma 2021). Hydrological model outputs, such as hydrographs, can be applied directly or integrated with other software tools to analyze flood risks, assess water availability, plan reservoir operations, and support integrated water resources management in large river basins (Khadka and Bhaukajee 2018). A suitable hydrologic model can be developed, calibrated, and validated using observed rainfall-runoff data from a gauged basin. Once calibrated, such a model can then be driven by SPPs, like CHIRPS, to evaluate runoff in ungauged basins, where ground observations are limited or absent (Subba et al. 2024). This approach holds particular promise in Nepal's mountainous terrain, where steep topography, sparse gauge networks, and limited accessibility constrain reliable hydrological analysis, posing challenges for hydropower planning, irrigation development, and flood management. Despite the proven utility of CHIRPS in other basins, its operational performance for continuous daily runoff simulation and peak flow estimation in high-altitude, topographically complex basins like the Sunkoshi remains critically under-assessed.

To address this critical research gap, the present study develops and calibrates a HEC-HMS hydrological model using observed Department of Hydrology and Meteorology (DHM) precipitation and discharge data, and for the first time applies CHIRPS precipitation inputs to simulate runoff for the mountainous basin. We hypothesize that CHIRPS, with its high spatial resolution, can effectively drive a calibrated HEC-HMS model to simulate daily and peak flows in the Sunkoshi Basin with an accuracy suitable for water resources planning, hydropower design, irrigation management, and flood risk mitigation where ground observations are scarce.

The objective of this study is to evaluate the applicability of CHIRPS precipitation datasets for runoff simulation in the Sunkoshi River Basin (SRB). To achieve this, the HEC-HMS hydrological model was calibrated and validated using observed precipitation data from the DHM, and its performance was assessed using CHIRPS-based precipitation inputs.

1.2 Study Area

The Sunkoshi River, originating from the Himalayas, is a major tributary of the Saptakoshi River in eastern Nepal. Flowing generally from northwest to southeast, it joins the Arun and Tamor rivers at Tribeni in Sunsari District to form the Saptakoshi, which comprises seven major tributaries (Kafle 2019). The basin lies between latitudes 26°50′-28°31′ N and longitudes 85°22′-87°09′ E and extends into Tibet, making it a transboundary watershed. The Sunkoshi Basin spans an extensive elevation range, from about 104 m above sea level in the southern lowlands to nearly 8,782 m in the northern high Himalayas. This pronounced altitudinal variation gives rise to distinct climatic zones, ranging from subtropical conditions in the lower valleys to alpine and tundra climates at higher elevations. Correspondingly, the basin's hydrological regime reflects this diversity, with streamflow sustained not only by seasonal rainfall but also by significant inputs from snowmelt and glacier melt, a defining characteristic of Himalayan River systems. The SRB is critical for hydropower generation and irrigation, with infrastructure such as the Sunkoshi-Marin Diversion Multipurpose Project (SMDMP) diverting water for energy production and agricultural use. The total catchment area of the Sunkoshi River Basin at the confluence with the Koshi River is 18,142.11 km^2. Figure 1 shows the study area of this study.

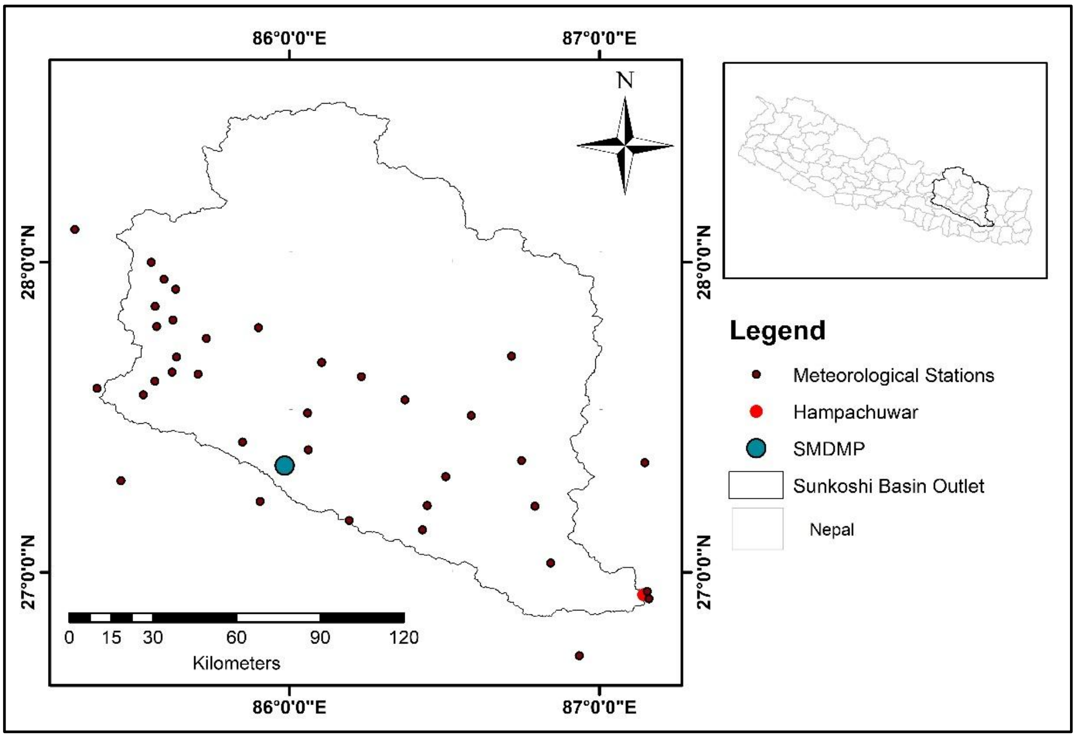

Figure 1. Location of Sunkoshi River Basin

2. Materials and Methods

2.1 Material and Data

The following section describes the datasets and methods employed to evaluate precipitation products and their application in hydrological modeling. Data required for hydrologic modeling by HEC-HMS in this study area are:

- Digital Elevation Model
- Climate Data
- CHIRPS Precipitation Datasets
- Discharge Data
- Land Use Land Cover map

2.1.1 Digital Elevation Model (DEM)

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) Version 3, with a 30 m spatial resolution, was employed with the data produced by the Sensor Information Laboratory Corporation, Tokyo, and projected to the World Geodetic System 1984 (WGS 84) Universal Transverse Mercator (UTM) Zone 45 N coordinate system to ensure spatial consistency for hydrological analyses. The DEM of study area is shown in Figure 2.

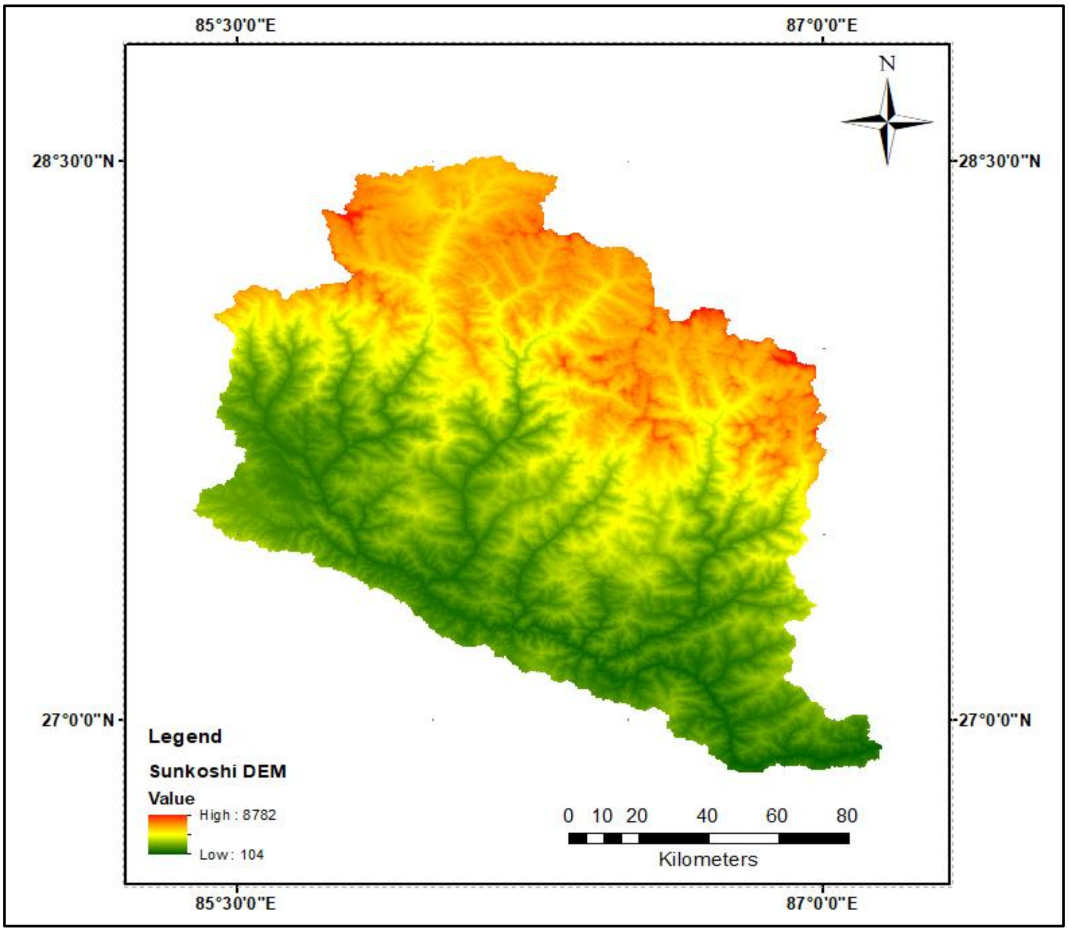

Figure 2. DEM of Sunkoshi River Basin

2.1.2 Precipitation Data

The precipitation data were collected from the DHM from 1997 to 2018. The meteorological stations used in this study is given in

Table 1.

Table 1. Meteorological Station

Station No.	Name	Station No.	Name
1212	Phattepur	1204	Aiselukharak
1009	Chautara	1211	Khotang Bazar
1008	Nawalpur	1219	Salleri
1055	Dhunche	1224	Siruwa
1206	Okhaldhunga	1023	Dolalghat
1210	Kurle Ghat	1024	Dhulikhel
1309	Tribeni	1027	Bahrabise
1325	Dingla	1036	Panchkhal
1207	Mane Bhanjyang	1101	Nagdaha

Station No.	**Name**	**Station No.**	**Name**
1104	Melung	1107	Sindhuli Madhi
1016	Sarmathang	1108	Bahun Tilpung
1017	Duwachaur	1123	Manthali
1018	Baunepati	1115	Nepalthok
1058	Tarke Ghyang	1022	Godavari
1103	Jiri	1222	Diktel
1025	Dhap	1322	Machhuwaghat
1049	Khopasi (Panauti)	1020	Mandan
1117	Hariharpurgadhi Valley	1202	Chaurikhark

The daily rainfall of each sub-basin was computed using the Thiessen Polygon method. There were some missing rainfall data in different rainfall station. So, Inverse distance square method was used to infill missing data due to its simplicity and effectiveness for this region.

2.1.3 Discharge Data

The hydrological daily data were collected from the DHM from 1997 to 2018. The hydrological stations used in study of this research is given in

Table 2.

Table 2. Hydrological Station

Station No.	**Name**	**Basin**
681	Hampachuwar	Sunkoshi

2.1.4 CHIRPS Datasets

The CHIRPS Version 2.0 daily precipitation datasets, with a spatial resolution of 0.05° (~5 km) were obtained for each sub-basin of the SRB for the period 1997-2018. The data were accessed through both the Google Earth Engine and Climate Engine platforms.

2.1.5 LULC Map

Land use map for SRB was downloaded from International Centre for Integrated Mountain Development (ICIMOD). As from the figure it is clear that Sunkoshi basin is divided into 9 categories as forest, shrubland, grassland, agricultural land (kharif), agricultural land (rabi), barren area, built-up area, water bodies and snow/glaciers. The basin is dominated by agricultural lands and forests. The Land use map of SRB is shown in figure 3.

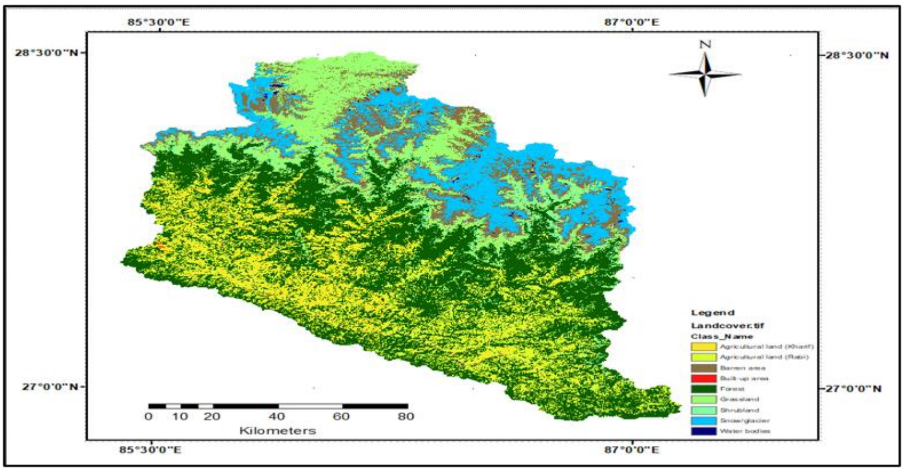

Figure 3. Land use map of Sunkoshi River Basin

2.2 Model Setup

For the prediction of runoff, the HEC-HMS model was used, which is a semi-distributed model. The model has four main components, namely Basin model manager, Meteorological model manager, Control specification manager and time-series data manager. A basin was created in basin model manager with 15 sub-basins. With time series data of daily rainfall and average monthly evapotranspiration, a meteorological model was prepared. Similarly, time series data was filled in the time series data manager. Moreover, the calibration period (1997-2010) and validation period (2014-2018) were specified using the control specification manager. The data from 2011 to 2013 were not available, so we choose the calibration and validation periods as mentioned above. The Basin model, for instance, contains the hydrologic element and their connectivity that represent the movement of water through the drainage system. The flowchart of the study is shown in figure 4.

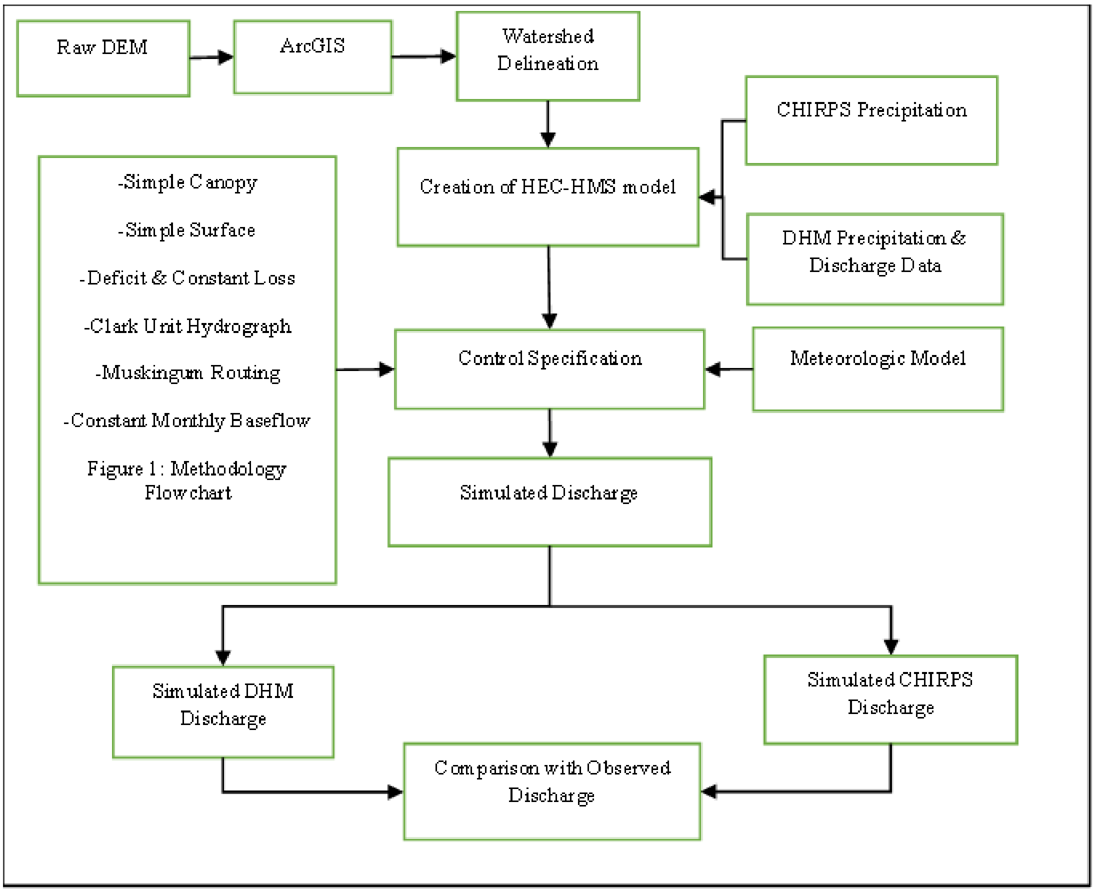

Figure 4. Methodology Flowchart

Topographic (DEM), land use, soil cover, and precipitation data were acquired from multiple sources. The DEM was processed in the ArcGIS based HEC-GeoHMS platform to delineate the river network and sub-basins and extract key physical characteristics such as reach length, basin area, and slopes. Land-use, soil, slope, and drainage maps were prepared, and the Thiessen polygon method was applied to distribute rainfall across sub-basins. Using these characteristics, model parameters were developed for input into the HEC-HMS hydrological model. The model employed the Deficit and Constant loss method to estimate infiltration losses, the Simple Canopy and Simple Surface methods to represent surface and vegetation processes, the Clark Unit Hydrograph for transform modeling, the Constant Monthly Baseflow method for groundwater contribution, and the Muskingum routing method for channel flow. The model was manually calibrated for the period (1997-2010) and validated (2014-2018) with DHM precipitation and discharge data. All the parameters were calibrated manually to bring the statistical indices in the range as suggested for the performance. The validated model was then forced with CHIRPS precipitation to simulate runoff, and performance was assessed using statistical indicators to evaluate the accuracy of both DHM and CHIRPS driven simulations.

Mean annual flow analysis were calculated using the long-term average discharge by averaging daily flow data over many years, while peak flow analysis were estimated using extreme flood events using statistical frequency analysis. For the statistical indices as shown in Table 3, Nash Sutcliffe Efficiency (NSE), Coefficient of Determination (R^2), Percent Bias (PBIAS), for performance benchmarks (D. N. Moriasi et al. 2007) was used as a reference.

Table 3. Performance Criteria Benchmarks

Performance Rating	**R^2**	**NSE**	**PBIAS**
Very Good	0.65 to 1	0.65 to 1	-15 to +15
Good	0.55 to 0.65	0.55 to 0.65	±15 to ±20
Satisfactory	0.4 to 0.55	0.4 to 0.55	±20 to ±30
Unsatisfactory	Less than 0.4	Less than 0.4	Greater than ±30

3 Results and Discussion

3.1 Results

The results obtained after the hydrological analysis using DHM and CHIRPS datasets are discussed below.

3.1.1 Hydrological Modelling

The hydrological model for SRB is calibrated manually and by automatic trial and error method and is validated by model using HEC-HMS 4.12 as it was the latest version available at that time. The calibration and validation were carried out using the closeness of the predicted and available flow at the outlet of the basin model. The parameters used in the hydrological modelling using the HEC-HMS are Simple Canopy, Simple Surface, Deficit and Constant loss method, Clark's Unit Hydrograph, Constant Monthly Base flow and Muskingum Routing. Three commonly used statistical hydrological model performance indices, i.e., NSE, R^2 and PBIAS were used to assess the performance of the model predictability and to represent the hydrological simulation of the basin using DHM & CHIRPS climate data.

3.1.1.1 Model Calibration & Validation with DHM data

The model was calibrated from the period of 1997/01/01 to 2010/12/31 and validated from 2014/01/01 to 2018/12/31 using daily rainfall data as the input in the HEC-HMS is shown in Figure 3 and Figure 4 respectively.

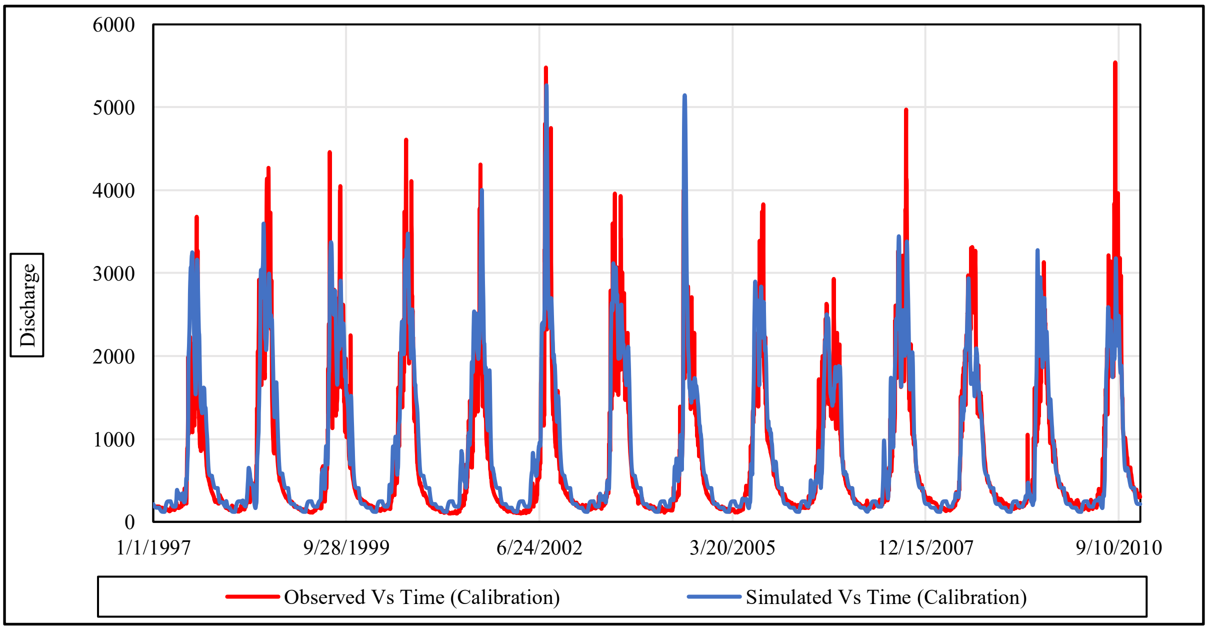

Figure 3. Comparison of observed and simulated discharge at Hampachuwar during calibration period (1997-2010) using DHM rainfall data

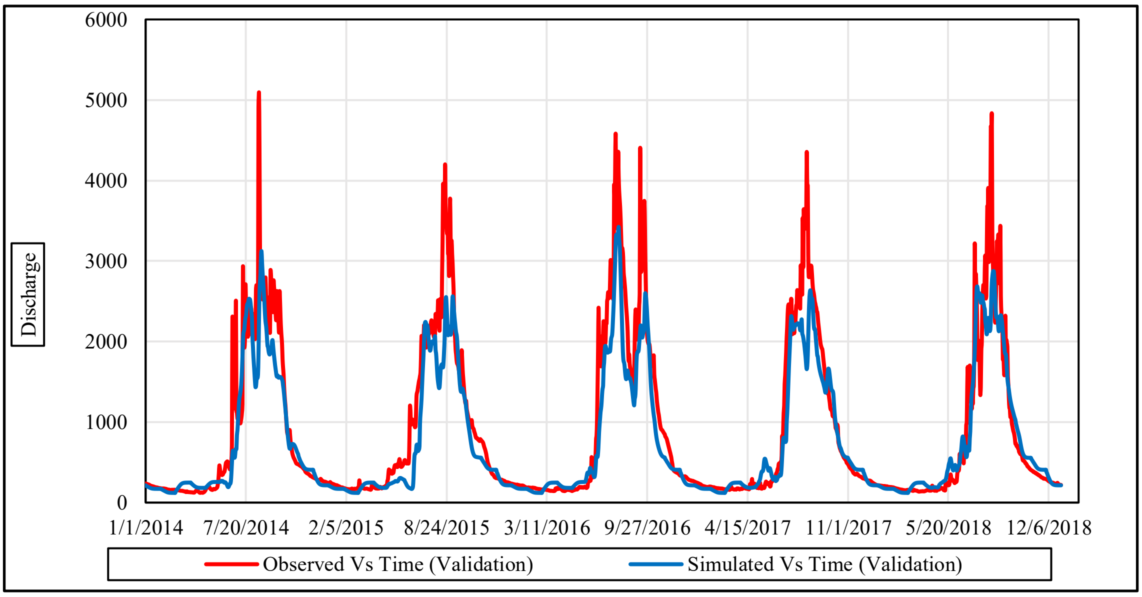

Figure 4. Comparison of observed and simulated discharge at Hampachuwar during validation period (2014-2018) using DHM rainfall data

The scatter plot between observed and simulated flow for calibration and validation at Hampachuwar Outlet is shown in Figure 5 and Figure 6 respectively.

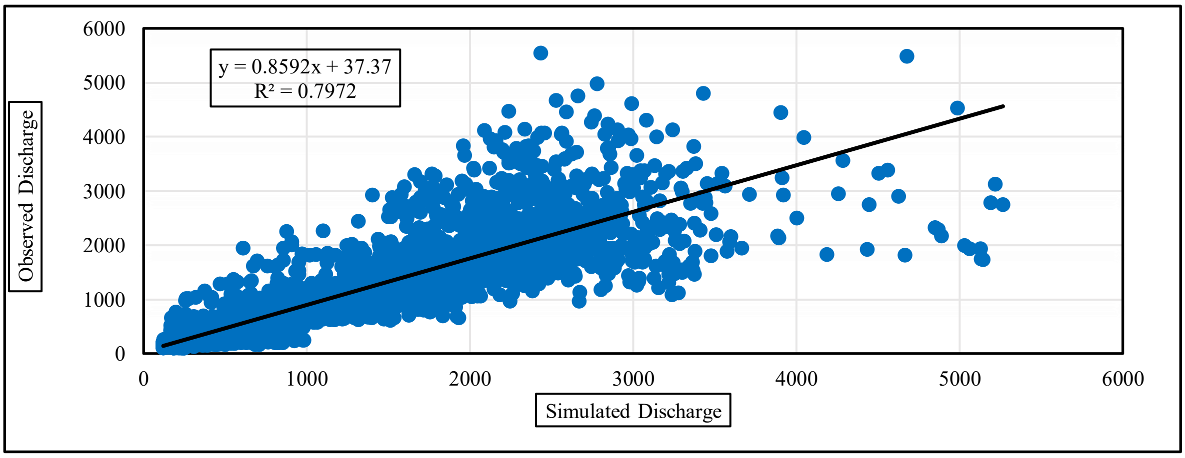

Figure 5. Scatter plot of observed vs simulated discharge during calibration (1997-2010) at Hampachuwar for DHM rainfall data

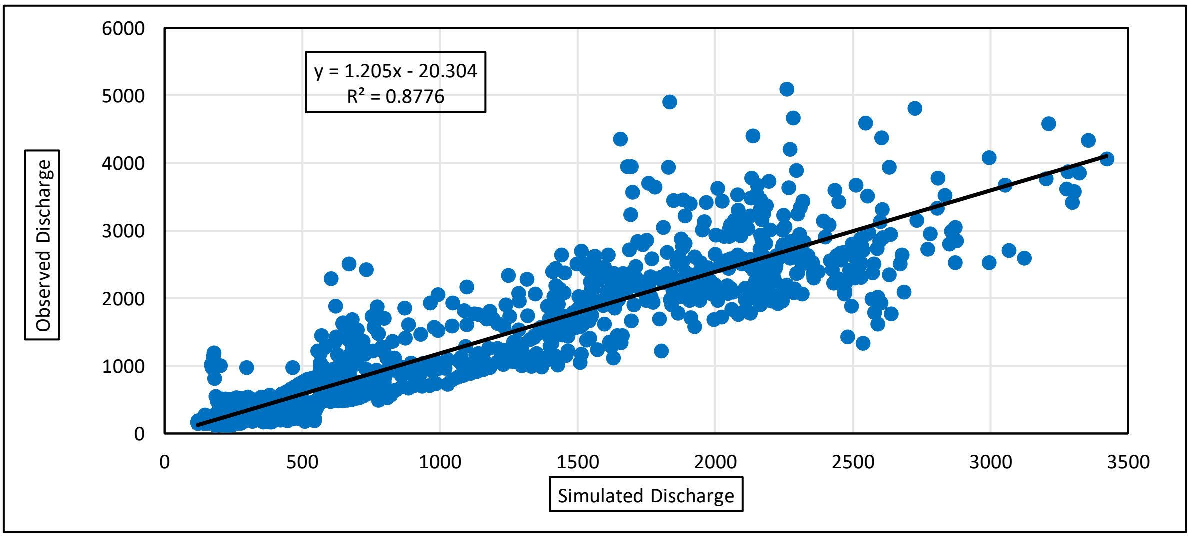

Figure 6. Scatter plot of observed vs simulated discharge during validation (2014-2018) at Hampachuwar for DHM rainfall data

The HEC-HMS model calibrated with observed DHM precipitation data of the basin and discharge data at Hampachuwar outlet demonstrated strong performance for the SRB. From the Table 3, it is clearly visible that the model performance for calibration and validation periods showed NSE values greater than 0.75, R^2 values greater than 0.79, and PBIAS within ±15%, indicating that the model effectively reproduced both low and high flows at the Hampachuwar outlet. Scatter plots and hydrographs demonstrated that the model accurately reproduced seasonal flow dynamics, interannual variability, and the magnitude and timing of peak discharge events, confirming its suitability for runoff simulation under diverse hydro-meteorological conditions and its relevance for flood risk assessment and water resources planning in the basin.

3.1.1.2 Model Performance with CHIRPS

CHIRPS daily precipitation data was fed to the DHM calibrated model to assess the effectiveness of the CHIRPS for the hydrological assessment. The results of the CHIRPS hydrological assessment are shown from Figure 7 to Figure 10.

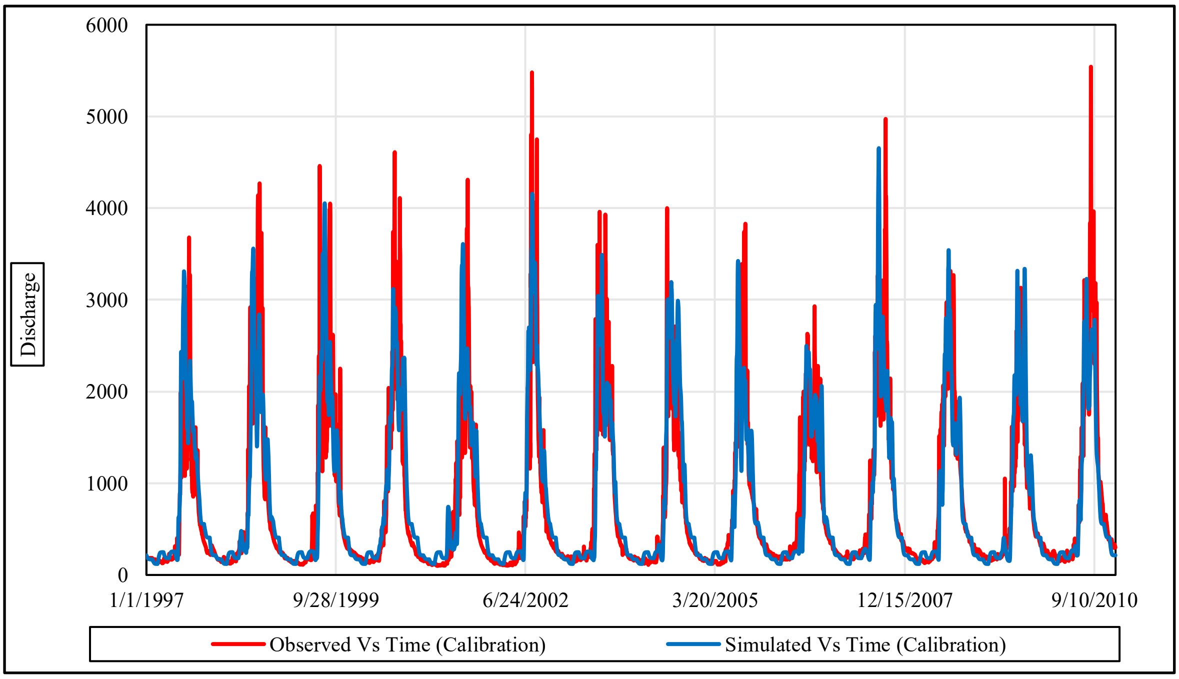

Figure 7. Comparison of observed and simulated discharge at Hampachuwar during calibration period (1997-2010) using CHIRPS rainfall data

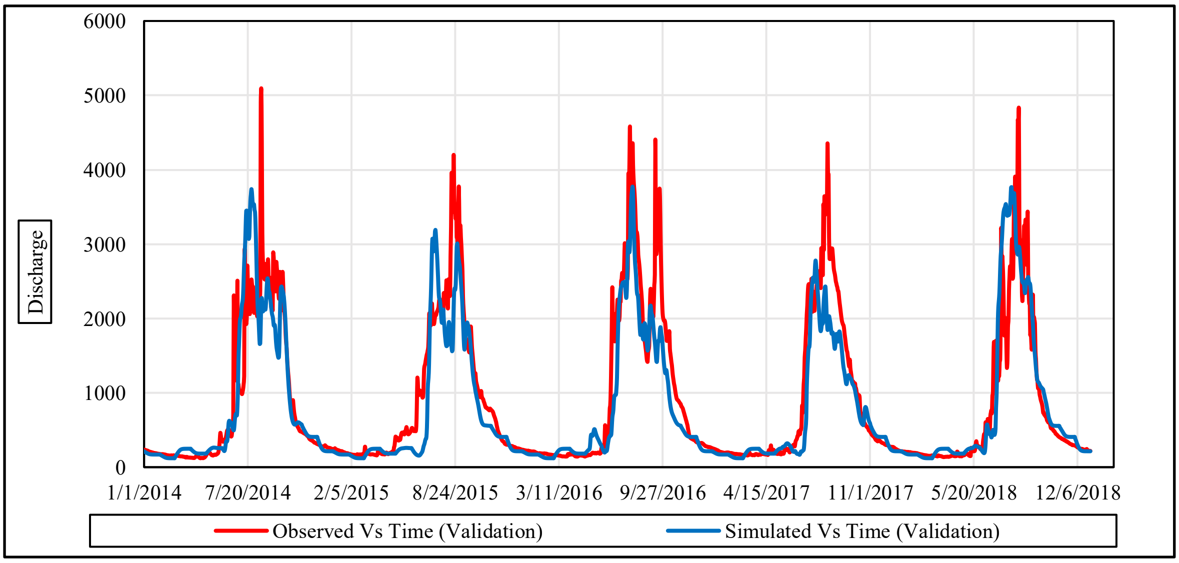

Figure 8. Comparison of observed and simulated discharge at Hampachuwar during validation period (2014-2018) using CHIRPS rainfall data

The scatter plot between observed and simulated flow for calibration and validation at Hampachuwar for raw CHIRPS is shown in Figure 9 and Figure 10.

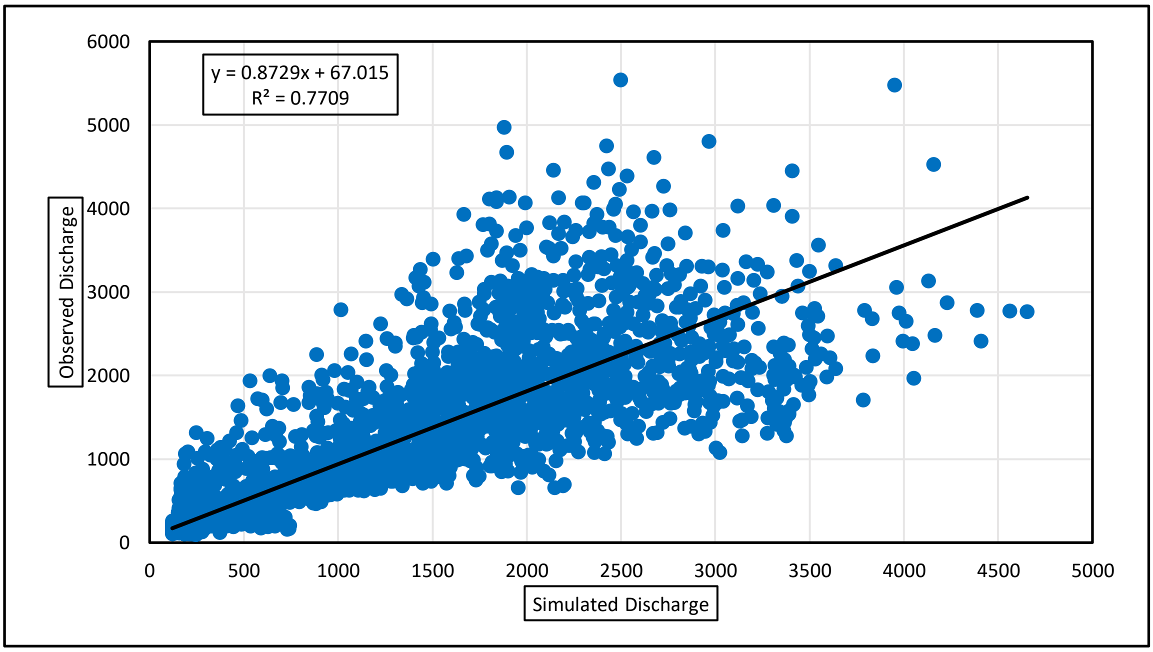

Figure 9. Scatter plot of CHIRPS datasets during calibration (1997-2010) at Hampachuwar for CHIRPS rainfall data

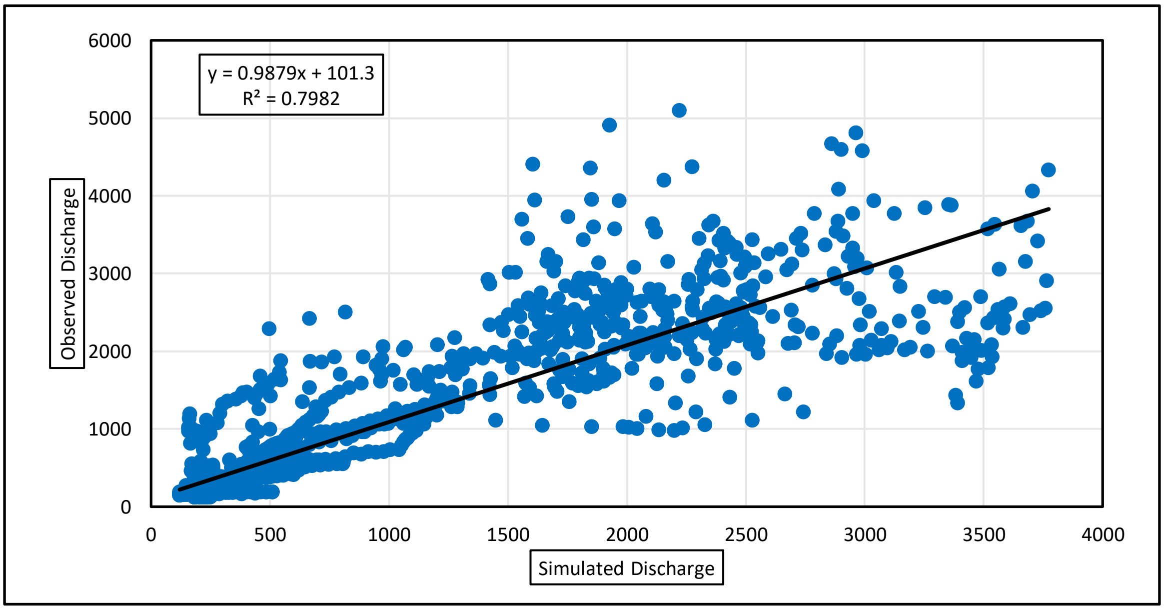

Figure 10. Scatter plot of CHIRPS datasets during validation (2014-2018) at Hampachuwar for CHIRPS rainfall data

Using CHIRPS precipitation as input, the calibrated HEC-HMS model demonstrated strong performance, with NSE values exceeding 0.75 and PBIAS and R² within acceptable limits as shown in Table 3. The CHIRPS-driven simulations effectively reproduced the temporal variability of observed discharge, accurately capturing both the rising and recession limbs of the hydrographs as well as seasonal flow patterns. Although slight under or overestimations occurred during extreme flow events likely reflecting the smoothing effects inherent in satellite derived rainfall estimates the overall agreement between simulated and observed flows highlights the capability of CHIRPS to represent basin-scale hydrological processes with reasonable accuracy. These findings affirm its suitability as a reliable precipitation input for rainfall-runoff modeling in data-scarce and ungauged catchments, consistent with results from other Nepalese basins (Shrestha et al., 2017; Talchabhadel, Aryal, et al., 2021).

Table 4. Calibration and Validation results at Hampachuwar after simulation

DHM	**NSE**	**PBIAS (%)**	**R^2**
Calibration	0.769	10.6	0.797
Validation	0.853	-15.1	0.878
CHIRPS	**NSE**	**PBIAS (%)**	**R^2**

DHM	**NSE**	**PBIAS (%)**	**R^2**
Calibration	0.753	4.3	0.771
Validation	0.814	-10.5	0.798

As from Table 4, we can see that the performance of model is within the limits as mentioned in Table 3.

3.1.2 Analysis of Model

3.1.2.1 Performance analysis on mean annual flow for DHM and CHIRPS

The simulated annual mean flow at the basin outlet, obtained from both DHM observed and CHIRPS precipitation data for the calibration and validation period is shown in Figure 11 and Figure 12.

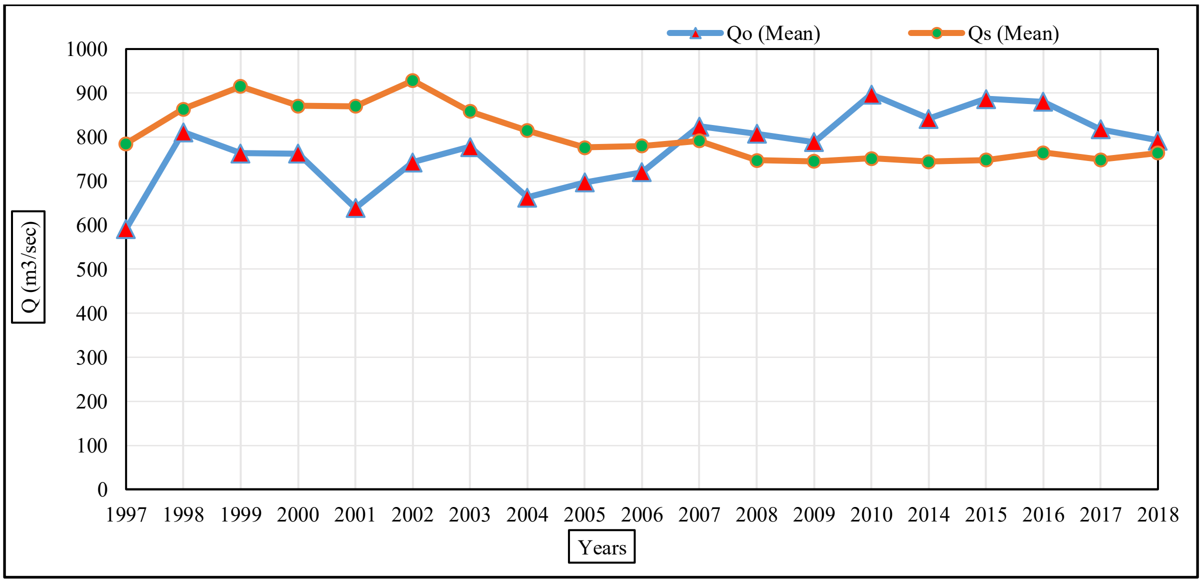

Figure 11. Performance analysis on mean flow for DHM observed data

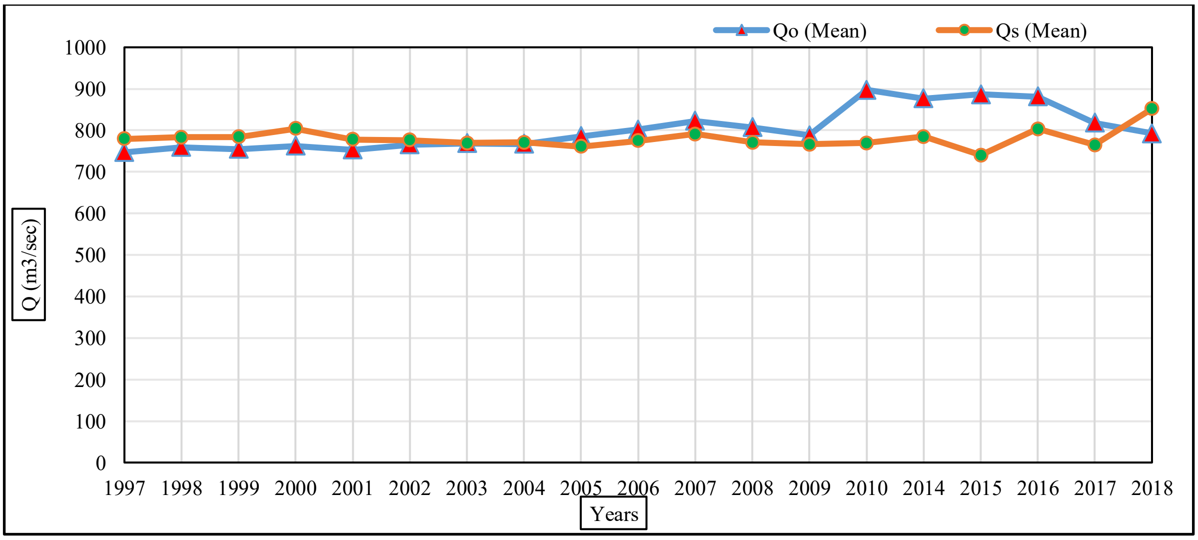

Figure 12. Performance analysis on mean flow for CHIRPS datasets

Using DHM data, the largest annual mean flow deviation of 230.89 m³/s was observed in 2001, while the smallest deviation of 28.28 m³/s in 2018. In contrast, simulations driven by CHIRPS data exhibited a maximum deviation of 145.83 m³/s in 2015 and a minimum of 0.51 m³/s in 2003. Notably, for DHM driven simulations, deviations during the validation period were generally lower than during calibration, suggesting improved predictive skill and stability, likely due to better representation of basin hydrology and relatively stable hydro climatic conditions. Conversely, for CHIRPS driven simulations, deviations were slightly higher during validation, which may be attributed to interannual variability in extreme rainfall events and inherent uncertainties in satellite-based precipitation estimates. Despite these differences, both datasets produced runoff simulations that closely followed observed flow patterns, effectively capturing seasonal variations and overall hydrological behavior. Comparatively, CHIRPS slightly underestimated peak flows relative to DHM, but its consistent performance across both calibration and validation periods underscores its reliability as an alternative input for rainfall-runoff modeling in data-sparse or ungauged regions like Nepal.

3.1.2.2 Performance analysis on Peak flow for DHM and CHIRPS

The simulated peak streamflow at the basin outlet during the calibration and validation periods, obtained using both DHM observed and CHIRPS precipitation is shown in Figure 13 and Figure 14 respectively.

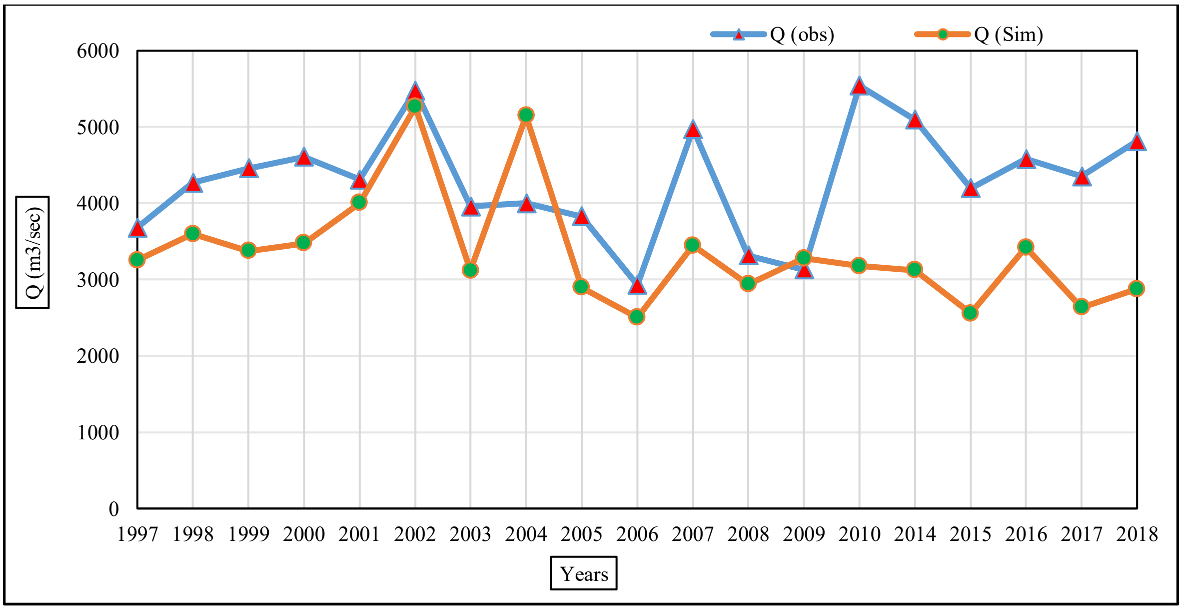

Figure 13. Performance analysis on DHM peak flow

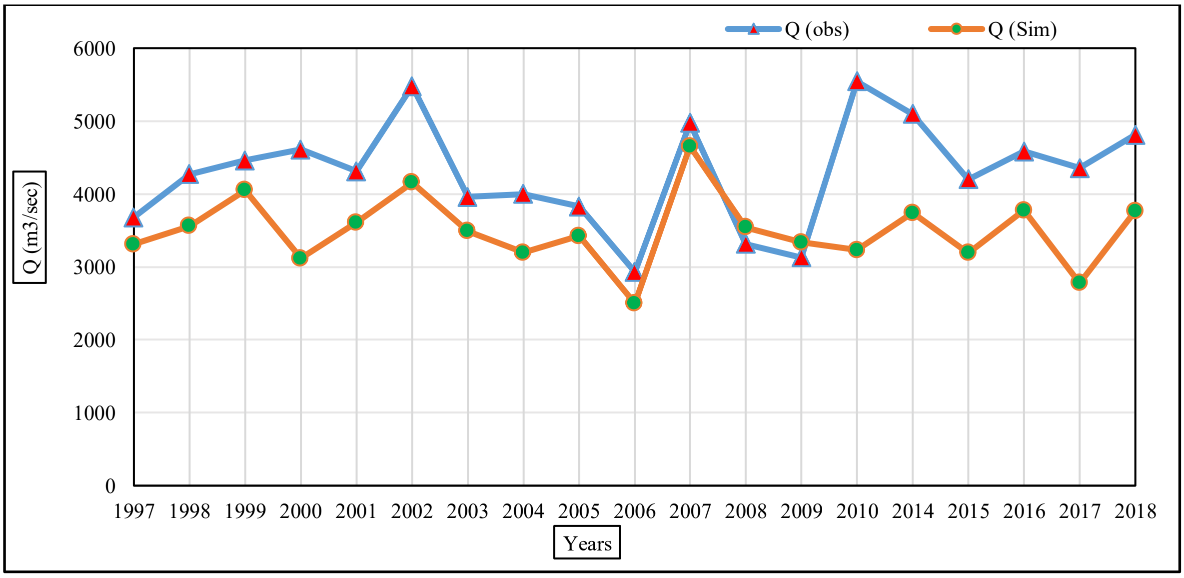

Figure 14. Performance analysis on CHIRPS peak flow

For DHM driven simulations, the maximum and minimum peak discharge deviation of 2362.7 and 145.7 m^3/s occurred in 2010 and 2009 respectively. In comparison, CHIRPS driven simulations yielded a slightly lower maximum peak discharge deviation of 2313.1 m^3/s in 2010 and a higher minimum deviation of 206.2 m^3/s in 2009. These results indicate that while both datasets effectively capture the overall peak flow dynamics, CHIRPS data slightly underestimated extreme peak flows compared to DHM and relatively higher deviations during low flow events. The close correspondence in maximum peak flows demonstrates the capability of CHIRPS to reproduce extreme hydrological events, despite minor differences likely arising from the spatial and temporal smoothing inherent in SPPs. Overall, the comparison underscores the utility of CHIRPS as a reliable alternative for simulating peak flows in ungauged or sparsely monitored basins.

3.2 Discussions

This study developed and validated an HEC-HMS hydrological model for the SRB using DHM observed precipitation and discharge data and evaluated the model performance with CHIRPS satellite precipitation inputs. Previous studies in various Nepalese river basins have reported mixed performances of SPPs in hydrological modeling. For instance, in the Karnali Basin, TRMM driven simulations achieved an NSE of 0.73, PBIAS of 18.18%, and R^2 of 0.84, indicating reasonably good model efficiency Mahotra (2023). Similarly, using Global Precipitation Climatology Project-One Degree Daily (GPCP-1DD) in SRB reported slightly lower performance in terms of NSE, PBIAS, and R^2 values. Chaudhary and Regmi (2025) used GPCP-1DD in SRB which resulted in NSE, PBIAS and R^2 values of 0.67, –11.4%, and 0.71 whereas this study resulted in NSE, PBIAS, and R^2 values of 0.753, 4.3%, and 0.771 respectively clearly stating that CHIRPS performance is superior to GPCP-1DD. Similarly, studies in the Bagmati Basin using PERSIANN reported comparatively poor performance in terms of NSE, PBIAS, and R^2 values. Sharma, Pandey, and Talchabhadel (2023)used PERSIANN SPP which showed the values of NSE, PBIAS and R^2 indicators as 0.45, 5.6%, and 0.47, respectively which are comparatively poorer to this study. Similarly, Shahid et al., (2021) used CHIRPS to study the hydrological modeling in the Upper, Middle and Lower Indus Basin, basically in Gilgit and Soan Basin resulted in NSE and PBIAS values of 0.67 and 10.37% during calibration whereas 0.60 and 13.74% during validation period which comparatively is inferior compared to this study.

The better performance of CHIRPS in this study can be mainly explained by its finer spatial resolution of 0.05° (~5 km), which allows it to better capture local rainfall variations across the rugged terrain of the SRB. This higher resolution helps represent the effects of topography on rainfall, which is important in mountainous regions where precipitation changes quickly with elevation. In addition, CHIRPS combines satellite estimates with ground station data, improving its accuracy compared to products like GPCP-1DD and PERSIANN, which rely more heavily on satellite only observations. Although CHIRPS reproduced the timing and pattern of streamflow reasonably well, it tended to slightly underestimate peak flows. This may be due to the smoothing of short, intense rainfall events, which can occur during monsoon storms, and the fact that small scale orographic effects are not always fully captured even at a 5 km resolution. Overall, the results indicate that CHIRPS can reliably represent rainfall and runoff patterns in the basin and is a suitable data source for hydrological modeling in regions with limited ground observations.

Despite the satisfactory performance of the HEC-HMS model and CHIRPS dataset, several limitations should be acknowledged. The model was calibrated and validated at a single outlet, representing the entire SRB, which may not fully capture the spatial variability of hydrological responses across different sub-basins. Moreover, the model configuration did not explicitly account for snow and glacier melt processes, even though the upper part of the basin includes snow-covered and glaciated areas. This simplification could lead to an underestimation of pre-monsoon and annual flow volumes, particularly in sub-basins where meltwater contributes substantially to runoff. In addition, the use of monthly average evapotranspiration data may overlook short-term variations in temperature, humidity, and vegetation, which influence actual evapotranspiration rates. A more refined, daily evapotranspiration dataset could potentially enhance model performance.

4 Conclusions

In this study, a hydrological model of the SRB was developed using HEC-HMS to evaluate rainfall-runoff simulation in a data-scarce mountainous region. The model calibrated and validated with observed precipitation and discharge obtained from DHM, achieved NSE, PBIAS, and R^2 values of 0.769, 10.6, and 0.797 during calibration, and 0.853, -15.1, and 0.878 during validation respectively. While, CHIRPS satellite precipitation data used obtained NSE, PBIAS, and R^2 values of 0.753, 4.3, and 0.771 during calibration and 0.814, -10.5, and 0.798 during validation respectively highly suggests CHIRPS as a primary alternative to gauge data in data-scarce region for water resources management, hydropower planning, and flood risk mitigation in regions. The results demonstrated that the model calibrated with observed DHM data and driven by CHIRPS Version 2.0 precipitation achieved very good statistical performance, confirming the potential of CHIRPS as a reliable input for hydrological modeling. The close agreement between CHIRPS and gauge-based simulations indicates that CHIRPS effectively captures the spatial and temporal rainfall variability of the basin, primarily due to its finer spatial resolution (0.05°) and the integration of ground station data into its satellite estimates.

5 Future Work

Future studies should focus on enhancing the model's ability to represent key hydrological processes and reduce uncertainty in runoff simulations. Integrating a temperature-based snowmelt module into the HEC-HMS model would improve the simulation of streamflow in snow and glacier-influenced areas of the SRB. Additionally, a comprehensive uncertainty assessment is recommended to better understand how inaccuracies in satellite rainfall estimates affect streamflow predictions. Further research could also involve testing other high-resolution satellite precipitation datasets, such as GPM, IMERG, alongside CHIRPS to evaluate their comparative effectiveness in mountainous regions.

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