Proceedings of 14th IOE Graduate Conference
Peer Reviewed
Year: 2023 Month: December Volume: 14
ISSN: 2350-8914 (Online), 2350-8906 (Print)

Application of HEC-HMS Model for Stream Flow Simulation at four Hydrological Stations of Narayani Watershed

Priyanka Bajracharya [a], Pawan Kumar Bhattarai [b], Nirajan Devkota [c], Ananta Man Singh Pradhan [d]

[a, b, c] *Department of Civil Engineering, Pulchowk Cmpus, IOE, Tribhuvan University, Nepal*
[d] *Water Resources Research and Development Centre, Lalitpur, Nepal*
[a] 078mswre009.priyanka@pcampus.edu.np, [a] nepalpawan@gmail.com, [a] 078phce112.nirajan@pcampus.edu.np, [b] anantageo@hotmail.com

Abstract
Hydrology is vital for understanding water on earth, its properties, distribution, and interactions with the environment amid changing factors like urbanization, industrialization, deforestation, and climate change. Continuous hydrological modeling using HEC-HMS was applied in the Narayani Watershed to simulate stream flows at four major hydrological stations. Calibration (1998-2006) was performed for Bimalnagar, Kotagaun, Devghat, and Kalikhola, evaluating model performance with metrics showing good results at Kalikhola and Devghat with NSE 0.76 and 0.86 respectively and satisfactory results at Bimalnagar and Kotagaun with NSE 0.69 and 0.65 respectively. After validation (2007-2010) the NSE obtained for Bimalnagar, Kotagaun, Devghat, and Kalikhola were 0.84, 0.76, 0.81 and 0.91.This stream flow simulation aids in flood investigations and studying climate and land use impact on future stream flow.

Keywords
Hydrological Modelling, HEC-HMS, Streamflow

1. Introduction

It takes a lot of resources to conduct hydrological observations with high geographical and temporal resolution. As a result, even though coverage has increased over time, many nations have not yet reached that level. Even if the coverage is acceptable, developing hydrological simulation models can offer precise projections for water yield and availability in a basin over a wide range of input watersheds [1]. Assessment methods for water and environmental planning choices include simulation models.By measuring threats to water and environmental security, they provide crucial insights for policymakers, implementing organizations, and practitioners. The allocation, use, and management of freshwater resources can be improved by using this knowledge to create successful policies, programs, and strategies [2]. Journal by [3] to assess model application gives an example about the need to perform hydrological modelling in order to understand spatio-temporal distribution of water resources.

There are numerous river networks in Nepal, which are spread out over the nation, some of which originates from India and China. Narayani watershed is one of the largest basin in our country. The rainfall pattern are different throughout the year in this watershed like any other watershed which results in changes in the discharge pattern as well. Hydrological model can be used to develop the model of any river basin as it helps to understand the hydrological cycle at present and predict future runoff and discharges to reduce water induced hazards.Nowadays, hydrological modeling is frequently used to research water resources, and its effective applications are turning it into the ideal tool for water resource management planning and decision-making. Hydrological modelling can be used to estimate and predict the hydrological components for watersheds based on the data that is currently available [4, 5]. A model consists of various parameters that define the properties of the model and determines the behavior of a system and helps to understand hydrological processes [6].

Hydrologic Engineering Center - Hydrologic Modeling System (HEC-HMS) is a hydrological model which is used to simulate the rainfall-runoff of a dendritic watershed. [7] state that computations are carried out from upstream to downstream and that the hydrologic components are constructed in a network.

Three sections comprise HEC-HMS namely, the basin, the meteorological model, and the control requirements. [8]. There are four primary parts of the HEC-HMS. 1) An analytical model that estimates channel routing and runoff from overland flows; 2) an advanced graphical user interface with interactive elements that displays the elements of the hydrologic system; 3) a mechanism to manage and store data, especially big, time-varying data sets; and 4) a presentation and reporting mechanism for model outputs [9]. To represent the physical characteristics of the watershed and the hydrologic processes that occur, HEC-HMS requires certain parameters. These parameters can include information about the soil properties, land use, topography, vegetation, and climate of the watershed, rainfall distribution, time of concentration, curve number to estimate runoff and many more. In order to represent the behavior of the watershed, these parameters are necessary which help to estimate the runoff and stream flows. It is important to collect the required data accurately and input the parameters correctly in order to calibrate and validate the model and acquire good results [10].

2. Study Area and Data

2.1 Study area

Narayani Basin extends from China in the north through Nepal to India in the south. It has a total catchment area of 36,498 km^2 which includes some portion of China. The total area occupied by Nepal is 35,780 km^2. The basin is bounded by Karnali basin to the west and and Koshi basin to the east [11]. The height of the basin varies greatly, from 180 meters above sea level in the south to over 8000 meters above sea level in the north as it travels through the high Himalayas (8167 meters above sea level) and Annapurna (8091 meters above sea level) [12]. The NRB covers the Himalayan range to the Terai plains, with elevations ranging from 18 meters in the south to more than 8000 meters in the Himalayas. Temperature fluctuates rapidly with elevation; for instance, it can drop to -25°C in the high Himalayas while rising to 35°C on the plains of Terai. The Narayani River, originating in the Himalayas near the southern Tibetan Plateau, consistently carries significant snow-fed flows, even during dry periods, and maintains its turbulent nature [13, 11] The area of Narayani River Basin used in this study is as shown in Figure 1.

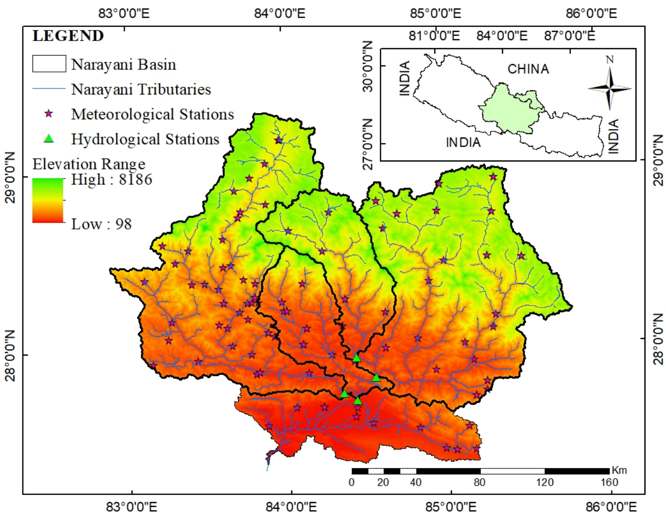

Figure 1: Location, hydro-meteorological stations, and elevation details of Narayani Basin

2.2 Data description

2.2.1 Geophysical data

It includes DEM data Soil data and LULC data. The dataset and data sources are showun in Table 1

DEM data

With a resolution of 1 arc second (or around 30 meters at the equator), the Global Digital Elevation Model Version 2 (GDEM V2) of the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) provided the Digital Elevation Model (DEM).

Soil and Landuse/Cover data

The soil map for Narayani Bain was acquired from Soil and Terrain Database (SOTER). 21 soil types were processed in the model. 6 types of soil were found for the portion of the basin in China and 15 types of soil were found for the portion of the basin in Nepal.Landuse/cover data for the year 2010 was acquired from ICIMOD.

Table 1: Data Sources

Dataset (unit)	Data type	Description	Source
Terrain datasets (m)	Spatial grids	Digital elevation model (DEM) 30m x 30m	ASTER GDEM Version 2
Soil	Spatial vectors	Soil classification and physical properties	SOTER
Land use/ land cover	Spatial grids	Resolution of 30m x 30m	ICIMOD (2010)
Precipitation (mm)	Time series	Daily observed precipitation	DHM, Nepal
Temperature (°C)	Time-series	Daily observed data	DHM, Nepal
River discharge (m^3/s)	Time-series	Observed stream flow	DHM, Nepal

2.2.2 Hydrological and meteorological data

Maximum temperature, minimum temperature and precipitation data at different meteorological stations and discharge data at different hydrological stations were collected from Department of Hydrology and Meteorology (DHM) for time period of 1980 to 2019. The observed data contain missing data which was filled using Normal Ratio Method to improve the quality of data. 86 precipitation stations and 16 temperature stations were taken which covers the entire watershed spatially and physiographic regions namely, Mountain region, Hilly region and Terai region.

3. Methodology

The overall framework of methods used is as shown in Figure 2. Spatial data, Observed discharge data and time series data were entered into the HEC-HMS model and the model was calibrated and validated in order to study the stream flows at 4 hydrological stations.

3.1 Hydrological Model Setup

HEC-HMS consists of interconnected components which includes basin model, meteorological models, control specifications and input data that simulate hydrological response in a watershed [8]. The basin model represents watershed which was developed in HEC-HMS after feeding the model with the DEM data to form stream network and delineate the watershed into 28 sub-basins. Daily precipitation data from precipitation gauges and daily discharge data from discharge gauges were entered in the model from 1980 to 2019 which was obtained from DHM. The precipitation input required by each sub-basin was also

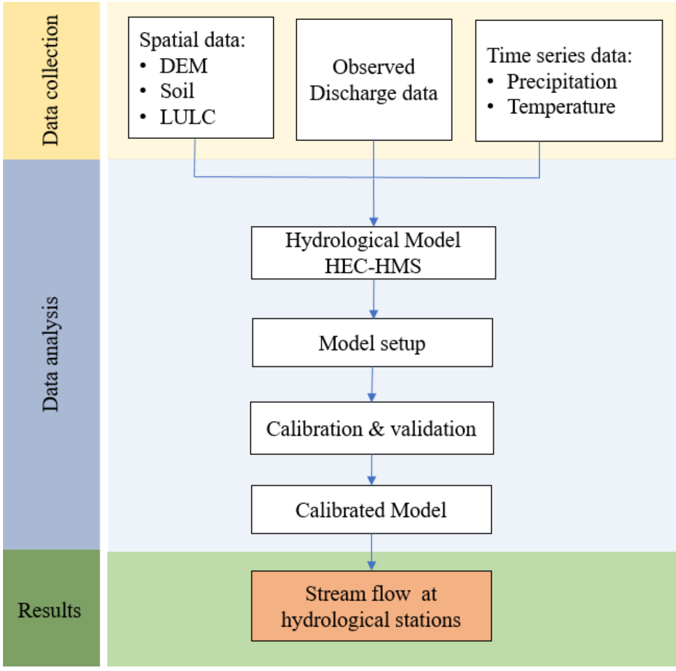

Figure 2: Methodological Framework

calculated by the meteorological model [8]. Evapotranspiration was calculated using thornthwaite method and assigned for each sub-basin and entered in the meteorological model. A total of twelve loss methods are available in HEC-HMS. For this study SCS Curve Number (SCS-CN) Method was used as a loss method due to its simplicity and flexibility [14]. CN was generated in ArcGIS using the soil and land use maps. Out of eight methods, SCS Unit Hydrograph Method was used for transformation. Muskingum method was used as a routing method out of the 8 methods available in HEC-HMS. For base flow method, out of five methods available, constant monthly discharge method was used [15]. Time series data from precipitation gauges and discharge gauges were entered into the model. After entering all the required data, the model was simulated and parameters were optimized to calibrate and validate the model for stream flow at the 4 hydrological stations.

3.2 Calibration and Validation

Parameters were entered as input to the model to produce the simulated runoff hydrographs. While some of the parameters were estimated through trial and error calibration for best fit, others were estimated through calculations and observation of the characteristics of the stream and basin. The optimal parameters were identified that produced the best fit between the simulated discharge and the observed discharge in the presence of rainfall and runoff data. Calibration of simulated discharge with observed discharge data were carried out at hydrological stations: Devghat, Kalikhola, Bimalnagar and Kotagaun for a time period of nine years from January 1998 to December 2006. Performance measures were calculated using formulae mentioned and were evaluated using Table 2. After model calibration, the same parameters were used for validation of the model for different time period. Validation of simulated discharge with observed discharge data were carried out for Devghat, Kalikhola, Bimalnagar and Kotagaun for a time period of four years from January 2007 to December 2010.

3.2.1 Performance evaluation for HEC-HMS model

The performance evaluation for HEC-HMS model can be carried out using PBIAS, NSE and R^2. These matrices were calculated and evaluated based on performance evaluation criteria provided by [16] as shown in Table 2 .

Nash Sutcliffe Efficiency (NSE)

The goodness-of-fit of the simulated discharge data and observed discharge data in line 1:1 is indicated by the Nash-Sutcliff efficiency (NSE), which can range from ∞ to 1. NSE evaluates a model's ability to predict outcomes in relation to the mean of the observations [17]. The NSE is calculated as:

$$NSE = 1 - \frac{\sum(Q_{\text{obs}} - Q_{\text{sim}})^2}{\sum(Q_{\text{obs}} - \bar{Q})^2} \tag{1}$$

Where $Q(_{\text{obs}})$ represents the observed data values, $Q(_{\text{sim}})$ represents the simulated model values, and $Q(_{\text{mean}})$ represents the mean of observed values.

Coefficient of Determination (R^2)

The coefficient of determination (R^2) describes how well simulated and measured data coincide. The correlation coefficient, which has a range of -1 to 1, measures how linearly related observed and simulated data are [17]). The percentage of variance in the measured data that the model can explain is expressed by R^2. Higher values of R^2, a measure of error variance that ranges from 0 to 1, indicate less error variance. Values greater than 0.5 are usually accepted. [18, 19]. R^2 is calculated as:

$$R^2 = \frac{\sum_{i=1}^{n}(Q_{\text{sim}} - \overline{Q}_{\text{mean}})^2 (Q_{\text{obs}} - \overline{Q}_{\text{mean}})^2}{\sum_{i=1}^{n}(Q_{\text{sim}} - \overline{Q}_{\text{mean}})^2 \sum_{i=1}^{n}(Q_{\text{obs}} - \overline{Q}_{\text{mean}})^2} \tag{2}$$

Where Q_{obs} represents the observed data, Q_{sim} represents the simulated model data, and $\overline{Q}_{mean}$ represents the mean of observed data.

Percent Bias (PBIAS)

Percentage bias (PBIAS) is used to calculate the average tendency of the simulated data to be larger or smaller than their observed counterparts. PBIAS values with low magnitudes denote accurate model simulation and 0.0 is the optimal value. Positive values denote a bias in the model's underestimation, whereas negative values denote a bias in the model's overestimation [20]. The PBIAS is calculated as:

$$PBIAS = \frac{\sum(Q_{\text{obs}} - Q_{\text{sum}})}{\sum Q_{\text{obs}}} \times 100 \tag{3}$$

Where Q_{obs} represents the observed data and Q_{sim} represents the simulated model data.

4. Results and Discussion

In order to simulate daily flows at Bimalnagar, Kotagaun, Kalikhola and Devghat, a hydrological model was developed. After the completion and satisfactory performance of the model, stream flow were described using simulated river flow.

Table 2: . Performance evaluation criteria for statistical performance measures [16]

Measure	Very Good	Good	Satisfactory	Not Satisfactory
R^2	> 0.85	$0.70 \le R^2 \le 0.85$	$0.50 \le R^2 \le 0.70$	≤ 0.50
NSE	> 0.80	$0.70 \le NSE \le 0.80$	$0.50 \le NSE \le 0.70$	≤ 0.50
PBIAS	$\le \pm 10$	$\pm 10 < PBIAS < \pm 15$	$\pm 15 \le PBIAS \le \pm 45$	$> \pm 45$

4.1 Hydrological model performance

The simulated hydrographs fairly represented the hydrological regime and matched the precipitation pattern. Daily plots as well as scatter plots of observed and simulated flow, were created during the calibration period from 1999 to 2006 and validation periods from 2007 to 2010 to examine the model's performance to simulate the hydrology based on the availability of the discharge data.

At Bimalnagar station (439.7):

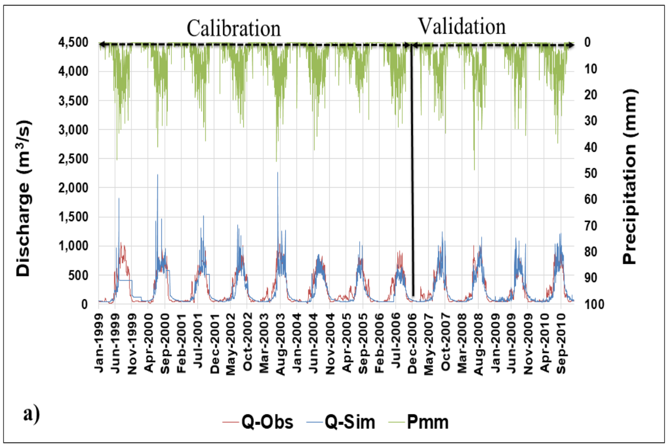

Figure 3: Daily Hydrograph at Bimalnagar

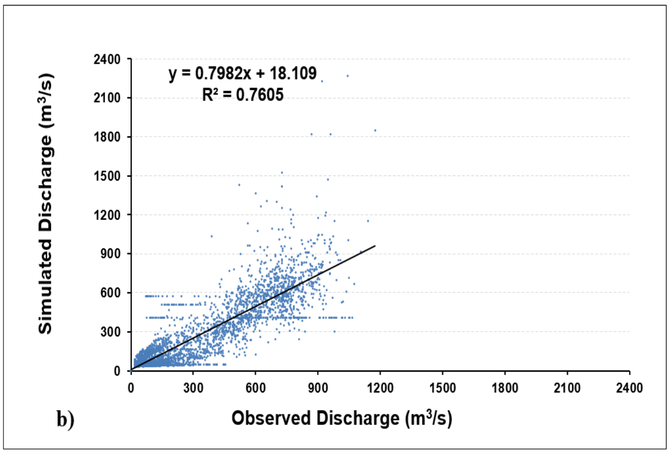

Figure 4: Daily Scatter Plot at Bimalnagar

The model was able to fairly accurately simulate the flows, as shown by the hydrographs on a daily basis. The figures (Figure 3, Figure 5, Figure 7 and Figure 9) show the daily hydrograph at Bimalnagar, Kotagaun, Kalikhola and Devghat respectively. The figures made it evident that the model was unable to account for extremes (both high and low flows) at all the four stations. Possible explanation for the model's overall low accuracy could be the large area of the basin as well as poor data quality. Figures (Figure 4, Figure 6, Figure 8 and Figure 10) show the scatter plots at Bimalnagar, Kotagaun, Kalikhola and Devghat respectively where the dots are widely spread suggesting weaker performance and an underestimation of high flow levels at all the four stations. However, the model effectively replicates average flow conditions to a significant extent in all the stations. The performance table shows that the performance statistics appear to be good as per the performance criteria and are within the required range. Summary of model performance after calibration and validation at the 4 hydrological stations is as per Table 3.

At Bimalnagar, the NSE value after calibration was 0.69 and after validation was 0.84. The R^2 value after calibration at this station was 0.72 and after validation was 0.83. The PBIAS at this station was -15.29 and after validation was -8.93.

Table 3: Model Performance after Calibration (1999-2006) and Validation (2007-2010)

Location	Period	NSE	R^2	PBIAS
Bimalnagar	Calibration	0.69	0.72	-15.29
	Validation	0.84	0.83	-8.93
Kotagaun	Calibration	0.65	0.81	10.4
	Validation	0.76	0.83	2
Kalikhola	Calibration	0.76	0.8	4.3
	Validation	0.81	0.85	-5.3
Devghat	Calibration	0.86	0.91	13.8
	Validation	0.86	0.92	18.3

At Kotagaun, the NSE value after calibration was 0.65 and after validation was 0.76. The R^2 value after calibration at this station was 0.81 and after validation was 0.83. The PBIAS at this station was 10.4 and after validation was 2.

At Kotagaun station (420):

At Kalikhola, the NSE value after calibration was 0.76 and after validation was 0.81. The R^2 value after calibration at this station was 0.8 and after validation was 0.85. The PBIAS at this station was 4.3 and after validation was -5.3. At Devghat, the NSE value after calibration was 0.86 and after validation was 0.86. The R^2 value after calibration at this station was 0.91 and after validation was 0.92. The PBIAS at this station was 13.8 and after validation was 18.3. The performance matrices obtained lie within good category as per the performance evaluation criteria provided by [16].

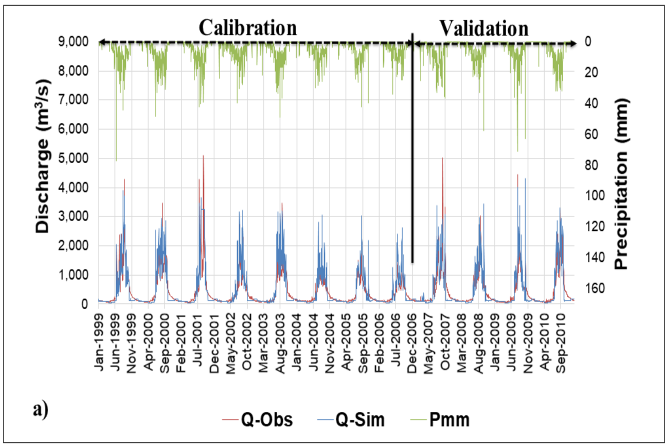

Figure 5: Daily Hydrograph at Kotagaun

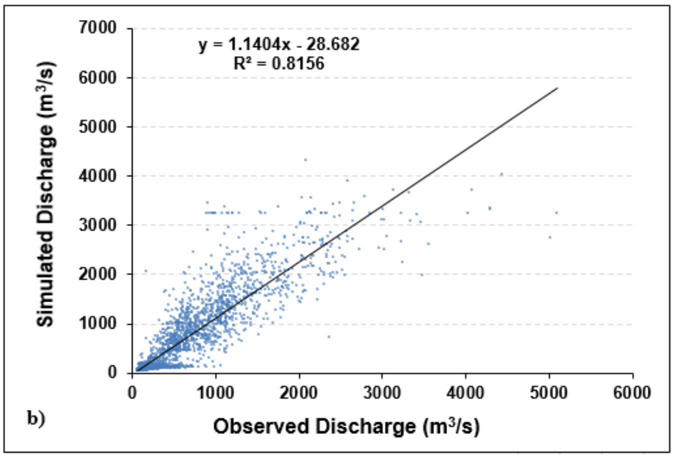

Figure 6: Daily Scatter Plot at Kotagaun

At Kalikhola station (449.91):

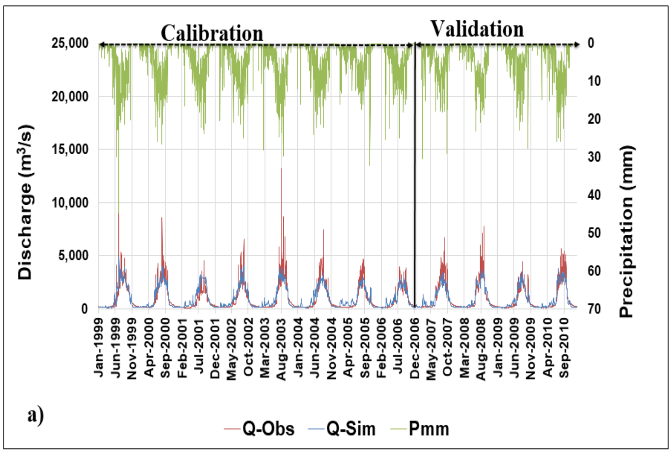

Figure 7: Daily Hydrograph at Kalikhola

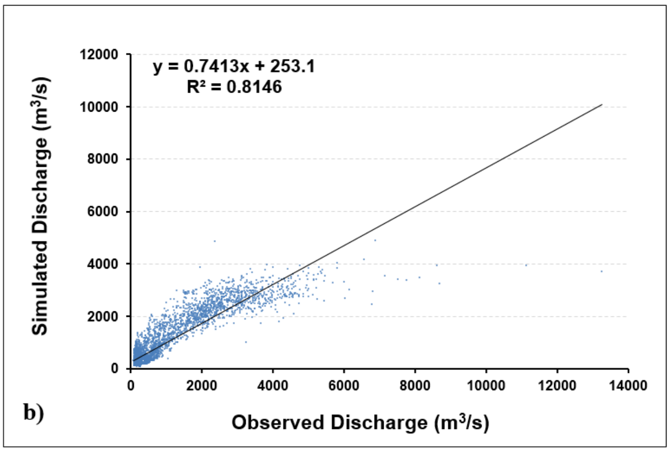

Figure 8: Daily Scatter Plot at Kalikhola

At Devghat station (450):

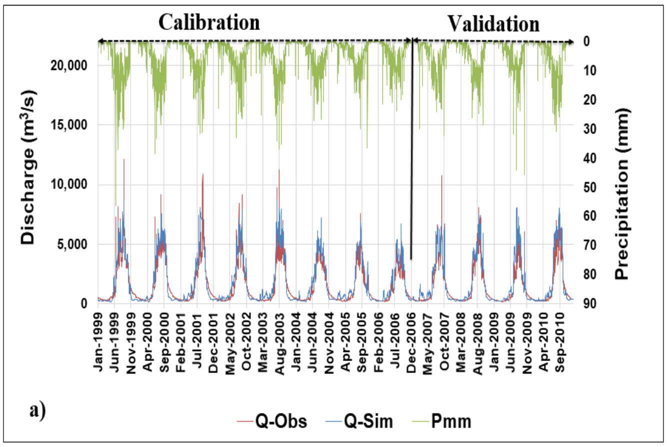

Figure 9: Daily Hydrograph at Devghat

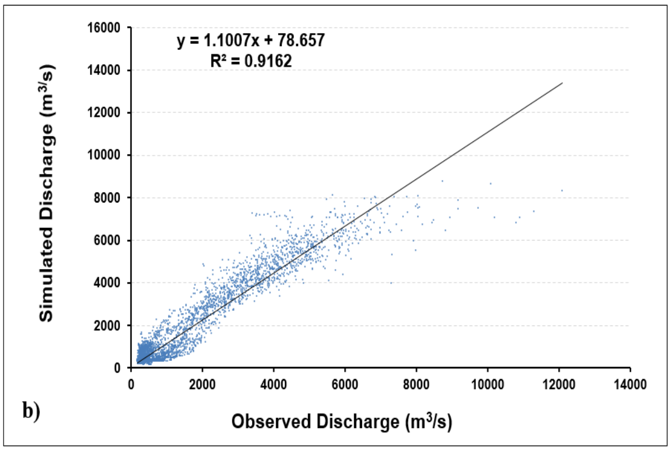

Figure 10: Daily Scatter Plot at Devghat

5. Conclusions

This study was carried out in order to simulate stream flow at four major hydrological stations in Narayani Watershed using HEC-HMS model by discretizing the basin into 28 sub-basins. Utilizing statistical indicators for average flows, the model was fairly calibrated and validated. The difference in runoff volume at Bimalnagar and Devghat respectively was less than 15%. Similarly, the difference in runoff volume at Kotagaun and Kalikhola respectively was less than 5%. SCS CN method was used in loss method as it makes use of soil and LULC data. The simulation of stream flow at these stations can further be used to estimate instantaneous flow to investigate flood events. Further the simulation can be used to predict future stream flow and in turn predict future flood events due to changes in climatic data and LULC data in future. The results obtained from the model are hence important for policy makers and planners of water resources for proper utilization of water resources and country's development.

Acknowledgments

The first author of this manuscript was supported by the Water Resources Research and Development Centre (WRRDC) through "WRRDC-interns and research mobilization program 79/80".

References

[1] Vishnu Prasad Pandey, Sanita Dhaubanjar, Luna Bharati, and Bhesh Raj Thapa. Spatio-temporal distribution of water availability in karnali-mohana basin, western nepal: Hydrological model development using multi-site calibration approach (part-a). *Journal of Hydrology: Regional Studies*, 29:100690, 2020.

[2] Kuniyoshi Takeuchi, Tianqi Ao, and Hiroshi Ishidaira. Introduction of block-wise use of topmodel and muskingum-cunge method for the hydroenvironmental simulation of a large ungauged basin. *Hydrological Sciences Journal*, 44(4):633–646, 1999.

[3] Raghavan Srinivasan, Tharacad S Ramanarayanan, Jeffrey G Arnold, and Steven T Bednarz. Large area hydrologic modeling and assessment part ii: model application 1. *JAWRA Journal of the American Water Resources Association*, 34(1):91–101, 1998.

[4] U Aryal, TR Adhikari, S Thakuri, and B Rakhal. Flood hazard assessment in dhobi-khola watershed,(kathmandu nepal) using hydrological model. *International Research Journal of Environmental Science*, 5(11):21–33, 2016.

[5] T Piman and MS Babel. Prediction of rainfall-runoff in an ungauged basin: case study in the mountainous region of northern thailand. *Journal of Hydrologic Engineering*, 18(2):285–296, 2013.

[6] Gayathri K Devia, B Pa Ganasri, and G Sa Dwarakish. A review on hydrological models. *Aquatic procedia*, 4:1001–1007, 2015.

[7] Surendar Natarajan and Nisha Radhakrishnan. An integrated hydrologic and hydraulic flood modeling study for a medium-sized ungauged urban catchment area: A case study of tiruchirappalli city using hec-hms and hec-ras. *Journal of the Institution of Engineers (india): Series A*, 101:381–398, 2020.

[8] Muhammad Ali, Sher Jamal Khan, Irfan Aslam, and Zahiruddin Khan. Simulation of the impacts of land-use change on surface runoff of lai nullah basin in islamabad, pakistan. *Landscape and Urban Planning*, 102(4):271–279, 2011.

[9] H Bajwa and U Tim. Toward immersive virtual environments for gis-based floodplain modeling and visualization. In *Proceedings of 22nd ESRI user Conference*, pages 7–23, 2002.

[10] Bitew G. Tassew, Mulugeta A. Belete, and K. Miegel. Application of hec-hms model for flow simulation in the lake tana basin: The case of gilgel abay catchment, upper blue nile basin, ethiopia. *Hydrology*, 6, 2019.

[11] Rocky Talchabhadel, Bibek Thapa, and Vishnu Prasad Pandey. Assessing future precipitation in gandaki river basin based on cmip6 projections. In *Proceedings of 10th IOE Graduate Conference. Institute of Engineering, Tribhuvan University, Nepal*, pages 1016–1024, 2021.

[12] Dipendra Lamichhane, Binod Dawadi, Ram Hari Acharya, Saroj Pudasainee, and Ishwar Kumar Shrestha. Observed trends and spatial distribution in daily precipitation indices of extremes over the narayani river basin, central nepal. *Appl. Ecol. Environ. Sci*, 8:106–118, 2020.

[13] Piyush Dahal, Nicky Shree Shrestha, Madan Lall Shrestha, Nir Y Krakauer, Jeeban Panthi, Soni M Pradhanang, Ajay Jha, and Tarendra Lakhankar. Drought risk assessment in central nepal: temporal and spatial analysis. *Natural hazards*, 80:1913–1932, 2016.

[14] D Halwatura and MMM Najim. Application of the hec-hms model for runoff simulation in a tropical catchment. *Environmental modelling & software*, 46:155–162, 2013.

[15] Shahla Azizi, Ali Reza Ilderomi, and Hamid Noori. Investigating the effects of land use change on flood hydrograph using hec-hms hydrologic model (case study: Ekbatan dam). *Natural Hazards*, 109(1):145–160, 2021.

[16] Daniel N Moriasi, Margaret W Gitau, Naresh Pai, and Prasad Daggupati. Hydrologic and water quality models: Performance measures and evaluation criteria. *Transactions of the ASABE*, 58(6):1763–1785, 2015.

[17] Daniel N Moriasi, Jeffrey G Arnold, Michael W Van Liew, Ronald L Bingner, R Daren Harmel, and Tamie L Veith. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE*, 50(3):885–900, 2007.

[18] Chinnasamy Santhi, Jeffrey G Arnold, Jimmy R Williams, William A Dugas, Raghavan Srinivasan, and Larry M Hauck. Validation of the swat model on a large rwer basin with point and nonpoint sources 1. *JAWRA Journal of the American Water Resources Association*, 37(5):1169–1188, 2001.

[19] Michael W Van Liew, Tamie L Veith, David D Bosch, and Jeffrey G Arnold. Suitability of swat for the conservation effects assessment project: comparison on usda agricultural research service watersheds. *Journal of Hydrologic Engineering*, 12(2):173–189, 2007.

[20] Hoshin Vijai Gupta, Soroosh Sorooshian, and Patrice Ogou Yapo. Status of automatic calibration for hydrologic models: Comparison with multilevel expert calibration. *Journal of hydrologic engineering*, 4(2):135–143, 1999.