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Rainfall-Runoff Simulation of Tamor River Basin using SCS-CN based HEC-HMS Model

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Abstract

Discharge data is one of the most important data in evaluating the reliability of water resources management in the watershed. Suitable approach for prediction of peak flow based upon the available historical precipitation data, land use condition, soil type and suitable routing method is necessary. This study intended to determine the suitablilty of The Soil Conservation Service- Curve Number (SCS-CN) based HEC-HMS model in continuous simulation of flows in the Mulghat outlet of Tamor river basin. Identification of the sensitive parameters for the model performance and estimation and analysis of discharges for each sub-basins of Tamor river basin has also been performed in this study. The catchment was delineated and its properties were extracted from a 30m×30m Digital Elevation Model (DEM). The meteorological model module within HEC-HMS was developed from rainfall data and control specifications defining the period and time step of simulation. To account for the loss, runoff estimation, baseflow and flow routing, Soil Conservation Service Curve Number (SCS-CN), Soil Conservation Service Unit Hydrograph (SCS-UH), recession and Muskingum-Cunge methods were used respectively. The result of the sensitivity analysis showed that the recession constant is the most sensitive parameter. Thereafter, a model calibration in daily time step was done from 1995-2002 with NSE, PBIAS and r^2 values of 0.76, 2.42% and 0.78 respectively.Validation results from 2003-2007 the Tamor river basin NSE=0.82 , percentage error in volume (PBIAS=-7.5%) and their r^2=0.82 showed that the model SCS-CN based HEC-HMS model can be successfully applied in flow simulation at ungauged points of the Tamor river basin.

Keywords
HEC-HMS, Rainfall-runoff, Tamor Basin, SCS-CN

1. Introduction

1.1 Background

Without water, life is unthinkable. Our lives are highly dependent upon the limited and dispersedly existing fresh water resources of our planet. Water availability and quality are the main issues for the society in climate change scenarios [1].A runoff model can be defined as a set of equations that helps in the estimation of runoff as a function of various parameters used for describing watershed characteristics [2]. Understanding the hydrological system is essential for the effective management of the water resources and to tackle the ever increasing water related problems [3]. Hydrologic models are useful in assisting decision makers for efficient water resources management [4]. The reason for building a hydrologic model to solve water related problems can be categorized into two : understanding the relation between catchment and hydrology and forecasting scenario analysis for design and planning [5]. Planning and designing of infrastructures like bridge, dam, hydropower etc. requires the detailed knowledge of hydrology, i.e. the quantity of water availability with respect to time [6]. Also the success and failure of infrastructure depends on the how the hydrology of the area has been studied and what values of the hydrological parameters have been used in design. In many engineering applications, the output of the hydrological models, i.e. hydrographs can be used directly or in conjunction with different software for the study of flood related issues, water availability issues, reservoir operation and safety issues, integrated water resources management issues of large basin [7]. All Rainfall-Runoff (R-R) models are the simplified description of the real world system [8].

1.2 Importance of hydrological modeling in Nepal

There is abundant water resource in Nepal. The available potential water resources have not been utilized yet all to meet the demand in various fields such as power production, irrigation, drinking water etc. To estimate the water resources potential for the development, use of hydrological modeling is one of the most popular tools in the world. In Nepal, gauging of runoff in relation with rainfall has not been carried out in general, for majority of watersheds. For the planning, designing and managing of water resources as well as water resources projects within the watershed, flow rates at different points, reaches of the catchment should be estimated [9]. Suitable hydrologic model can be developed and can be calibrated and validated with the use of known rainfall-runoff data of gauged watershed. The calibrated and validated model can be used for the above stated purpose. With this objective, in the present study, HEC-HMS model has been developed for rainfall runoff simulation of the Tamor basin, Nepal. The simulation of runoff can be extremely helpful for watersheds with ungauged stream for planning of hydropower, irrigation and other water related infrastructure projects.

1.3 Objective of the study

- The general objective of the above study is to check the suitability of the SCS-CN based HEC HMS model in the continuous rainfall-runoff simulation for Tamor sub basin.
- The specific objective is to calibrate the HEC-HMS model at Mulghat outlet from 1995-2002 and validate the model from 2003-2007 and then simulate the outflow at ungauged points at each sub-basins of the Tamor river basin.

2. Study Area

The Tamor river basin is located in the eastern part of Nepal. It is a sub-basin of the Koshi river basin. It is located between 26º 51' 30" N to 27º 57' 07" N latitude and between 87º 9' 28" E to 88º 12' 7" E longitude. The basin is bordered by China on its northern part and it forms the border with India on its eastern part. The total catchment area of the basin is 5861 km^2 at the Mulghat gauging station (286m a.s.l). The basin covers Taplejung, Panchthar, Terathum and Dhankuta districts. It is one of the seven sub basins of the Koshi river basin, the largest river basin in Nepal. It begins around Kanchenjunga and joins the Sunkoshi river at Tribenighat to form Saptakoshi river. Upper and lower Tamor, Ghunsa, Mewa, Khorunga, Kabeli and Hewa khola are the major rivers on the Tamor basin.

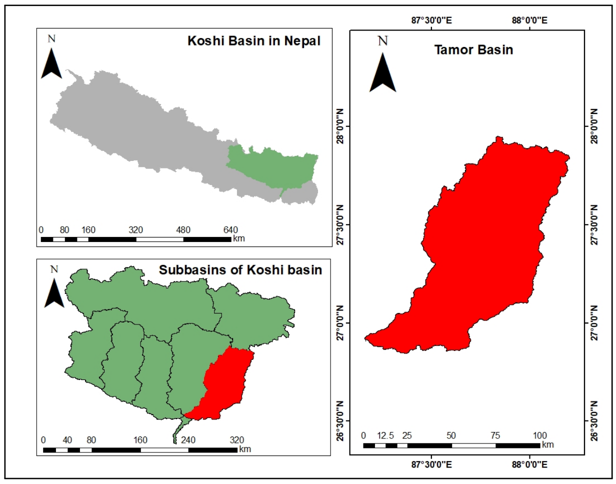

Figure 1: Location map of Tamor basin

The topography of Tamor basin is highly varied. The elevation ranges from 115m to 8107m a.s.l. The basin can be sub divided into three major physiographic regions, namely Middle Mountain, High mountain and High Himalayas.

3. Materials and Methods

3.1 Data Acquisition and Analysis

Data required for hydrologic modeling by HEC-HMS in this study area are:

- Digital Elevation Model (DEM)
- Land use map
- Soil cover map
- Climate data (precipitation, temperature, evapotranspiration)
- Flow Data

A good understanding of the topographical, hydrological and climatic condition of the study area and proper set of data defining them are very important for analyzing and replicating the actual hydrologic and hydraulic situation. Further, the quality of data used for modeling directly affects the output, so the collected data should be screened and processed before using them. The DEM data is preprocessed in arc-GIS by filling sinks before its use in the model application.

3.1.1 Digital Elevation Model (DEM)

Digital Elevation Model (DEM) represented the topographic feature of the study area. For the Tamor basin, a 30 m resolution DEM was downloaded from an open source, USGS. The DEMs acquired for both study areas were refined using tools in HEC-GeoHMS .The DEM of Tamor basin is shown in the Figure 2.

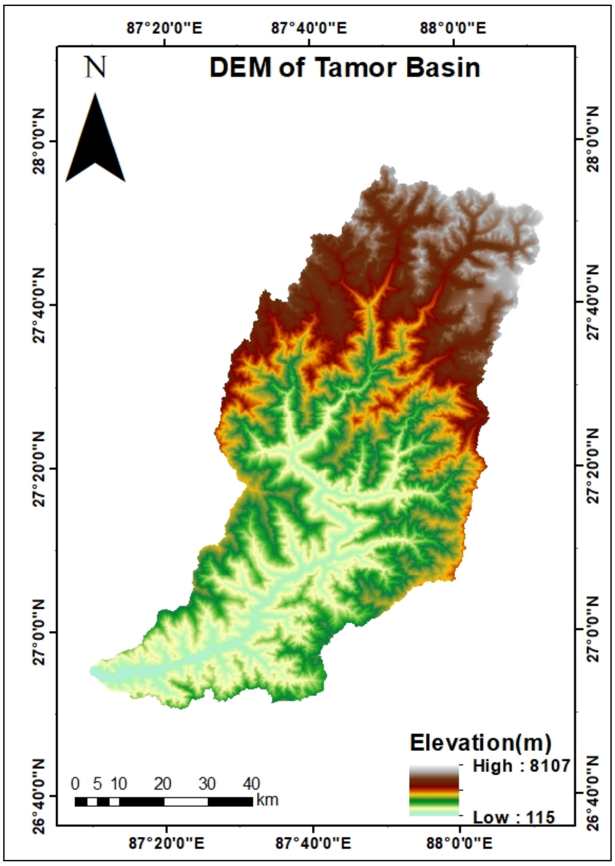

Figure 2: DEM of Tamor basin

3.1.2 Land Use

Land use map for Tamor basin was downloaded from International Centre for Integrated Mountain Development (ICIMOD). As shown in the Figure 3, the land use in the Tamor River basin has been classified into five categories as forest, shrubland, grassland, cropland, water bodies, developed area, barren land and snow bodies. [10]. The basin is dominated by forest and agricultural land whereas built-up area in the river basin is very less.

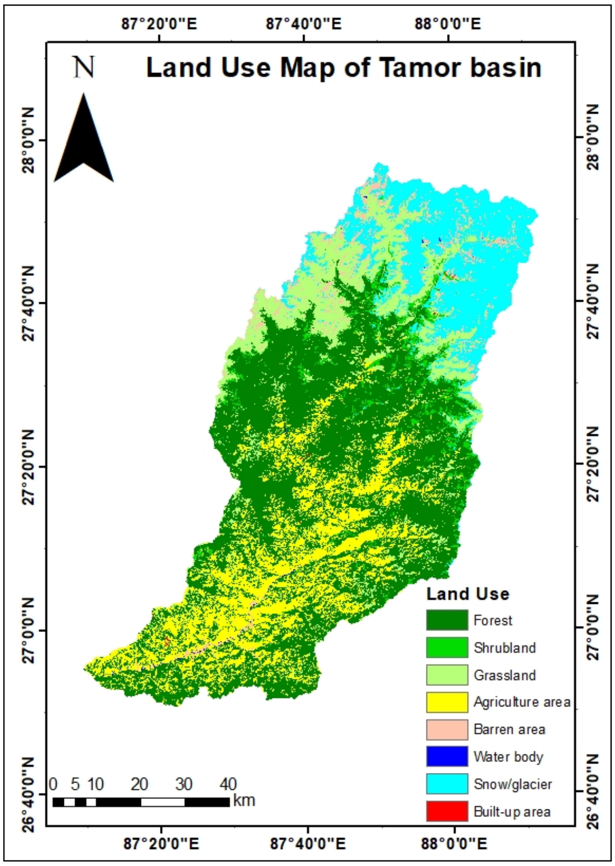

Figure 3: Land use map of Tamor basin

3.1.3 Soil Cover

The Soil cover map of Tamor River basin was clipped from Harmonized World Soil Database (HWSD) prepared by Food and Agriculture Organization (FAO). The HWSD is a 30 arc-second raster database with over 16,000 different soil mapping units that combines existing regional and national updates of soil information worldwide [11]. Soil layers for Tamor basin were categorized into four major classes: Dystric Cambisols, Humic Acrisols, Lithosols and Snow/Glaciers. Soil classification map of Tamor basin is shown in Figure 4.

3.1.4 Climate Data

Climate data includes precipitation ,temperature and evapotranspiration data. For Tamor river basin, climate data were obtained from Department of Hydrology and Meteorology (DHM), Government of Nepal. Data for precipitation was used from ten distributed precipitation gauging stations. Nine stations are located within the study area whereas one station that is outside the basin but very close to the basin has also been considered. Temperature and humidity data were also obtained from climatology

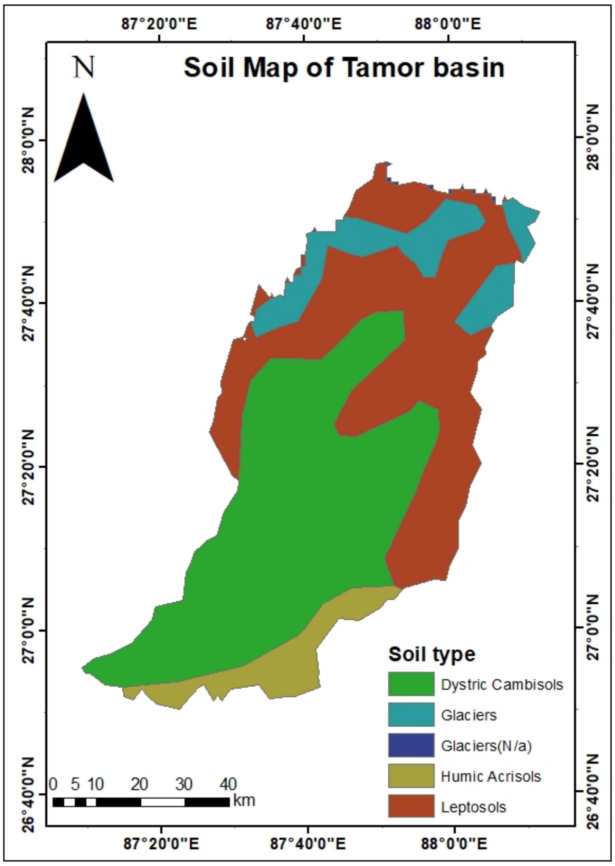

Figure 4: Soil cover map of Tamor basin

stations for the computation of evapotranspiration values. The precipitation stations within the study area that have been considered for the study are shown below. Temperature data for the year 2007 for stations Taplejung (1744m a.s.l) and Dhankuta (1192m a.s.l) of Tamor basin has been shown along with average precipitation of Dhankuta and Terhathum for years 2000-2004. These graphs represent the pattern of rainfall and temperature of the study area. Evapotranspiration data is required for

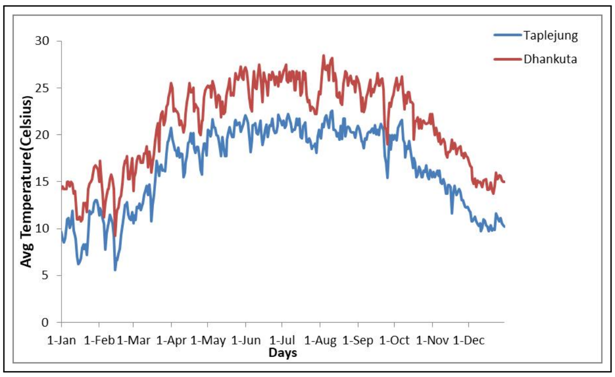

Figure 5: Average temperature in Tamor river basin in 2007

computing the potential evapotranspiration over the

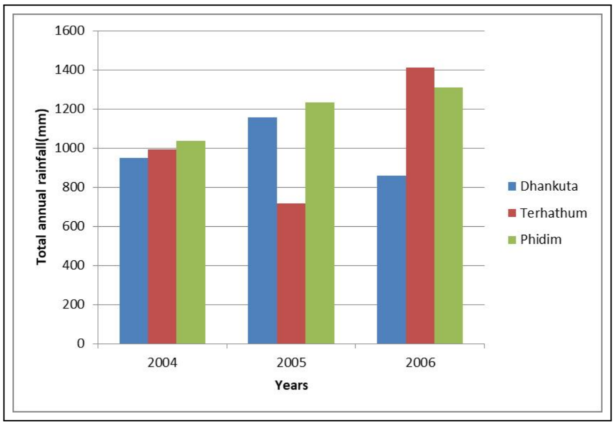

Figure 6: Total annual rainfall in Terhathum and Dhankuta station(2000-2004)

land surface. Evapotranspiration is responsible for returning some portion of precipitation back to the atmosphere. Hence, it is an important component for continuous modeling. For event modeling, it may be omitted. Monthly Average method is the simple method to represent evapotranspiration. CLIMWAT data have been downloaded and the calculation are done in CROPWAT. The monthly average potential evapotranspiration for the basin is shown in the Figure 7.

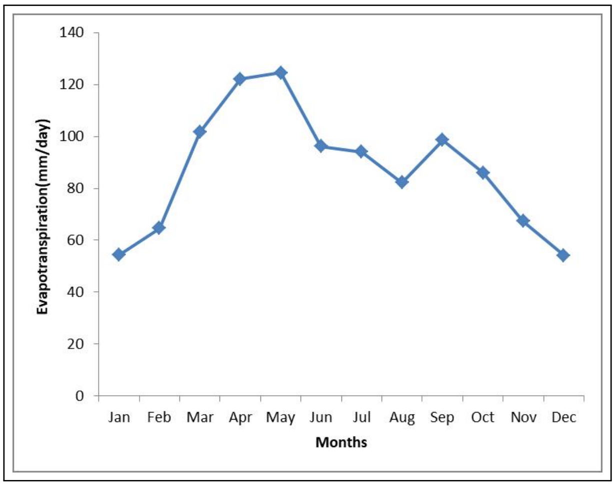

Figure 7: Monthly average potential evapotranspiration of Tamor basin

3.1.5 Flow Data

Daily discharge data were used for the calibration of hydrological model. There are two discharge stations in Tamor River basin namely Manjhitar and Mulghat. Daily discharge data of the Mulghat station from 1995-2007 was considered for calibration and validation purposes in this study. Discharge data was obtained from Department of Hydrology and Meteorology (DHM), Government of Nepal. The maximum flow at river occurs at monsoon season (between June to September) due to heavy rainfall, and the discharge significantly decreases during winter season (between November to February). The peak observed flow of 4862 m3/s has been recorded in 10th August 1997 AD.

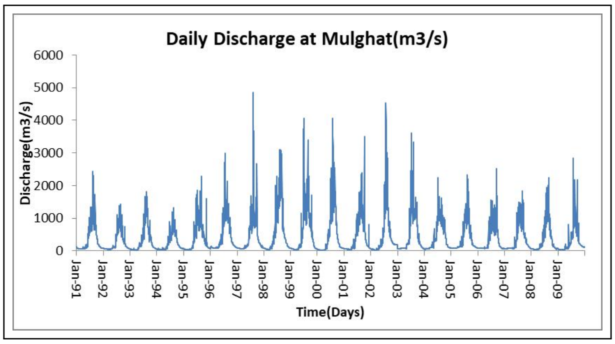

Figure 8: Daily Discharge of Mulghat Station from 1991-2000

3.2 Modeling using HEC-HMS

The study was conducted with numerical simulation with model software Hydrologic Modeing System.It is developed by U.S. Army Corps of Engineering´s Hydrologic Engineering Center that helps in simulating the hydrologic cycle (precipitation, evapotranspiration, infiltration, surface runoff and base flow) of a catchment by describing its physical and meteorological properties. A simple schematic representation of runoff process replicated in HEC-HMS is shown in figure. Varieties of mathematical models for all the hydrological components that conceptually represent watershed behavior are incorporated in this program. The program uses separate model to represent each component of the runoff process like model to compute runoff volume, model of direct runoff/base flow/channel flow as well as alternative models to account for the cumulative losses for e.g.: SCS CN loss model. Then, it computes runoff volume by subtracting losses (infiltration, storage, interception, evaporation etc.) from precipitation. [12]. HEC-HMS 4.3 was used during this project. HEC-HMS uses a separate model to represent each component of the runoff.

- Runoff volume model (Loss model)
- Direct runoff model (transform model)
- Base flow model
- Routing model

Loss model represents the volume of water lost due to interception, infiltration, storage, evaporation, and transpiration. Excess precipitation computed after subtracting losses is transformed into direct runoff by using runoff transform model. Base flow model represents the contribution of groundwater. Routing model computes a downstream hydrograph, given an upstream hydrograph as a boundary condition.

3.3 Methodology Flow Diagram

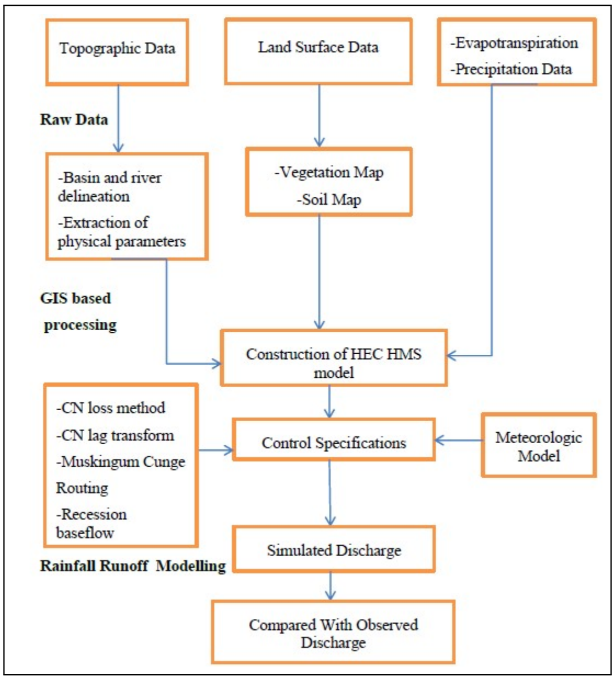

Figure 9: Methodology Flowchart

The research design is shown in Figure 9. First, raw data in the form of topographcal data(DEM), land use, soil cover as well as the precipitation and temperature data was acquired from different sources as explained in the previous section. Then the DEM was processed in Arc-GIS based HEC-Geo-HMS platform in order to deliniate the river and the subbasins. All the physical characteristics of the river such as the reach length, river width,longest flow path, slope etc as well as the physical characteristics of the sub-basin like basin area, basin slope,etc were exctracted in this step.Likewise, for estimation of loss and transform parameters using the SCS CN method, the CN grid was prepared with the use of Land Use and Soil map as shown in figure.Thiessen polygon technique was used to determine the gauge weights and the spatial distribution of rainfall in each subbasin was incorporated to use the HEC-HMS model in a semi-distributed manner. The basin initially was divided into 25 subbasins but for the ease of operation and for physical relevance,the basin was divided into nine subbasins. Then the model was run after inputing all the necessary parameters of loss, transform, baseflow and routing.These results were compared with the observed values at Mulghat outlet and calibration of the parameters was done by first identifying the sensitive parameters.After calibration, the validation was carried and the model performace was analysed using suitable statistical methods.

3.4 Selection of Models

In HEC-HMS, the hydrological procedure of changing rainfall into runoff for this study has been represented by four processes: Loss, Transform, Baseflow and Routing. The following methods were used in this study:

SCS-CN loss method

According to SCS-CN method, the rainfall excess is computed by [13]:

$$P_e = \frac{(P-I_a)^2}{(P-I_a+S)} \tag{1}$$

where

P_e is Accumulated Precipitation excess at time t (mm),

P is Accumulated rainfall depth at time t (mm),

I_a is Initial Abstraction (mm)

S is Potential maximum retention(mm)

From analysis of results of many small experimental watersheds, the SCS developed an imperical relationship of I_a and S

$$I_a = 0.2S \tag{2}$$

For SI system, the maximum retention,S can be estimated as:

$$S = \frac{25400-254CN}{CN} \tag{3}$$

SCS Unit Hydrograph

In this study, the Soil Conservation Service Unit Hydrograph model was chosen to transform excess precipitation into runoff. It is a parametric model based on the average Unit Hydrograph (UH) derived from gauged rainfall and runoff data of a large number of small agricultural watersheds throughout the United States. The SCS proposed the Unit Hydrograph (UH) model, and it is included in the HEC-HMS program. The lag time is the only input for this method. It is the time from the center of mass of excess rainfall to the hydrograph peak and is calculated for each watershed based on the time of concentration T_c, as:

$$T_{lag} = L*0.8\frac{(S+1)^{0.7}}{1900\sqrt{Y}} \tag{4}$$

where

T_{lag} = lag time in hours.

L = hydraulic length of watershed in feet.

Y = watershed slope in percent.

S = maximum retention in the watershed in inches as defined by:

$$S = \frac{1000}{CN} - 10 \tag{5}$$

Recession Baseflow method

The recession model has been used often to explain the drainage from natural storage to a watershed.It defines the relationship of Q_t, the baseflow at any time t,to an initial value as:

$$Q_t = Q_0 * k^t \tag{6}$$

WhereQ_0=initial baseflow,k=an exponential decay constant

Muskingum-Cunge Method

Muskingum-Cunge method has been used for river routing because of its high accuracy over other methods. Muskingum-Cunge routing method is based on simplification of convective diffusion equation which is combination of continuity equation and momentum equation

3.5 Model Setup

To represent the heterogeneity of the hydrological characteristics, the basin is divided into several sub-basins. The sub-basin division is based on the major ungauged rivers of this basin where flow data would be useful. The schematization of the basin for running HEC-HMS model is shown in Figure 10. The schematic consists of 9 sub-basins, 4 reaches and 4 junctions.

4. Results and Discussions

4.1 Sensitivity Analysis

Sensitivity analysis determines how different values of an independent variable affect a particular dependent variable A sensitivity under a given set of

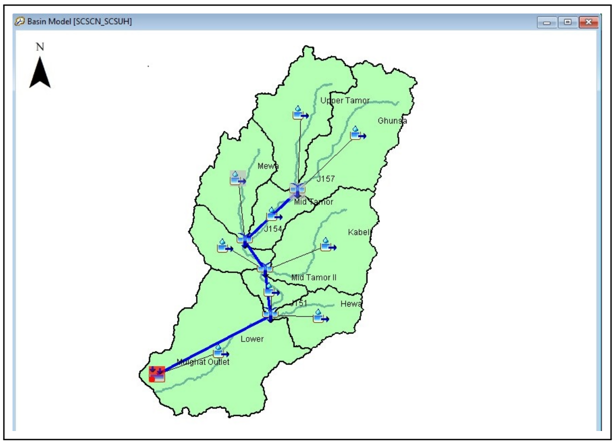

Figure 10: HEC-HMS schematic for Tamor basin

assumptions. The impact of each parameter was determined through a sensitivity analysis. The value of each parameter was increased by 10%, holding the other parameter values constant, and the percent change in the total discharge volumes at the outlet of the whole sub-basin was recorded. The average percent change values are shown in Figure 11. The positive values indicate that a 10% increase in the parameter led to an increase in the discharge at the outlet of the sub-basin, while the negative values indicate a reduction in the discharge at the outlet of the sub-basin. Based on this analysis, varying the baseflow recession constant(k) had the highest impact, while varying the manning's n value had the lowest impact on the total streamflow discharge.

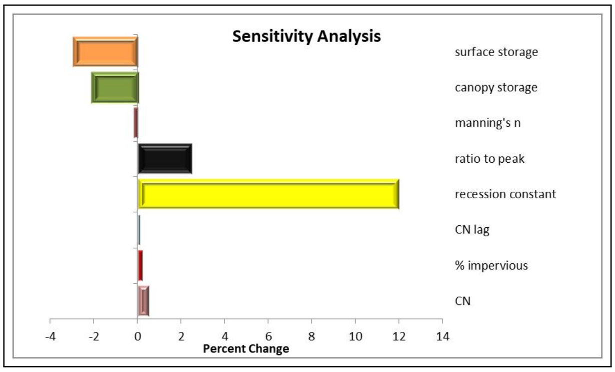

Figure 11: Sensitivity Analysis

4.2 Calibration and Validation results

Manual and automatic calibration techniques were applied to estimate values of the parameters. After Calibration at Mulghat station (which is the outlet of the basin), total simulated outflow volume was found to be almost equal to the total observed volume. As seen in figure , the outflow pattern for calibrated years more or less accurately represents the observed flow. Low flows during non-monsoon periods are found to be almost similar in both the observed and simulated hydrographs. The time of the peak flow simulated during the calibration period matches the time of peak observed at the flow gauging station. However, the extreme peaks seen in observed flow are due to flash floods i.e. for a very short period and are underestimated by the model. Except those peaks, the HMS model is successfully able to represent almost all the peaks at Mulghat station with great accuracy. Failure to capture all the peak flows is mainly due to sparsely distributed precipitation gauging station and inability to feature varying climatic scenario within the basin. Thiessen Polygon Method is used for spatial distribution of rainfall in this model. However, this method was more suitable for flat terrain rather than hilly areas. Therefore, some ambiguities in the simulated flow might be due to error in spatial distribution of rainfall. **Coefficient of determination**

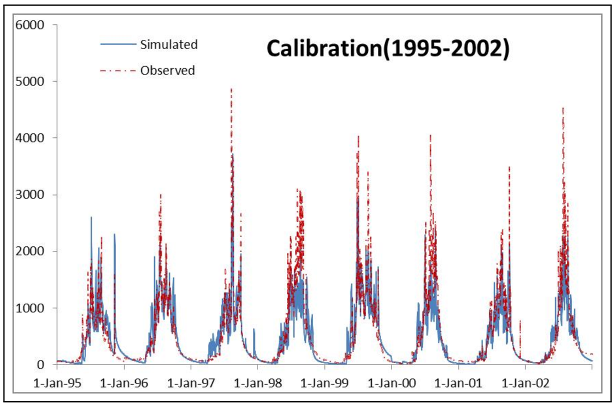

Figure 12: Calibration Hydrograph

describes the proportion of the variance in measured data explained by the model. r2 ranges from 0 to 1, with higher values indicating less error variance. The model obtained the r square value of 0.78 for daily time step, which further supports the success of the model during calibration period.

For validation,The calibrated parameters were kept the same and the model was run for the year 2003-2007. The hydrograph below shows the comparison of observed flows with the simulated flows during validation period. Like the calibration period, the model was successfully able to predict the flow pattern of the basin during validation period. The observed flows are shown with the dotted red line and the simulated flows are shown with the solid blue line as shown below: From the hydrograph it can be seen that the model has simulated the peak flows better

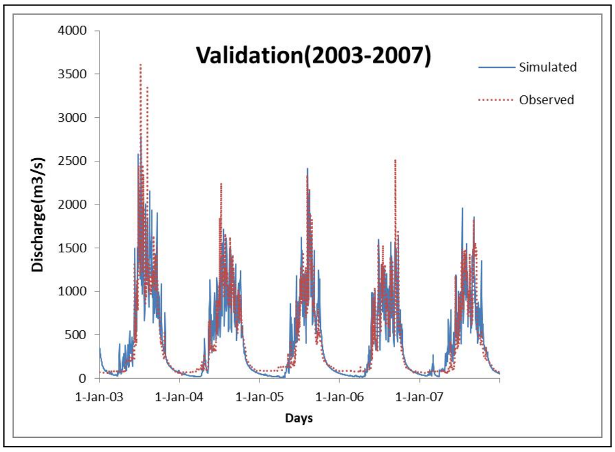

Figure 13: Validation Hydrograph

than the calibration period though it has overestimated the low flows in some periods. Statistically, the results of the validation period are better than the calibration period. The NSE for the validated years was found to be 0.8. The total simulated volume is 11648.24 mm while the total observed volume is 10845.95 mm. Hence, for the validation period, the model slightly overestimates the volume as compared to the calibration period. The PBIAS for the validation period was found to be -7.46%.

4.3 Model Parameters

The SCS Curve Number grid as shown in figure14 was obtained by the use of land use and soil map of the basin. This CN grid helped in the deterination of the SCS CN loss parameters and the SCS UH parameters which are tabulated below:

Table 1: Curve Number for Sub-basins

Basin Name	Basin Area (sq km)	CN
Ghunsa Subbasin	1000	89.8
Upper Tamor Subbasin	770	84.8
Mewa Subbasin	578	72.8
Mid Tamor Subbasin	277	65.9
Kabeli Subbasin	887	71
Khorunga Subbasin	309	68.8
Hewa Subbasin	369	71
Mid Tamor-2 Subbasin	165	72
Lower Tamor Subbasin	1504	69

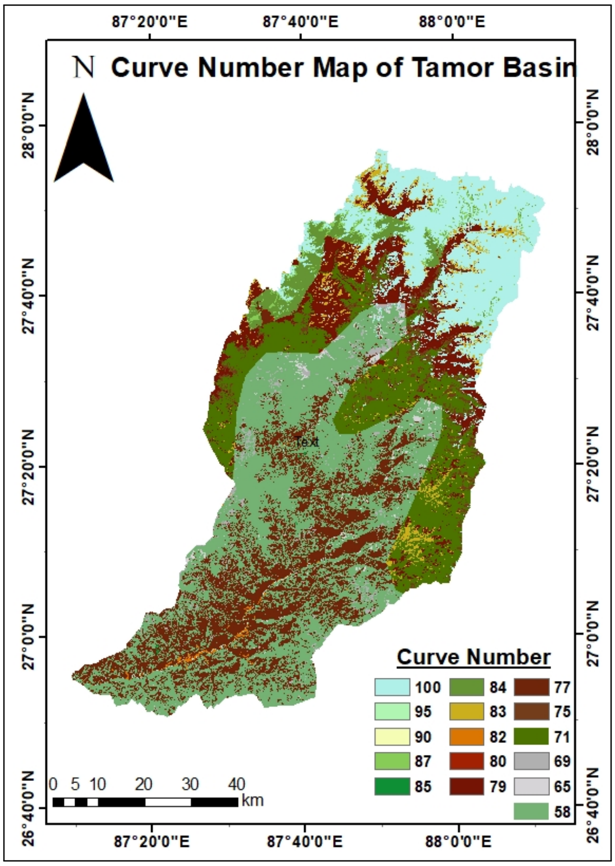

Figure 14: CN grid of Tamor basin

Table 2: CN lag time results

Subbasin	L(feet)	S	Lag(min)
Ghunsa	237749.4	1.9	577.6
Upper Tamor	205311.7	4.0016	673.2
Mewa	161263.1	1.1	499.9
Mid Tamor	121919.3	5.5	471.2
Kabeli	197303.2	4.4	549.3
Khorunga	131243.4	5.1	457.4
Hewa	132982.3	4.4	273.8
Mid Tamor-2	88664.7	4.1	455.9
Lower Tamor	269357	4.8	847.6

4.4 Performance Analysis

4.4.1 Performance analysis on annual mean flow

The simulated annual mean stream flow that occurred at the outlet of the basin in response to the modeling during calibration and validation period is shown in Figure 15. The annual mean flow obtained was almost similar to the predicted flows. The maximum annual mean flow deviation of 91.39 m^3 is observed in year 1998 and the minimum annual mean flow deviation of 9.14 m^3 in year 2007. It is seen the deviation is lesser in validation period as compared to calibration period,

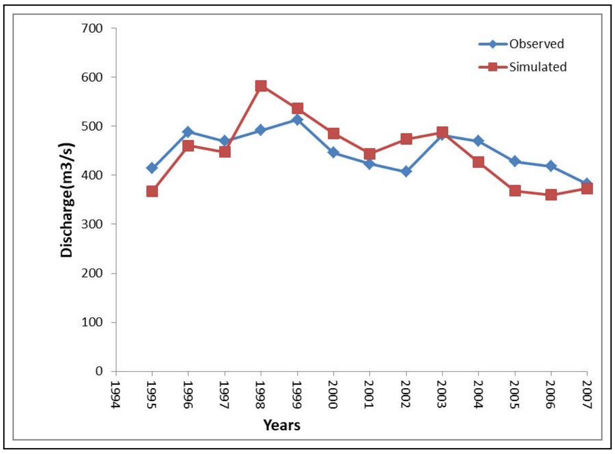

Figure 15: Performance analysis on mean flow

which also shows the model is working well in validation period as compared to calibration period. The observed vs simulated annual mean flow that occurred at the outlet of the basin is presented in table below:

Table 3: Mean Flows at outlet

Year	Observed(m3/s)	Simulated(m3/s)
1995	413.8	367.4
1996	488.2	460.2
1997	469.8	447.7
1998	491.4	582.8
1999	513.4	536.2
2000	445.7	485.6
2001	423.1	444.1
2002	406.8	473.6
2003	481.7	487.6
2004	469.4	426.3
2005	427.7	367.9
2006	418.5	359.7
2007	382.3	373.1

4.4.2 Performance analysis on peak flow

The simulated peak stream flow that occurred at the outlet of the basin in response to the modeling during calibration and validation period is shown in Figure 16. The time of peak in simulation is same to the observed time of peak in calibration and validation periods. However, it is observed that the peak value of the simulated discharge is under predicted in the model as compared to the observed discharge of the outlet station with maximum deviation in the range of $2000m^3$/s in 2002 and minimum deviation in the range of 173 m^3/s in 2005 AD.

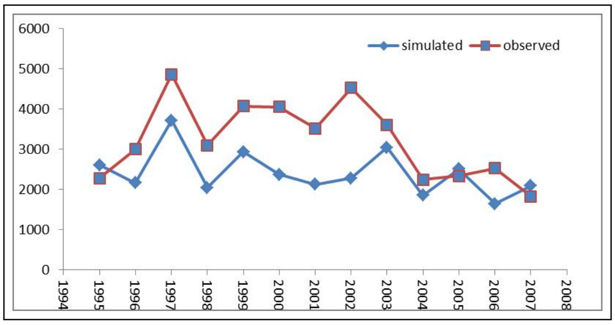

Figure 16: Performance analysis on peak flow

Summary of results

Table 4: Calibration and Validation Summary

Performance Factor	Calibration (1995-2002)	Validation (2003-2007)
NSE	0.765	0.8
PBIAS	2.42	-7.46
R-square	0.78	0.82

4.5 Flow simulation of Subbasins

The outlet point of any sub basin is one of the most important points for the estimation of river flow. Most of the infrastructure projects select the points nearby the outlet for the feasibility analysis of hydropower, dam, bridge, etc. Based on the calibration and validation of hydrological model of Tamor river basin using HEC-HMS, the estimated river runoff of major sub-basins has been represented by the graphs in following subsections.

4.5.1 Flow simulation of Upper Tamor subbasin

The upper tamor subbasin has a catchment area of 770.75 sq km. It lies in the north western part of Tamor basin. From the name of the sub basin itself, it is clear that the tamor river is the major river of this sub-basin. Most of the area in this basin is covered with snow and impervious rocks. The peak simulated flow is 633.5 m^3/s on July 1, 2000 AD. The mean annual flow of this basin is 84.5 m^3/s. The time series discharge simulated by the model for the upper tamor sub-basin is shown in Figure 17.

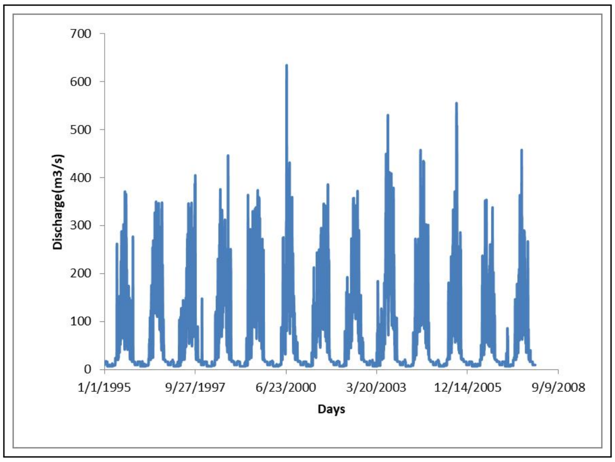

Figure 17: Flow simulation of Upper Tamor subbasin

4.5.2 Flow simulation of Ghunsa khola subbasin

Ghunsa khola sub basin is located on the north eastern part of the basin. The sub basin has topographical features similar to that of the upper Tamor sub basin. The total catchment area of the sub basin is 1000.74km^2. The time series discharge simulated by the model for the Ghunsa sub-basin is shown in Figure 18.The peak flow simulated is 814.8m^3/s on 1st july,2000 AD. The annual mean flow as simulated by the model is 77m^3/s.

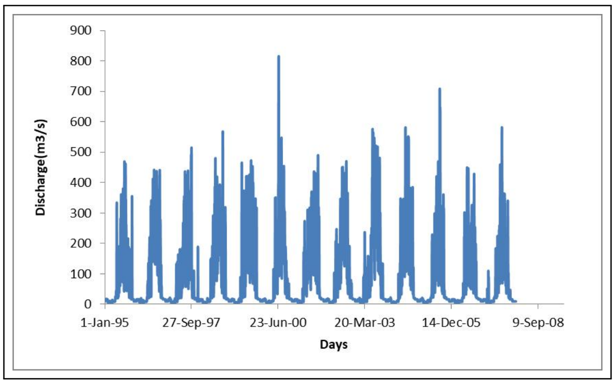

Figure 18: Flow simulation of Ghunsa subbasin

4.5.3 Flow simulation of Kabeli khola subbasin

Kabeli khola sub basin has a catchment area of 886.9 sq km. The sub basin is located in the lower north eastern area of the whole basin. This subbasin has forest and shrubland as the major land cover. The peak flow simulated by the model for the sub basin is 532.7m^3/s on 11 July,1996. The mean annual flow is 89 m^3/s.

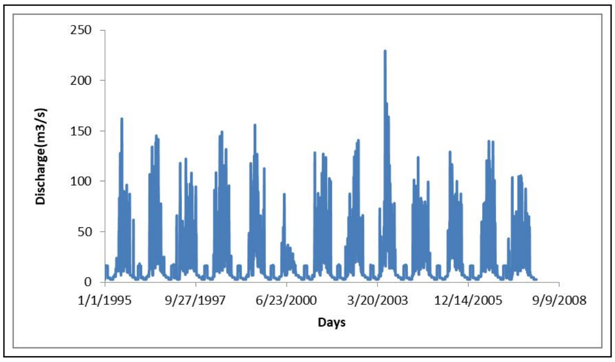

Figure 19: Flow simulation of Kabeli subbasin

5. Conclusions and Recommendations

5.1 Conclusion

In this study, the hydrological model of Tamor basin was prepared in HEC-HMS in order to check the suitability of the model in performing rainfall-runoff simulation and to analyze the effect of rainfall on surface runoff and peak discharges. SCS curve number method was adopted for evaluating infiltration loss, SCS unit hydrograph was used for transforming excess runoff, recession baseflow method was used for modeling the baseflow and Muskinghum Cunge method of channel routing was adopted. Evapotranspiration, canopy and surface storage losses were also quantified. The sensitive parameters that affected the model performance the most were identified. Baseflow recession constant and surface storage values were the most sensitive parameters.

Thus, the HEC HMS model was successfully able to perform hydrological modeling with good accuracy as backed up by the statistical performance evaluation methods. The NSE for calibration period of 1995-2002 is 0.765 which indicates high efficiency of the model, the PBIAS in volume is 2.42% which indicates highly accurate estimation of flow volume and the r^2 is found to be 0.78 which represents a good linear relationship. Similarly, for the validation period, the NSE is improved to 0.8, PBIAS is -7.46% and r^2 is 0.82. In general the performance of continuous simulation of rainfall-runoff process using HEC-HMS model for the Tamor basin is found satisfactory. However the peak flows were under predicted in some cases, which is a common limitation of hydrological models. The simulated flows at the ungauged outlet points of the major rivers of the Tamor basin, namely Upper Tamor, Kabeli, Khorunga and Ghunsa are also obtained. As there are many ungauged rivers located in similar zones of Nepal, this approach can be reliably applied in order to simulate river flows in the rivers lying in such zones.

5.2 Recommendations

The HEC HMS model can be used for modeling and projection of future impacts of climate changes on runoff for Tamor river basin and can be applied to other catchments with similar hydro-meteorological and land use characteristics. Flows simulated at ungauged points using this model can be used in planning and management of water resources at that location. Further studies using recent data can be done in the basin to analyse the effects of climate and land use changes in the hydrology of Tamor basin.

References

[1] IPCC Climate Change. Impacts, adaptation and vulnerability. fourth assessment report. *Synthesis report*, 2007.

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

[3] Serena Ceola, Alberto Montanari, Tobias Krueger, Fiona Dyer, Heidi Kreibich, Ida Westerberg, Gemma Carr, Christophe Cudennec, Amin Elshorbagy, Hubert Savenije, et al. Adaptation of water resources systems to changing society and environment: a statement by the international association of hydrological sciences. *Hydrological Sciences Journal*, 61(16):2803–2817, 2016.

[4] J Vaze, P Jordan, R Beecham, A Frost, and G Summerell. Guidelines for rainfall-runoff modelling. *Australian Government Department of Innovation, Industry, science and Research*, 2012.

[5] ZX Xu and JY Li. Short-term inflow forecasting using an artificial neural network model. *Hydrological Processes*, 16(12):2423–2439, 2002.

[6] Ram Chandra Paudel, Keshav Basnet, and Bikash Sherchan. Application of hec-hms model for runoff simulation: A case study of marshyangdi river basin in nepal. In *Proceedings of IOE Graduate Conference*, 2019.

[7] Jeevika Khadka and Jagritee Bhaukajee. Rainfall-runoff simulation and modelling using hec-hms and hec-ras models: Case studies from nepal and sweden. *TVVR 18/5009*, 2018.

[8] Hamid Moradkhani and Soroosh Sorooshian. General review of rainfall-runoff modeling: model calibration, data assimilation, and uncertainty analysis. In *Hydrological modelling and the water cycle*, pages 1–24. Springer, 2009.

[9] MR Kafle. Rainfall-runoff modelling of koshi river basin using hec-hms. j hydrogeol hydrol eng 8: 1. *of*, 9:2, 2019.

[10] ICIMOD. Regional database system. https://rds.icimod.org/Home/DataDetail?metadataId=9224, 2020.

[11] ISRIC. Soil and terrain database programme. https://www.isric.org/projects/soil-and-terrain-soter-database-programme, 2020.

[12] 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.

[13] Arlen D Feldman. Hec hms technical reference manual. *CPD-74B US Army Corps of Engineers. March*, 2000.