Proceedings of 11th IOE Graduate Conference
Peer Reviewed
ISSN: 2350-8914 (Online), 2350-8906 (Print)
Year: 2022 Month: March Volume: 11

Characterizing the Hydrologic Response of a Mountainous Basin: A Case Study of Marsyangdi River Basin

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Abstract

Understanding the hydro-climatic conditions and rainfall-runoff behavior in a data-scarce mountainous river basin has been a challenging issue for hydrologists and planners. In this study, Soil and Water Assessment Tool (SWAT) has been used to characterize the hydrological responses of Marsyangdi basin at spatial and temporal scale, indicated by the water balance components. Flow, climate, topography, land use and soil type data along with their indicator (parameters) are used as model input to simulate the hydrological responses inside the basin. The basin was discretized into 27 sub-basins and 334 hydrological response units (HRUs). Calibration and validation were carried out at two hydrological stations, namely Bhakundebesi and Bimalnagar, using 13 years daily streamflow data. TLAPs (snow related parameter) was found to be most sensitive to streamflow in this snow-fed river basin. The hydrological model performance ranked “very good” during entire simulation period as indicated by the values of three statistical indicators: Nash–Sutcliffe efficiency (NSE), percent bias (PBIAS), and coefficient of determination (R^2). The low flows have been well captured at both station during the entire simulation. Average annual water yield and evapotranspiration of the basin constitutes 65% and 27% of the precipitation (2157.5mm). The maximum and minimum flow occurs at August and March respectively. Higher water yield was observed in the central part of the basin. This study demonstrated the applicability of SWAT in mountainous river basins with complex topography and diverse hydro-climatic conditions. Our results are useful for planners and decision makers in developing strategy for the development of water resource sector of the basin.

Keywords

Hydrological model, Marsyangdi, mountainous basin, simulation, SWAT

1. Introduction

1.1 Background

Geo-physical environment and hydro-climatic conditions controls the characteristics of the river basins [1]. Due to the steep topography, fragile geology, climate variability, and many other factors, hydrology of Himalayan river basin is complex [2]. Nepal has many fast-flowing rivers and rivulets flowing from north to south direction originating from mountains and hills. These rivers not only carry the discharge but due to complex geometry and many type of land distribution, reasonable amount of sediment is also carried by different rivers. The hydrological alteration and variations are causing problems to the water resources planner. Due to the limited resources and studies as well as lack of proper planning in the water resources management and its sustainable use, the water related projects are facing different problems after the operation of these projects. Water resources planner are facing complexity in acquiring knowledge and understanding the mountain hydrology. Due to the urbanization, deforestation and many other human related activities, natural calamities such as landslides, hydrological alteration and soil erosion are increasing in a moderate rate. These natural disasters as well human related activities have directly impacted in the flow and sediment discharge of respective rivers inside a catchment. The spatio-temporal variability in climate variables has also contributed in the alteration of the hydrology.

Climate change and variability impact the river hydrology, and the studies suggest that the impact is intensifying [3][4]. Studies projected warming temperature in the future and higher flow in wet

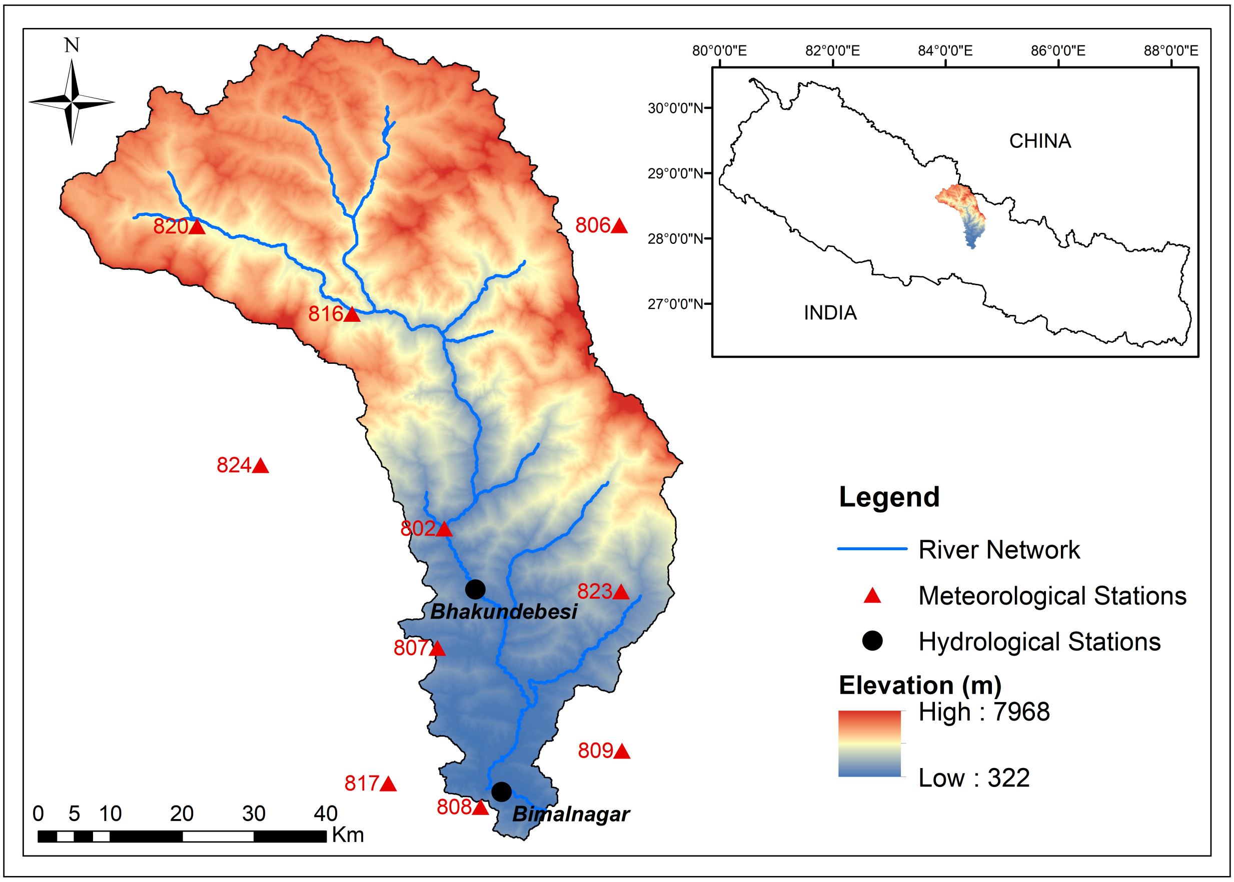

Figure 1: Study area map showing the location map and topography of Marsyangdi river basin

season but, reduction in dry season flow [5][6]. There are many hydropower and irrigation projects existing in the river which are directly impacted by the characteristics of basin, climatic extremes, hydrology and sedimentation. Therefore, a proper study of catchment regarding its possibilities of flow and sediment discharge under different circumstances is of utmost importance for planning water resource development.

For characterizing the hydrologic response of a watershed, widely used landscape indicators include drainage area, channel length, channel slope, forested area and relief ratio [7]. Many researchers and policy makers demand the model that can be easily parameterized and that can simulate both water quality processes and hydrology at the basin scale. But these models need parameter values that reflect the effect of soil, geology, topography, land use and land cover on the hydrologic response. Hence physically based models that can characterize the hydrologic response of a basin with the soil related, climate related, landscape related, geology related and others indicators are being used for simulation and analysis over the empirical and statistical models. The model that performs under the fundamental hydrology equation (water balance equation) can be more reliable for hydrological response simulation in a basin. Researchers used Soil and Water Assessment Tool (SWAT) as an effective tool to model impacts of climatic change on hydrologic and biogeochemical cycles in a variety of watersheds [8]. As a physically based model, SWAT uses hydrologic response units (HRUs) to describe spatial heterogeneity in land cover and soil types within a watershed. The model estimates relevant hydrologic components such as surface runoff, water yield, lateral flow, and evapotranspiration for each HRU. SWAT includes snow melting and lake/wetland algorithms, which enhances it's applicability in snow-covered and glaciated mountainous regions.

Several studies explored the climate changes impact in hydrology of the Nepali and Indian basin using hydrological modeling tool [9][10][11][12]. Some other researchers used hydrological modeling tool to find out the spatio-temporal water availability and hydrological characteristics of the complex mountainous basins [13][14]. In this study, we characterized the hydrological response of

Marsyangdi basin using hydrological model and also analyzed the spatiotemporal distribution of major water balance components.

1.2 Study Area

Marsyangdi basin is selected as the study area for the application of the hydrological modeling. It is one of the major tributaries of Gandaki River Basin. It lies in the Gandaki Pradesh of Nepal having upper elevation of 7968 masl and lower elevation of 168 masl. So, it is a mountainous basin having average basin slope 29.42° and basin area of 4120.34 km^2. The snow fed Marsyangdi river flowing in the basin begins from the two mountain rivers confluence, the Jharsang khola and the Khangsar khola above 3600 m elevation, northwest of Annapurna range and joins with the Trishuli river at Mugling after covering the flow length of 150 km. At higher altitudes Polar frost type climate is found and at the lower belt Tropical Savannah type climate is found [15]. This basin contains different large hydropower projects in operational phase such as Middle Marsyangdi (70 MW), Lower Marsyangdi (69 MW), Upper Marsyangdi (50 MW). Other hydropower projects located in the tributaries like Nyadi, Midim, Chepe, Dordi and Daraudi are also in the phase of operations. The study and construction are ongoing for other large hydropower projects such as Manang Marsyangdi (135 MW), Lower Manang Marsyangdi (140 MW), Upper Marsyangdi 1 (138 MW) and so on. The basin is one of the major sources for the hydroelectricity generation in Nepal. Understanding of hydrology is the most crucial and a pre-requisite for planning and development of water resource infrastructures. This insinuates the importance of hydrological modelling and analysis for water related infrastructure development under different scenarios and period of times.

2. Materials and Methods

2.1 Datasets

2.1.1 Topography Data

We selected Digital Elevation Model (DEM) of 30 m resolution from ALOS PALSAR for the study. The DEM was then processed and analyzed in ArcGIS 10.3 before proceeding. The impact of DEM resolution and source did not have significant influence on the SWAT model results for Nepal [16]. The processed DEM that we used for watershed delineation in hydrological modeling is shown in the Figure 1.

2.1.2 Land Use/Cover (LULC)

The land use map used for this study was obtained from ICIMOD [17]. Land use map of year 2010 was used for hydrological modelling as per the requirement of simulation period. The basin occupies more than 25 % of the snow-covered mountains. The grassland (18.8%) and snow cover (29%) occupy more than 47% of the total land area of the basin, which is followed by barren land (13%). The forest area in the basin covers almost 24.3% of the total basin area. The other land cover types are agriculture (10.8%), shrubland (3.9%), water bodies (0.5%), and built-up (0.4%). The basin is located in a remote area of the country and is less impacted by human intervention (built-up area nearly 0.4%). The runoff, soil erosion and evapotranspiration are affected majorly by the landcover of the area. Around 29% of the area is covered by glacier which created major possibility of direct runoff during rainfall in these areas as the impervious area is greater.

2.1.3 Soil Map

The soil map (scale 1:1 million) was collected from the Soil Terrain Database (SOTER) [18]. It was then processed in ArcGIS 10.3. First the downloaded map was clipped for the study area and it was converted to raster form and was projected to the MUTM84 coordinate. This final projected map (Figure 2) is used for modeling the streamflow in basin. Marsyangdi basin has 8 soil types, with Gelic Leptosols (soil texture clay loam) as the dominant soil type.

2.1.4 Precipitation Data

Precipitation data is the major input data of the modeling. The precipitation data for this basin was obtained from the Department of Hydrology and Meteorology (DHM), Nepal. There are five meteorological stations located inside the Marsyangdi basin namely Manang Bhot, Chame, Kunchha, Gharedhunga and Khudi and three stations namely Larke Samdo, Ranipauwa and Gorkha were outside the Basin (Figure 1). We applied Normal Ratio method for filling the missing precipitation data. The collected data are analyzed, studied and prepared but only daily timeseries from 2000 to 2012 was used for the study. The climate stations are listed in Table 1. Average precipitation of basin is shown in Figure 4.

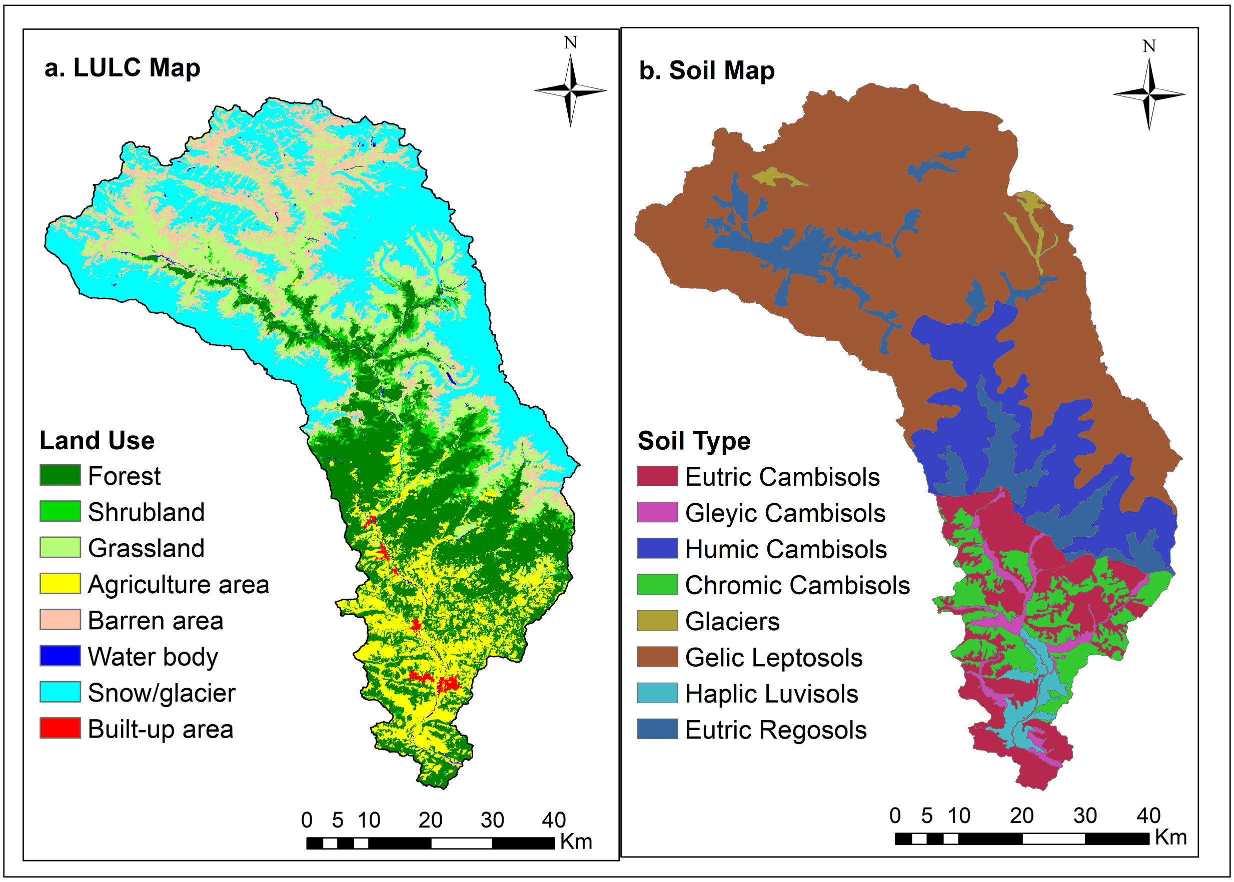

Figure 2: LULC and Soil Map of Marsyangdi Basin

2.1.5 Temperature Data

The temperature data was obtained from the Department of Hydrology and Meteorology (DHM), Nepal. Chame and Khudi are among the two temperature stations located inside the Marsyangdi basin. We analyzed these data from years 2000 to 2012 for hydrological modeling. Figure 3 shows the temperature data range of Chame station inside the basin.

2.1.6 Discharge Data

We collected daily discharge data for Marsyangdi basin from the DHM, Nepal. There were four hydrological stations located inside the Marsyangdi basin but only Bhakundebesi station (station no.439.35) and Bimalnagar station (station no.439.7) were used for the calibration and validation of the model. The data of these two stations were collected for several years but after the data assessment, only data from 2000-2012 were used for the study. Figure 4 shows that from June to August maximum flow at river occur due to heavy rainfall; the discharge significantly decreases during winter season (between November to February) and discharge slightly increases (between March to May) due to melting of snow.

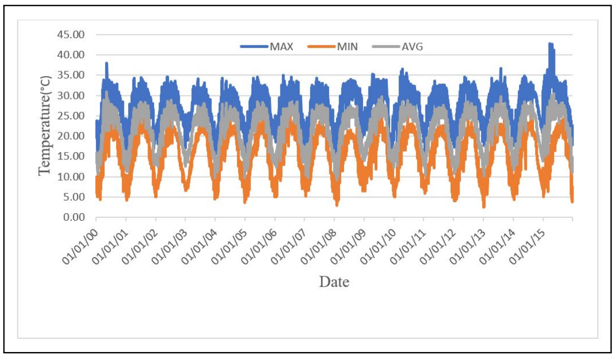

Figure 3: Maximum, Minimum and Average Temperature observed at Chame station

2.2 SWAT Model

Soil and Water Assessment Test (SWAT) is a process based; semi-distributed continuous-time river basin simulation model developed by the United States Development of Agriculture (USDA) [8]. It is used for modelling the streamflow as well as sediment load

Table 1: Precipitation Stations for Marsyangdi Basin

Station ID	Station Name	District	Latitude	Longitude	Elevation(m)
802	Khudi	Lamjung	28° 10’ 12”	84° 13’ 12”	823
806	Larke Samdo	Gorkha	28° 24’ 00”	84° 22’ 12”	3650
807	Kunchha	Lamjung	28° 04’ 48”	84° 12’ 36”	855
809	Gorkha	Gorkha	28° 00’ 00”	84° 22’ 12”	1097
816	Chame	Manang	28° 19’ 48”	84° 08’ 24”	2680
820	Manang Bhot	Manang	28° 24’ 00”	84° 00’ 36”	3420
823	Gharedunga	Lamjung	28° 07’ 12”	84° 22’ 12”	1120

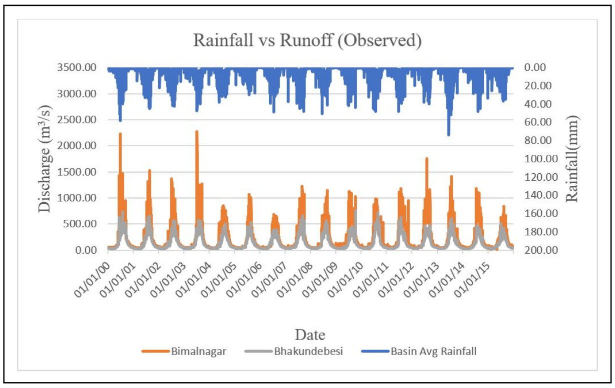

Figure 4: Observed Daily Discharge and Precipitaion Data

and nutrient yield in a catchment [19][20][21]. SWAT Model consists of a SWAT Project Setup, Watershed Delineator, HRU Analysis, Write Input Tables, Edit SWAT Input and SWAT Simulation. The basin is divided into a number of subbasins. Further discretization of sub-basins into a number of hydrologic response units (HRUs) is done. HRUs are formed with the combinations of soil map, land use map and slope classes provided by a user. The model simulates processes at HRU level and aggregate for each subbasin. The streamflow thus simulated is routed through the river system. Routing methods available are variable storage and Muskingum method. SWAT uses the climate data from station nearest to the centroid of each sub-basin. The SWAT model simulates the various hydrological processes occurring in the river basin based on water balance within the basin as given by equation 1.

$$SW_t = SW_0 + \sum_{i=1}^{t} R_{day} - Q_{surf} - E_a - W_{seep} - Q_{qw} \quad (1)$$

Where, SW_t is the final soil water content (mm),SW_0 is the initial soil water content (mm), t is the time in days, R_{day} is the amount of precipitation on day i (mm), Q_{surf} is the amount of surface runoff on day i (mm), E_a is the amount of evapotranspiration on day i (mm), W_{seep} is the amount of water entering the vadose zone from soil profile on day i (mm), Q_{qw} is the amount of return flow on day i (mm).

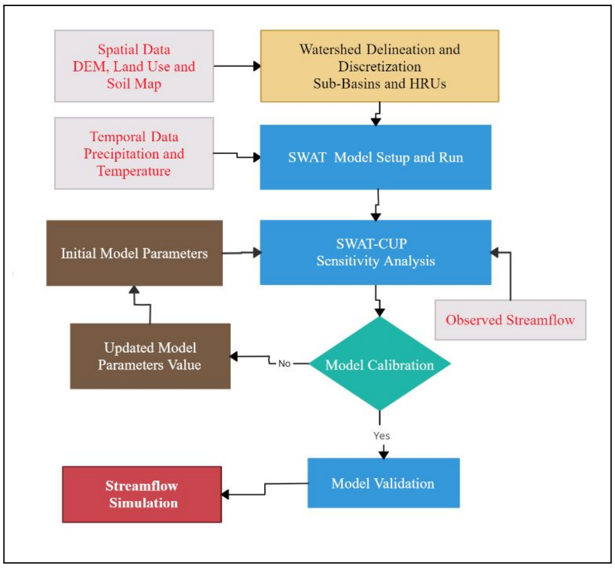

Figure 5: Methodology adopted in the study

2.2.1 Model Setup and Simulation

We used ArcGIS 10.3 and SWAT version 12 as a graphical user interface for modelling hydrology of the Marsyangdi Basin. Using the projected DEM, we delineated Marsyangdi basin into 27 subbasins. Slope classes were divided into five categories. The unique combinations of land use, soil map and slope class formed 334 hydrologic response units (HRUs). Weather data were defined for the Meteorological stations for 2000 – 2012. We selected Hargreaves method for potential evapotranspiration calculation since we didn’t have measured solar radiation, wind speed and relative humidity for this basin. SCS curve number (SCS-CN) method estimated the surface runoff. To initially stabilize the model a warm up period is necessary. The set of initial parameters were selected and the model was run to simulate the streamflow for thirteen years (2000-2012) including four years (2000-2003) as warm up period. The overall methodology of model setup and simulation is shown in Figure 5.

2.2.2 Model Calibration and Validation

The model was calibrated using six years of study period (2004-2009) and validated using remaining three years (2010-2012). We used SWAT Calibration and Uncertainty Program (SWAT-CUP) as a tool for calibration and sensitivity analysis of the basin parameters. Sequential Uncertainty Fitting (SUFI-2) algorithm was selected as calibration method. In SUFI-2, uncertainty applies to all variables and data. This study uses global sensitivity analysis to define the rank of the model parameter. Parameters having larger t-stats and smaller p-values represents greater sensitivity to the optimization function and thus the streamflow.

The Nash-Sutcliffe efficiency coefficient (NSE) (2), percentage bias (PBIAS) (3), and determination coefficient (R^2) (4) are used as performance evaluation indexes to evaluate the quality of hydrological models. These indexes are calculated by following equations:

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Q_{\text{oi}} - Q_{\text{si}})^2}{\sum_{i=1}^{n}(Q_{\text{oi}} - Q_{\text{avg}})^2} \tag{2}$$

$$PBIAS = \frac{\sum_{i=1}^{n}(Q_{\text{oi}} - Q_{\text{si}})}{\sum_{i=1}^{n}(Q_{\text{oi}})} * 100\% \tag{3}$$

$$R^2 = \frac{[\sum_{i=1}^{n}(Q_{\text{oi}} - Q_{\text{avg}})(Q_{\text{si}} - Q'_{\text{avg}})]^2}{\sum_{i=1}^{n}(Q_{\text{oi}} - Q_{\text{avg}})^2 \sum_{i=1}^{n}(Q_{\text{si}} - Q'_{\text{avg}})^2} \tag{4}$$

where n is the number of the data values; Q_{oi} and Q_{si} are the observed and simulated values at month i, respectively; and Q_{avg} and Q'_{avg} are the mean values of the observed data and simulated values, respectively. The PBIAS was used to evaluate the overall deviation between the simulated and observed values. The smaller the absolute value of PBIAS, the closer the total value of the simulated value is to the measured value [22]; the R^2 describes the degree of co-linearity and the NSE determines the residual variance between the simulated values and observed values [23]. The closer the two coefficients are to 1, the better the simulated value fit to the observed values.

2.3 Hydrological Responses Characterization

Hydrologic response of a basin is the runoff response of the basin during rainfall, sediment yield response based on land type, soil type and runoff in the basin, evapotranspiration response based on temperature, precipitation in the basin and other similar responses depending upon the different characteristics of the basin. Hydrologic response indicators and landscape-climate indicators in a watershed must be identified and quantified to represent the landscape, climate and hydrologic response. Hydrologic response variables like minimum, maximum and mean flow represents the hydrologic response indicators. Flow duration curve is the most suitable hydrologic response indicator since it synthesizes a lot of response of a watershed [24].

Characterization of hydrologic response can be indicated by the amount of water balance components in the basin. The amount of flow and evapotranspiration based on elevations, latitudinal influence, seasonal variability and spatial variability of water balance components, groundwater flow and flow from snowmelt for a mountainous basin characterize the basin. These results can be interpreted to observe the variation of water availability in different region of basin, low flow and high flow region inside the basin during different seasons and mean monthly flow of the basin.

3. Results and Discussions

3.1 Sensitivity Analysis

To calibrate the SWAT model, we selected 30 initial parameters in accordance with the characteristics of the basin. After 1000 numbers of iterations and sensitivity analysis in SWAT-CUP, 20 sensitive parameters were selected and calibrated until good performance of the model was achieved. Most sensitive parameters are TLAPS, PLAPS, SMFMX, CN2 and SFTMP. Fitted value of calibrated parameters is shown in Table 2. Different sets of parameters were seen to be sensitive in modeling. Surface runoff parameters like CN2 and OV_N impact the surface flow, parameters like LAT_TIME and SURLAG impacts the lateral flow whereas parameters like ALPHA_BF, GWDELAY, GWQMIN, and SOL_AWC impact the baseflow from the basin. There are snow related parameters like snowfall temperature (SFTMP), snowmelt temperature (SMTMP), snow cover (SNOCOVMX), degree-day factors (SMFMX, SMFMN), temperature lapse rate (TLAPS) which are used to calculate the snow component of the total flow.

3.2 SWAT Model Performance

Bhakundebesi station (station no. 439.35) and Bimalnagar station (station no. 439.35) were the two outlet points used for calibration (2004-2009) and validation (2010-2012) of the SWAT model in Marsyangdi basin. The calibration and validation charts of Bhakundebesi Station and Bimalnagar Station are shown in Figure 6 and Figure 7, respectively.

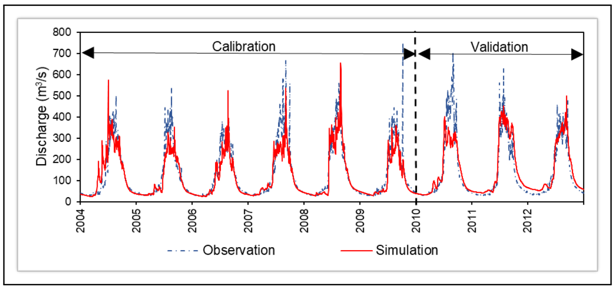

Figure 6: Calibration and Validation of SWAT Model at Bhakundebesi Station (station no. 439.35)

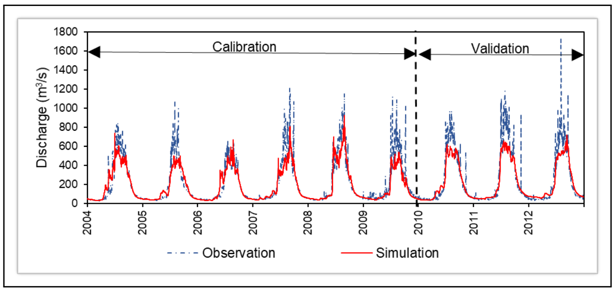

Figure 7: Calibration and Validation of SWAT Model at Bimalnagar Station (station no. 439.7)

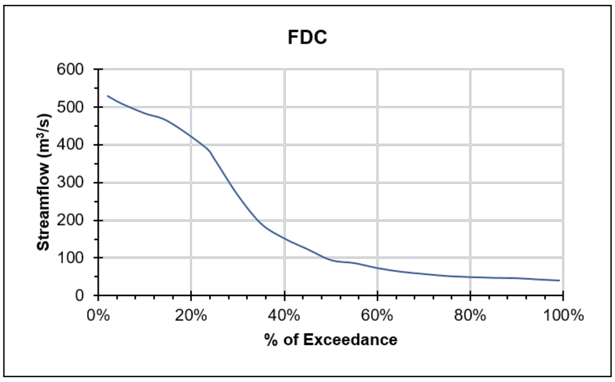

Figure 8: Flow duration curve at basin outlet

We can see from the figures, the base flow at both stations is well captured and peak flow is also captured. The NSE, PBIAS, R^2 values for the calibration period of Bhakundebesi station (station no. 439.35) are 0.82, 8.6, 0.83 respectively. The NSE, PBIAS, R^2 values for the validation period are 0.81, -6.6, 0.81 respectively. The NSE, PBIAS, R^2 values for the calibration period of Bimalnagar station (station no. 439.7) are 0.82, 9.2, 0.84 respectively. The NSE, PBIAS, R^2 values for the validation period are 0.82, 11.3, 0.88 respectively. The model, in general underestimated the flow (up to 11.3%) except a 6.6% overestimation during validation at Bhakundebesi. Based on the criteria prescribed by [25][26], all these indices fall in the 'very good' category. The hydrograph comparison and performance indicators value (Table 3) show that the model is well calibrated and validated and was able to simulate the flow pattern of the Marsyangdi Basin.

3.3 Characterization of Hydrologic Response

3.3.1 Flow Duration Curve

Flow duration curves cover a wide range of flow conditions and provide valuable information about streamflow variability over time [27]. It is also the most suitable hydrologic response indicator. Flow Duration Curve is a widely used tool while designing the water infrastructure in the river basin. We generated FDC at the basin outlet located at the intake of Lower Marshyandi Hydropower Project (Figure 8). The high and low flows corresponding to 5% and 95% exceedance are 508.8 and 42.7 m^3/s, respectively. Mostly, design discharge of the water resource projects is fixed at around 40 to 50 % of flow exceedance. These results can help to suitably estimate design discharge and locate the upcoming water related projects inside the basin.

3.3.2 Spatial Water Balance Variations

We updated the calibrated parameter from SWAT-CUP to the SWAT model and simulated the historical hydrological characteristics of the basin. SWAT computed the streamflow at each outlet and various water balance component at each subbasin level in daily time scale. It was found that the average annual precipitation is 2157.5 mm. Water yield and evapotranspiration constitutes 65% and 27% of the precipitation, respectively. The spatial distribution of these three major water balance components is shown in Figure 9. The spatial variability of water

Table 2: Sensitivity Rankings of Parameters and their Fitted Values from SWAT-CUP

Rank	Parameter	P-value	Lower bound	Upper bound	Fitted Value
1	10: V_TLAPSsub	0.000	-10.00	-4.39	-7.58
2	12: V_PLAPS.sub	0.000	-84.87	245.50	-35.24
3	24: V_SMFMX.bsn	0.006	5.31	10.00	5.74
4	1: R_CN2.mgt	0.010	35.00	86.00	varies
5	26: V_SFTMP.bsn	0.010	-2.79	1.62	-0.37
6	8: R_SLSUBBSN.hru	0.031	-0.09	0.12	0.04
7	18: R_SOL_ALB(..).sol	0.071	-0.20	-0.08	-0.15
8	22: V_CH_K1.sub	0.105	68.66	222.90	165.53
9	5: V_ESCO.bsn	0.179	0.18	0.54	0.45
10	3: V_GW_DELAY.gw	0.204	97.60	292.88	176.00

Table 3: Performance Evaluation Indicators of SWAT Model

	Calibration			Validation		
Hydrology Station	NSE	R^2	PBIAS	NSE	R^2	PBIAS
Bhakundebesi(station no. 439.35)	0.82	0.83	8.6	0.81	0.81	-6.6
Bimalnagar(station no. 439.7)	0.82	0.84	9.2	0.82	0.88	11.3

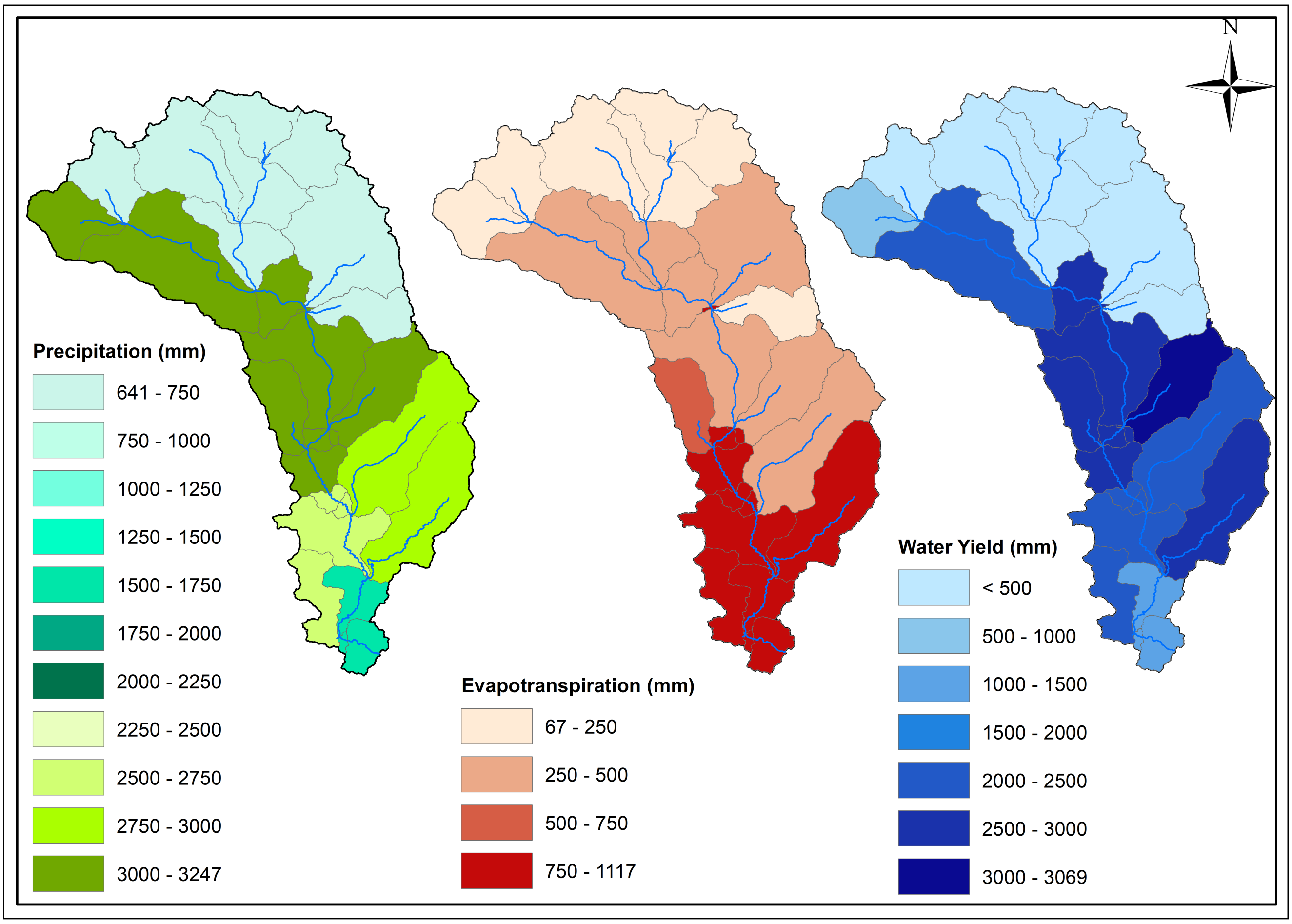

Figure 9: Spatial variability of water balance components

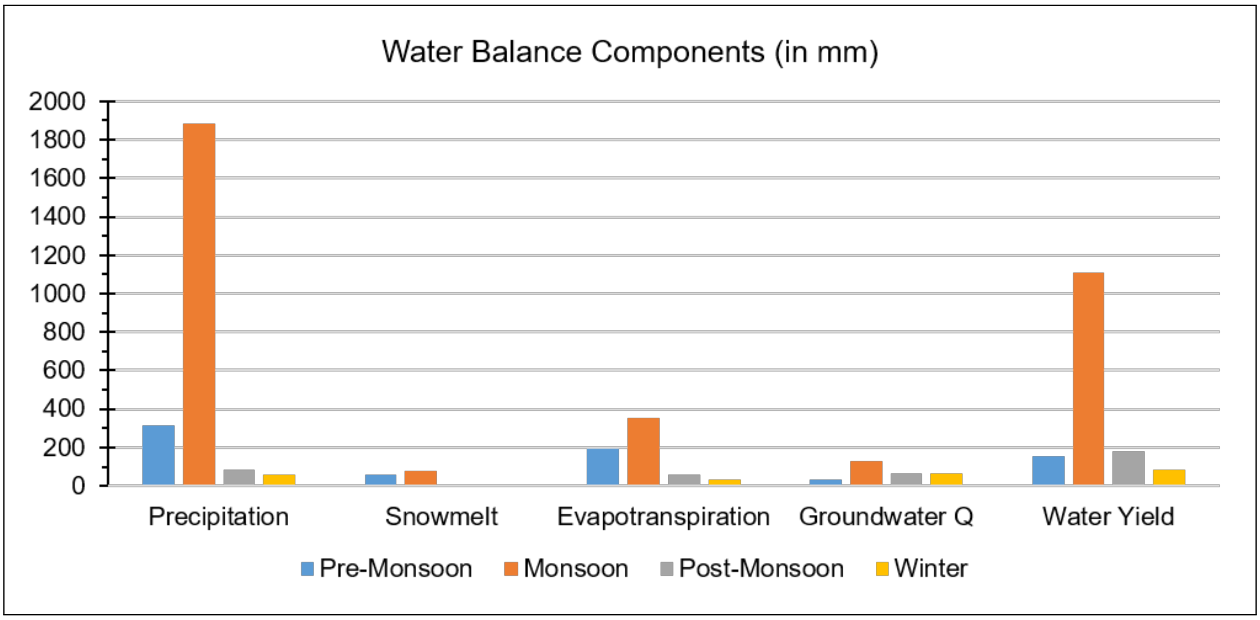

Figure 10: Temporal variability of hydrologic responses of Marsyangdi Basin

availability across the basin shows a greater potential for the development of water resource infrastructure. The elevation difference within small subbasins adds to the hydropower potential of the basin. It can be realized from the growing number of licensed hydropower projects (KW to MW scale) in the tributaries like Nyadi, Midim, Chepe, and Dordi.

3.3.3 Temporal Hydrologic Response Variations

We can observe that the maximum precipitation occurs in the monsoon season followed by pre-monsoon and post-monsoon. The runoff response is found to be maximum in monsoon season followed by post-monsoon and pre-monsoon which indicates that groundwater flow and snow melt flow is contributing to the post monsoon flow (Figure 10). Greater water yield in winter season despite the less precipitation concurs the characteristic of mountainous basin and is indicating that the post monsoon flow is the response of snow melting inside the basin. During pre-monsoon and monsoon season the evapotranspiration and snowmelt is observed to be higher which indicates temperature inside the basin are of greater magnitude at these seasons. In this way the temporal distribution characterizes the hydrologic responses of a basin under different topographic and climatic indicators.

4. Conclusions

Hydrological characterization of the basin could be used for the regionalization of watershed management that helps for planning the water resources projects. This study tested the applicability of SWAT in simulating hydrologic characteristics in mountainous river basins with complex topographic, diverse climatic, land and soil type characteristic within the basin at uniquely combined HRUs level. Land use and soil map are the most important data for defining HRUs. TLAPs was found to be the most sensitive parameter in the basin. Snow, base flow and runoff parameters are thoroughly studied and applied during the calibration of model. The model was then validated using the calibrated parameters. During calibration and validation at both the station, the model performed very well and was ranked as “very good”. The model was able to capture the low flows during the entire simulation period which concludes the appropriateness of the model for future scenario simulations. The average annual values of precipitation, evapotranspiration, and water yield were found to be 2157.5, 584.9, and 1394.9 mm, respectively. The physically based semi-distributed SWAT model was capable of simulating the river hydrology at different spatio-temporal scale. SWAT model is of practical importance for planners and decision makers in developing strategy for the development of water resource sector of the basin. We conclude that the SWAT model can be applied in analyzing the influence of hydrologic parameters on the streamflow variability. Further research can incorporate analysis of future hydroclimate variables, sediment modeling, assessment of land use and climate change impact on hydrology, and assessing the effect of the dams on the hydrological cycle in the watershed.

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