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Spatio-Temporal Distribution of Water Availability in Marshyangdi Basin: Hydrological Model Development

Sunil Thapa[1*], Diksha Dahal[2], Aastha Risal[3], Sujan Shrestha[4], Sunil Thapa[5], Susan Thapa[6], Nirajan Devkota[7]
[1]*Dept of Civil Engineering, Kathmandu Engineering College,* E-mail: thapa92sunil@gmail.com
[2]*Dept of Civil Engineering, Kathmandu Engineering College,* E-mail: drdahal49@gmail.com
[3]*Dept of Civil Engineering, Kathmandu Engineering College,* E-mail: aastharisal07@gmail.com
[4]*Dept of Civil Engineering, Kathmandu Engineering College,* E-mail: sujanstha6112@gmail.com
[5]*Dept of Civil Engineering, Kathmandu Engineering College,* E-mail: thapasunil78645@gmail.com
[6]*Dept of Civil Engineering, Kathmandu Engineering College,* E-mail: susanthapa2411@gmail.com
[7]*Senior Lecturer, Dept of Civil Engineering, Kathmandu Engineering College,* Email address: nij.dev47@gmail.com

Abstract- **This Study has developed a hydrological model for the Marshyangdi river basin in Western Nepal, showing considerable potential for developing water resources and overall national prosperity. The model is also used to characterise hydrology and assess the availability of water resources across different spatial and temporal dimensions, hence improving our comprehension of water availability and its possible applications. The newly developed hydrological model in the Soil and Water Assessment Tool (SWAT) replicates the mean flows, hydrological pattern, and flow duration curve at the basin and 54 sub-basin outputs. Additionally, the model undergoes calibration and validation, employing Sufi-2 to fine-tune hydrological parameters. Based on the data generated by the model, the annual average precipitation (P) in the Marshyangdi basin is projected to be 1843 mm. Approximately 17.88% of the average yearly rainfall is lost via evapotranspiration; however, this varies significantly across different locations and time periods. Contrasting the two, the mountains have a higher moisture level than the Himalayan regions. The predicted average annual flow volume at the basin outflow is 9467.423 million cubic metres (MCM). Examining water shortages, finding regions with excess water, and developing solutions to address the competing needs of agriculture, industry, urban areas, and ecosystems are advantageous. Therefore, this method may improve the effectiveness of strategic planning and the long-term management of water resources.**

Keywords— Marshyangdi Basin, Hydrology, SWAT, Water balance, Sufi-2.

Introduction

Developing a better understanding of the availability of water resources, particularly their temporal and spatial variability, is essential to progress toward sustainable development. Due to worldwide changes brought on by anthropogenic influences as well as inherent hydro-climatic variability, water availability is fluctuating both geographically and temporally. Evaluating the presence of water in different locations and periods of time assists in the efficient management of water resources, guaranteeing the sustainable utilisation and distribution of water. It also helps in evaluating the influence of climate change on hydrological systems and ecosystems. Though scientific progress in hydrology and water assessment, the current knowledge of water availability across a range of spatial and temporal scales is still limited [1]. Studies have looked at the geographical and temporal variability of water supplies in many parts of the world. Water resources are unevenly distributed worldwide, resulting in discrepancies in access and availability. Some locations have plentiful water, while others experience persistent shortages [2].

In Nepal, the availability of water varies greatly over time and geography, necessitating an understanding of the water balance components in order to determine the availability of water. Data scarcity in Nepal is a notable obstacle, leading to the use of hydrologic simulation approaches as cost-efficient instruments for managing water resources and mitigating hazards [3]; [4]; [5]. There are many areas across the country where there is a scarcity of data, which can be overcome by employing this type of investigation. Modelling helps in understanding hydrological processes as well as water resources planning and management. The variability in the frequency and intensity of extreme events impacts the availability of water over time [6]. Highly useful hydrological models with spatial resolution are used to examine the impact of various scenarios on water availability and distribution.

Nepal is noted for its extensive water resources, including several rivers that flow from the Himalayas. Large lakes serve multiple purposes, including irrigation, hydropower generation, and fishing. Glacier melt from the Himalayas greatly affects river flows in Nepal. Western Nepal is often regarded as one of the most economically disadvantaged

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* *Corresponding Author*

areas in the nation, characterised by low levels of education, restricted progress, high poverty rates, few market opportunities, and other comparable drawbacks.[7]. As a result of this factor, there is an enormous lack of study on the hydrological patterns in this region. Evaluating the availability of water over space and periods of time is crucial for the efficient management of water resources, guaranteeing the long-term use and distribution of water in the Marshyangdi River basin as it features a variety of significant hydropower projects that are currently in the operational phase, including Middle Marsyangdi (70 Megawatts), Lower Marsyangdi (69 Megawatts), and Upper Marsyangdi (50 Megawatts).

. Many studies use the SWAT model with calibration at only the outlet to characterise hydrology [1]. Similarly, for modelling in this study, SWAT-CUP is used as an auto-calibration tool and SUFI-2 for uncertainty analysis. The goal is to create a hydrological model that thoroughly examines the temporal and geographical patterns of water balance. It evaluates the sensitive parameters for the hydrological model and assists in uncertainty analysis.

Materials and Method

A. Study area

The Marshyangdi Watershed, which is a subordinate basin within the Gandaki River Basin, is a significant river network in Nepal. The region spans over 4,748 square kilometres and is situated between the latitudes of 27°50'42" N and 28° 54'11" N and the longitudes of 83°47'24" E and 84°48'04" E (Fig. 1). The Marshyangdi River spans around 150 km, starting from its source in the northern region of the Annapurna range and extending until it meets the Trisuli River. The water volume of streams in this catchment region increases due to the addition of meltwater from glaciers since glaciers cover a portion of the total suspended solids (TSS). This watershed's altitude varies from 274 to 8,042 m above mean sea level (masl), representing bioclimatic zones ranging from subtropical (1,000 – 2,000 m) to alpine (4000-5000 m) [9]. The predominant portion of the watershed has a gradient above 45% and is characterised by the presence of snow and glaciers. Specifically, the terrain is within the altitude range of 4,000 to 6,000 meters above sea level. The climate within the watershed exhibits a range of temperatures, with tropical conditions prevailing in the lower sections and arctic cold prevailing in the upper altitudes. This basin has a mean slope of 29.4 degrees. In June, the average maximum temperature reaches 27°C; in January, it drops to -6°C. The population inside the watershed is 0.77 million people, distributed over four districts. The predominant land use/cover patterns in the watershed are grassland, barren land, and agricultural land. This location is situated along the primary Annapurna Trekking route originating from Besisahar, hence contributing to the sustenance of the local economy in the study area. This river is a significant hydroelectric resource and a popular destination for water adventure activities like rafting and kayaking. It also has significant cultural importance. Marshyangdi River originates at the confluence of the Khangsar and Jharsang Mountain Rivers; it is a dendritic perennial river. The journey starts from Manang District eastward and continues southwards via Lamjung District, Gorkha District, and Tanahu District.

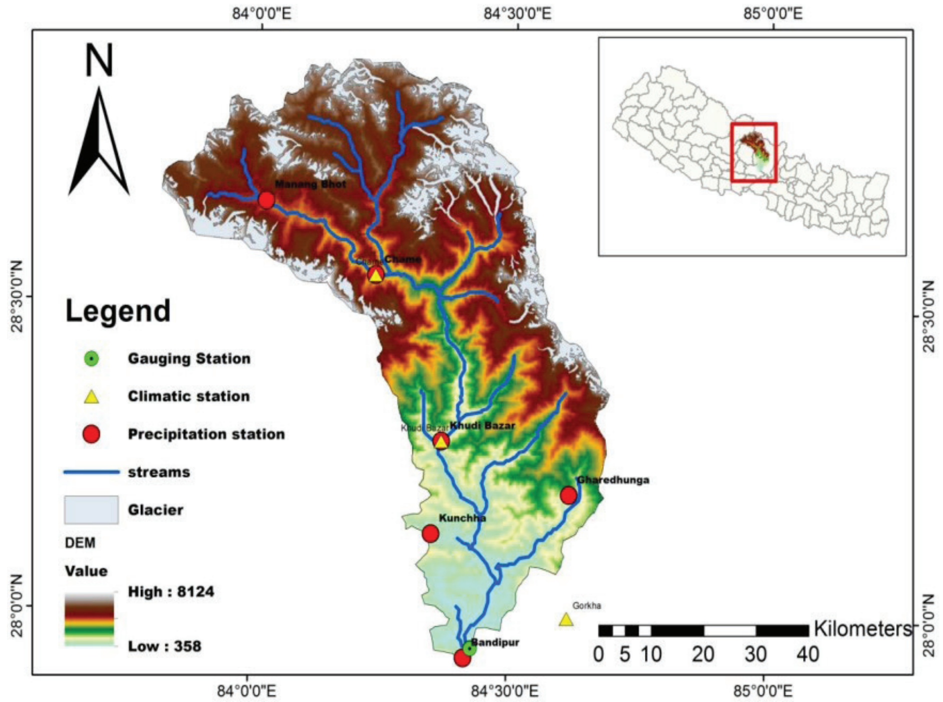

Fig 1 Location, topographical and meteorological stations

The land use land cover data was retrieved from ICIMOD (2010). The classification showed that forest covers 33.63%, followed by grassland with 21.0447%, barren with 17.0373%, snow 16.9588%, and agricultural land with 10.8973%, in the sub basin. Water covers 0.312% and urban land covers 0.114% as shown in Fig. 2(a). Similarly, spatial distribution in soil within the watershed was obtained from the Soil and Terrain (SOTER) map. In the basin LPi is the major soil type covering 47.3161% followed by CMe (13.6711%), Cmu (13.1665%), CMx (10.265%), Rge (10.1008%), CMg (2.629%), LVx (1.59368%) and GG (1.25631%) as shown in Fig. 2(b).

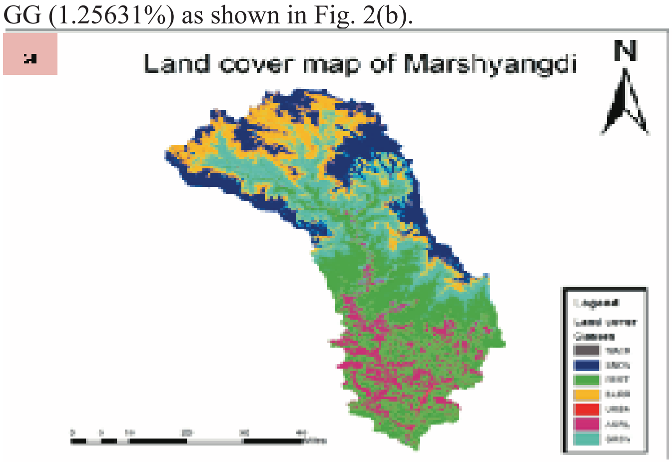

Fig 2 (a) Land use map of Marshyangdi River basin ICIMOD (2010)

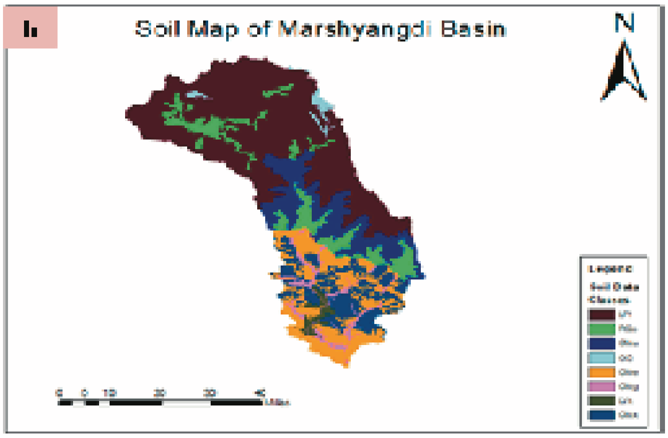

Fig 2 (b) Soil map of Marshyangdi Basin (SOTER)

The flowchart depicted in Fig. 3 illustrates the comprehensive frameworks and succinctly outlines the methodological methodology employed in this research. Different spatial and time series data were collected. Time series data were converted to the format that SWAT 2012 accepts, after giving different weather inputs in the SWAT 2012. The SWAT model is set, and it is run. Detailed information about the methodology is discussed further. Topographic, LULC and soil data were collected. ArcGIS was used to process and organise spatial data. The watershed boundary was delineated using the DEM data. The watershed was divided into Hydrologic Response Units (HRUs) based on land use, soil type and slope. SWAT Input Data was prepared, and the SWAT model was set up by providing input meteorological data such as precipitation, temperature, humidity, wind speed, and solar radiation.

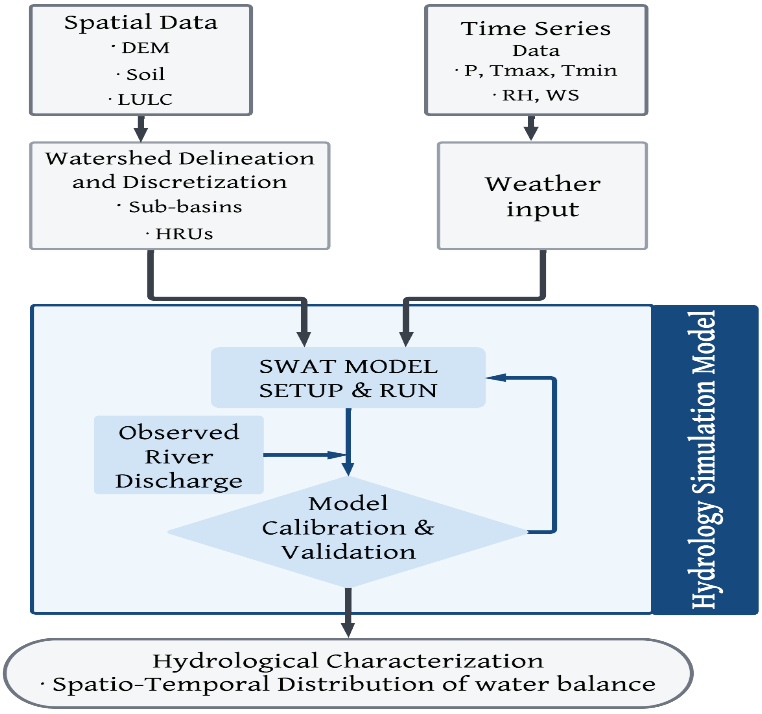

Fig 3 Methodological framework for establishing and using a hydrological model to assess water yield. DEM refers to a digital elevation model. LULC stands for land use /cover. PCP represents precipitation in millimetres. Tmax and Tmin indicate the highest and lowest temperautre in degrees Celsius. RH refers to relative humidity WS represents wind speed in meters per second. SH is for solar radiation in megajoules per square meter per day.

B. Model Overview

The Soil and Water Assessment Tool (SWAT) is a river basin or watershed, scale model. It is a continuous time model that operates on a daily time steps at basin scale. The SWAT model is a continuous-time, semi-distributed, process based river basin model, originally developed to predict the long-term impact of climate change and land use management practices on water, sediment, and agricultural chemical yields in large complex basins [10].

SWAT is a physically-based hydrologic model that is open-source and has a number of add-ons for calibration and uncertainty assessment [11]. Among other things, SWAT can simulate subsurface and surface flow as well as the cycling and transport of nutrients [10]. Soil water assessment tools are instruments or methods used to evaluate and measure the water content, distribution, and other related properties in the soil, predicting the impacts of climate change by varying soils, land use and management conditions. These tools are essential for agricultural, environmental, and geological studies, helping researchers, farmers, and land managers understand and manage water resources effectively. To depict geographical heterogeneity, a watershed may be discretised into sub-basins and hydrologic-response units (HRUs) based on the distribution of soil and land use. Here, SWAT divides the basin into sub-basins. The sub-basin is connected through a stream channel. 54 sub-basins of area 479340.3093 ha were created for the Marshyangdi basin. It is again divided into Hydrologic Response Units (HRUs). HRU is a spatial unit used in hydrological modelling to represent a homogeneous area with similar land use, soil type, and topography. HRUs are essential for simulating and understanding the movement of water through a watershed. Soil, DEM, land use, and climatic data are inputs used by SWAT. Elevation bands and lapse rate illustrate how temperature and precipitation vary with height. Using GCM climatic data, SWAT may also simulate future discharge. Future climatic data may be added to a model to forecast future discharge once the model has been calibrated and verified. SWAT's Weather Generator files aid in completing any data gaps. It is among the most significant benefits of using SWAT.

The general equation for the SWAT model is given below:

$$SW_1 = SW_0 + \sum_{i=1}^{n}(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \quad (1)$$

The ultimate soil water content (SW1) is measured in millimetres (mm), whereas the beginning soil water content is denoted as SW0. The daily quantities of precipitation, runoff, evapotranspiration, and percolation are represented by Rday, Qsurf, Ea, and Wseep, respectively, all measured in mm. Qgw represents the quantity of water that is returned to the system to calculate the water balance at the HRU level.

C. Model input and setup

The SWAT model received pre-processed input data that had been gathered from a variety of sources, evaluated for quality, and fed into the model. The model in Marshyangdi Watershed was made using the Arc SWAT 2012 interface. DEM was used to derive the stream network and sub-basin boundaries. For this, we selected a threshold area of 5000ha. Monitoring points were added manually based on all the hydropower stations, and the watershed was divided into 54 sub-basins and 392 HRUs. To define the HRUs, we derived a slope map from the DEM and separated them into five classes with breaks at 5%, 15%, 30%, 60% and 100%. We used 10%, 15%, and 20% thresholds for land use, soil, and slope, respectively. To simulate the snowmelt process and orographic distribution of temperature and precipitation, five elevation bands with a 500 m interval were developed. All snow-related input parameters (SFTMP, SMTMP, SMFMX, SMFMX, and TIMP) were collected during model calibration and validation to characterise the influence of glaciers and snowmelt on water availability. As a result, the projected water availability in the current and future scenarios has been estimated within an acceptable statistical range. The weather conditions of those meteorological stations within the watershed were accurately represented using the model's built-in weather generation tool. By calibrating the model using factors like temperature and precipitation lapse rate, the overall climatic state of the watershed has been accurately represented with high statistical performance.

Then, the model was fed with daily weather data. The SCS curve number approach was used to assess surface runoff. This technique calculates daily curve numbers based on soil moisture levels. Penman-Monteith method was used to calculate PET. Similarly, the channel flow was routed using a variable storage method.

1. Model calibration and validation

The Marshyangdi basin was characterised using a calibration strategy that used both single-station and multi-variable techniques in order to accurately capture the geographical heterogeneity. The calibration and validation were first performed at one station, which is Bimalnagar station. The parameter that was used is shown in the table below with the initial value and fitted values.

TABLE 1

SWAT PARAMETERS FOR CALIBRATION OF MARSHYANGDI BASIN

Parameter	Definition	Unit	Level	Range	Initial value
ALPHA_BF	Baseflow recession constant	days	HRU	0.01 – 0.7	0.048
GW_DELAY	Delay time for aquifer recharge	days	HRU	25 – 70	31
GW_REVAP	Groundwater revap Coefficient	–	HRU	0.02 – 0.12	0.02
GWQMN	Threshold depth of water in shallow aquifer	mm	HRU	500 – 2500	1000
RCHRG_DP	Deep aquifer percolation fraction	–	HRU	0.01– 0.1	0.05
REVAPMN	Threshold depth of water in shallow aquifer for revap to occur	mm	HRU	150 – 400	750
CANMX	Maximum canopy storage	mm	HRU	0 – 50	0
EPCO	Plant uptake compensation factor	–	HRU	0.5 – 1	1
ESCO	Soil evaporation compensation factor	–	HRU	0.4 – 1	0.95
LAT_TTIME	Lateral flow travel time	days	HRU	5 – 90	0
SOL_AWC	Available water storage capacity of the soil layer	–	HRU	–0.2 – 2	varies
SOL_K	Saturated soil conductivity	mm/hr	HRU	–0.2 – 2	varies
SOL_Z	Depth from soil surface to bottom of layer	mm	HRU	–0.2 – 2	varies
CN2	SCS runoff curve number for moisture condition II	–	HRU	–0.1–0.2	varies
CH_K2	Effectivity hydraulic conductivity in main channel alluvium	mm/hr	Reach	0 – 500	0
CH_N2	Manning's "n" value for the main channel	–	Reach	0.014 – 0.15	0.014
TLAPS	Temperature lapse rate	°C/km	Sub-basin	−7.5 – –4.5	0
PLAPS	Precipitation lapse rate	mm/km	Sub-basin	−200 – 250	0
CH_N1	Manning's "n" value for the tributary channel	–	Sub-basin	0.01 − 0.05	0.014
SFTMP	Snowfall temperature	°C	Basin	−1 − 2.5	1
SMTMP	Snow melt base temperature	°C	Basin	1 − 5	0.5
SMFMX	Melt factor for snow on June 21	mm H2O/ºC-day	Basin	0 − 10	4.5
SMFMN	Melt factor for snow on December 21	mm H2O/ºC-day	Basin	0 − 10	4.5
TIMP	Snow pack temperature lag factor	–	Basin	0 – 1	1
SURLAG	Surface runoff lag coefficient	–	Basin	0.05 – 5	4
SOL_BD	Moist bulk density	Mg/ m^3	HRU	–0.2 – 0.2	varies
SOL_ALB	Moist soil albedo	–	HRU	–0.2 – 0.2	varies
SLSUBBSN	Average slope length	m	HRU	15 – 80	varies
OV_N	Manning's "n" value for overland flow	–	HRU	0.01 – 0.5	varies
ALPHA_BNK	Baseflow alpha factor for bank storage	days	Reach	0.3 – 0.9	0

I. Result and Discussions

A. Evaluation of SWAT model

The modelling team's past expertise and the study paper [12] were taken into consideration while shortlisting thirty model parameters for sensitivity analysis. The sub-watersheds upstream of each calibration site are predicted to have different parameter sensitivity. Certain sub-watersheds may have very sensitive parameters, whereas other sub-watersheds may have less sensitive parameters.

TABLE 2

CALIBRATED VALUES OF SWAT PARAMETERS

Parameter	Suggested Range	Fitted values	Adjustment
ALPHA_BF	0.01 – 0.7	0.57649	Replace
GW_DELAY	25 – 70	57.175003	Replace
GW_REVAP	0.02 – 0.12	0.0421	Replace
GWQMN	500 – 2500	1890	Replace
RCHRG_DP	0.01– 0.1	0.09217	Replace
REVAPMN	150 – 400	287.75	Replace
CANMX	0 – 50	48.150002	Replace
EPCO	0.5 – 1	0.9895	Replace
ESCO	0.4 – 1	0.9958	Replace
LAT_TTIME	5 – 90	16.305	Replace
SOL_AWC	–0.2 – 2	–0.038000	Relative
SOL_K	–0.2 – 2	0.142	Relative
SOL_Z	–0.2 – 2	0.01	Relative
CN2	–0.1–0.2	0.1421	Relative
CH_K2	0 – 500	307.5	Replace
CH_N2	0.014 – 0.15	0.068264	Replace
TLAPS	−7.5 – –4.5	–5.265000	Replace
PLAPS	−200 – 250	220.749985	Replace
CH_N1	0.01 − 0.05	0.02572	Replace
SFTMP	−1 − 2.5	0.7045	Replace
SMTMP	1 − 5	2.436	Replace
SMFMX	0 − 10	1.43	Replace
SMFMN	0 − 10	5.95	Replace
TIMP	0 – 1	0.317	Replace
SURLAG	0.05 – 5	3.26255	Replace
SOL_BD	–0.2 – 0.2	0.1604	Relative
SOL_ALB	–0.2 – 0.2	–0.077200	Relative
SLSUBBSN	15 – 80	55.754997	Replace
OV_N	0.01 – 0.5	0.41915	Replace
ALPHA_BNK	0.3 – 0.9	0.4518	Replace

The most sensitive parameters are PLAPS, LAT_TTIME, GW_DELAY, CN2, and TLAPS. The lateral flow is influenced by parameters such as LAT TIME and SURLAG, whereas the base flow from the basin is affected by parameters like ALPHA BF, GWDELAY, GWQMIN, and SOL AWC. The snow's impact on the total flow is determined by considering specific snow-related attributes, including the temperature at which snowfall happens (SFTMP), the temperature at which snow melts (SMTMP), the extent of snow cover (SNOCOVMX), the degree-day factors (SMFMX, SMFMN), and the rate at which temperature changes with altitude (TLAPS). The result was similar to the result obtained by [13] in the Narayani basin. Table 2 displays the fitted value of the calibrated parameters. Various parameters were found to be responsive in the modelling process. Surface runoff characteristics such as CN2 and OVN have an influence. The lateral flow is influenced by parameters such as LAT TIME and SURLAG, whereas the base flow from the basin is affected by parameters like ALPHA BF, GWDELAY, GWQMIN, and SOL AWC. The snow component of the total flow is determined by snow-related parameters, including snowfall temperature (SFTMP), snowmelt temperature (SMTMP), snow cover (SNOCOVMX), degree-day factors (SMFMX, SMFMN), and temperature lapse rate (TLAPS) as in TABLE 3.

TABLE 3

SENSITIVE PARAMETERS OF CALIBRATION

Parameter Name	Ranking	t-Stat	p-Value
V__PLAPS.sub	1	62.728	0
V__LAT_TTIME.hru	2	-21.872	0
V__GW_DELAY.gw	3	-11.51	0
R__CN2.mgt	4	9.739	0
V__ALPHA_BF.gw	5	5.378	0
V__SLSUBBSN.hru	6	-3.739	0
V__GW_REVAP.gw	7	-3.317	0
V__SMFMN.bsn	8	-3.12	0.001
R__SOL_BD(..).sol	9	3.031	0.002
V__CH_N2.rte	10	2.905	0.003
V__ESCO.hru	11	2.831	0.004
V__TLAPS.sub	12	2.158	0.031
V__ALPHA_BNK.rte	13	2.006	0.045
V__REVAPMN.gw	14	1.997	0.046
V__CH_K2.rte	15	1.974	0.048

Model calibration refers to the process of determining a specific combination of model parameters that accurately represent the behaviour of a system. This is accomplished by comparing the predictions made by the model with real measurements obtained from the system. The SWAT-CUP interface, which was specifically designed for SWAT, was used for the purpose of automatic calibration and validation of the model. We used SUFI2 software with SWAT CUP version 5.1.6.2 for model calibration, validation sensitivity, and uncertainty analysis, out of many programs provided by SWAT-CUP (including PSO, GLUE, Para Sol, and MCMC). Discharge data is crucial for the model's validation and calibration processes. The Marshyangdi river basin flow data at Bimalnagar has been used for calibration.

For the Bimalnagar outlet, the period from 1988 to 2019 was selected for simulation. The calibration period was from 01-Ian-1988 to 31-Dec-2005. The Validation period was from 01-Jan-2006 to 31-Dec-2019. The time period for the overall simulation, calibration, and validation is shown in TABLE 4.

TABLE 4

TIME PERIOD FOR SIMULATION

Period	From	To
Simulation period	01-Jan-88	31-Dec-19
Calibration period	01-Jan-88	31-Dec-05
Validation period	01-Jan-06	31-Dec-19

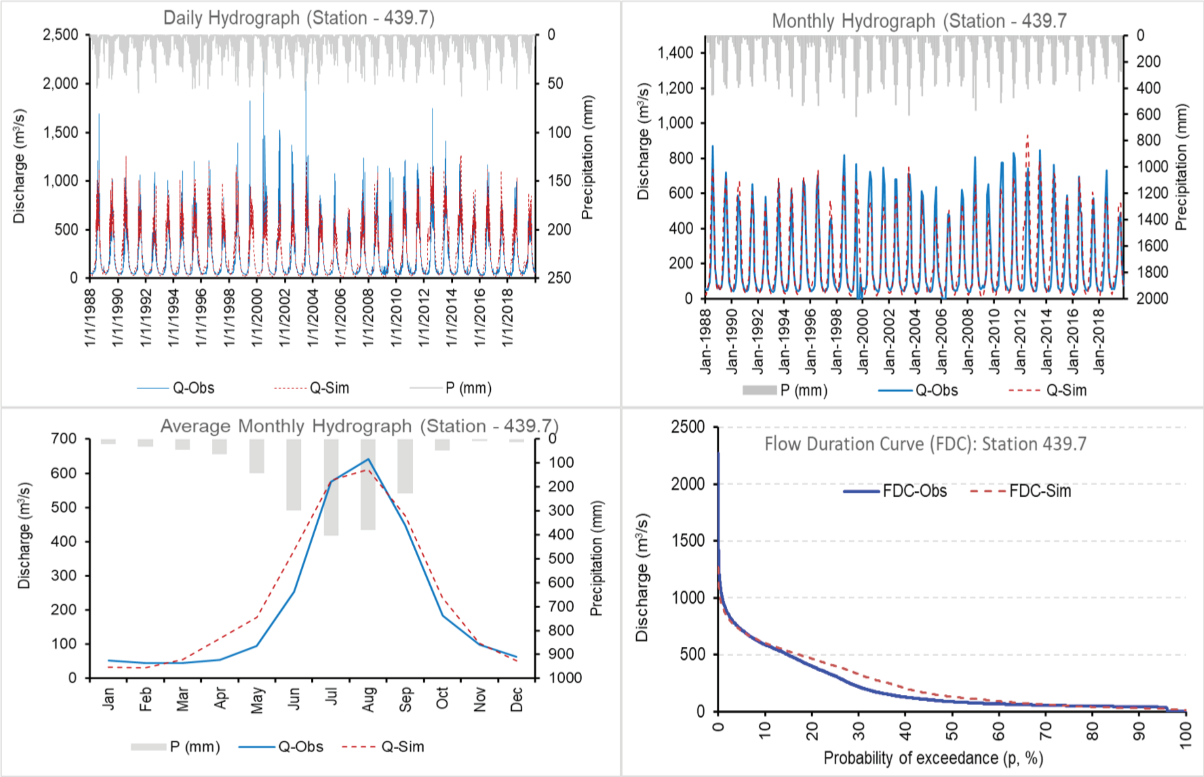

Fig 4 Observed and simulated daily as well as monthly hydrographs & Flow Duration curve

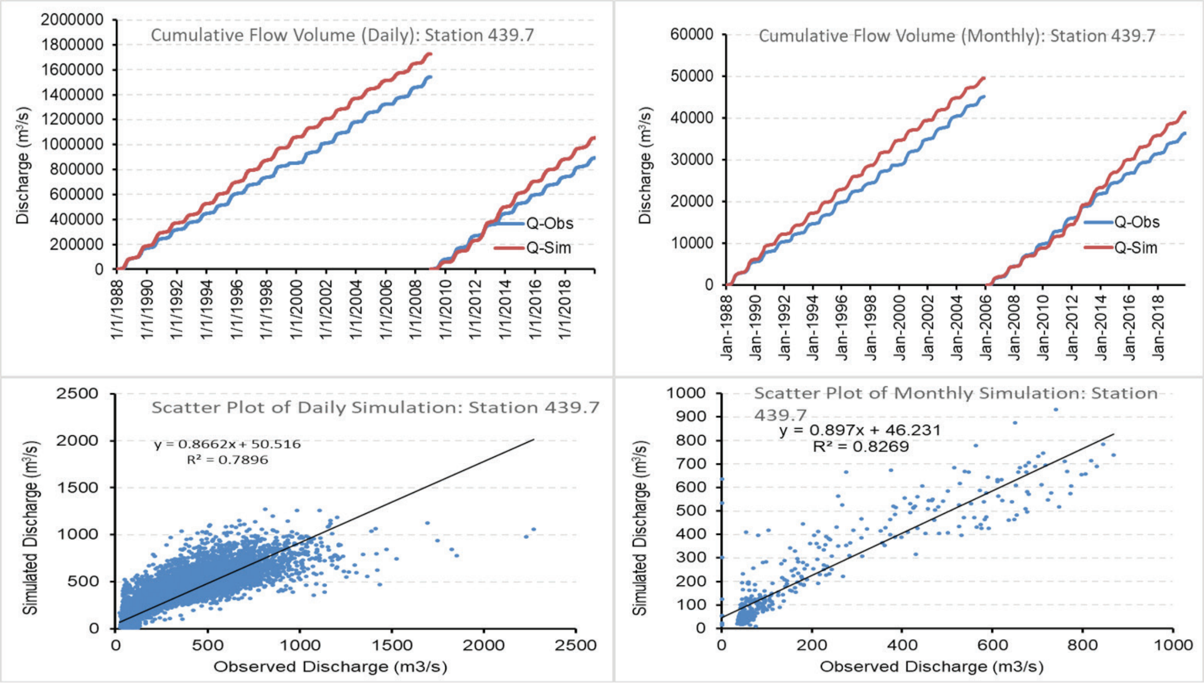

Fig 5 Scatter plot for daily and monthly simulation

TABLE 5

PERFORMANCE INDICATION FOR THE MODEL CALIBRATION AND VALIDATIOn

	Daily			Monthly		
	Calibration	Validation	Entire Period	Calibration	Validation	Entire Period
R^2	0.71	0.77	0.74	0.82	0.83	0.82
wR^2	0.627	0.673	0.648	0.754	0.768	0.761
NSE	0.69	0.74	0.71	0.8	0.82	0.81
NSE_{rel}	0.77	-0.01	0.45	0.81	0.2	0.52
PSR	0.56	0.51	0.54	0.45	0.43	0.44
PBIAS	14.3	14	14.1	11.6	10.2	10.9

Daily and monthly hydrograph simulations at a Marshyangdi basin station from 1988 to 2019 are observed. The NSE for daily flow validation and calibration is 0.69 and 0.74, respectively, with improved monthly simulation performance. Also, the calibration and validation R2 values are greater than 0.8 for monthly simulation and less than 0.8 for daily simulation. Monthly simulation PBIAS was 11.6 and daily simulation 14.1 for the whole time. Daily simulation PSR was 0.54, and monthly simulation was 0.44, which was slightly better. Positive PBIAS during calibration indicates an underestimate in simulated volume. Simulated-observed dots disperse remarkably low, indicating that the flow pattern is highly consistent across the seasons. The obtained result was compared with the rating value of percentage bias given by [14]. Our obtained result fell in the category of very good for the performance of monthly simulation, whereas the performance of daily simulation fell under the good category. Two indices were considered to evaluate the proficiency of model calibration and uncertainty: the p-factor (observations bracketed by the prediction uncertainty) and the r-factor (achievement of small uncertainty band). The findings from the SWAT simulations revealed that the p-factor and r-factor recorded during the calibration and validation phase were 0.85 and 0.69, respectively.

B. Temporal Distribution of water balance

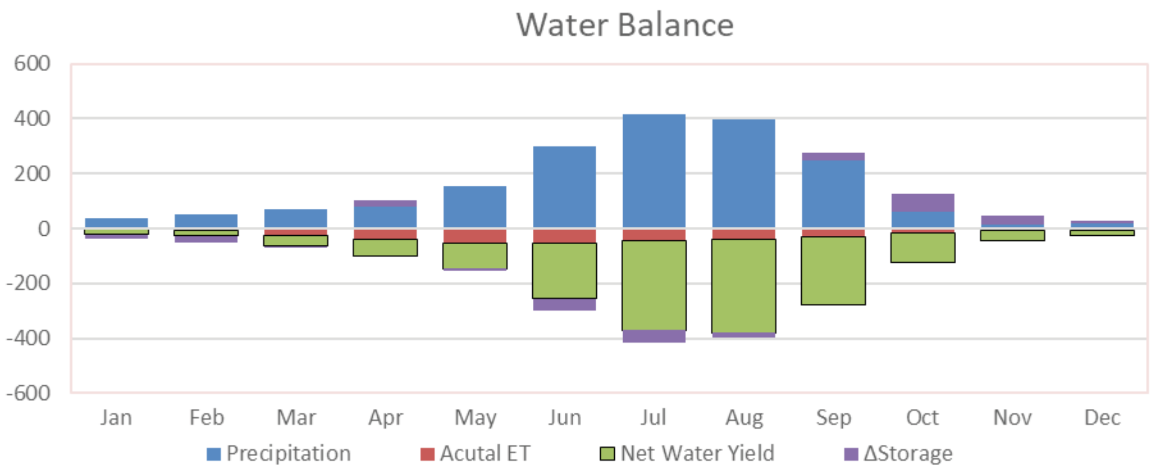

Fig 6 Mean monthly simulated(1988-2019) water balance in the Marshyangdi basin. The Phrase ‘Δ storage’ encompasses the replenishment of groundwater, variations in soil moisture storage in the unsaturated zone, and flaws in the model. A negative number of ‘Δ storage’ suggests the aquifer is being recharged, whereas a positive value indicates the opposite.

The baseline monthly average water balance varies significantly over time. Snowmelt accounts for 12.8% of total precipitation. The mean seasonal P distribution is 73.8 mm in the post-monsoon (ON) season and 1358.1 mm in the monsoon (JJAS). The basin's mean seasonal AET ranges from 17.6 mm in winter (DJF) to 167.6 mm in monsoon. NYW ranges from 57.9 mm in winter to 1115.5 mm in monsoon. Precipitation intensity, soil characteristics, subsurface storage, and land use/cover impact the NWY; therefore, it does not necessarily follow P trends. P, AET, and NWY reach their peak during the monsoon, the main hydrological driver. Monsoon season (JJAS) provides 73.68%, 50.84%, and 73.77% of the Marshyangdhi basin outflow average annual P, AET, and NWY, as in Fig. 6.

SWAT simulations show that the basin outlet's average annual flow volume under the present climate is 9467.43 million cubic meters (MCM), with 71% accessible during JJAS. During the monsoon season (JJAS), "Δ storage" has a negative absolute value of 18.8 mm, indicating aquifer recharging. In August, the soil is saturated. Thus, delta storage is lower than in July and even positive in September despite identical rainfall and water yield. Recharge capacity declines in August, and groundwater adds to water yield after September. From December on, it is positive until December, when it turns negative but low. The post-monsoon (ON) season's highest positive value of 64.5 mm shows groundwater input to streamflow. Winter precipitation explains the low negative numbers from January onwards.

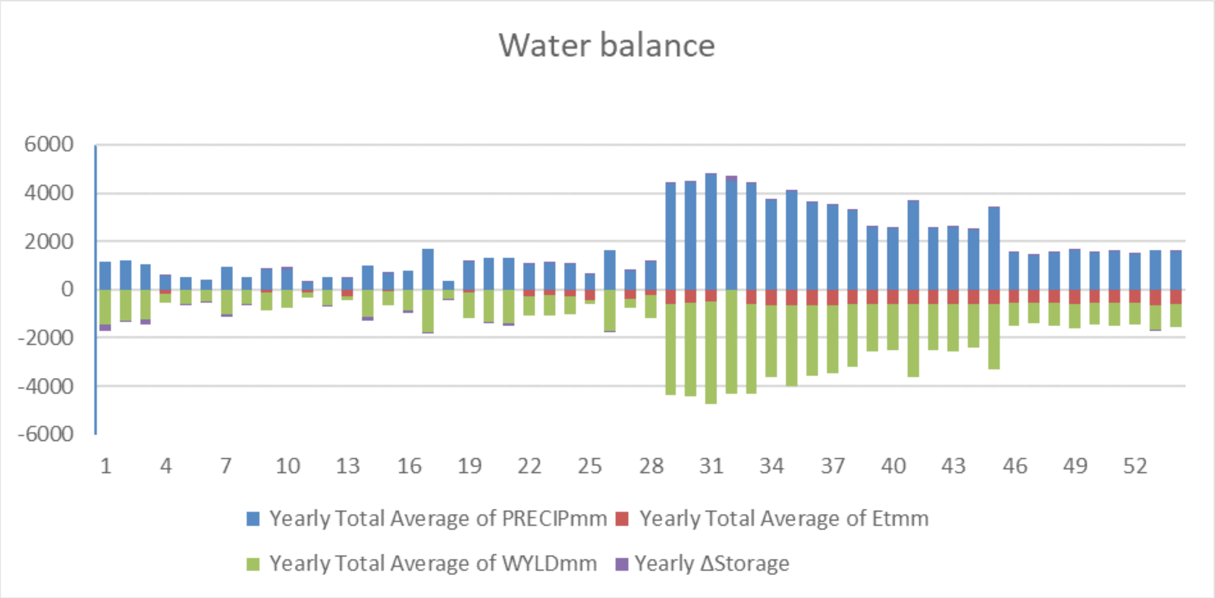

Fig 7 Annual water balance values (precipitation, actual ET, and net water yield) for sub-basins in the Marshyangdi basin, averages for 1988-2019

From the Fig. 7 we can figure out that the sub-basin 31 has the highest and sub-basin 11 has the lowest contribution on water balance components. Starting from sub-basins 29 to 41 has high contribution on water balance components. These sub basins are mainly located in Lamjung district. Lamjung typically receives about 263.6 millimetres (10.38 inches) of precipitation and has 206.19 rainy days (56.49% of the time) annually. Sub basins 1–23 make a significant contribution to water balance components. These sub-basins are primarily located in the Manang district**.**

C. Spatial distribution of water balance

During the hydrological baseline period (1988–2019), Figure 8 shows the distribution of the three main components of the water balance average annual P, AET, and net water yield across the Marshyangdi basin as predicted by the model. Surface runoff, lateral flow, and groundwater flow are all components of the net water yield (NWY), which is further reduced by transmission losses and pond abstractions [15]. The whole basin receives an average of 1843 mm of precipitation every year. There is a net water yield of 1511.8 mm. Throughout the basin, the average yearly AET is 329.6 mm or about 17.88% of the average yearly P. But it differs from one place to another.The average annual precipitation in the Himalayan region is 856.5 mm, with an AET of 69 mm and a net water yield of 845. The mountain region receives 2459.44 mm of precipitation annually, with an AET of 523.61 mm and a net water yield of 2007.985 mm. Lamjung has a 2417.6 mm net water yield, 497.72 mm AET, and 2954.2 mm average annual precipitation, whereas Tanahu has 1574.02 mm, 589.825 mm AET, and 960.125 mm net water yield. Gorkha's average annual precipitation, AET, and net water yield are 1878.1 mm, 567.3 mm, and 1266.23 mm. Sub-basins have average annual AETs from 0 to 610 mm. AET values are greater in Mnt (523.61 mm) than in Himl (69 mm) (Fig. 8). The AET decreases from the southern plains to the northern Himalayas. The Koshi River valley in eastern Nepal also has a similar trend, with AET rising from the Hill to the Himalayas region [12]. The Himl and Mnt have 8.05% and 21.26% AET P shares, respectively. Marshyangdi sub-basin NWY varies from 168 to 4252.8 mm (Fig. 8). Location-wise, the average long-term NWY decreases upstream from Mnt to Himalaya. NWY is 2007 mm in Mnt and 845 mm in Himl (Fig. 8). NWY exceeds 80% of P in 14 sub-basins (24.95%). 44% from surface runoff, 37% from lateral flow, and 19% from groundwater contribute to basin water availability. Due to short-term intense rain during monsoon seasons, surface runoff is slightly higher than lateral flow. The negative indicator for storage denotes the contribution to groundwater recharge [12].

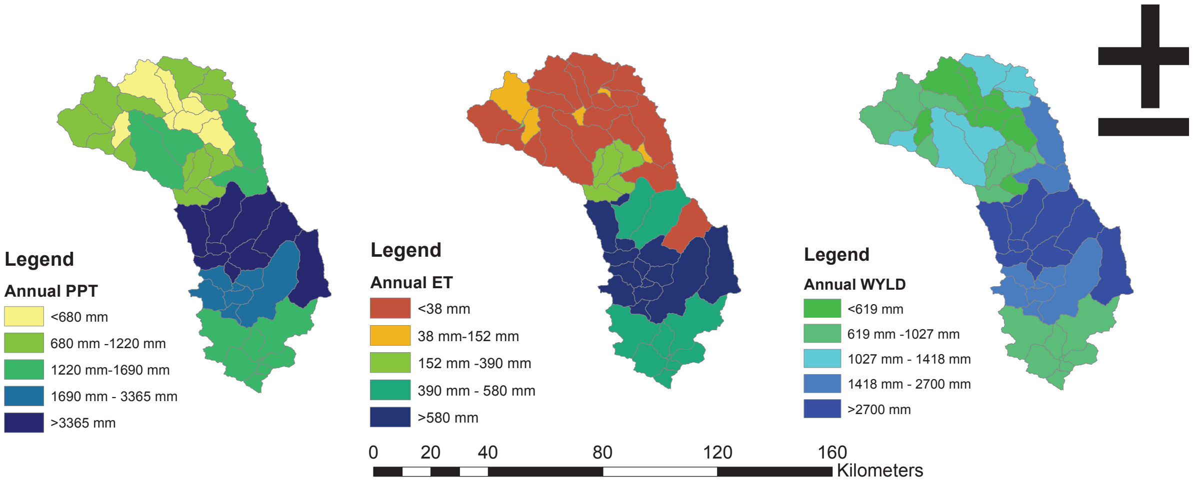

Fig 8 Map showing the distribution of yearly precipitation (P), actual evapotranspiration (AET), and net water yield (NWY) among sub-basins in the Marshyangdi basin..

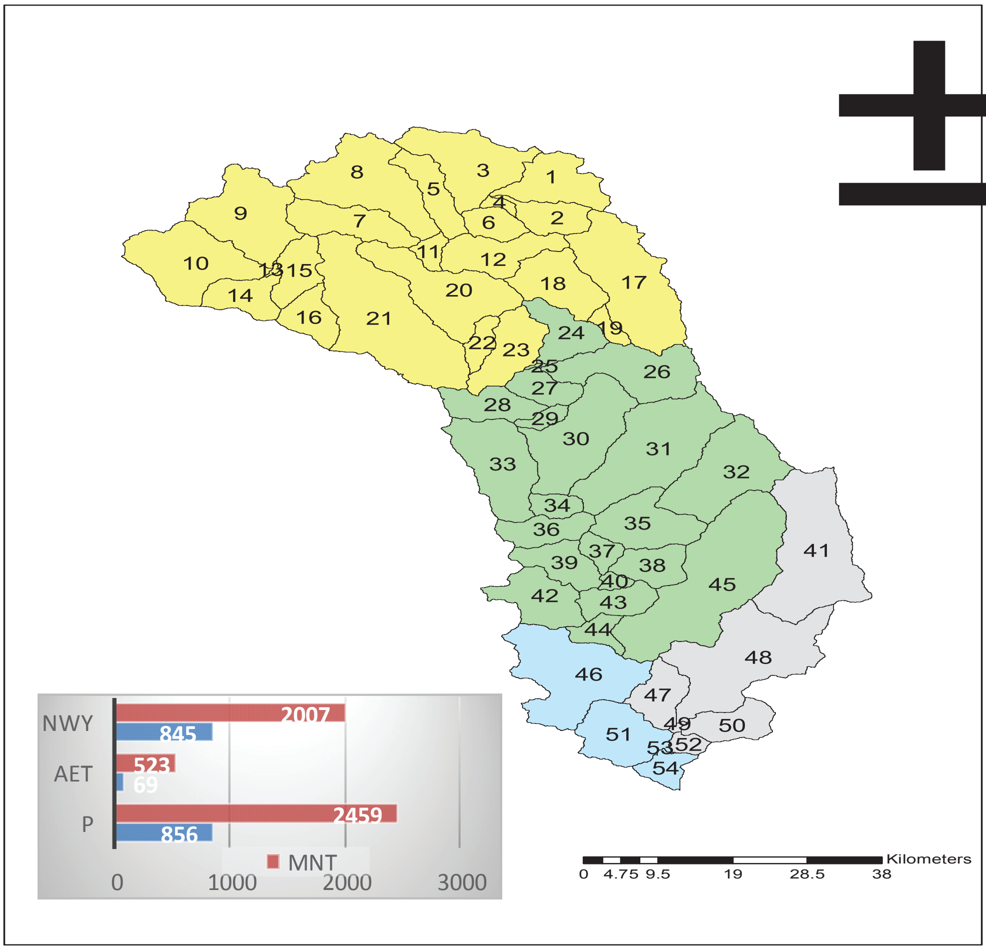

Fig 9 Spatial distribution of average annual precipitation (P), actual evapotranspiration (AET), and net water yield (NWY) across different geographical regions within the Marshyangdi river basin. Himl refers to the Himalaya, Mnt stands for Mountain region.

II. Conclusion

A hydrological model was constructed in SWAT using a calibration approach to characterize the spatio-temporal distribution of water availability. The Marshyangdi basin in Western Nepal was discretised into 54 sub-basins for the purpose of this study. The SUFI-2 algorithm, which is a semi-automated approach for model calibration, validation, sensitivity, and uncertainty analysis, was used in this study. Visual inspection of the hydrological pattern and statistical indicators for average flows and biases were employed to credibly calibrate and validate the model. The simulation period was 31 years, the Validation period was 13 years and the calibration period was 17 years. The average annual flow volume at the basin outlet is projected as 9467.423 million cubic meters (MCM). The annual average precipitation (P) of the Marshyangdi basin is estimated as 1843 mm, and actual evapotranspiration (AET) is 17.88% (approximately) of the average annual precipitation in the Marshyangdi basin, however, with a substantial spatiotemporal variation. The model simulated number indicates that 12.8% of the total rainfall is accounted for by snowmelt. In terms of seasons, P varies from 73.8 mm (post-monsoon) to 1358.1 mm (monsoon), AET from 17.6 mm (winter) to 167.6 mm (monsoon), and NWY from 57.9 mm (winter) to 1115.5 (monsoon). At the Marshyangdhi basin, the average annual P, AET, and NWY are 73.68%, 50.84%, and 73.77% during the monsoon season (JJAS).

The findings of this study may provide scientific guidance for determining the spatial and temporal distribution of water resources and hydrological processes at a basin scale in basins across the world with similar natural characteristics. It is helpful for analysing water shortages, locating regions with surplus water and developing distribution methods to fulfil competing needs from agriculture, industry, urban areas and ecosystems. This work acknowledged these challenges by presenting model outputs with certain percentage prediction uncertainty bands. The soil type is assumed based on the land use map. In the future, we recommend further studies incorporating the land use change and the use of soil maps of the basin.

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