Assessment of Run-of-River Hydropower Potential Using SWAT Modeling and GIS in the Marsyangdi River Basin, Nepal

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ABSTRACT

The purpose of this study is to determine the run-of-river (ROR) hydropower potential in the Marsyangdi River basin using the SWAT (Soil and Water Assessment Tool) modeling and Arc GIS. Watershed delineation generates a river network, which provides information like stream link, stream order, stream length, and slope, considering the outlet at intake. The catchment area of the Marsyangdi River basin is 4787.86 km^2. Intake points in the SWAT model were chosen with consideration for the head, the distance between the intake and the powerhouse, and the stream order of the river. Seventy-nine potential hydropower locations were identified based on these criteria. The SWAT model was run from 1982 to 2016 with a two-year warm-up period. Model calibration and validation were performed using SUFI-2 within SWAT-CUP by adjusting fifteen parameters. The model was calibrated from 2001 to 2009 and validated from 2010 to 2015. R^2, NSE and PBIAS were the statistical indices used to evaluate the model's performance. The corresponding values for calibration and validation based on mean monthly flow were 0.83, 0.765, -15.57% and 0.82, 0.82 and -2.82% respectively. For mean daily flow, the value of R^2, NSE and PBIAS were 0.58, 0.55, 18.62% and 0.61, 0.56, 23.70% respectively. The hydropower potential was estimated at different exceedance probabilities based on mean daily flow and monthly flow. Based on the mean daily flow and flow duration curve, the results showed that the estimated hydropower potential at 40% and 30% probability of exceedance was 1568.96 MW and 2191.68 MW respectively.

Keywords: Hydrological model, run-of-river, GIS, SWAT and SWAT-CUP.

1. Introduction

Various energy sources, such as thermal, nuclear, solar and hydropower are consistently utilized to fulfill the world's energy demands. Among these, hydropower stands out as the most prevalent and significant source of renewable energy for electricity generation, playing a vital role in reducing greenhouse gas emissions. In Nepal, the demand for hydropower is increasing, as it is a clean, renewable, and reliable source of energy derived from water (Kusre et al., 2010). Hydropower is particularly well-suited to Nepal's diverse geography, which ranges from elevations of 8,848.86 meters at Mt. Everest in the north to 60 meters in the south, along with over 6,000 rivers and streams. Its affordability, economic viability and environmental benefits make it an ideal energy source for the country (WECS, 2019). With increasing global urbanization and resource scarcity, the push for renewable energy solutions like hydropower has intensified, especially in mountainous regions such as the Himalayas where topographical conditions are conducive to such projects (Bhattarai et al., 2024). The high Himalayas, which are the source of major river basins such as Saptakoshi, Narayani, Karnali, and Mahakali contribute to Nepal's enormous hydroelectric potential. Dr. Hari Man Shrestha estimated Nepal's overall hydropower potential to be 83,181 MW considering annual mean flow and 80% efficiency in 1966 while conducting research for his Ph.D. in the former USSR (Bajracharya, 2015). A similar type of study suggested that the total potential on run-of-river basis at 40% flow exceedance and 80% efficiency is 53386 MW and the total hydropower potential of Marsyangdi River basin on run-of–river basis is 3251.8 MW (Jha, 2010). According to WECS, the theoretical hydropower potential of Nepal is estimated as 72,544 MW and the techno-economical hydropower potential is estimated as 32,680 MW. The Run-of-river (ROR) hydropower projects operate with minimal control over natural water flow. Typically functioning as base load plants due to their nearly constant hydraulic head, these facilities are designed to optimize river flows, particularly during the dry season. The installed capacity of ROR plants must reflect the dependable flow available throughout the year, which is usually based on the river's discharge at a specific percentile. In Nepal, ROR plants are commonly engineered to deliver a dependable flow of 40%, ensuring consistent energy production while remaining adaptable

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to seasonal variations in water availability (Bajracharya, 2015).

Numerous tools for modeling rainfall-runoff including SWAT, TOPMODEL and HEC-HMS have been developed through hydrological modeling technologies. SWAT is a semi-physical, semi-distributed, continuous-time conceptual model that utilizes daily data to interconnect various physical processes (Almeida et al., 2018). For the SWAT model setup and simulation DEM, daily precipitation, temperature, land use and soil data within a GIS framework are used for the hydropower potential of a river basin can be calculated (Pandey et al., 2015; Pokharel et al., 2020). GIS spatial analyses have allowed the development of a number of methodologies to calculate hydropower potentials (Feizizadeh and Haslauer, 2012). SWAT is a basin-scale, continuous-time model that runs on a daily time step and is intended to forecast how management will affect water, sediment, and agricultural chemical yields in ungauged watersheds. The model is physically grounded, effectively computed, and capable of long-term continuous simulation. Weather, hydrology, soil temperature and characteristics, plant development, nutrients, pesticides, bacteria and diseases, and land management are important model components. A watershed is split up into several sub-watersheds in SWAT and these sub-watersheds are then split up into hydrologic response units (HRUs), which are composed of uniform land use, management, and soil characteristics. Alternately, a watershed can be separated into only those sub-watersheds that share a common land use, soil type, and management (Gassman et al., 2007).

The calibration procedure consists of changing the model parameter values so that the simulated values closely resemble the observed values and so more accurately reflect the simulated process and the validation is based on the application of the model with calibrated parameters in an independent data mass (Almeida et al., 2018). Hydrological and meteorological parameters such as precipitation, temperature, and discharge play a crucial role in calibrating models like SWAT which simulates watershed hydrology and identifies viable hydropower sites. High-resolution spatial data, such as digital elevation models (DEMs) combined with GIS-based analysis enhance the understanding of topographic head and river flow, essential for locating potential hydropower sites (Bhattarai et al., 2024). SWAT-CUP is a program for the calibration of SWAT models. The program could be used to perform calibration, validation, sensitivity analysis (one at a time, and global) and uncertainty analysis. The sensitivity, calibration, and validation of the model can be examined using the SWAT-CUP software module SUFI2.

2. Study Area

The study area is the Marsyangdi River basin. It is an important tributary of the Narayani basin. The Marsyangdi River starts from the west of the Thorung peak of Manang. It meets Nar Khola at Chame and Dudh Khola at Dharapani. It joins Chepe Khola at Chepe Ghat and Dorondi Stream at Siling and finally meets the Trishuli River at Mugling. The catchment area of basin is 4787.86 km^2 and the altitudes vary from 243 m to 7938 m. The major part of catchment area lies in Manang, Lumjung, Gorkha and Tanahun districts of Nepal. Two rain gauge stations are available in Marsyangdi River basin which are located at Manang Bhot in Manang District (28.66°N, 84.02°E, elevation 3556 m) and Gharedhunga in Lamjung District (28.14°N, 84.58°E, elevation 1088 m).

In this study, the hydrological station at Bimalnagar (Station No. 439.7) is used as the outlet to calibrate and validate discharge for all intake points, which are the sub-basin outlets in the SWAT model. Intake locations are strategically selected between the Bimalnagar outlet and the upper reaches of the main river as well as its tributaries. This selection is based on the criteria of head and discharge which vary significantly due to the high altitudinal range across the catchment. This altitude variation influences the potential hydropower sites, with topographic features and discharge playing a key role in determining optimal intake points within the basin.

Figure 1: Location of the Study Area.

3. Data and Materials Used

Topographical information, such as digital elevation model (DEM) data, soil type data, land use/land cover data, and weather information like temperature and precipitation are the major inputs for SWAT model. Data required for this study and their sources are as shown in Table 1.

Table 1: Data Sources and Their Resolutions/Frequencies

Data Type	Resolution/ Frequency	Source
Digital Elevation Model (DEM)	30 m	ASTER Global DEM, earthexplorer.usgs.gov
Land Cover data	30 m	earthexplorer.usgs.gov
Soil data	30 m	Digital Soil Map of the World (DSMW)
Rainfall	Daily	Office of Hydrology and Meteorology, Kaski, Nepal
Discharge	Daily	Office of Hydrology and Meteorology, Kaski, Nepal
Temperature, wind, humidity	Daily	https://power.larc.nasa.gov/ data-access-viewer

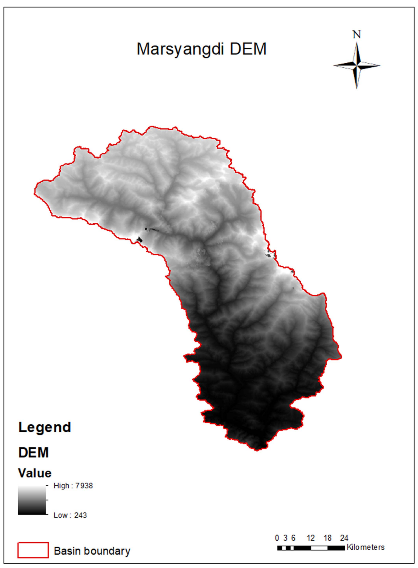

Figure 2: DEM of Marsyangdi River Basin.

In SWAT, a basin is divided into several sub-basins which are then further divided into hydrologic response units (HRUs) that are made of homogeneous topographical, soil, and management features. The DEM of Marsyangdi River basin was obtained by clipping DEM of Nepal with Marsyangdi River basin boundary (Fig.2).

Land use/land cover affects the runoff in the basin. The required portion of map was clipped with the help of Marsyangdi basin boundary polygon using the Arc spatial analyst tool. The raster was then projected at the Nepal Nagarkot coordinate system. There are seven land use classes, 22.63% water (WATR), 0.208% urban high density (URHD), 28.049% forest (FRST), 21.272 grassland herbaceous (RNGE), 9.822% agricultural land-row crop (AGRR) and 6.451% wetlands-forested (WETF) (Fig. 3).

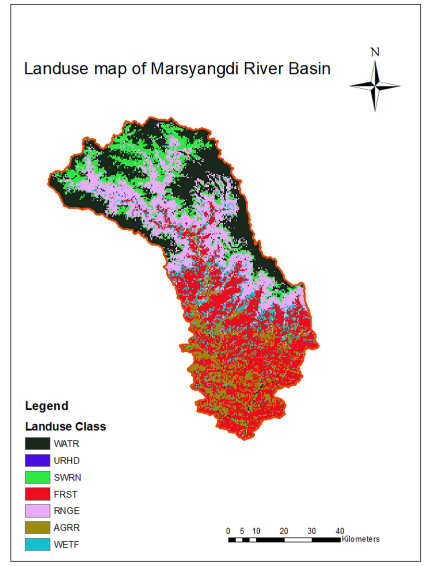

Figure 3: Landuse map of Marsyangdi River Basin.

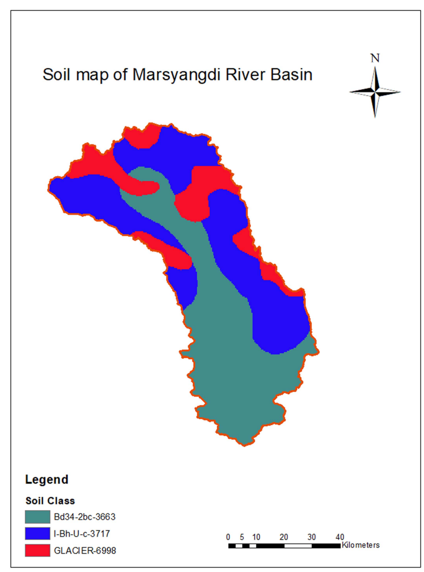

Figure 4: Soil classification of Marsyangdi River Basin.

Soil data significantly impacts the modeling of streamflow, sediment load and nutrient content due to variations in soil erodibility, hydraulic conductivity and infiltration capacity. This soil data was also clipped to the catchment area using the Marsyangdi River basin polygon, converted to raster format and projected in the Nepal Nagarkot coordinate system with the resultant clipped soil map presented in Fig. 4. Two rain gauge stations are available on

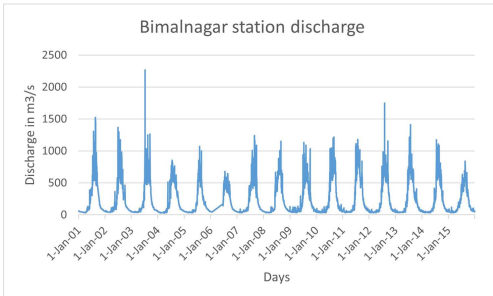

Figure 5: Daily discharge data of Bimalnagar station.

Marsyangdi River basin and daily precipitation data were collected for the period 1982 to 2016. Daily discharge data of Bimalnagar station (station no. 439.7) was collected from the Office of Hydrology and Meteorology, Pokhara, Kaski for the period 2001-2015 as shown in Fig. 5. This dataset supports model calibration and validation for discharge.

4. Methodology

ArcGIS 10.3, a popular geographical information system (GIS) program, was used to process the digital elevation model (DEM). The proposed sites were marked, and their elevations were determined using the ArcGIS tool. The SWAT model was used for analysis of discharge in an ungauged basin by using land use/land cover data, soil data, and meteorological data as input. After running the SWAT model, discharge at intake points was calculated. Calibration and validation were carried out using SWAT_CUP software with discharge data from the Bimalnagar station. Plotting the flow duration curve (FDC) and determining the percentile discharges were the goals of the discharge analysis.

Hydropower potential is a function of head drop and discharge at a certain flow exceedance. The theoretical run-of-river (ROR) hydropower potential is calculated using the equation:

$$P = \eta \times \rho \times g \times Q \times H \tag{1}$$

where, η = Efficiency (%), P = Power generated in Watt (W), ρ = Mass density of water (kg/m^3), g = Acceleration due to gravity (m/s^2), Q = Discharge (m^3/s), H = Gross head drop (m).

For several sub-basins in a given basin, the total power of the basin can be calculated by summing the potential of all sub-basins:

$$P = \sum_{i=1}^{n} \eta \times \rho \times g \times Q \times H \tag{2}$$

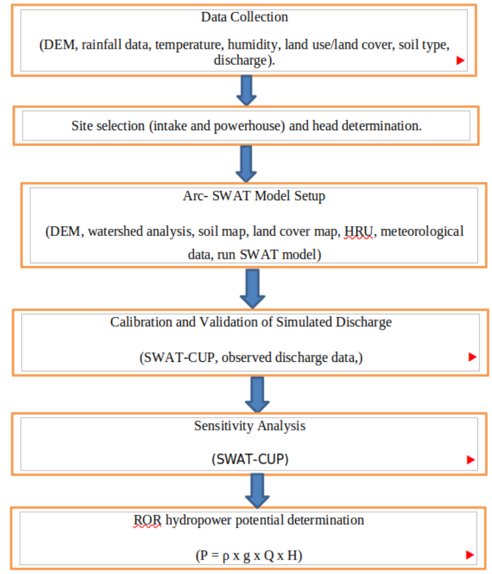

Figure 6: Methodology for assessment of hydropower potential by using SWAT model.

4.1. Potential Location of Run-of- River Hydropower Sites

The potential sites for the intake and powerhouse in the Marsyangdi River basin were identified using ArcGIS guided by specific selection criteria. First, each potential site needed to have a minimum head of 50 meters to ensure sufficient potential energy for generating a significant amount of power. Additionally, to support the ecological health of the river a minimum distance of 500 meters was established between hydropower intake sites. This separation is crucial for the restoration and preservation of the river's natural ecosystem, as it allows for recovery and balance mitigating the adverse ecological impacts associated with hydropower activities that disrupt natural flow patterns. Furthermore, the selection process favored 3rd, 4th, and 5th order streams which provide a more consistent and reliable water flow year-round making them better suited for continuous power generation essential for a stable energy supply (Kusre et al., 2010; Pandey et al., 2015). The intake sites were located downstream of tributary confluences to maximize the utilization of their discharge. Following these criteria, a total of seventy-nine run-of-river (ROR) hydropower sites have been identified within the basin, as illustrated in Fig. 7.

4.2. Hydrological Processes in SWAT

In this study, the SWAT model is chosen because of its accessibility and cost of the tools. Arc SWAT 10.3 version runs on Arc Map and it is installed as a plug-in. The SWAT model is a river basin model developed by the US

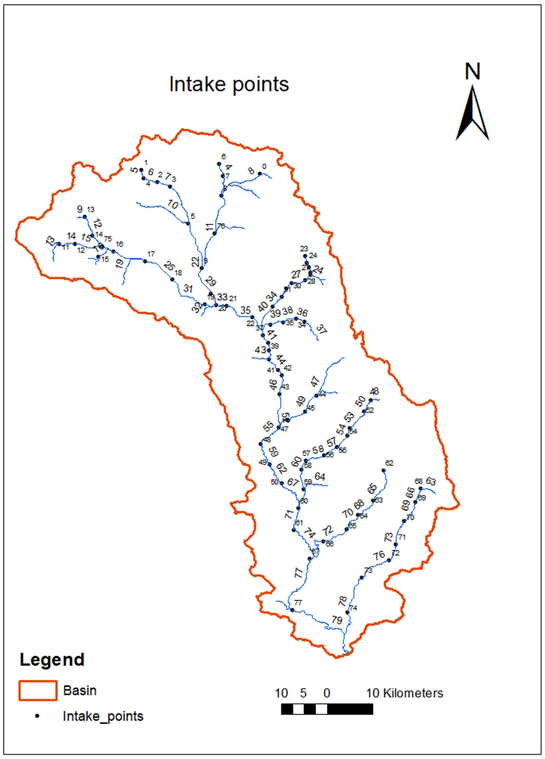

Figure 7: Location of intakes.

Department of Agriculture-Agricultural Research Service (ARS). Utilizing the SWAT program discharge along the river basin was identified. The SWAT is a conceptual semi-distributed hydrology model with a physical foundation. SWAT includes the effects of weather, surface runoff, evapotranspiration, irrigation, sediment transport, nutrient yielding, groundwater flow, crop growth, pesticide yielding, water routing and the long-term effects of varying agricultural management practices (Neitsch et al., 2011);(Arnold et al., 2012). The sub-basin components of SWAT can be classified into eight major components: hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, and agricultural management (Gassman et al., 2007).In SWAT, a watershed is divided into numerous sub-watersheds, which are further divided into hydrologic response units (HRUs), which are composed of homogeneous land use, management, and soil characteristics. The most commonly used statistics for hydrologic calibration and validation are the regression correlation coefficient (R^2) and the Nash-Sutcliffe efficiency (NSE) coefficient (Nash and Sutcliffe, 1970). The R^2 value assesses how closely the regression line of simulated versus observed values matches an ideal fit. It ranges from 0 to 1, where 0 indicates no correlation, and 1 signifies that the predicted dispersion perfectly matches the observed dispersion (Krause et al., 2005). Fig. 8 shows the framework for hydrological modeling in SWAT.

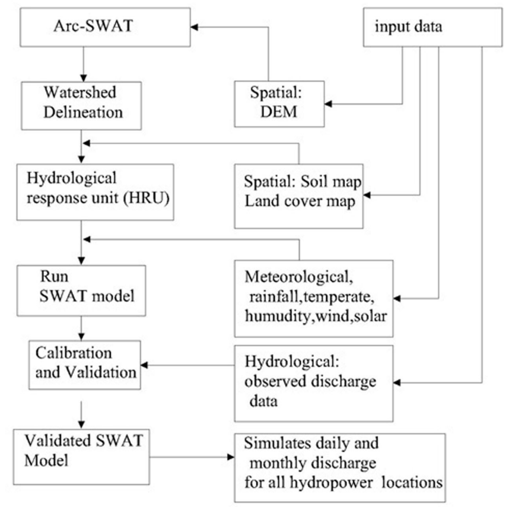

Figure 8: Framework for hydrological modelling in SWAT

The SWAT model setup for this study involved several key steps to analyze hydrology and predict discharge. First, Watershed Delineation was conducted using a projected DEM to define streams, inlets, and outflows, and to calculate sub-basin parameters. This process divided the watershed into sub-basins according to a set threshold value for the catchment area.

Following delineation, Hydrologic Response Unit (HRU) Analysis was performed. This step required land use and soil data, which were overlaid with the watershed boundary and connected to a lookup table. The land use and soil data were then reclassified and defined. SWAT used these data layers to segment the watershed into smaller units known as HRUs, each with a unique combination of land use, soil type, and slope range (Bajracharya, 2015).

Next, the Write Input Tables stage added daily weather data including temperature, relative humidity, solar radiation, and wind speed. Specifically, daily rainfall data were obtained from two stations Gharedhunga and Manang Bhot while temperature, humidity, and wind data were sourced from NASA's data access viewer (https://power.larc.nasa.gov/data-access-viewer).

In the Edit SWAT Input step, the Hargreaves-Samani (HS) method was used to calculate potential evapotranspiration (ETo) based on daily minimum and maximum temperatures. This method, frequently used for its simplicity and reliance solely on temperature data, calculates ETo using the following formula.

$$ET_o = K \times RS \times (T + 17.8) \quad (3)$$

where K is a coefficient, RS is solar radiation, and T is the mean daily temperature.

The final step is the SWAT setup and run, which includes model execution and simulation. In this study, the model was initially run from 1999 to 2009 for calibration, with a two-year warm-up period, and then from 2010 to 2015 for validation. After completing calibration and validation, the SWAT model was run from 1982 to 2016 to determine the average daily and monthly discharge at the intake point. Once the simulation was successful, all input and output data were stored in the TxInout folder within the scenario directory.

4.3. Performance Evaluation

Statistical indices such as the coefficient of determination (R^2), Nash-Sutcliffe Efficiency (NSE), and percentage bias (PBIAS) were used to evaluate model performance. The coefficient of determination (R^2) is the portion of the total variation explained by fitting a regression line and is regarded as a measure of the strength of a linear relationship between observed and simulated data.

$$R^2 = \frac{\sum_{i=1}^{n}(O_i - O_{\mathrm{av}})(S_i - S_{\mathrm{av}})}{\sqrt{\sum_{i=1}^{n}(O_i - O_{\mathrm{av}})^2}\sqrt{\sum_{i=1}^{n}(S_i - S_{\mathrm{av}})^2}} \tag{4}$$

where O_i is the ith observed value, O_{av} is the mean of observed values, S_i is the ith simulated value, S_{av} is the mean of simulated values, and n is the total number of data points.

The Nash-Sutcliffe efficiency (NSE) indicates how well the plot of observed versus simulated data fits the 1:1 line. An NSE value of 1 corresponds to a perfect match of the model to the observed data, an NSE equal to 0 indicates that the model predictions are as accurate as the mean of the observed data, and $-\infty < \mathrm{NSE} < 0$ indicates that the observed mean is a better predictor than the model.

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n}(\mathrm{OBS}_i - \mathrm{SIM}_i)^2}{\sum_{i=1}^{n}(\mathrm{OBS}_i - \overline{\mathrm{OBS}})^2} \tag{5}$$

where OBS_i is the observed value, SIM_i is the simulated value, and $\overline{\mathrm{OBS}}$ is the average of observed values.

PBIAS measures the average tendency of the simulated values to be larger or smaller than their observed counterparts. The optimal value of PBIAS is zero, with low-magnitude values indicating accurate model simulation. Positive values indicate an overestimation bias, whereas negative values indicate a model underestimation bias.

$$\mathrm{PBIAS} = 100 \times \frac{\sum_{i=1}^{n}(\mathrm{SIM}_i - \mathrm{OBS}_i)}{\sum_{i=1}^{n}\mathrm{OBS}_i} \tag{6}$$

4.4. Calibration and Validation of Discharge

The SWAT model was run from 1999 to 2009 for calibration and from 2010 to 2015 for validation, with a two-year warm-up period. Here, sub-basins were divided into 2013 Hydrologic Response Units (HRUs) by the SWAT model. Model calibration is the adjustment of model parameters within a recommended range so that the model output matches the observed data as closely as possible Pokharel et al. (2020). Calibration and validation of discharge were carried out using DHM flow data from the Bimalnagar station from 2001 to 2015.

The hydraulic conductivity of a channel (`CH_K2`), which affects the flow rate within the channel network, is represented by its effective hydraulic conductivity. It controls surface runoff routing and channel flow velocity. The base flow recession rate from the watershed is determined by the base flow alpha factor (`ALPHA_BF`), which regulates groundwater's contribution to streamflow during times of low flow, affecting the watershed's total flow regime. The Manning coefficient for the main channel (`CH_N2`) represents Manning's roughness coefficient for overland flow in the channel network. It characterizes the resistance to flow over the land surface within the channel, affecting the velocity and routing of surface runoff. The mass of soil per unit volume is represented by the soil characteristic known as moist bulk density (`SOL_BD`). This parameter influences infiltration, runoff, and water balance within the watershed by affecting soil water movement, storage capacity, and other soil hydraulic properties.

The shallow aquifer's "revap" threshold depth (`REVAPMN`) indicates the point at which surface water evaporation starts to occur and contributes to groundwater recharge. This affects how water is distributed among surface evaporation, infiltration, and recharge to groundwater, impacting the watershed's hydrological response. Another Manning roughness coefficient specific to tributary channels is Manning's "n" value for channels (`CH_N1`), describing the flow resistance in the network of tributary channels, influencing streamflow's velocity and route. The threshold depth of water in the shallow aquifer required for return flow (`GWQMN`) establishes the minimum aquifer water depth required for groundwater to influence base flow dynamics by contributing to streamflow. The transmission time for lateral flow throughout the watershed is represented by the lateral flow travel time (`LAT_TTIME`). This affects surface runoff and streamflow dynamics by varying the pace at which lateral flow traverses the terrain. The groundwater's response to variations in hydrological inputs is delayed, as shown by the groundwater delay time parameter (`GW_DELAY`), which affects base flow dynamics by calculating the latency between variations in precipitation or other inputs and the corresponding response in groundwater levels.

The Soil Conservation Service (SCS) curve number approach is the source of the SWAT parameter known as the initial SCS runoff curve number II (`CN2`), which is used to estimate initial abstraction and runoff, determining how rainfall is divided into infiltration, surface runoff,

Table 2: Calibrated Parameter Values

Rank	Parameter	Definition	Range	Fitted Value
1	CH_K2	Effective hydraulic conductivity of the channel (mm h^{-1})	-0.05–500	177.32
2	ALPHA_BF	Base flow alpha factor (days)	0–1	0.20
3	CH_N2	Manning coefficient for the main channel (s $m^{-0.33}$)	-0.01–0.3	0.17
4	SOL_BD	Moist bulk density	0.9–2.5	1.95
5	REVAPMN	Threshold depth of water in the shallow aquifer for "revap" to occur (mm)	0–500	500
6	CH_N1	Manning's "n" value for the tributary channels	0.01–30	8.47
7	GWQMN	Threshold depth of water in the shallow aquifer for return flow to occur (mm)	0–5000	1000
8	LAT_TTIME	Lateral flow travel time	0–180	14.98
9	DEEPST	Initial depth of water in the deep aquifer (mm)	0–50000	2000
10	GW_DELAY	Groundwater delay	0–500	31
11	CN2	SCS runoff curve number	35–98	65
12	RCHRG_DP	Deep aquifer percolation fraction	0–1	0.25
13	SURLAG	Surface runoff lag time	0.05–24	17
14	EPCO	Soil evaporation compensation factor	0–1	1
15	TLAPS	Temperature lapse rate	-10–10	-4.9

and potential evapotranspiration. It symbolizes the watershed's initial conditions. The depth to percolation for each HRU at which the evapotranspiration (ET) deficit is fulfilled is determined by the deep aquifer percolation fraction (RCHRG_DP), affecting groundwater recharge dynamics by regulating the amount of water percolating to groundwater after meeting the ET demand. The coefficient governing surface runoff delay is represented by the surface runoff lag coefficient (SURLAG), which controls the timing and size of peak flows by determining the lag time between precipitation input and the start of surface runoff. The compensation factor for soil evaporation, known as the soil evaporation compensation factor (EPCO), modifies the rate of soil evaporation based on environmental factors, including temperature, moisture content, and vegetation cover, influencing water distribution between soil evaporation and infiltration. The temperature lapse rate (TLAPS) is used for elevation adjustments, accounting for elevation-related temperature variations, which affects evapotranspiration, snowmelt processes, and other temperature-dependent hydrological processes (Neitsch et al., 2011).

The SWAT-CUP software module SUFI2 was used to analyze the calibration, validation and sensitivity of the model. Calibration was done by adjusting 15 parameters, Table 2 shows the calibrated parameters and their fitted values.

5. Results and Discussion

Graphically, it can be observed that the simulated flow replicates observed flow in almost all the years. In general, model simulation can be judged as satisfactory if NSE ¿ 0.50 and if PBIAS ± 25% for streamflow (Moriasi et al., 2007). Figs. 9a-b shows the monthly flow calibration at Bimalnagar station for the period 2001-2009 and Coefficient of determination for monthly flow calibration at Bimalnagar station respectively. The values of monthly simulated discharge at Bimalnagar station were compared with the observed discharge at Bimalnagar for model validation as shown in Fig. 9c. The validation was done from 2010 to 2015 with a two-year warm-up period. The coefficient of determination for monthly flow validation at Bimalnagar station is shown in Fig. 9d.

The model underwent calibration and validation using daily flow data, as illustrated in Figures 10a and 10c, respectively. Calibration was conducted for the period from 2001 to 2009, while validation covered the period from 2010 to 2015, each incorporating a two-year warm-up phase. The coefficient of determination for both the calibrations and validations concerning daily flow at Bimalnagar station is presented in Figures 10b and 10d, respectively. There is a strong relationship between precipitation and runoff generation across the land surface. Rainfall is the primary supply of water for rivers within a basin that is influenced by its underlying surface conditions, topography, geomorphology, and climate (Miao et al., 2020). Fig. 11 shows the relationship between rainfall and runoff obtained by the SWAT model for the period 2001-2009.

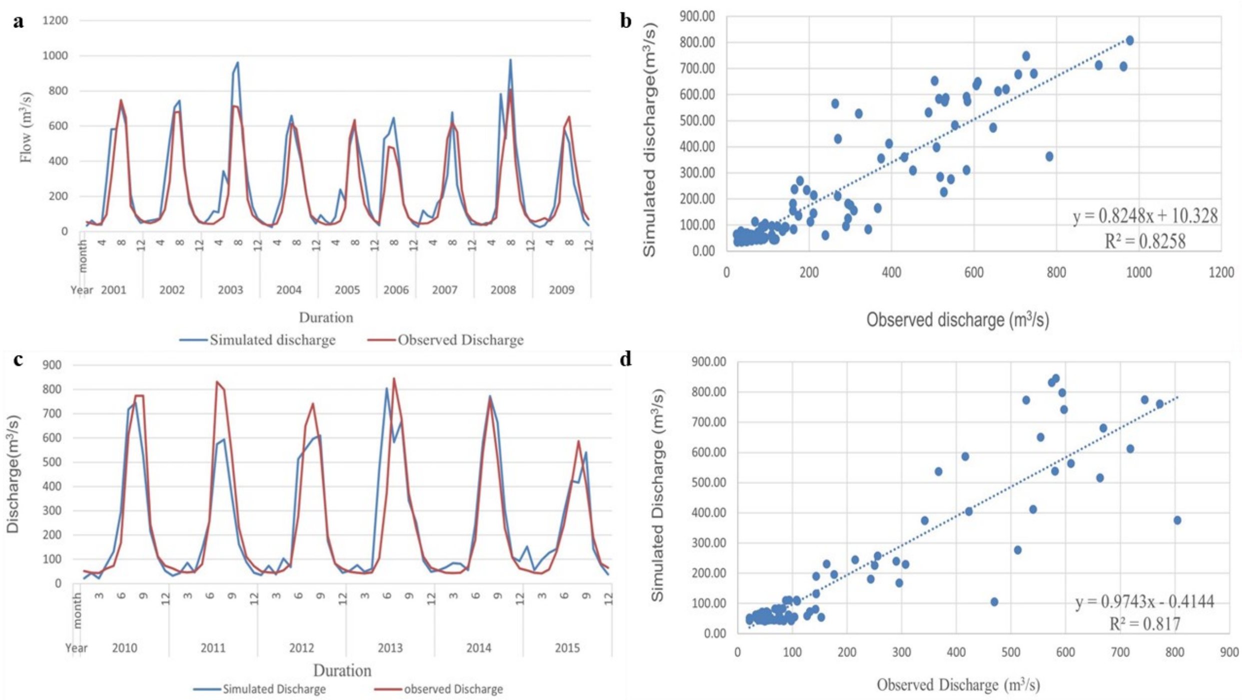

Figure 9: (a) Monthly flow calibration at Bimalnagar Station, (b) Coefficient of determination for monthly flow calibration (2001-2009) at Bimalnagar Station, (c) monthly flow validation with Bimalnagar Station, (d) Coefficient of determination for monthly flow validation (2001-2009) at Bimalnagar Station.

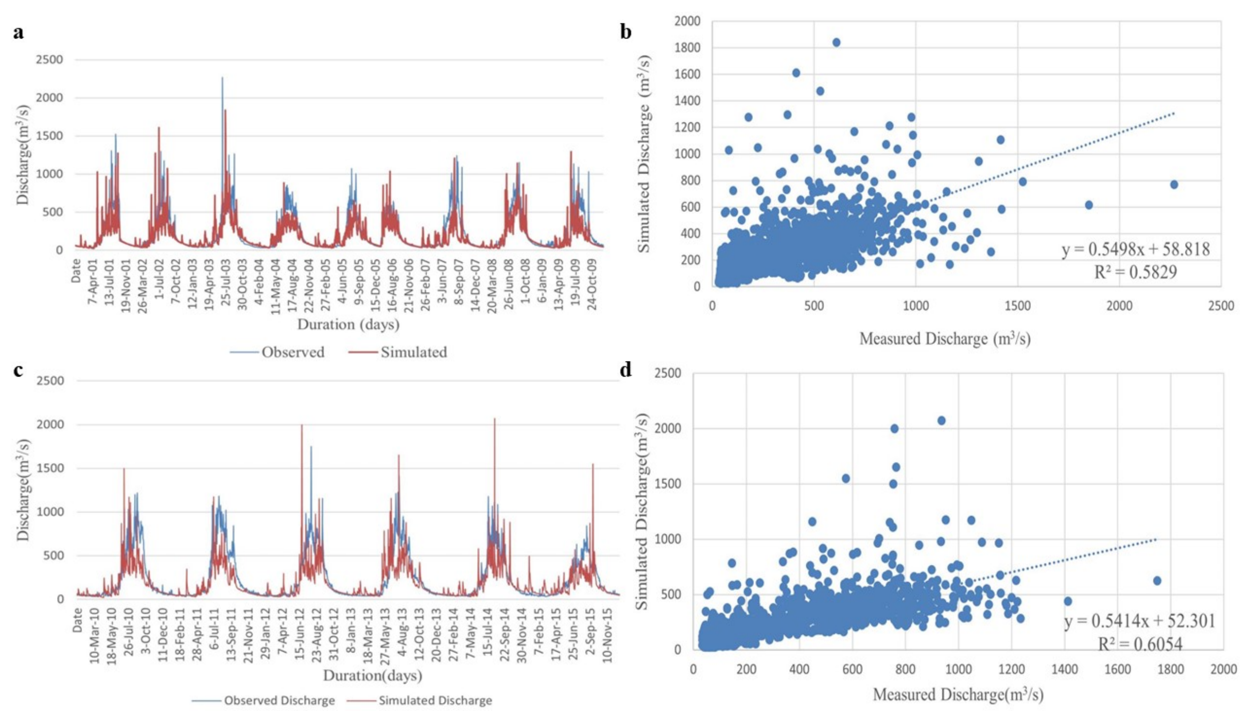

Figure 10: (a) Daily flow calibration with Bimalnagar Station, (b) Coefficient of determination for daily flow calibration (2001-2009) at Bimalnagar Station, (c) Observed and simulated daily flow validation hydrograph at Bimalnagar Station, (d) Coefficient of determination for daily flow validation (2001-2009) at Bimalnagar Station.

Table 3: Sensitivity Rank of Parameters

Rank	Parameter	Parameter Description	P-Value	t-Stat
1	CH_K2	Effective hydraulic conductivity of the channel	0.00	-123.51
2	ALPHA_BF	Base flow alpha factor (days)	0.00	44.42
3	CH_N2	Manning coefficient for the main channel	0.00	-13.07
4	SOL_BD	Moist bulk density	0.0594	1.913
5	REVAPMN	Threshold depth of water in the shallow aquifer for ”revap” to occur (mm)	0.11	-1.58
6	CH_N1	Manning’s ”n” value for the tributary channels	0.12	1.53
7	GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	0.14	1.487
8	LAT_TTIME	Lateral flow travel time	0.26	-1.12
9	DEEPST	Initial depth of water in the deep aquifer (mm)	0.43	0.77
10	GW_DELAY	Groundwater delay	0.60	0.51
11	CN2	SCS runoff curve number	0.67	0.42
12	RCHRG_DP	Deep aquifer percolation fraction	0.71	-0.360
13	SURLAG	Surface runoff lag time	0.79	0.25
14	EPCO	Soil evaporation compensation factor	0.83	-0.20
15	TLAPS	Temperature lapse rate	0.88	0.14

5.1. Sensitivity Analysis

Sensitivity analysis is a technique used to examine the behavior of a system or model based on changes in its parameters or inputs. Its purpose is to determine how sensitive the outcome of a model is to changes in one or more of its inputs. The analysis involves identifying the critical factors that affect the model’s performance, evaluating the range of values that these factors can take and determining the impact of these changes on the model’s output. The t-stat is the ratio of parameter coefficient to its standard error. Parameters with p-values less than or equal to 0.05 are taken as sensitive (Bhattarai et al., 2024). The categorization of sensitive parameters is shown in Table 3. $CH_K 2$, $ALPHA_B F$ and $CH_N 2$ were found to be the most sensitive parameters for Marsyangdi River basin.

5.2. Statistical Evaluation of Model

Table 4: Classification of statistical indices (Almeida et al., 2018)

NSE	PBIAS	R^2	Classification
0.75 < NSE ≤ 1.00	$PBIAS \leq \pm 10$	$0.75 < R^2 \leq 1.00$	Very good
0.60 < NSE ≤ 0.75	$-10 < PBIAS \leq \pm 15$	$0.60 < R^2 \leq 0.75$	Good
0.36 < NSE ≤ 0.60	$-15 < PBIAS \leq \pm 25$	$0.50 < R^2 \leq 0.60$	Satisfactory
0.00 < NSE ≤ 0.36	$-25 < PBIAS \leq \pm 50$	$0.25 < R^2 \leq 0.50$	Bad
NSE ≤ 0.00	$PBIAS \leq -50$	$R^2 \leq 0.25$	Inappropriate

In general, model simulation can be judged as satisfactory if 0.36 < NSE ≤ 0.60, ±15 < PBIAS ≤ ±25, and $0.50 < R^2 \leq 0.60$ (Almeida et al., 2018), as shown in Table 4. The results of statistical analysis for the calibration and validation of monthly and daily discharge are presented in Table 5.

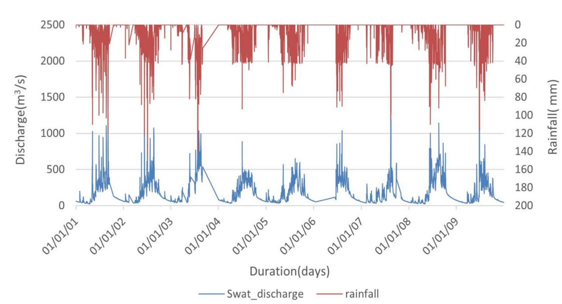

Figure 11: Simulated discharge and precipitation relationship with respect to duration.

5.3. Hydropower Potential Estimation

Update flow data according to the mean daily flows and develop an upgraded flow duration curve (DOED, 2018). FDCs enabled to determination of discharge corresponding to varying degrees of dependability. Mostly installed capacities of the hydropower sites are designed for 40–60% flow exceedance (Thin et al., 2020). After characterizing the streams in terms of head and FDC, the available hydropower at the identified sites was estimated using an established power equation. The sites identified in the present investigation are only theoretically potential sites identified based on model outputs. Fig. 12 shows a com-

Table 5: Calibration and validation statics assessing model performance at Bimalnagar hydrological station.

Index	**Monthly**		**Daily**	
	Calibration	**Validation**	**Calibration**	**Validation**
Correlation Coefficient (CC)	0.909	0.904	0.763	0.778
Coefficient of Determination (R^2)	0.83	0.818	0.582	0.605
Percent Bias (PBIAS)	-15.57	-2.817	18.616	23.75
NSE	0.765	0.816	0.552	0.555

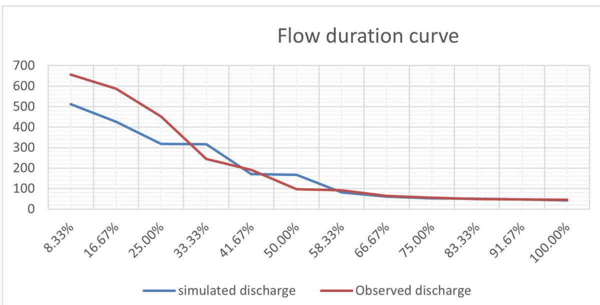

Figure 12: FDC of observed and simulated discharge at Bimalnagar hydrological station.

parison between the simulated and observed FDC data at the Bimalnagar hydrological station The Marsyangdi basin comprises 79 potential run-of-river hydropower sites with a total capacity of 1,568.96 MW. The majority of potential sites (39) are in the 10–50 MW range, contributing 59% of the total power. Sites with capacities over 50 MW represent a smaller portion: 6 sites (19%) in the 50–100 MW range and 1 site (13%) over 100 MW. Additionally, 33 smaller sites, each between 1 and 10 MW, contribute 9% of the total power. The number of potential sites and hydropower potential at 40% and 30% dependability having efficiency 80% based on power generation and mean daily FDC were determined as shown in Tables 6.

The estimated hydropower potential in the Marsyangdi River varies depending on whether daily or monthly mean flow discharge is considered. At a 40% probability of exceedance, the theoretically achievable hydropower is 1568.96 MW using daily flow duration curves (FDC) and 2727.70 MW with monthly FDC. Similarly, at a 30% exceedance probability, the potential is 2191.68 MW using daily mean flows compared to 4293.12 MW with monthly flows. This indicates that hydropower potential is generally higher when based on monthly rather than daily mean flow discharge.

5.4. ROR hydropower potential determination by other researchers and institutions

The ROR hydropower potential of Marsyangdi basin determined by this study was compared with those reported in the literature. The gross hydropower potential reported by Jha (2010) is closer to this study. Compared to results of this study, Bajracharya (2015) and WECS (2019) report higher power potential. WECS carried out a study on the assessment of the hydropower potential of Nepal and two hydrological parameters, namely average monthly flow (AMF) and flow duration curve (FDC) are computed for each potential hydropower generation site. It should be noted that the figures reported in the literature are computed under different assumptions than this study. Bajracharya (2015) estimated the power potential at mean annual flow whereas Jha (2010) used 40% dependable flow similar to this study as shown in Table 7.

Jha (2010) used the FORTRAN computer language-written hydropower model. The hydropower potential is determined on a run-of-river basis at a flow exceedance of 40% and an efficiency of 80%. Bajracharya (2015) used the SWAT hydrological model and a GIS-based spatial tool was used to determine the hydro potential. The calibration is done by trial and error manually. The sensitivity is measured by relative sensitivity index (RSI) which is defined as:

$$\mathrm{RSI} = \frac{(y_2 - y_1)}{(X_2 - X_1)} \cdot \frac{x_a}{y_a}$$

Where RSI is the relative sensitivity index x1 and x1 are the minimum and maximum values of input parameter y1 and y2 are the minimum and maximum values of the model output, xa is the average value of x1 and x2, ya are the average value of y1 and y2. WECS (2019) used HEC-HMS (hydrologic engineering center-hydrologic modeling system) was used to determine hydrological parameters. The performance of the model calibration and validation was assessed by comparing the observed and simulated hydrographs and computing some statistical performance indicators. The indicators considered are normalized root mean square error (NRMSE), Nash-Sutcliffe coefficient of efficiency (NSE) and volume bias (VB).

Table 6: Hydropower sites on the basis of production capacity at 40% and 30% dependability.

S.N.	Hydropower sites based on capacity	40% Probability of exceedance			30% Probability of exceedance		
		No. of potential sites	Power (MW)	% Power	No. of potential sites	Power (MW)	% Power
1	> 1 MW and ≤ 10 MW	33	136.53	9%	25	85.87	4%
2	> 10 MW and ≤ 50 MW	39	924.53	59%	39	890.76	41%
3	> 50 MW and ≤ 100 MW	6	401.22	19%	12	802.47	37%
4	> 100 MW	1	107.37	13%	3	412.57	19%
Total		79.00	1568.96	100%	79.00	2191.68	100%

Table 7: Comparison between the ROR hydropower potential of Marsyangdi reported in the literature and current study

Institutions/Researcher	Discharge	% Exceedance	Hydropower Potential (MW)
Jha (2010)	Mean monthly	40	3251.8
Bajracharya (2015)	Mean annual	Mean flow	6476
WECS (2019)	Mean monthly	40	4614
Current study	Mean monthly	40	2727.70
	Mean daily	40	1568.96

6. Conclusions

In this study, the SWAT model and ArcGIS were used to assess the run-of-river (ROR) hydropower potential in the Marsyangdi River basin. Discharge at various intake points was determined by developing a hydrological model, using available meteorological data such as precipitation, temperature, humidity, and wind speed as inputs for the SWAT model. Model calibration and validation were conducted using the SUFI-2 algorithm within SWAT-CUP, where fifteen parameters were adjusted. Among these, CH_K2, ALPHA_BF, and CH_N2 were identified as the most sensitive parameters. The model was calibrated for the period from 2001 to 2009 and validated from 2010 to 2015. To evaluate the performance of the model, statistical metrics including the coefficient of determination (R^2), Nash-Sutcliffe efficiency (NSE), and percent bias (PBIAS) were used. A total of 79 hydropower potential sites were identified based on factors such as head, discharge availability, minimum distance between sites, and stream order of the river. Hydropower potential was estimated at various exceedance probabilities, with results showing potential capacities of 1568.96 MW at 40% exceedance probability and 2191.68 MW at 30% exceedance probability, based on mean daily flow. These findings offer valuable insights for hydropower developers, water resource planners, and policymakers to optimize water resource utilization in the Marsyangdi River basin. The study also provides a foundation for future academic research into the key factors influencing hydropower potential. Despite the promising results, this study faced limitations due to the sparse availability of hydrological stations and meteorological data. The calibration of the entire basin was constrained by a single hydrological station located downstream and only two meteorological stations. To improve future assessments, efforts should focus on obtaining upstream hydrological data and expanding meteorological monitoring infrastructure. Such enhancements would enable more accurate hydrological modeling and benefit other meteorological and physiographic studies within the basin.

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References

Almeida, R. A., Pereira, S. B., and Pinto, D. B., 2018. Calibration and validation of the SWAT hydrological model for the Mucuri river basin. *Engenharia Agrícola*, 38, 55–63.

Arnold, J. G., Moriasi, D. N., Gassman, P. W., Abbaspour, K. C., White, M. J., Srinivasan, R., Santhi, C., Harmel, R., Van Griensven, A., Van Liew, M. W., and Coauthors, 2012. SWAT: Model use, calibration, and validation. *Transactions of the ASABE*, 55 (4), 1491–1508.

Bajracharya, I., 2015. Assessment of run-of-river hydropower potential and power supply planning in Nepal using hydro resources. Ph.D. thesis, Technische Universität Wien.

Bhattarai, R., Mishra, B. K., Bhattarai, D., Khatiwada, D., Kumar, P., and Meraj, G., 2024. Assessing Hydropower Potential in Nepal's Sunkoshi River Basin: An Integrated GIS and SWAT Hydrological Modeling Approach. *Scientifica*, 2024 (1), 1007 081.

DOED, 2018. Guidelines for Study of Hydropower Projects. URL http://www.doed.gov.np/storage/listies/December2019/guidelines-for-study-of-hydropower-projects-2018.pdf.

Feizizadeh, B., and Haslauer, E. M., 2012. GIS-based procedures of hydropower potential for Tabriz basin, Iran. *International Journal*, 495–502.

Gassman, P. W., Reyes, M. R., Green, C. H., and Arnold, J. G., 2007. The soil and water assessment tool: historical development, applications, and future research directions. *Transactions of the ASABE*, 50 (4), 1211–1250.

Jha, R., 2010. Total run-of-river type hydropower potential of Nepal. *Hydro Nepal: Journal of Water, Energy and Environment*, 7, 8–13.

Krause, P., Boyle, D., and Bäse, F., 2005. Comparison of different efficiency criteria for hydrological model assessment. *Advances in geosciences*, 5, 89–97.

Kusre, B., Baruah, D., Bordoloi, P., and Patra, S., 2010. Assessment of hydropower potential using GIS and hydrological modeling technique in Kopili River basin in Assam (India). *Applied Energy*, 87 (1), 298–309.

Miao, C., Zheng, H., Jiao, J., Feng, X., Duan, Q., and Mpofu, E., 2020. The changing relationship between rainfall and surface runoff on the Loess Plateau, China. *Journal of Geophysical Research: Atmospheres*, 125 (8), e2019JD032 053.

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., and Veith, T. L., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE*, 50 (3), 885–900.

Neitsch, S. L., Arnold, J. G., Kiniry, J. R., and Williams, J. R., 2011. Soil and water assessment tool theoretical documentation version 2009. Tech. rep., Texas Water Resources Institute.

Pandey, A., Lalrempuia, D., and Jain, S., 2015. Assessment of hydropower potential using spatial technology and SWAT modelling in the Mat River, southern Mizoram, India. *Hydrological Sciences Journal*, 60 (10), 1651–1665.

Pokharel, N., Basnet, K., Sherchan, B., and Thapaliya, D., 2020. Assessment of hydropower potential using SWAT modeling and spatial technology in the Seti Gandaki River, Kaski, Nepal. *vol*, 8, 87–102.

Thin, K. K., Zin, W. W., San, Z. M. L. T., Kawasaki, A., Moiz, A., and Bhagabati, S. S., 2020. Estimation of run-of-river hydropower potential in the Myitnge river basin. *Journal of Disaster Research*, 15 (3), 267–276.

WECS, 2019. Assessment of hydropower potential of Nepal. Water and Energy Commission Secretariat Kathmandu.