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Assesement of Surface Water Availability of Kathmandu Valley Using SWAT Model

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Abstract: The study used the Soil and Water Assessment Tool (SWAT) model to analyse the surface water availability in the Kathmandu Valley. The model was calibrated and validated at Khokana station of basin area 592 km^2 for the period from 2000 to 2015. To test the model's performance for smaller subbasins, it was validated at Sundarijal station of basin area 16 km^2. The daily runoff simulation statistics indicated that the model's performance was satisfactory and the model effectively captured the runoff trend for the entire basin and subbasin catchment areas. This study demonstrates that the model can be adopted for assessing stream flow within the basin by selecting appropriate parameter values. The calibrated and validated model was subsequently applied to determine the surface water availability in surrounding mountainous, forested regions less affected by urbanisation, by setting up the model at 66 watersheds. The results indicate that the upper reaches of the Bagmati River basin and its tributary, the Nakkhu River, possess substantial surface water resources that can be utilised to alleviate water stress in the valley.

Key words: Water scarcity, surface water availability, SWAT, hydrological modelling.

Introduction

The flat terrain and rich soil of the Kathmandu Valley (KV) have long drawn settlers. However, urbanisation in Nepal has accelerated since 1980. Consequently, the population of KV is rapidly growing, with the Kathmandu metropolitan area expanding at a rate of 6.5% per year. This growth has led to the concretisation of large areas, reducing the amount of groundwater recharge and increasing the risk of flooding (Kc et al., 2021). These factors have led to a shortage of water for both households and industrial use, prompting many Kathmandu residents to rely on private water tankers for their daily water needs.

The mountainous regions surrounding KV supply a significant amount of water to the area, where the demand exceeds 500 MLD (million litres per day). However, in 2016, the supply was only 133.38 MLD (Udmale et al., 2016). The Melamchi Water Supply Project is a large infrastructure project that aims to provide clean drinking water to the residents of KV in Nepal. The project involves diverting water from the Melamchi River, located about 27 kilometers east of Kathmandu, into the city's existing water supply system (Udmale et al., 2016). Once completed, the Melamchi project will bring around 170 million liters of water per day to the KV, which is expected to significantly alleviate the water scarcity problem in the region.

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However, even with the completion of the Melamchi project, it’s not guaranteed that the water needs of the KV would be completely satiated (Molden, 2020).

In this scenario, investigating the availability of surface water in surrounding regions can offer valuable insight for ensuring water security and utilising water sources efficiently to benefit people living there (Thapa et al., 2016). These resources are crucial in meeting the water needs of the KV and addressing the water shortage in the area (Udmale et al., 2016).

The study quantified the available stream flow to evaluate the quantity and distribution of surface water resources in the Bagmati River basin in the KV by applying the SWAT model. The model was deployed for the period between 2000 and 2015. It is widely utilised to quantify water scarcity. The model can simulate the impact of LU change, climate change, and water resources usage strategy on the hydrological cycle and estimate the water availability. It can simulate water scarcity in a specific region by analysing precipitation, evapotranspiration, soil moisture, and water flow (Baker & Miller, 2013; Bal et al., 2021; Bera & Maiti, 2021; Guug et al., 2020; Saade et al., 2021).

Study Area

The research is focussed on KV, situated in the middle mountain region of central Nepal, and includes the catchment of the Bagmati River in the capital city. The area is positioned between the latitudes of $27^{o}25'$ and $25^{o}50'$, and the longitudes of $85^{o}10'$ and $85^{o}50'$ which is shown in Figure 1. It has a temperate climate with dry winters and hot summers, with a mean annual temperature of $16^{o}C$ to $20^{o}C$ and an average annual precipitation of 1200 to 1400 mm, mostly occurring during the monsoon season. The elevation range in KV varies from 1300m to the surrounding mountain peaks of around 2600 m.

Materials and Methods

Data Acquisition and Processing

The hydrological and meteorological data from 2000 to 2015 used in this research were sourced from the Department of Hydrology and Meteorology (DHM). The land use (LU), soil, elevation and slope maps are necessary to develop the Hydrological Response Unit

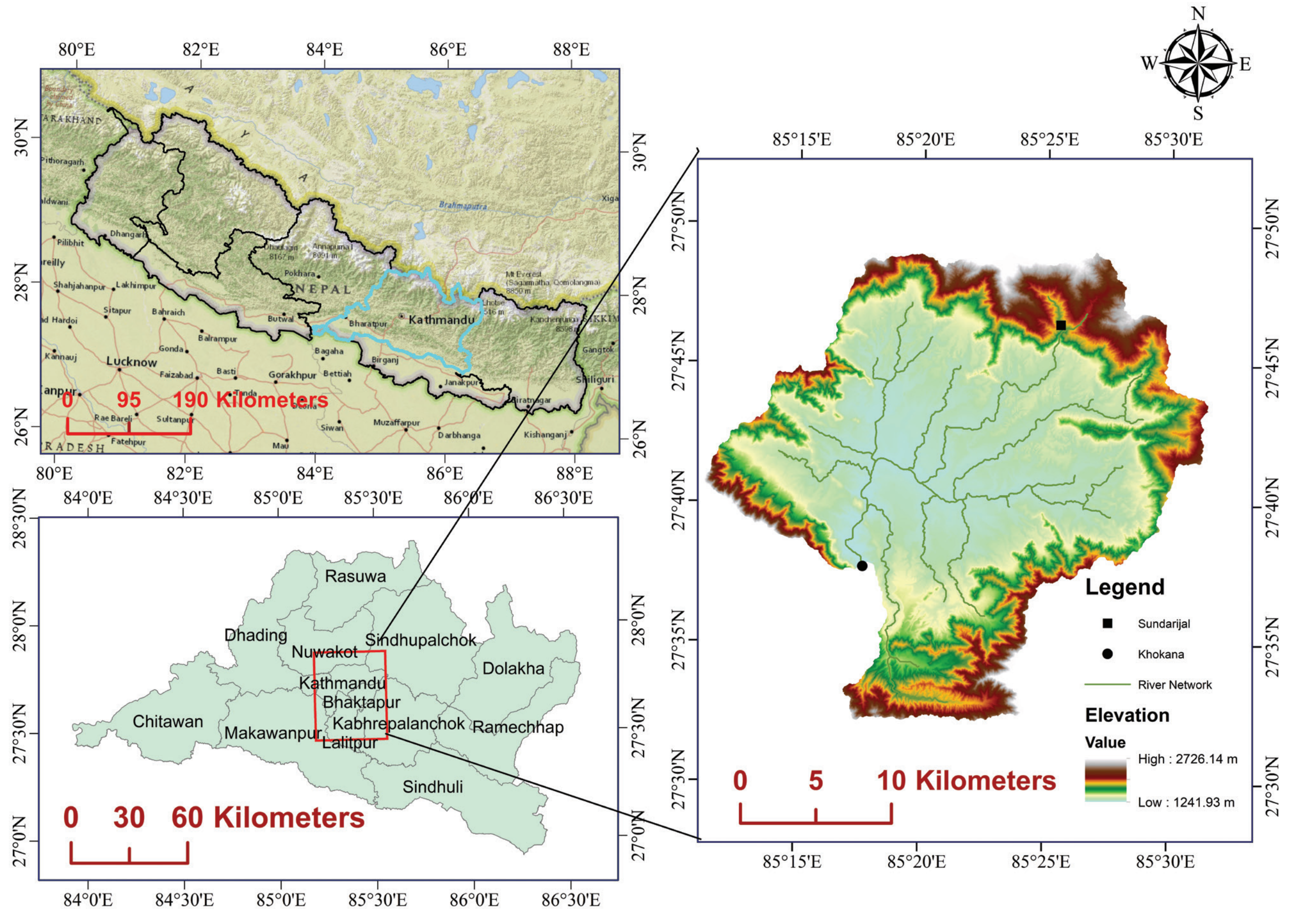


Figure 1: The study area map includes Kathmandu, the capital city of Nepal.

(HRU) in the SWAT model. The required maps were collected from various sources.

The LU map for modeling was taken from the LU classification of the region by Pokhrel & Shakya (2021). The soil map was acquired from the soil data repository of SOTAR Nepal. The digital elevation map (DEM) was obtained from SRTM and the slope map was produced utilising the DEM. The spatial resolution of all maps for the study measured 30 m × 30 m. Figure 2 displays data utilised in this study.

SWAT Model Setup, Sensitivity Analysis, Calibration and Validation

SWAT is a physically based, semi-distributed model known for its flexibility and its capability to incorporate human impacts on water resources. It is frequently utilised by researchers, water managers, and policymakers to examine the effects of LU change, water management practices, and climate change on water resources, and to assist in formulating and executing effective conservation strategies (Bhatta et al., 2019; Jordan et al., 2022; Sharma et al., 2022).

Hydrology in SWAT Model

The overall methodological framework adopted for the study is shown in Figure 3. Hydrological processes in SWAT are simulated by dividing the watershed into sub-watersheds or subbasins which are further divided into HRUs having similar hydrologic characteristics. Each HRU is defined by a unique combination of soil, LU, and management practices. Each HRU's daily water budget is calculated as follows:

$$SW_T = SW_o + \sum_{k=i}^{T}(R_i - Q_{surf,k} - Q_{et,k} - Q_{perc,k} - Q_{gwrf,k})$$

Here, SW_T refers to the soil water content at the end of time 'T' measured in days, while SW_0 represents the soil water content in millimeters at the beginning of 'T'. Accordingly, R_k signifies the precipitation on day 'k' measured in millimeters, $Q_{surf,k}$ denotes the surface runoff on day 'k' measured in millimeters, $Q_{et,k}$ stands for evapotranspiration on day 'k' measured in millimeters, $Q_{perc,k}$ represents percolation on day 'k' measured in millimeters, and $Q_{gwrf,k}$ indicates the

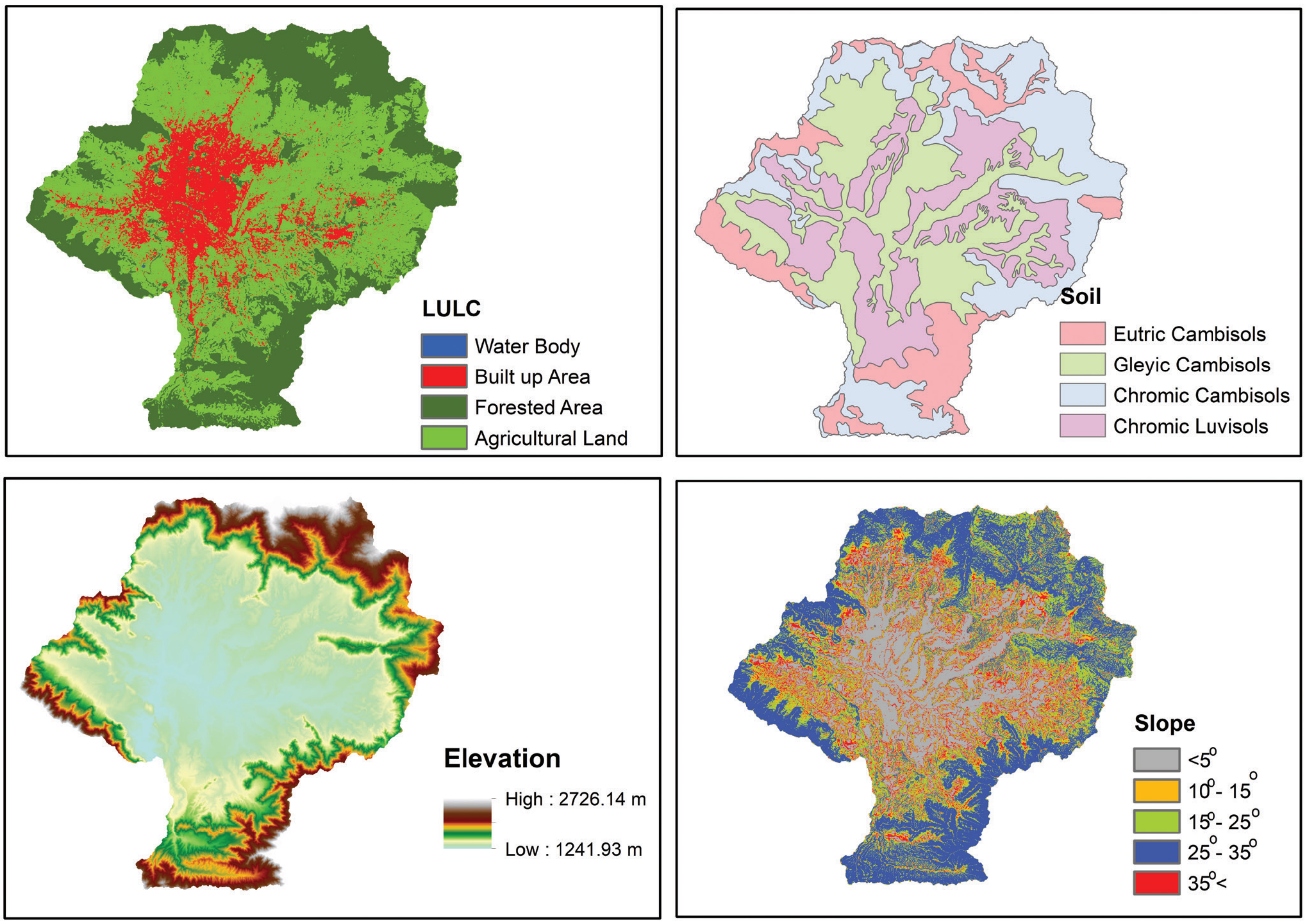


Figure 2: Landuse, Elevation, Soil and Land Slope Map for the SWAT Modeling.

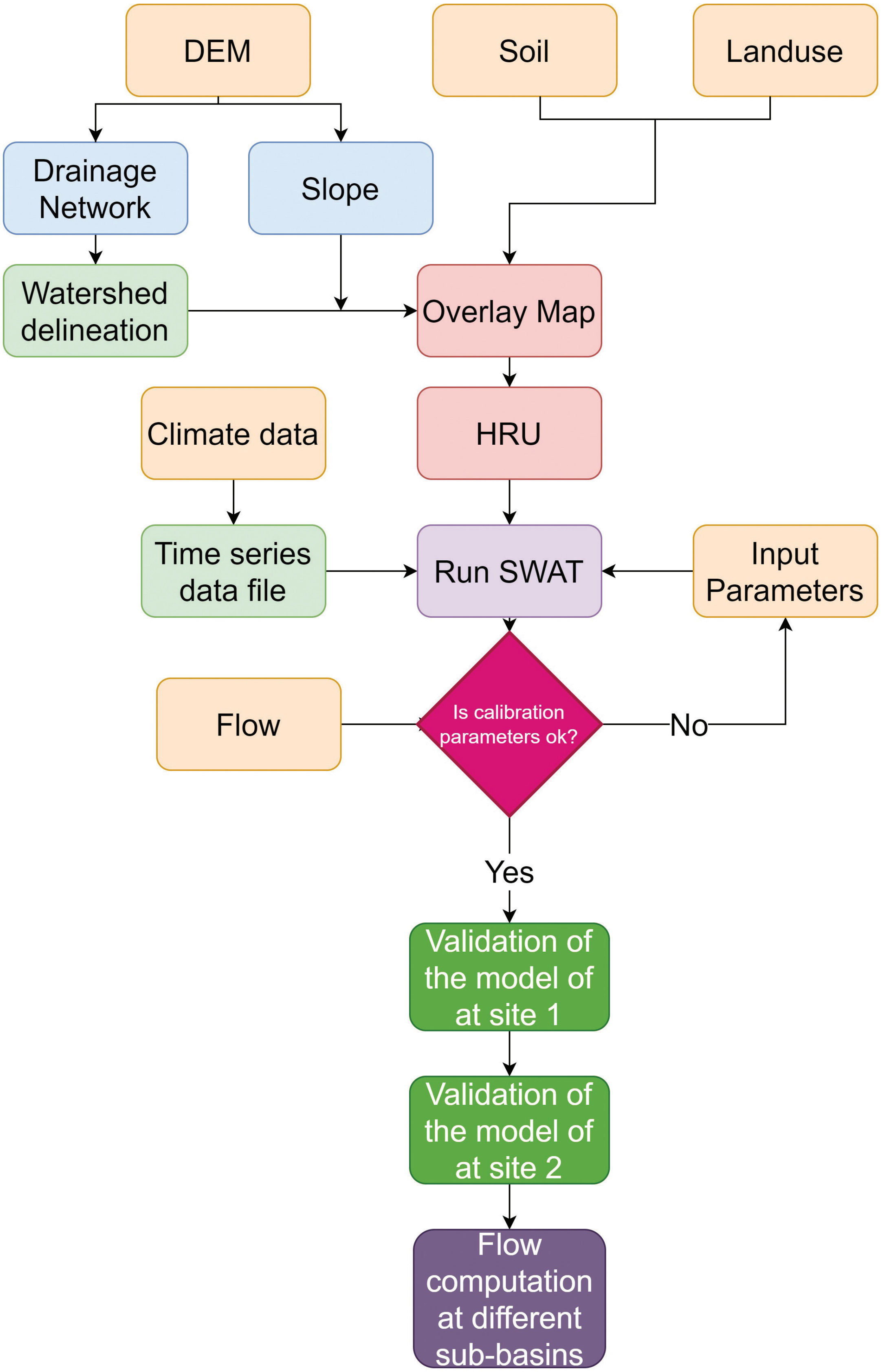


Figure 3: Overall methodological diagram for flow simulation in SWAT Model.

groundwater return flow on the same day, measured in millimeters (Neitsch et al., 2005).

SWAT employs the Soil Conservation Service (SCS) curve method for daily rainfall runoff modeling. The SCS curve equation uses the following equation to determine accumulative runoff or excess rainfall (Neitsch et al., 2005).

$$Q_{surf,k} = \frac{(R_k - 0.2Sr)^2}{R_k + 0.8S_r} \quad (2)$$

where S_r is the retention parameter in mm.

$$S_r = 25.4\left(\frac{1000}{CN} - 10\right) \quad (3)$$

where CN is SCS curve number.

SWAT uses a modified rational equation to determine the peak runoff rate for the basin. The peak flow for a given event occurs when the duration of rainfall exceeds the time of concentration. The peak flow is given by the following equation.

$$q_{\text{peak}} = \frac{CIA}{3.6}$$

where q_{peak} is the peak runoff in m^3/s, C is runoff coefficient, I is the intensity of rainfall in mm/hr, and A is the Area in km^2.

Time of concentration of each basin is defined as the time of travel of water from the farthest point of the sub-basin to its outlet it can be expressed as the total time for overland flow and channel flow (Neitsch et al., 2005).

$$t_{conc} = t_{ov} + t_{ch}$$

A storage routing technique is employed to determine the movement of water across different strata in the soil. In the model, shallow aquifers and deep aquifers are located below the soil profile. Water that replenishes the shallow aquifer can contribute to stream flow and evapotranspiration from deep-rooted plants, known as "revap". On the other hand, water that recharges the deep aquifer is not considered in the model (Arnold et al., 2012).

Configuration in Arc-SWAT

The Arc-SWAT utilises DEM data to subdivide the watershed into smaller, hydrologically linked sub-watersheds. It employs the capabilities of the Spatial Analyst extension to carry out the task of watershed delineation. (Nazari-Sharabian et al., 2020).

DEM of 30 meters' resolution and a threshold size of 1000 hectares was used for the stream network generation. Additionally, data from streamflow gauge stations were added during the process of subbasin delineation. In order to reduce computation time, HRUs that represented less than 5% of the combination of soil, LU, and slope were removed from the analysis.

The modeling duration was set to 2000-2015, including calibration years 2002-2009 and validation years 2010-2015. The "NYSKIP" parameter was set to 2, indicating the first two years of the simulation period (2000-2001) as warm-up years.

Modelling in SWAT-CUP

The SWAT-CUP, employing the sequential uncertainty fitting (SUFI-2) algorithm, was utilised for calibration, validation, and sensitivity analysis in this study. The methodological diagram for SWAT-CUP is shown in Figure 4. The parameters Nash-Sutcliffe coefficient (NSE), coefficient of determination (R^2) and Percent bias (PBIAS) were used for the evaluation of the model's outcomes (Arnold et al., 2012; Gupta et al., 1999; Moriasi et al., 2007).

The SUFI-2 algorithm in SWAT-CUP can identify the key parameters that have a significant influence on model outcomes through a process called sensitivity analysis. It takes into account the input data, model structure, parameters, and observations. To determine parameter sensitivity, t-values and p-values of the parameters are calculated before and after updating the statistical model (Thavhana et al., 2018).

For the calibration process, the algorithm was employed to evaluate the parameters using a t-test hypothesis. A greater *t*-value relative to the critical value indicates better performance. The relevance of the *t*-value can be determined by the *p*-value. A lower *p*-value indicates a more significant parameter. A sensitive parameter is considered to be one with a *t*-statistic value greater than 5% (Arnold et al., 2012).

In the sensitivity analysis, the parameters recommended by Abbaspour et al. (2007) were utilised. A total of 14 parameters were included in the analysis. The parameters were arranged based on their sensitivity to the model during calibration. Plots were created to show the distribution of simulations and the sensitivity of the parameters was assessed by evaluating them against objective functions such as R^2 and NSE.

Result and Discussion

SWAT Model Parameterisation and Parameter Sensitivity Analysis

The findings from the sensitivity analysis are presented

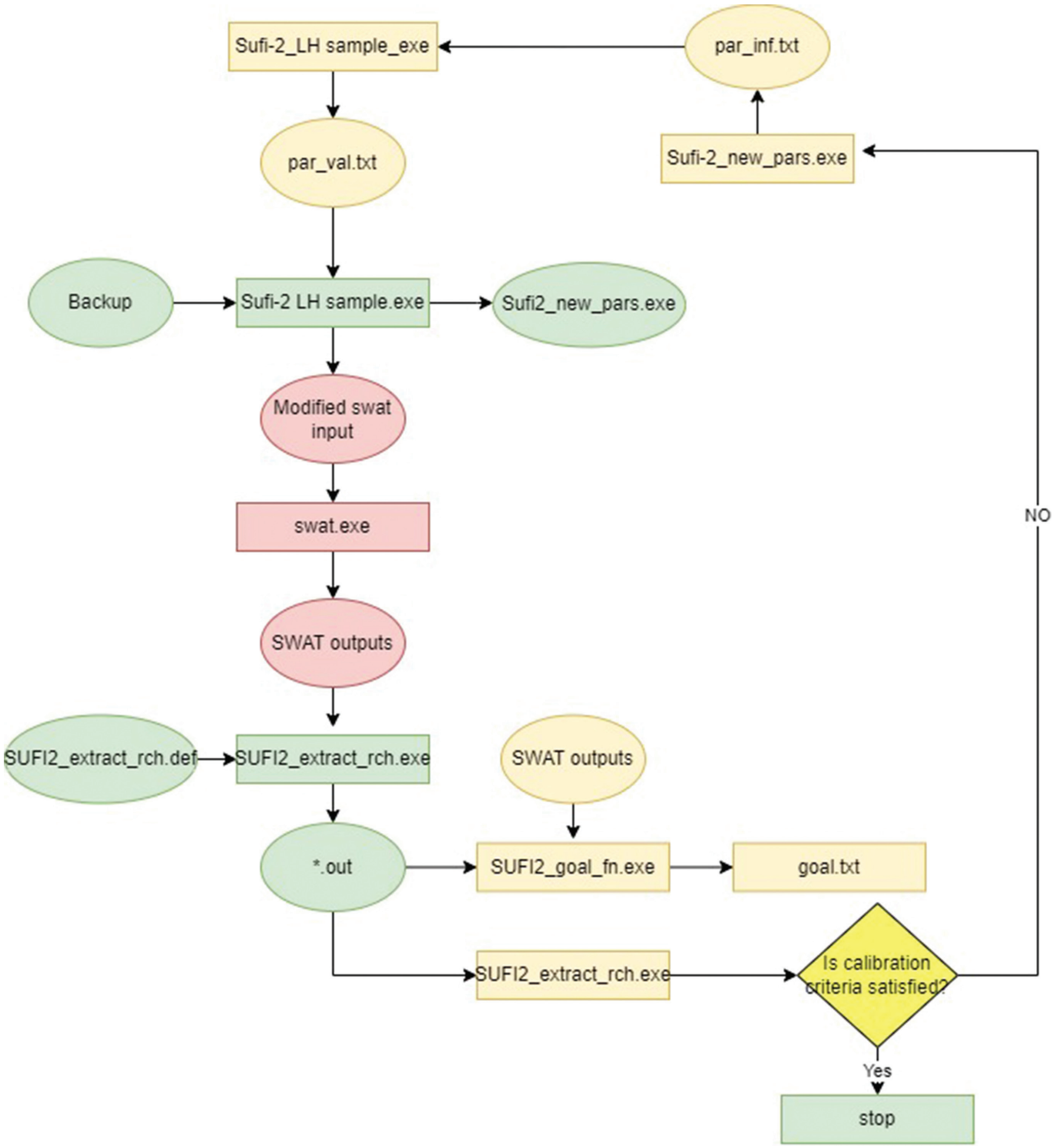


Figure 4: Methodological diagram of calibration and validation in SWAT CUP adopted from Abbaspour, 2015.

in Figure 5. It shows that the streamflow in the Bagmati River in KV is primarily affected by three parameters: CN2, SOL_K, and OV_N. The SCS curve number is dependent on the soil's permeability, LU, and previous soil water conditions. Similarly, OV_N is also dependent on the characteristics of the land surface. On the other hand, SOL_K measures the soil's capacity for water to move freely within. While SOL_K pertains to the movement of water within the soil.

Flow Calibration and Validation for Daily Model

The model was established through flow calibration in the overall basin and a multi-site validation process. The Sundarijal station and Khokana stations were considered for calibration and validation using stream gauge data. Parameters for calibration were chosen based on the sensitivity analysis findings. The comparison between simulated flow and observed flow on a daily basis is illustrated in Figure 6. The period from 2002 to 2009 was used for calibration, and the data that remained

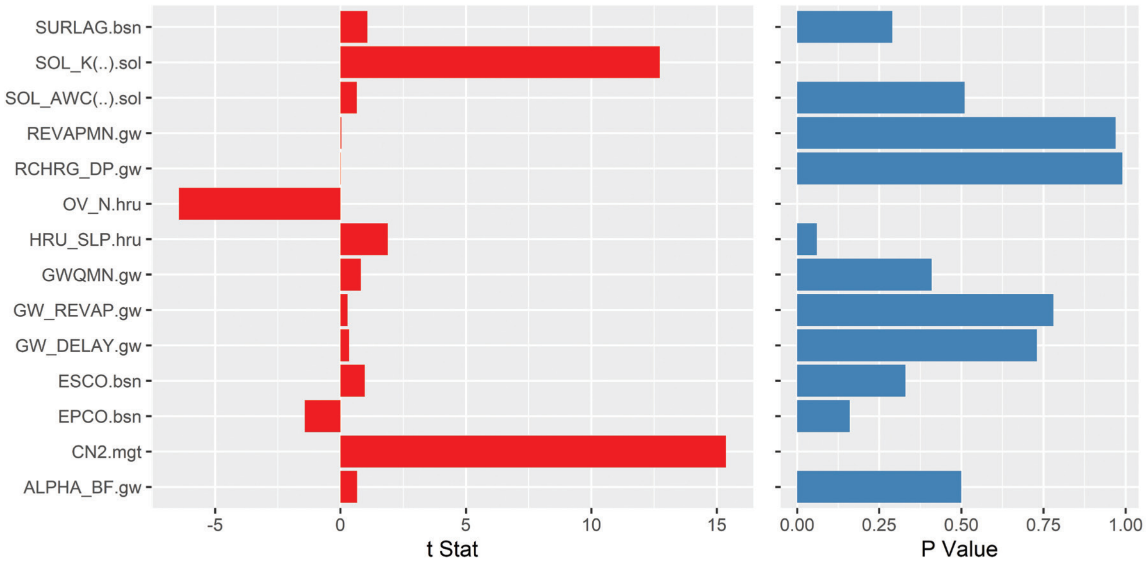


Figure 5: Sensitivity Analysis of Parameters: P-value and *t*-Stat for Flow Modeling.

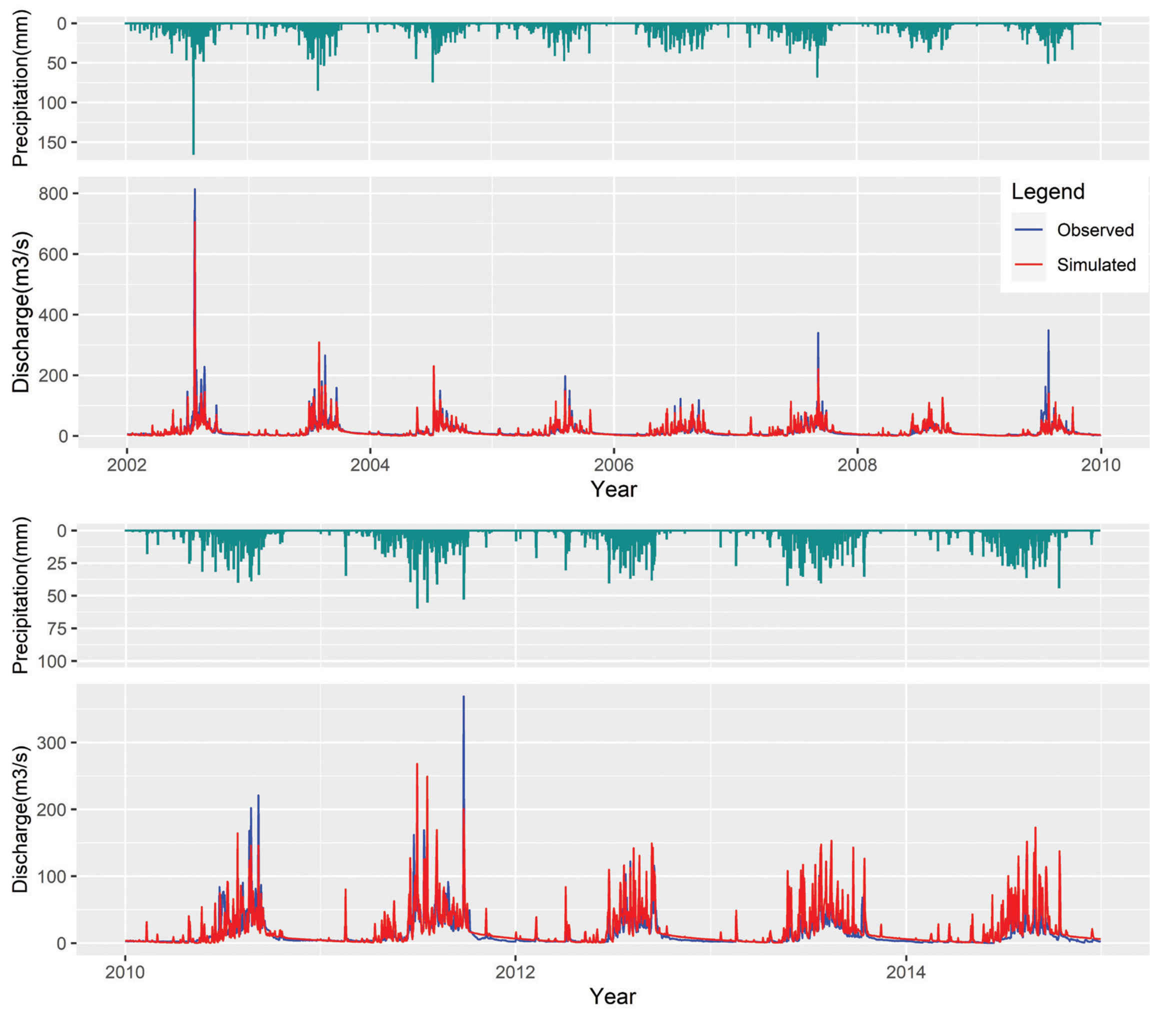


Figure 6: Hydrograph of simulated flow and observed flow for calibration (2002-2009 and validation (2010-2015) period in Khokana Station.

was employed for validation. The summary results are presented in Table 1. The scatter plots, cumulative volume, and flow duration curves are shown in Figure 7. The calibration and validation at the Khokana station indicate that the model was capable of simulating flow data that was closer to the observed data.

The results of the daily flow simulation at Khokana were comparable to those obtained from previous studies using other models. A study by Devkota &

Table 1: Calibration and validation result for Khokana and Sundarijal stations

Station	*Variable*	*R^2*	*NS*	*PBIAS*
Khokana	Calibration	0.8	0.79	2.3
	Validation	0.62	0.6	13.4
Sundarijal	Validation	0.64	0.62	21.3

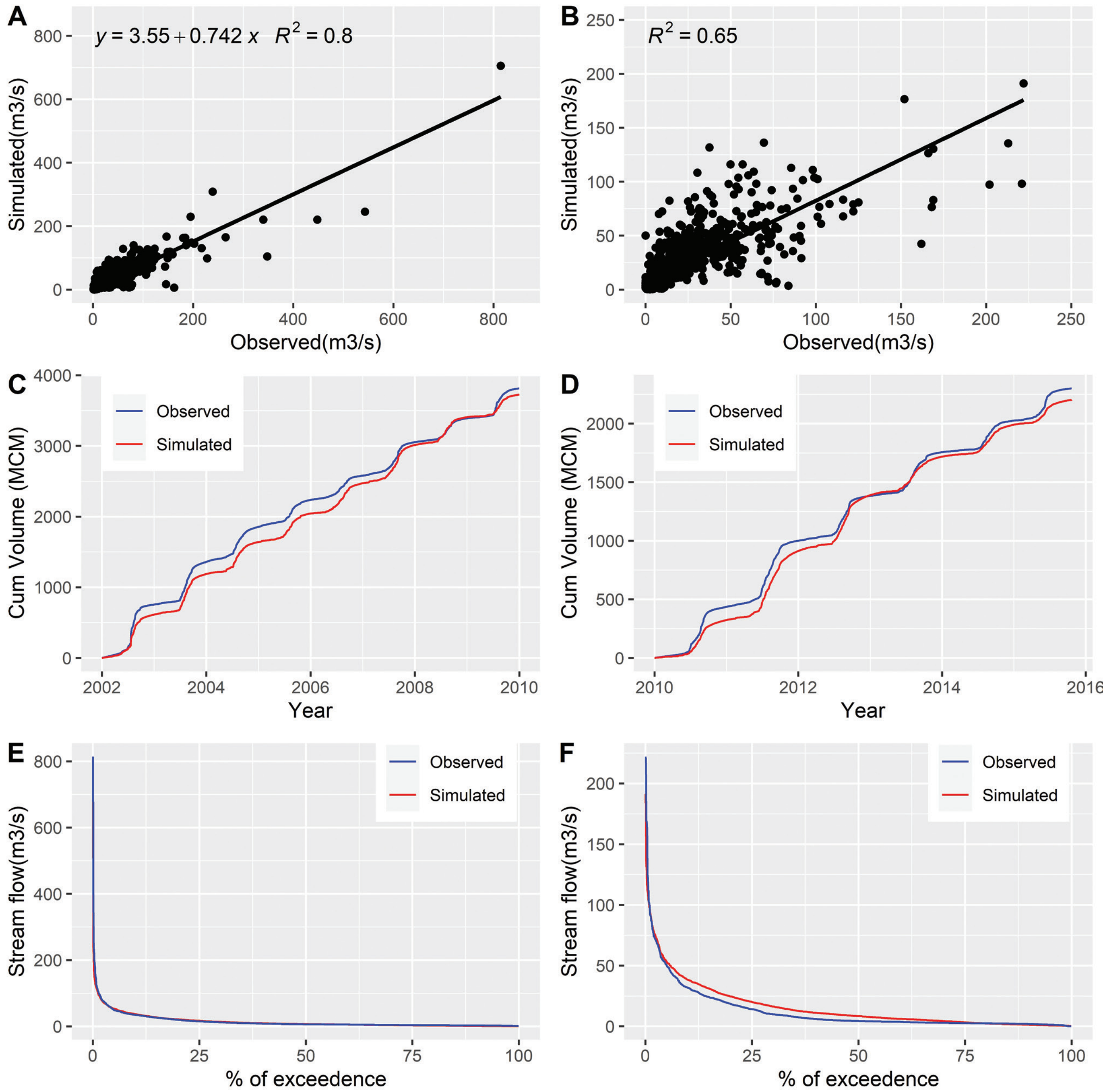


Figure 7: Model simulation result in calibration and validation in Khokana station. Figure A, C, E and B, D, F shows the scatter-plots, cumulative volume and flow duration curve for calibration and validation respectively.

Shrestha (2021) using HEC-HMS reported a Nash-Sutcliffe coefficient of 0.72. The SWAT model was able to simulate flow with better statistical coefficients. However, the scatter-plots for both the calibration and validation periods indicate that the model underestimated the flow, particularly for higher discharge values.

The results of the validation at the Sundarijal station are displayed in Table 1. The parameters such as NSE, R2, and PBIAS indicate that the model was well-established. The hydrograph, scatter plots, cumulative volume, and flow duration curve for calibration and validation are shown in Figure 8, respectively.

The SWAT model was successfully calibrated to simulate flow in watersheds of 592 km^2 and validated in watersheds of 592 km^2 and watersheds of 16 km^2. This demonstrates that the model and its parameters can be effectively applied to both small and large sub-basins in KV. Previous hydrological studies in KV (Devkota & Shrestha, 2021; Lamichhane & Shakya, 2019) have also found success in using the model for simulating flow in specific locations. Therefore, the parameters of the SWAT model can be confidently utilised for simulating flow in the Bagmati river sub-basin in KV.

The annual water balance of the Bagmati Basin at Khokana, as represented by an average of 2002 to 2015 shown in Figure 9 and Table 2, displays the following characteristics. Streamflow in comparison to precipitation accounts for roughly 0.6 times the total flow, with the ratio of base flow to total flow being 0.63. This outcome is in line with the findings of Thapa et al. (2017), the research determined that the ratio of evaporation to that of precipitation was 0.41, 0.45 and 0.43, while the remaining fraction of precipitation contributed to streamflow for the period of 2000 to 2010 using the SWAT, HVB and BTOPMC model, respectively.

Table 2: Ratio of water yield in the basin averaged for the study period

SN	*Process*	*Value*
1	Streamflow/Precipation	0.61
2	Baseflow/Total flow	0.63
3	Surface runoff/Total flow	0.37
4	ET/Precipitation	0.37

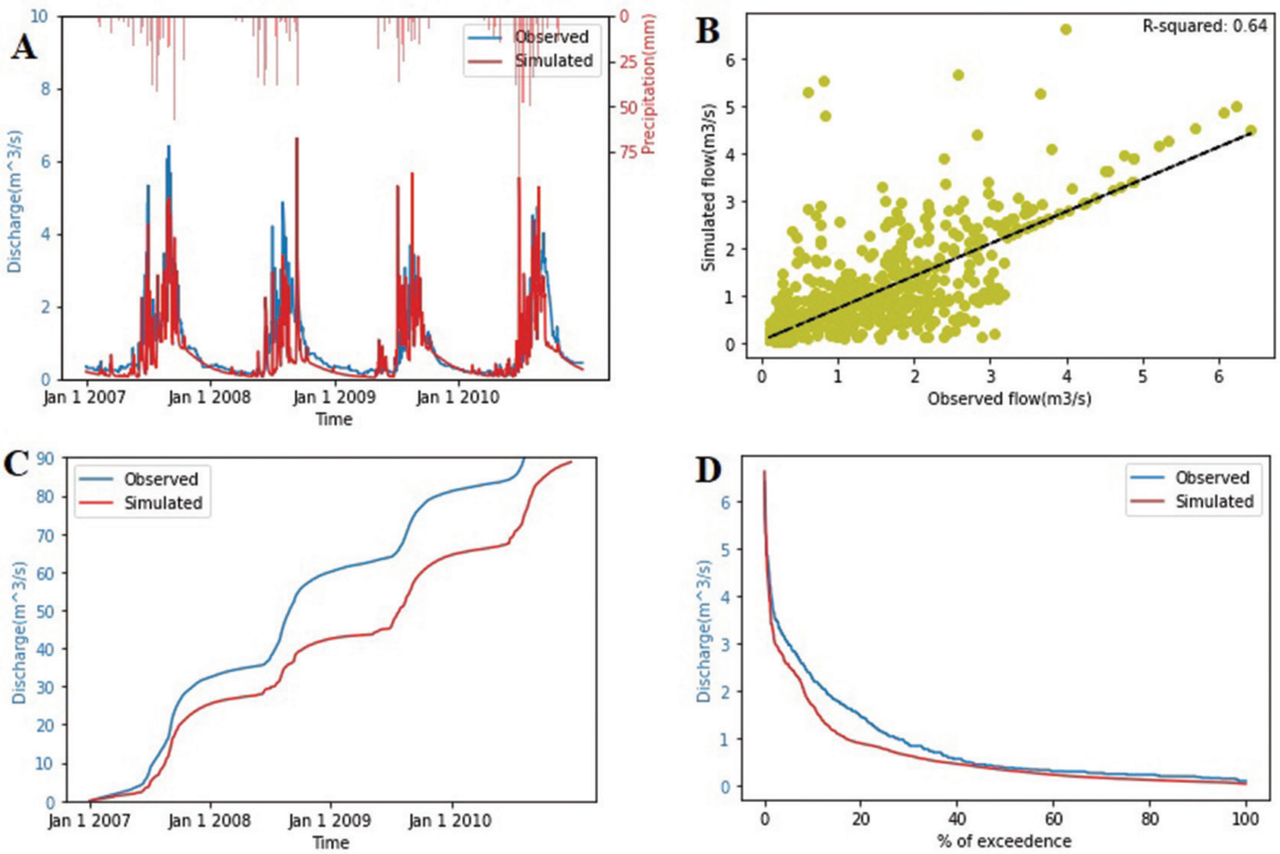


Figure 8: Model simulation result for validation in Sundarijal station. Figure A, B, C, D shows the simulated and observed flow, scatter-plots and cumulative volume, flow duration for validation respectively.

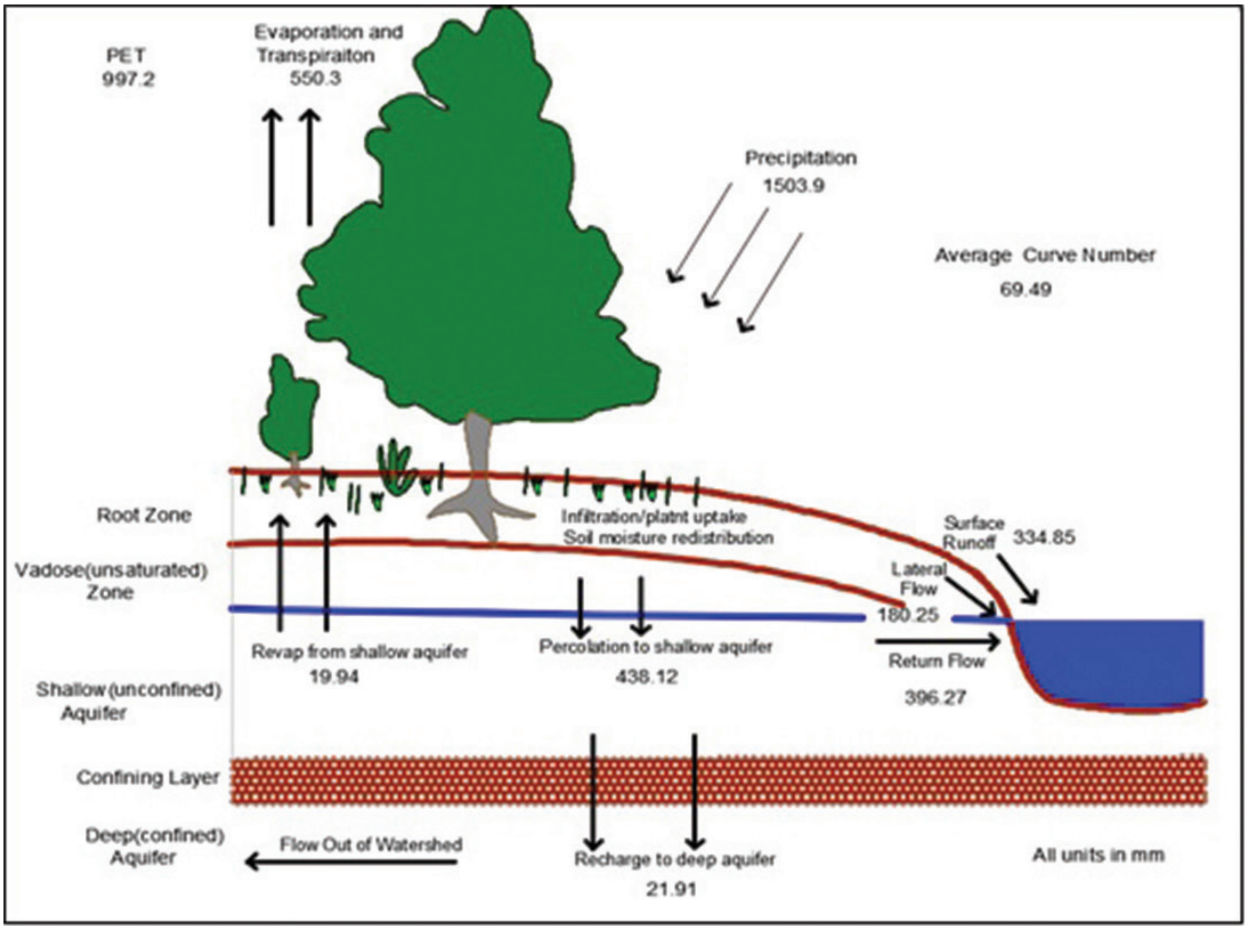


Figure 9: Water balance of the basin, an average computed for the period of 2000 to 2015 from the SWAT model (Winchell et al., 2008).

Assessment of Surface Water Availability of KV

The areas surrounding the KV region contain important water resources that supply the region. The study evaluated surface water in KV by utilising the SWAT model to 66 outlets located in the higher hills surrounding the valley, which have historically been considered water sources. Care was taken to select outlets that were not affected by human settlements or agricultural activities to ensure the purity of the source water. The outlets chosen for analysis are illustrated in Figure 10. They are situated in the peripheral region of the valley.

Figure 12 illustrates the monthly availability of surface water in different regions of KV. It shows that the upper regions of the Bagmati River basin and Nakkhu River have a greater availability of surface water compared to other streams in the valley. Specifically, the Godawari municipality and Gokarneshowr municipality have the highest potential for harnessing stream water for the valley's water supply. The examination of surface water availability in the region, as shown in Figure 11, demonstrates that there is more surface water available than what is currently being utilised by Kathmandu Uppatyaka Khanepani Limited (KUKL) (KUKL, 2019) for drinking water purposes.

Conclusion

The SWAT model was established for the Bagmati River basin. It underwent calibration for the Khokana station, situated at the basin's outlet, and validation for both the Khokana and Sundarijal stations, located in the northern mountain region of the valley. The model performed well according to statistical indices. These results informed the adoption of similar parameters for computing surface water availability in the region. As the region experiencing a severe water crisis and the completion of major water transfer projects such as Melamchi, the demand for water in KV is unlikely to be met. In this situation, surface water is crucial to meet the demand. The results indicate that there is potential for tapping surface water in the KV from May to November.

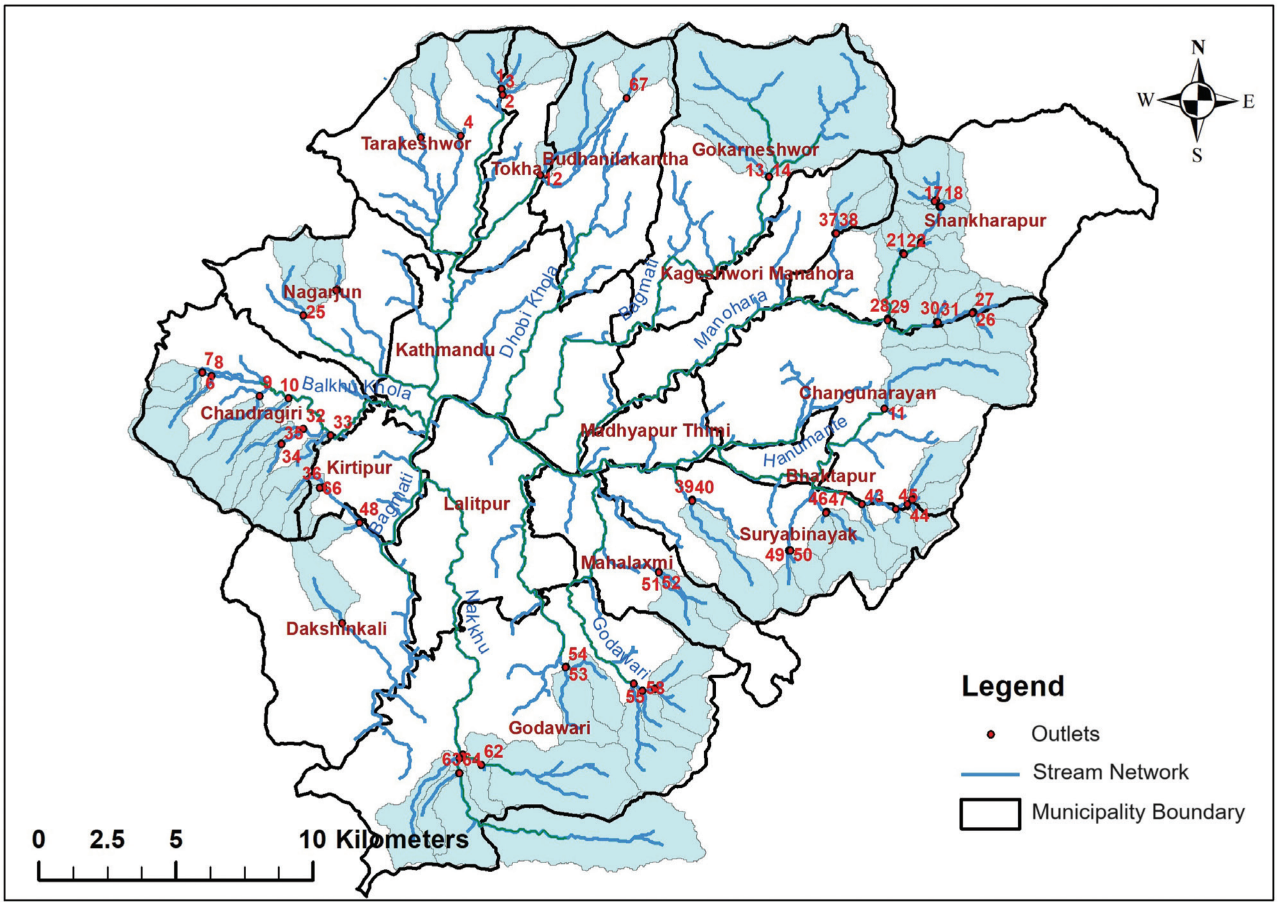


Figure 10: Subbasin and their outlets along with stream networks for the surface water quantification of surrounding region of KV.

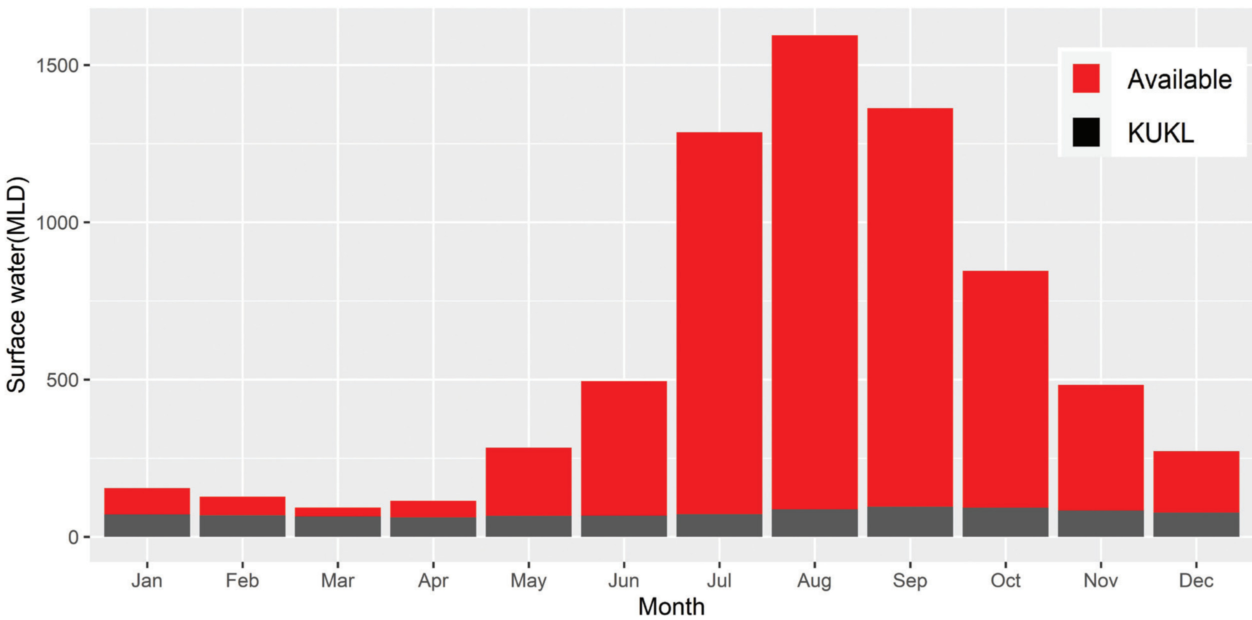
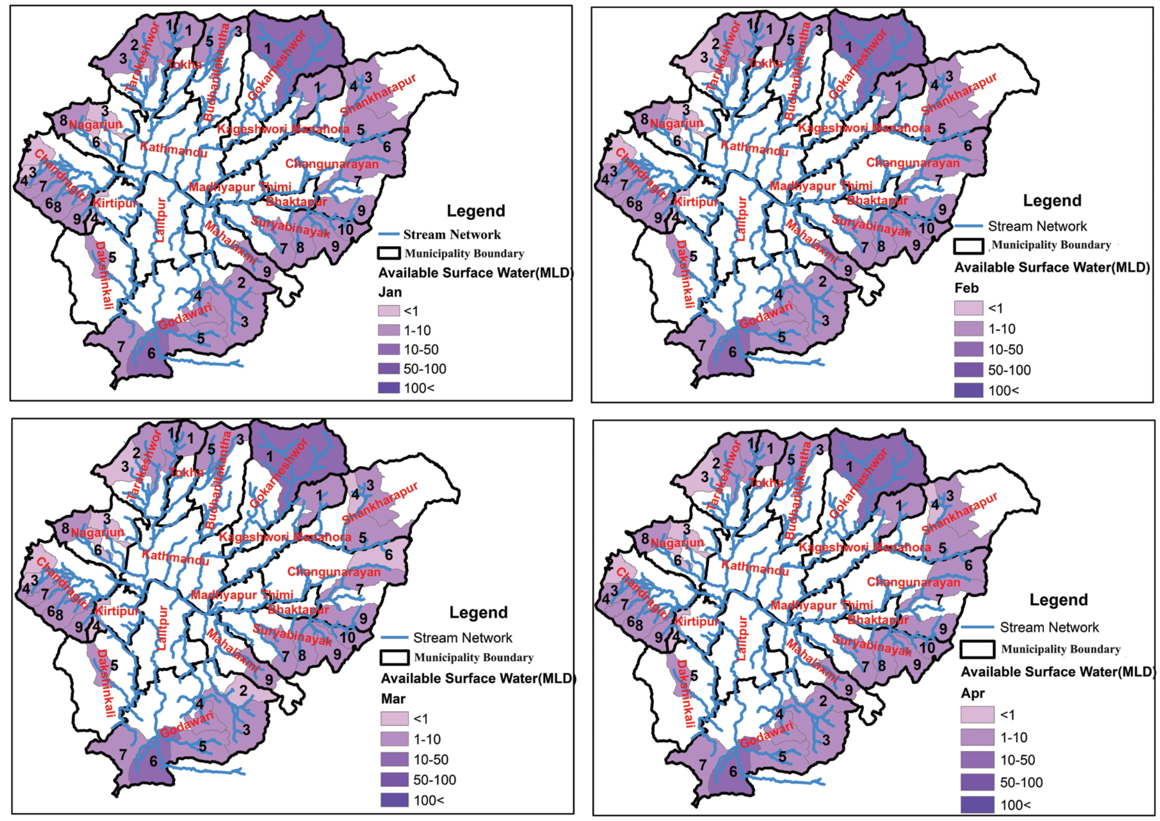
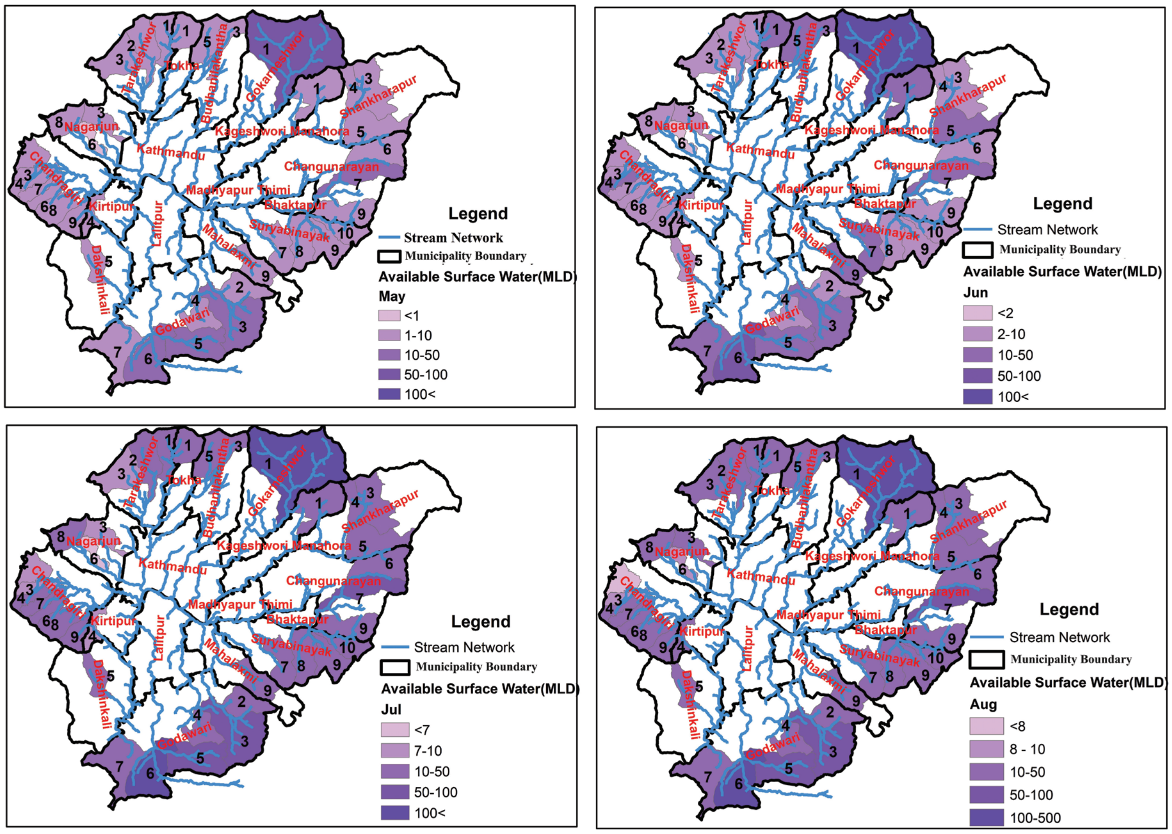


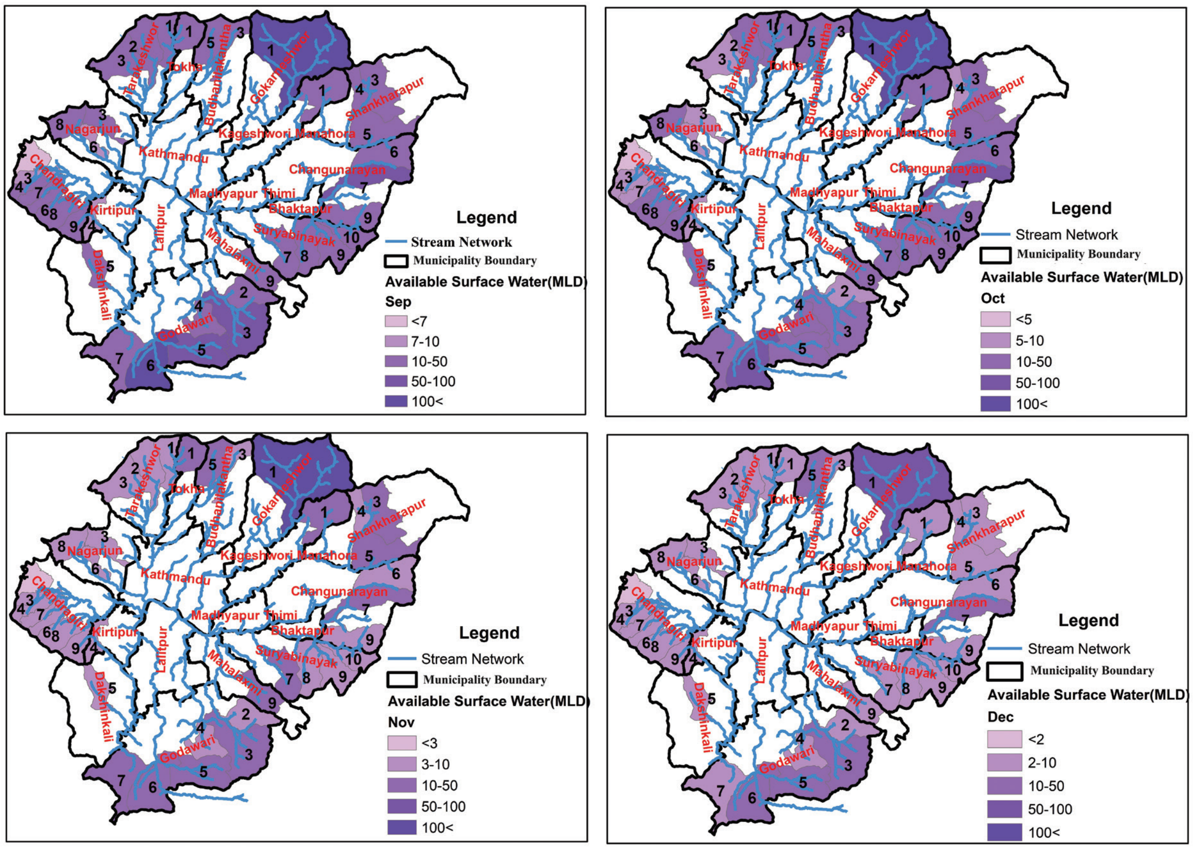
Figure 11: Surface water available in surrounding region and utilized by KUKL for water supply in 2018/2019 (KUKL, 2019).


Tarkeshwor
Tokha
Budhanilkantha
Gokarneshwor
Shankharapur
Nagarjun
Kageshwori Manahora
Kathmandu
Changunarayan
Chandragiri
Madhyapur Thimi
Kirtipur
Bhaktapur
Lalitpur
Suryabinayak
Mahalaxmi
Dakshinkali
Godawari
Legend
Stream Network
Municipality Boundary
Available Surface Water(MLD)
Jan
<1
1-10
10-50
50-100
100<
Feb
<1
1-10
10-50
50-100
100<
Mar
<1
1-10
10-50
50-100
100<
Apr
<1
1-10
10-50
50-100
100<

(a)


Legend
Stream Network
Municipality Boundary
Available Surface Water(MLD)
May
<1
1-10
10-50
50-100
100<
Jun
<2
2-10
10-50
50-100
100<
Jul
<7
7-10
10-50
50-100
100<
Aug
<8
8 - 10
10-50
50-100
100-500

(b)



(c)

Figure 12: Monthly surface water available in MLD at surrounding regions in KV.

These resources can be harnessed during the monsoon season by building dams (Altinbilek, 2002) in some of the tributaries, as results from this study indicate that tributaries such as the Nakhu River, the Balkhu, Godawari, and the upper reach of the Bagmati River are potential candidates for this purpose.

As the study by Udmale et al. (2016) highlighted the importance of utilising surface water in conjunction with other sources to reduce water supply deficits in the region, this outcome of this study is useful for creating region-specific water utilisation policies that can make the area self-sufficient by the development of targeted actions to ensure water security in the area.

The study made use of data that was already available on climate, hydrology, and LU, but it is anticipated that changes in LU, urbanisation and climate will have an impact on the region's future climate and hydrology (Lamichhane & Shakya, 2019). This will have a significant effect on the availability of surface water in the area. In future studies, it is necessary to consider the future climate, LU, and socioeconomic environment. Additionally, it is recommended to conduct validation of the model for small subbasins by observing the flow in streams. This ensures the validity of the model in capturing flow characteristics within these small subbasins.

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