Runoff Simulation of Ungauged Catchments: Importance in the Nepalese Context

School of Engineering, Design & Built Environment

Master of Research

Researched and Prepared by

Chet Narayan Gurung

Student ID: 17562557

Supervised by

Surendra Shrestha

Western Sydney University

2021

Acknowledgement

I want to express my gratitude to those whose support and goodwill helped me complete this work. First, I offer my sincerest gratitude and respect to my supervisor, Associate Professor Surendra Shrestha, School of Engineering, Design & Built Environment, for his valuable advice, guidance and tremendous support from the inception stage of this research for providing extraordinary experiences throughout the work. Without his esteemed guidance and encouragement, it would not be possible to reach this far. I feel very fortunate to have had him as my supervisor.

Last but not least, I would like to express my gratitude to my parents, mother-in-law Goma Devi Gurung, wife Pramila Gurung, sister-in-law Koushila Gurung and daughter Aayusha Gurung for their love and moral support, love and source of motivation for the completion of this research.

Chet Narayan Gurung

Table of Contents

List of Tables

List of Figures

List of Abbreviations

95PPU	95 Percent Prediction Uncertainty
ADB	Asian Development Bank
AR	Area Ratio
ArcGIS	Aeronautical Reconnaissance Coverage Geographic Information System
ArcSWAT	Arcview interface of SWAT
asl	Above sea level
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
BF	Baseflow
CFSR	Climate Forecast System Reanalysis
DEM	Digital Elevation Model
DHM	Department of Hydrology and Meteorology
ENS	Nash-Sutcliffe coefficient
ET	Evapotranspiration
FAO	Food and Agriculture Organization
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GIS	Geographical Information System
ha	Hector
HDI	Human Development Index
HEC-HMS	Hydrologic Engineering Centre’s Hydrologic Modeling System
hr	Hour
IAHS	International Association of Hydrological Science
IPP	Independent Parameter Perturbation
km	Kilometre
MAD	Mean Absolute Deviation
MAPE	Mean Absolute Percentage Error
masl	Meters above sea level
mcs	Meter Cube per second
mm	Millimetre

MoAD	:	Ministry of Agricultural Development
MSD	:	Mean Square Deviation
MW	:	Megawatts
NEA	:	Nepal Electricity Authority
NGO	:	Non-Governmental Organization
NSE	:	Nash-Sutcliffe Efficiency
PS	:	Physical Similarity
PT	:	Parameter Transfer
PUB	:	Prediction of Ungauged Basin
QGIS	:	Quantum Geographic Information System
SCS CN	:	Soil Conservation Service Curve Number
SOTER	:	Soil and Terrain database
SP	:	Spatial Proximity
SQM	:	Square kilometre
SUFI-2	:	Sequential Uncertainty Fitting algorithm version 2
SWAT	:	Soil & Water Assessment Tools
SWAT-CUP	:	SWAT Calibration and Uncertainty Programs
UN	:	United Nations
UNDP	:	United Nations Development Program
UNESCO	:	United Nations Educational, Scientific and Cultural Organization
USAID	:	United States Agency for International Development
USDA	:	United States Department of Agriculture
UTM	:	Universal Transverse Mercator
WECS	:	Water and Energy Commission Secretariat
WGS	:	World Geodetic System

Abstract

Nepal is a landlocked country in the foothills of the Himalayan region in South Asia and a country endowed with rich water resources. However, the country is unable to utilize and manage the full potential of available water resources. One of the reasons for this is the lack of an adequate network of river gauging stations necessary to collect hydrologic data. Installation of hydrological stations is an expensive proposition and not financially viable for small water resources projects (water supply, irrigation, mini and micro-hydro projects). This research aims to address the challenges via an alternative strategy - i.e. the use of a hydrological model which can reliably simulate runoff in ungauged catchments even in the absence of adequate hydrologic data.

SWAT (Soil & Water Assessment Tool), a popular simulation model with ArcGIS and QGIS interface, was chosen to simulate flow in an ungauged catchment in the mid-western region of Nepal. The model was applied to the West Rapti River basin using five years (1981-1985) of data from the Global Runoff Data Centre (GRDC). The GRDC was the only source, and the dataset was incomplete, limiting the model calibration and validation process. This limitation was addressed by using another simulation model, HEC-HMS (Hydrologic Engineering Centre’s Hydrologic Modeling System), for comparison. The results of the SWAT model were compared with those from HEC-HMS, one of the most widely used rainfall-runoff simulation models. Comparative analysis showed that both models generated comparable results. In general, HEC-HMS overestimated the runoff volume and depth by about 7-20%, and the SWAT model overestimated peak discharge by about 30-50%. SWAT also provided additional information on ecology and water quality aspects. Therefore, SWAT was chosen for additional study, including runoff simulation in the Jhimruk Khola sub-catchment. The sub-catchment is one of the major drainage systems of the West Rapti river basin, and it provides water for irrigation systems and possible locations for several micro-hydropower projects.

Historical rainfall data (1979-2009) were extracted from the Global Weather Data for SWAT to predict the rainfall trend in the West Rapti Watershed. This trend in rainfall pattern was used to extract rainfall and simulate runoff for 2023 to 2026, considering rainfall data of 2013 as a baseline. The simulated results showed a minor shift in time to peak and increased peak discharge. Similarly, the simulated runoff trends matched perfectly with the observed rainfall trend in SWAT. Thus, the results proved the reliability of SWAT to simulate runoff in the West Rapti Basin. The conclusion was drawn that the

SWAT model can be used reliably to predict runoff in ungauged catchments that assist with managing water resources and contribute to the development of Nepal’s economy.

Chapter 1: Introduction

Nepal is rich in water resources (WECS 1994). The country could derive huge benefits from these resources if able to utilize them optimally. However, the utilization of water resources through various hydropower and irrigation projects depends on the availability of hydrological data. Unfortunately, obtaining hydrological data is expensive and difficult, in the Nepalese context, due to the lack of adequate hydro-meteorological gauging stations. As a result, several available water resources remained unexploited in Nepal (Shrestha et al. 2010).

As stated above, establishing a comprehensive hydrological gauging station is an expensive proposition. Being one of the poorest countries in the world, setting up dense hydro-meteorological stations is not financially viable. Major water resource projects in Nepal establish their own gauging stations. However, this is not feasible for small-scale water resources projects such as water supply and irrigation. Thus, developing a method that could predict reliable river flow conditions in the absence of detailed hydrological data is essential in our ability to exploit and manage available rich water resources in Nepal.

1.1 Background

Water is a vital natural resource and a key component in socio-economic development. It also influences every aspect of the environment supporting life on earth (Gohar & Cashman 2016). However, water sources worldwide are under stress due to increased demand and water availability limitations (Burek et al. 2016). Sustainable water management, therefore, is essential to minimize the gap between demand and supply, and it is also necessary to ensure a long-term stable and flexible water supply to meet water demand for various purposes.

Managing water resources requires systematic approaches that include a good understanding of hydrological components and the links, relations, interactions, consequences, and implications among these components. Changes in land cover and flow regulation of rivers, for example, significantly impact seasonal and annual hydrological variations (Bonacci 2004). Therefore, thorough knowledge and understanding of different hydrological components are essential for successful water management for various purposes such as power generation, land irrigation and flood control.

1.2 Streamflow Prediction/Simulation

Streamflow is the integrated results of all meteorological and hydrological processes in a catchment (Peters 1994). Reliable continuous streamflow estimation, therefore, is an essential factor in engineering design and water resource management (Parajka et al. 2013), planning water supply and irrigation projects (Jain & Singh 2003), delineating river floodplains (Merwade et al. 2008), managing flow on dams and channels (Hirsch & Costa 2004), optimizing hydropower productions, designing hydraulic structures and others (Swain & Patra 2017), and assessing hydrologic behaviors due to change in climate and land-use practices (Patil & Stieglitz 2012).

Prediction of streamflow requires reliable long-term hydrological data, particularly precipitation (Caracciolo et al. 2014; Singh & Saravanan 2020). However, many river basins in the world lack hydrological data, and they are termed poorly gauged or completely ungauged basins (Goswami et al. 2007; Sivapalan et al. 2003). The ungauged basins also lack a series of streamflow and evapotranspiration data (Blöschl 2006).

Runoff estimation in ungauged basins is essential for obtaining a good knowledge of flow variability in basins (Razavi & Coulibaly 2013) and understanding the hydrological phenomena, which is the product of interactions between atmospheric and land surface conditions (Rui et al. 2013). However, hydrological processes and their components in a catchment area are highly variable in time and space (Bras 1999). Understanding these phenomena requires adequate knowledge about hydrological theories, models, and empirical methods (Sivapalan 2003a). However, the existing practical techniques and theories are insufficient to recognize the links between the hydrological functions and physical properties of ungauged or poorly gauged basins (Hrachowitz et al. 2013). Thus, the prediction of runoff in ungauged basins has been attracting attention globally from hydrologists and researchers.

According to Castellarin et al. (2007), ungauged basins often exist in mountainous regions and rural or remote places (Makungo et al. 2010). The complex topography and harsh climatic conditions make meteorological data collection difficult in these basins (Chalise 2002). In Nepal, most rivers originate in the mountainous region, which covers approximately 86% of the country's total land area (Karki et al. 2016). These rivers are ungauged or poorly gauged. As a result, the country has not been able to utilize available water resources to their full potential, adversely impacting energy and irrigation sectors. In the meantime, the country depends heavily on water resources for hydropower generation and land irrigation purposes (Gurung et al. 2019; WECS 2005a, 2005b, 2011).

Nepal's rivers possess the potential to generate 83,000 MW hydropower, out of which 42,000 MW is commercially viable (KC et al. 2011). However, of 42,000 MW commercially viable hydropower generation capacity, only 689.3 MW (about 2%) of the total capacity has been generated (KC et al. 2011).

Sustainable hydropower generation is also essential to balance the country’s electricity supply deficit in the dry season and generate revenue through exports of electricity during the wet season, when river flows are high (ADB & ICIMOD 2006; Bhatt 2017; Rai et al. 2020). Likewise, developing sufficient hydropower energy might control forest degradation because fuelwood supplies about 80% of all household energy, and demand for energy is growing consistently (Pokharel 2001). However, achieving tangible results in hydroelectricity development is only possible with qualified human resources with sufficient funds within the country (Pokharel 2001).

Similarly, approximately 18% (2,642,000 ha) of the total land area of Nepal is cultivated, and about two thirds (66%) of the total cultivated area is potentially irrigable (Poudel & Sharma 2012). However, only 17% of cultivated land gets water in all seasons, and 42% gets irrigated intermittently only, leaving 41% of the potential irrigable area not receiving any irrigation water. Thus, crop production in the majority of the hills and mountain areas rely heavily on rainfall (WECS 2005a).

According to Chalise (2002), the improved knowledge of flow regimes in river basins may help assess and exploit water resources more effectively to irrigate the land, generate electricity, and even manage floods and droughts. However, it takes a significant time to achieve success in understanding the flow regimes of Nepalese river basins due to the lack of knowledge and resources.

Significant success has been achieved on ungagged catchments with the introduction of PUB (Predictions in Ungauged Basins) by IAHS (International Association of Hydrological Science) (Sivapalan et al. 2003). The PUB has developed a wide range of new data acquisition techniques and methods to estimate accurate model uncertainty and predict hydrological behaviour in ungauged basins (Emmerik et al. 2015). However, the current understanding of basin response is not sufficient due to the global scale of anthropogenic activities, land use and climate changes. Thus, new invention in data collection, process knowledge and understanding hydrological behaviour is necessary for accurate runoff simulation in ungauged basins (Sivapalan 2003a).

Understanding watershed response and behaviour because of climate change and changes in land-use practices can be achieved with a hydrological model. Therefore, different hydrologic models have been developed and used for a variety of purposes, such as managing water resources and estimating flood events (Bárdossy & Singh 2008). Each model has advantages and limitations; thereby, selecting a specific model is a challenging proposition. However, Singh and Saravanan (2020) suggested that a physically-based hydrological model is the best preference for streamflow estimation and prediction.

This study, therefore, is conducted to select and calibrate a physically-based semi-distributed hydrological model that can be used confidently for runoff simulation in an ungauged catchment located in Nepal. Simulation of runoff in ungauged catchments is essential to manage water resources for power generation, land irrigation, and flood management, thereby contributing substantially to the country's economic development and poverty alleviation.

1.3 Research Aim and Objectives

This research aims to select and calibrate a reliable physical-based hydrological model, which can be used for runoff simulation in the ungauged basins in Nepal.

Some of the specific objectives of the study are:

1. To identify a suitable hydrological model that can be utilized to predict flow characteristics in ungauged basins.
2. To calibrate the hydrological model that can be used confidently to simulate runoff in ungauged basins.

The research questions of this study are:

1. Which hydrological models are available for runoff prediction in catchments?
2. Which model is applicable for the runoff estimation in ungauged basins?
3. Can the SWAT model be used reliably to simulate runoff in ungauged basins?
4. Can the SWAT model be implemented reliably in Nepal for runoff simulation in ungauged basins?

1.4 Significance of the study

A dense spatial gauging station is necessary for obtaining hydrological data from catchments. However, the installation of a well-developed gauging network involves huge costs, which may not be financially viable for many developing countries like Nepal. This constraint has resulted in many river basins in Nepal being ungauged or poorly gauged. Estimating runoff generated in these basins requires understanding basin responses resulting from anthropogenic activities and land-use changes.

This study will advance knowledge on runoff estimation in ungauged catchments by selecting and calibrating a hydrological model that can assess a dynamic hydrological system of ungauged basins. This knowledge will be significant in managing water resources in ungauged basins for hydropower generation, land irrigation, and flood management, contributing to economic development and reducing poverty.

The study may also help advance the runoff prediction knowledge in ungauged catchments in Nepal. Nepal still depends on empirical methods such as WECS/DHM (Water and Energy Commission Secretariat/ Department of Hydrology and Meteorology) and MIP (Medium Irrigation Project) to assess the flow conditions of the ungauged catchments for different medium-to-small scale water resource projects (Shrestha et al. 2010). While these methods have served the nation well for the last four decades (WECS and MIP methods were developed in 1982). Implementation of new techniques that take advantage of the development in technology can also benefit the flood estimation process. Eventually, the research findings will help enhance the existing knowledge of the scientific community in Nepal.

1.5 Scope and Limitations of the Study

The scope of the study is limited to identifying a method and finding a hydrological model to predict runoff reliably in a rain-fed ungauged catchment. The study area for this project was chosen from a developing country, Nepal, which is very rich in water resources. However, the country is unable to utilize the full potential of water resources due to the lack of knowledge to predict the hydrological behaviours of ungauged or poorly gauged river basins.

The study uses the concepts of the regionalization approach integrated with a hydrological model to estimate runoff in ungauged basins. The method assumes that the catchment displays similar hydrological responses if climate, geology, topography, soil, and vegetation are similar within a given region (Rees et al. 2004).

Although this research utilized scientific approaches to estimate streamflow in an ungauged catchment, it has several limitations, including but not limited to:

i. Use of the SWAT Global Weather Data (https://globalweather.tamu.edu/) for rainfall, temperature, solar, wind and relative humidity data to prepare and calibrate the SWAT model. As the data is limited, all limitations resulting from a limited dataset are carried within this study findings as well. Unfortunately, this was the only source of data freely available.

ii. Use of the GRDC (Global Runoff Data Center) (https://www.bafg.de/) for observed discharge data. Most of the GRDC data in the study area are monthly data; only one station has daily observed discharge data, which is also only from 1976 to 1985. This data was used to generate other data sets; hence the reliability needs to be further tested.

iii. The study does not consider the climate change impacts on rainfall patterns and its effect on flooding events.

iv. The study also did not consider the land use impact due to anthropogenic activities to estimate surface runoff.

Chapter 2: Literature Review

2.1 Introduction

Runoff estimation without enough hydrological data was difficult before introducing PUB (Decade on Predictions in Ungauged Basins). As a result, the PUB has developed and analyzed various methods to predict runoff in ungauged basins. However, these methods still are insufficient to thoroughly understand the complex relationship between rainfall and runoff in ungauged basins.

This section, therefore, analyses the role of the PUB discusses the available and most broadly used runoff prediction methods in ungauged catchments, including some advantages and limitations. The chapter also highlights hydrologic modelling and its importance.

2.2 Prediction of Ungauged Basins (PUB)

An accurate and reliable runoff estimation in ungauged basins is highly significant in making an independent judgment about actions required for sustainable water management and prevention of natural disasters (Sivapalan et al. 2003). However, the current understanding of basin response to estimate accurate and reliable runoff is not sufficient due to heterogeneity of the land surface conditions, soils, vegetations, land uses and excessive anthropogenic activities (Sivapalan 2003a). Modern data collection techniques, process knowledge, and understanding are required to solve these problems. Hence, prediction in ungauged basins remains a challenging and unsolved problem (Sivapalan 2003a).

Before introducing PUB, the subject of hydrology was divided into several other disciplines. Therefore it lacked the solid scientific basis to explain the role of hydrology at the interface of different disciplines (Hrachowitz et al. 2013; Sivapalan 2003b). Furthermore, the PUB recognized the primary factors contributing to the resulting predictive uncertainties. As such, (i) a lack of knowledge of the systems that support hydrological responses and the catchment-scale feedbacks which results in an unrealistic model with high predictive uncertainties; (ii) a lack of knowledge to understand the multi-scale spatial-temporal heterogeneity of process across various landscapes and climate; (iii) a lack of comprehensive studies to recognize appropriate techniques that can be used to transfer hydrological response patterns from gauged to ungauged settings (Hrachowitz et al. 2013).

In response to these challenges, PUB formulated and implemented suitable science programs to engage and motivate the scientific community towards achieving advances in conducting reliable predictions in ungauged catchments (Hrachowitz et al. 2013; Sivapalan et al. 2003). Similarly, the PUB has researched various scientific fields and developed various predictive tools (e.g. lumped models, empirical models, distributed models, and statistical regionalization) to make an objective and quantitative decision for water resources, water quality management, and natural hazards assessments (Sivapalan et al. 2003). In general, the PUB has shifted the paradigm of hydrology from the use of Nilometer (Sivapalan 2003a), the earliest hydrological model which predicted the river flow without understanding the changes in river behaviour (National Research Council 1991).

As shown in Figure 2.1, there was a lack of knowledge on various aspects before introducing the PUB. For example, knowledge about obtaining data, understanding processes, selecting suitable models, analyzing uncertainties, classifying catchment and understanding theories.

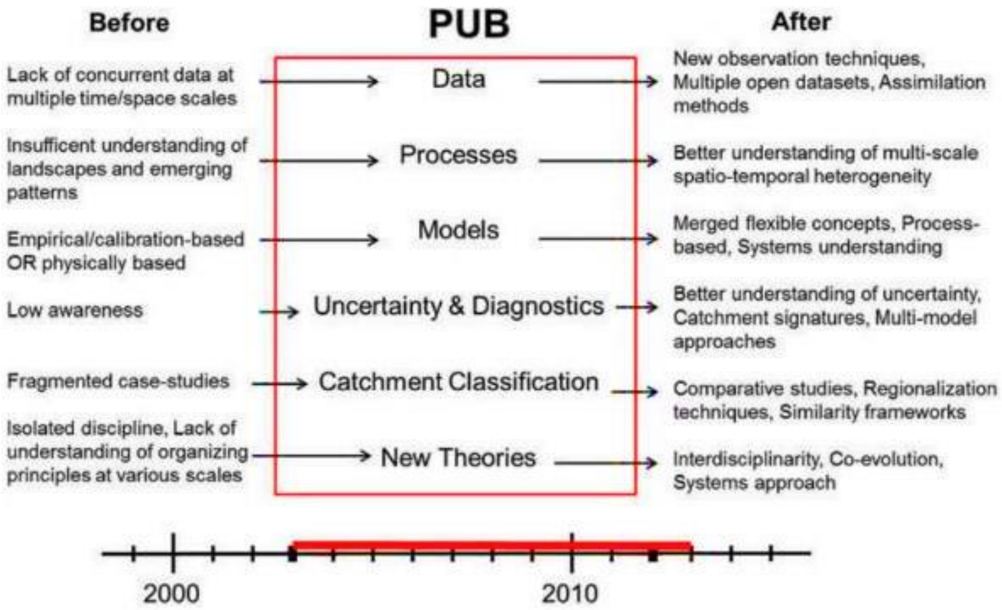


Figure 2.1: Outline of knowledge shifting in PUB (Source: Hrachowitz et al. (2013))

In response to these knowledge gaps, PUB exploited the working groups (WGs) network globally to research the prediction of ungauged basins. The WG is a team of researchers interested in predicting ungauged basins from any discipline (Hrachowitz et al. 2013). PUB, therefore, mobilized the hydrologic communities globally through different educational and research activities to achieve the objective – i.e. the prediction of ungauged basins. Thus, the primary region for the success of the PUB initiative was a movement of grassroots level activities and accommodation of the diverse interests of hydrologists worldwide (Hrachowitz et al. 2013).

Regardless of the several years of effort, the runoff prediction in poorly gauged basins is still challenging (Seibert & Beven 2009; Sivapalan 2003a) because not much success has been achieved in predicting the ungauged basin. Therefore, more rigorous scientific research, data sharing and promoting strategy, including global open-access databases, are essential to enhance knowledge about the prediction of ungauged basins (Hrachowitz et al. 2013).

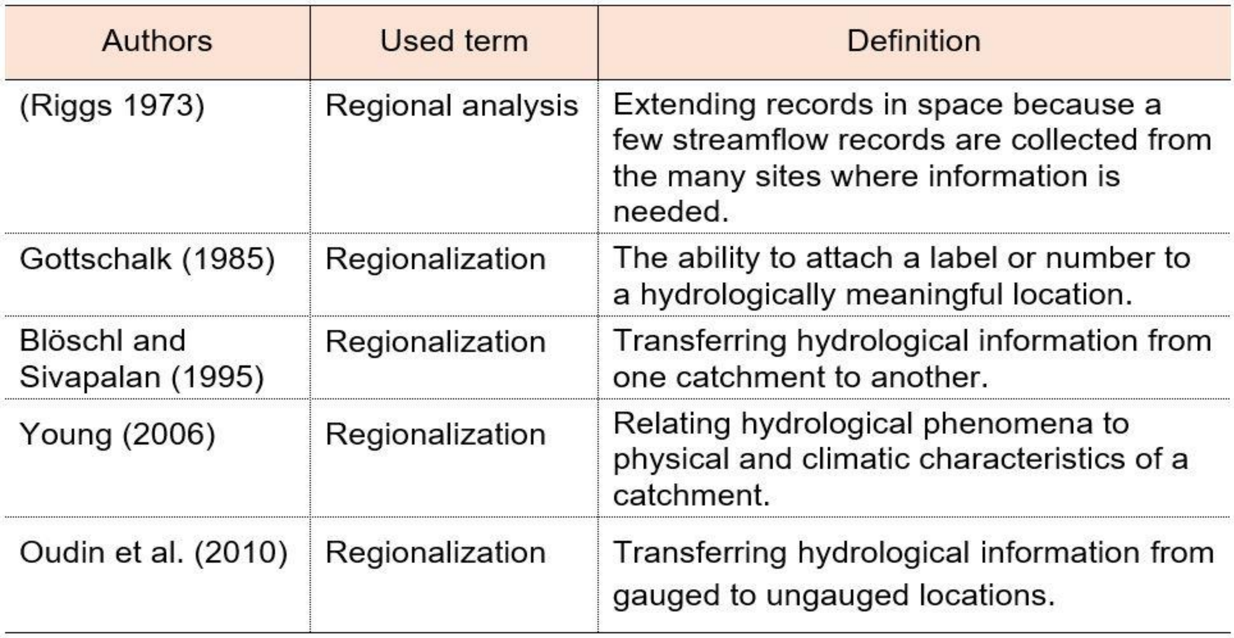
2.3 Regionalization method

A regionalization method is one of the popular approaches that many researchers have applied to predict runoff in poorly gauged basin areas (Zhang & Chiew 2009b). Therefore it is a famous, fundamental and the oldest process that many developing countries still rely on to estimate and simulate runoff in ungauged basins (Tamalew & Kemal 2016; Tegegne & Kim 2018).

There is no exact definition of regionalization. However, it refers to transferring the hydrological information from one catchment to another (Blöschl & Sivapalan 1995) using different methods, such as simulating the hydrologic model, extrapolating hydrologic information, integrating meteorologic and hydrologic model, and using remote sensing observation data (Goswami et al. 2007).

The term regionalization has been used with almost identical concepts in the literature, with some minor differences among researchers. Table 2.1 shows the different terms and definitions used to explain the term regionalization.

Table 2.1: Definition of regionalization appears in the literature



Authors	Used term	Definition
(Riggs 1973)	Regional analysis	Extending records in space because a few streamflow records are collected from the many sites where information is needed.
Gottschalk (1985)	Regionalization	The ability to attach a label or number to a hydrologically meaningful location.
Blöschl and Sivapalan (1995)	Regionalization	Transferring hydrological information from one catchment to another.
Young (2006)	Regionalization	Relating hydrological phenomena to physical and climatic characteristics of a catchment.
Oudin et al. (2010)	Regionalization	Transferring hydrological information from gauged to ungauged locations.

Source: Extracted from He et al. (2011)

Regionalization generally used two approaches: (i) flow-based and (ii) parameter-based approaches for runoff prediction in ungauged basins. The flow-based approach includes flow components such as observed flood discharge, flood duration curve parameters, and the peak time of flood periods. The parameter-based approach considers watershed area, elevation, soil type, land covered area, slope, temperature and precipitation, and length of the main river (Goodarzi 2019; He et al. 2011).

According to Wagener and Wheater (2006), a functional relationship between conceptual model parameters and the catchment attributes may generally be expressed as:

$$\hat{\theta}_L = H_R(\theta_R|\Phi) + \upsilon_R \qquad (2.1)$$

Where

$\hat{\theta}_L$ = ungauged locations' estimated model parameter

H_R = functional relation for $\hat{\theta}_L$ using sets of catchment characteristics such as physiographic and meteorological characteristics (Φ)

θ_R = set of regional hydrological variables of interest

υ_R = error (Wagener & Wheater 2006)

According to Razavi and Coulibaly (2013), there are about five essential phases in regionalization. The first phase involves collecting and managing basin characteristics, such as land use, soil type, topography, mean annual rainfall and temperature. The second phase includes determining and clarifying hydrological variables of interest, such as collecting streamflow data of a similar gauged basin. The third step is developing the relationship between the flow or model parameters and the properties of the basin. The fourth step involves the model performance evaluation and validation before applying it in an ungagged basin. The final step is uncertainty analysis due to uncertainties in selecting basin characteristics and regionalization procedures.

The statistical test is inevitable in regionalization due to errors in parameter selection. Standard statistical tests to evaluate the performance of the flow estimation are NSE (Nash-Sutcliffe Efficiency), BIAS, PBIASr (Relative BIAS), RMSE (the root mean square error) and V.E. (volume error) (Wagener & Wheater 2006).

Table 2.2: Validation tests used for regionalization

Common validation test	Suggested equation
Nash-Sutcliffe Efficiency	NSE = 1- $\left[\sum_{i=1}^{N}(y_i - y'_{i=1})^2 \,/\, \sum_{i=1}^{N}(y_i - y_{mean})^2\right]$
Volume Error	V.E. = $(\sum_{i=1}^{N} y'_i - \sum_{i=1}^{N} y_i \,/\, \sum_{i=1}^{N} y_i)$
Bias	BIAS = $\sum_{i=1}^{N}(y'_i - y_i)$
Mean Relative Bias	BIAS r = $\sum_{i=1}^{N}(y'_i - y_i)\,/y_i$

Source: Razavi and Coulibaly (2013)

Where

y_i = observed runoff values
y'_i = modelled runoff values
y_{mean} = mean observed values
N = number of times

2.3.1 Classification of regionalization approaches

Several regionalization methods have been developed and analyzed for different climatic conditions and contexts after the initiation of PUB. Several authors, such as Blöschl et al. (2013), Hrachowitz et al. (2013), Parajka et al. (2013), Razavi and Coulibaly (2013) and Guo et al. (2020), provided reviews of the development of regionalization approaches. Studies suggested that distance-based approaches such as spatial proximity, physical similarity and regression-based approaches are very popular among the available regionalization methods (Kanishka & Eldho 2020; Yang et al. 2017). These methods have been utilized in various landscapes, topographies and climatic regions to predict runoff in ungauged basins globally (Li et al. 2019; Razavi & Coulibaly 2013; Tamalew & Kemal 2016; Tegegne & Kim 2018; Zhang & Chiew 2009b).

Spatial proximity (SP) is an easy and simple method to use in practice (Arsenault et al. 2019). The SP was used in many studies because of its simplicity. For example, Oudin et al. (2008) used SP in 913 basins in France. It performed better due to the high density of the hydrological stations. Even with a relatively sparse hydrological network, Arsenault and Brissette (2014) discovered that the SP method is slightly better than the PS method.

SP method is based on the assumption that basins in close proximity have similar physical characteristics, such as land ad soil type, slope, elevation and climate data. According to this theory, the adjacent basins are similar enough based on their proximity. Thus, there is no need to search for the most similar catchment (Arsenault et al. 2019). However, in terms of hydrological response, basins that are geographically close to each other are not necessarily hydrological identical. Thus, identifying similar hydrological watersheds with a similar hydrological response to precipitation is difficult when applying the regionalization approach (Shu & Burn 2003).

Physical Similarity (PS) is another popular approach that uses similar characteristics of different basins during the regionalization process (Merz & Blöschl 2004). The process is based on the assumption that watersheds with similar climatic and land use conditions, altitudes, soil characteristics, and climatic variables (such as mean annual rainfall) have similar hydrological characteristics (Blöschl 2006; Guo et al. 2020; Oudin et al. 2010).

One of the advantages of the PS method over the SP is that PS can be used in a large area. For example, Parajka et al. (2005) suggested that the PS method outperformed the SP in 308 Austrian catchments. However, it requires some well-gauged catchments, which must be in proximity to the ungauged catchment (Swain & Patra 2017), and selecting physical characteristics upon which to base the similarity measure is difficult (Pagliero et al. 2019). Therefore, the method may not be suitable for the region with sparse gauging stations.

The regression method is less popular than SP and PS methods. The widely used regression-based regionalization technique is the regression between model parameters and physiographic characteristics of catchments (Parajka et al. 2005). In this method, the relationship between the optimized parameter values of the gauged watershed and the parameter values of the ungauged watershed are established. Afterwards, estimate the parameter values of the ungauged watershed on its attributes and established relationships to estimate parameter values (Zhang & Chiew 2009a).

According to recent studies, the performance of the regression approach was poorer than the SP and PS method (Parajka et al. 2007) because the interpretation of regressions is not always straightforward. Therefore, careful attention is needed to interpret the physical meaning of the parameter descriptor relationship produced by regressions (Parajka et al. 2007).

A few studies have applied combined methods and compared them to a single conventional regionalization method, and some improvements have been found. For example, Yang et al. (2017) used a combination of spatial proximity and physical similarity methods. The study's findings showed that the combined method performed slightly better than other single approaches. Similarly, Li et al. (2019) compared ENS values using a collaboration of PT (parameter transfer) and AR (area ratio) approaches. The study concluded that the combined method produced better results than that of the single method.

Selection of the most appropriate regionalization approach is still considered difficult in hydrology (Oudin et al. 2008; Samuel et al. 2011; Sivapalan et al. 2003; Stoll & Weiler 2010) due to insufficient universal method for regionalization (Razavi & Coulibaly 2013). However, Merz and Blöschl (2004) suggested that the spatial proximity outperformed the process based on physiographic catchment attributes.

The advantages and limitations of some popular regionalization methods are shown in Table 2.3.

Table 2.3: Advantages and limitations of some regionalization methods.

References	Regionalization methods	Positive aspects	Possible drawbacks
Tegegne and Kim (2018)	Physical similarity (PS)	PS uses catchment attributes to identify a donor catchment.	The ability to select properties for the similarity of catchments is critical to the success of the project.
Samuel et al. (2011)	Spatial proximity (SP)	SP predicts model parameters applying interpolation technique, considering that the neighbouring basins are in a `1homogeneous region.	This method ignores catchment attributes. It considers that ungauged basins already exist in homogenous and geographically similar regions.
	Regression (RG)	RG considers basin attributes as independent and hydrological model parameters as dependent variables.	The dependent variable may differ depending on the catchment; therefore, the relationship between the independent and dependent variables may be weak.
Li et al. (2019)	Area ratio method	Hydrological parameters are transferred from gauged to ungauged basins on the assumption that the area of a watershed is a major component that controls the amount of water generated by precipitation.	AR method ignores hydrological processes. Thus, it cannot explain the characteristics of the hydrological model.

2.3.2 Importance of Regionalization in Nepalese context

In Nepal, very little research has been conducted on the regionalization of river flows (Hannah et al. 2005; Kansakar et al. 2002). Regionalization refers to a grouping of basins in similar hydrological areas (Mishra et al. 2008). Previous studies, such as Rees et al. (2002), regarded the entire country as a single region due to limited data availability. The Water and Energy Commission Secretariat (WECS 1982) derived regional equations for estimating long-term mean monthly flows, flood- and low-flow. The WECS (1982) approach further developed WECS (1990), where the entire country is considered a single homogeneous region or divided based on traditional physiographic or climate zones. Alford (1992) studied a linear relationship between the specific runoff and altitude for Himalayan Basins. According to Kansakar et al. (2002), previous studies did not consider the spatial and temporal complexities of stream flows which are essential for estimating the hydrological behaviour of catchments.

Regionalization of Nepal’s river flow is essential for assessing and utilizing water resources in irrigation and hydropower generation (Kansakar et al. 2002). Approximately 33% of Nepal's agricultural production currently depends on the irrigation system, and about 91% of Nepal's electricity is produced by Hydropower generation. The advancement of the irrigation system is necessary to meet the country’s food security requirement (WECS 2005a). However, a significant land area is barren, and only one-tenth of people have access to electricity. Progress toward utilization of Nepal's water resources for economic growth is plodding due to the highly seasonal nature of rainfall and discharge. This seasonal uncertainty creates complex problems utilizing the regionalization approach and funding water development projects in Nepal (Singh 2005).

Moreover, the regionalization approach is essential to introduce an advanced technique in water resource projects in Nepal. The country's water resource projects relied upon WECS/DHM (Water and Energy Commission Secretariat/ Department of Hydrology and Meteorology) and MIP (Medium Irrigation Project), previously developed empirical methods, for runoff prediction in ungauged basins. However, these methods are not upgraded, and their reliability is not verified since their development (Shrestha et al. 2010). Thus, these tools may not be reliable to predict runoff in ungauged catchments. Therefore, regionalization might be the reliable and advanced option to estimate runoff in ungauged basins in the context of Nepal.

2.4 Hydrological modelling

The hydrological model allows hydrologists to understand hydrological processes and predict the system behavior of catchments (Gao et al. 2017). Hence, a Hydrological model is considered one of the most critical and necessary tools for water and environment resource management. A hydrological model requires a set of rainfall data and drainage areas as input data. Along with these, other data such as soil properties, watershed topography, soil moisture data, vegetation cover and groundwater data are essential to define the model's characteristics (Devia et al. 2015).

Many hydrologic models (Table 2.4) have been developed and applied for various purposes; therefore, a model selection problem has existed in hydrologic studies for a long time (Addor & Melsen 2019; Marshall et al. 2005). The best model tends to produce results close to the real scenario with less model complexity and fewer parameters (Devia et al. 2015). However, the literature discussed very little about the theoretically and practically sound method that can broadly apply for best model selection (Marshall et al. 2005). As a result, no single model can be selected as ideal due to the range of possible hydrological processes and catchment conditions. Therefore, the hydrological model selection primarily depends on the research's objective, convenience, experience, and habit (Addor & Melsen 2019).

A list of hydrological models used for various purposes, including advantages and disadvantages, is presented in Table 2.4.

Table 2.4: Some hydrological models with advantages and limitations

Sources	Model type	Advantages	Limitations
Singh (2018)	HEC-1 (Hydrologic Engineer Center), which is the current form of HEC-HMS (Hydraulic Modelling Simulation)	It is a widely used software that simulates the rainfall process in a single outlet watershed. A helpful tool for designing reservoir spillways and forecasting water quality, erosion and sediment transport, and streamflow.	The model cannot be used for branching or looping stream networks and backwater in the stream network.
	SWMM (Stormwater Management Model)	It simulates streamflow quality and quantity. It also categorizes drainage systems into the atmospheric, land surface, groundwater, and transport components.	It is more likely an analytical tool than a design tool.
Devia et al. (2015)	SWAT model (Soil & Water Assessment Tool)	It is used widely in hydrologic studies, climate change studies, and water quality studies. It examines and forecasts the water and sediment circulation in ungauged catchments. It also stimulates surface and groundwater to predict environmental impacts due to land-use change,	Spatial representation of Hydraulic Response Units (HRUs) overlooks routing within a sub-watershed. The model formulas are empirical, and the model is not helpful for 2D or 3D hydraulic applications. The model limited sediment transport and erosion.

		climate change, and change in land managing methods. The model can run on an array of GIS platforms and is compatible with the groundwater modelling software MODFLOW.	
	HBV-EC model (Hydrologiska Byrans Vattenbalansavdelning-Environment Canada model)	A useful model for mountainous topography to transfer parameters from gauged basin to another similar ungauged basin using the Monte Carlo analysis technique.	Dam parameters are not included in the development of the model. It transfers flow data in a Comma Separated Value (CSV) file.
Pradhan et al. (2008)	TOPMODEL	A model simulates the hydrologic flux of water in the shallow catchment with homogeneous soils and negligible deep groundwater.	The prediction of soil moisture distribution is not possible with TOPMODEL
Blöschl (2006)	CART Model (Classification and Regression Tree model)	The model considers catchment attributes independent and the model parameters dependent variables. Regression trees divide the heterogeneous domain into several homogeneous regions by maximizing the homogeneity of model parameters and catchment attributes.	It is not a stable method. A small change in data can lead to a significant change in the model structure. Moreover, they are relatively often inaccurate. Preparing a decision tree is time-consuming and complicated.

2.5 Conclusion

Streamflow estimation in ungauged basins was difficult before PUB (Prediction of Ungauged Basins). Thus, PUB has analyzed and developed several approaches, and regionalization is the most popular approach to estimate runoff in ungauged basins. The method allows transferring hydrological information from gauged to an ungauged basin. The regionalization methods such as spatial proximity, physical similarity, and regression approach are widely used in various climatic conditions. However, selecting a single specific method is still difficult due to the absence of a universal method for regionalization.

Understanding hydrological processes in watersheds requires a hydrological model. A hydrologic model helps to predict the system behaviour of catchments. Many hydrologic models have been developed for various purposes, but no specified procedure is available for selecting a specific model. Therefore, selecting the most appropriate model for the study area relies on research objectives and personal interests.

Regionalization of Nepal's river flow is essential for assessing and utilizing water resources in irrigation and hydropower generation; however, very little research has been conducted about the regionalization of river flows in Nepal. Moreover, seasonal uncertainty creates complex problems utilizing the regionalization approach and funding water development projects in Nepal. Therefore,

The water resource projects in Nepal rely upon the previously developed empirical methods to predict runoff in ungauged basins. However, these methods are not upgraded, and their reliability is not verified since their development; therefore, they may not be reliable to predict accurate runoff in ungauged basins. Thus, research into an improved and reliable approach is essential to estimate runoff in ungauged catchments in Nepal.

Chapter 3: Methodology

3.1 Introduction

Flow prediction in a catchment without hydrological data is one of the most challenging tasks in hydrological science and engineering. In response to this challenge, various hydrologic models have been developed with different underlying philosophies to understand the nature of the hydrological behaviour that impacts streamflow in catchments without hydrological data. Selecting the preferred model, however, is a challenging task for many hydrologists. It has been widely accepted that the research objective, personal interest, and experience are critical in selecting the most appropriate model.

In this study, the SWAT (Soil and Water Assessment Tools) model was selected to simulate runoff in the West Rapti River basin, which is a rainfall fed, and flood-affected river basin in Nepal. In addition, SWAT-CUP (SWAT Calibration Uncertainty Program) was utilized to calibrate the model analyze the sensitivity and uncertainty of the model parameters. An overview of the adopted methodology is shown in Figure 3.1.

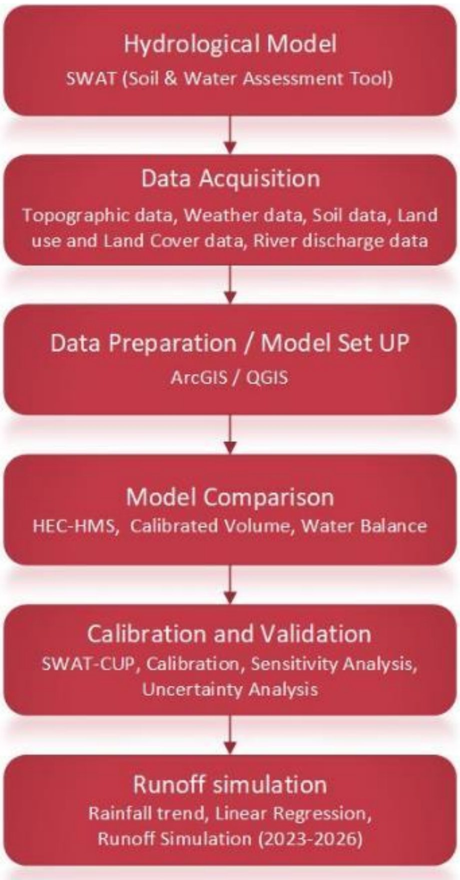


Figure 3.1: General methodological approach, extracted and modified from Magaju (2018)

3.2 Hydrological Model

A hydrological model helps us understand the impact of natural and anthropogenic disturbances on hydrological features, which is essential for the accurate prediction of the hydrological processes. The hydrologic modelling also allows forecasting water resource changes to support water resource management (Zhao et al. 2018). However, the accurate prediction of watershed systems is challenging because of many environmental factors such as changes in climate, changes in land-use practice and other anthropogenic disturbances (Uniyal et al. 2015). The modelling process consists of three stages: (i) model setup, (ii) model calibration, and (ii) model validation (McCuen 1973).

This study completed the model formulation and [partial] model calibration processes successfully; however, the missing values of GRDC (observed runoff) data restricted the model validation process. This was addressed through comparison with a second simulation model.

3.2.1 SWAT Introduction

SWAT (Soil and Water Assessment Tool) is a public domain, semi-distributed and process-based basin model (Abbaspour et al. 2019; Gassman et al. 2007) broadly used for surface and groundwater simulation. The model was developed by the US Department of Agriculture (USDA) Agriculture Research Service (ARS). It has been successfully applied to predict the impacts of land management practices, land use, nutrients, sediments, and chemicals (agricultural) in various basin sizes globally (Neitsch et al. 2011).

SWAT is based on mathematical descriptions of "…physics, bio-geochemical and hydro-chemical processes, combined with physical and semi-empirical nature…" (Krysanova & White 2015). The major components of the model include weather, hydrology, temperature, soil, and land management (Gassman et al. 2007).

Setting up and running the SWAT model involves three main processes (states) as shown in Figure 3.2: (I) division of the basin into sub-basins using DEM; (II) creation of HRUs utilizing land and soil data; and (III) creation of geodatabase (files and tables) based on weather data. The details of these stages are explained in section 3.5 Model setup.

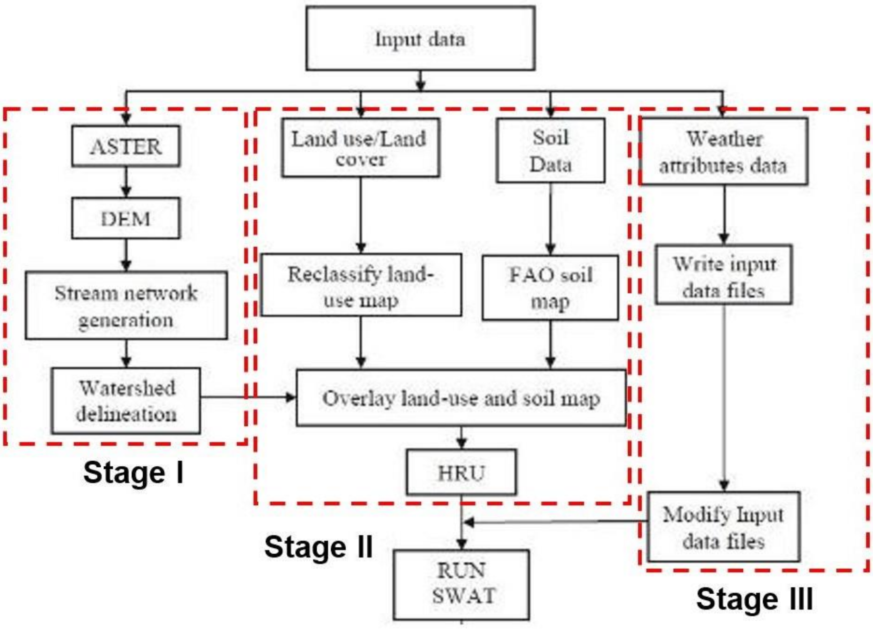


Figure 3.2: Schematic flowchart of SWAT model (Source: extracted and modified from Bera et al. (2019))

The primary data for SWAT includes DEM, land use, soil map, and climate data (rainfall, temperature, solar radiation, relative humidity, and wind speed). However, climate data in many places may not always be accessible and may have missing values or poor quality (Shrestha et al. 2018). Therefore, the missing climate data are generated and filled by a WXGEN, a built-in stochastic weather generator stochastic weather model in SWAT. This makes SWAT attractive and useful for the simulation of hydrology in ungauged or poorly gauged watersheds (Shrestha et al. 2018).

The process-based model contains spatial disaggregation structures, such as sub-basins and hydrological response units (HRUs). Therefore, a basin is first delineated into several small basins according to the quality of DEM. Further, the basin is split into HRUs utilizing similar land use, soil types, and slops (Shrestha et al. 2016). As a result, the homogenous characteristics and spatially distributed parameters are preserved within a sub-basin (Srinivasan & Arnold 1994). The SWAT model uses land use management information, soil data and elevation data to control the discharge and manage routing in the sub-watershed (Easton et al. 2010). These attributes make SWAT a semi-distributed simulation model.

The SWAT model is supported by online resources, multiple geographic information systems (GIS) interface tools, and other supporting software (Gassman et al. 2014) that allow adding additional digital information, topographical, land use and soil data. The model can read recorded data directly or generate simulation results from provided daily or monthly observed data. Likewise, the model can simulate surface discharge, lateral flow, evapotranspiration, infiltration, return discharge, redistribution of water within the soil profile and recharge by seepage from surface water bodies, including ponds and tributary channels in the basins (Arnold et al. 2012).

The SWAT model has been extensively used in various geographically variable places across the globe to simulate a wide range of hydrologic processes (Jajarmizadeh et al. 2014; Neitsch et al. 2011; Shrestha et al. 2018). For example, assessing water resources in terms of water quantity (river flow, soil water, groundwater, snow dynamics and water management) and determining environmental issues (the impacts of climate change on river flow, groundwater recharge, water yield, and pollutant transport) (Krysanova & Arnold 2008). However, because the SWAT model requires a range of information to run, unskilled users may feel exhausted by the number and range of inputs (Arnold et al. 2013).

The SWAT model's main flaw is its non-spatial representation of HRUs within each sub-basin (Glavan & Pintar 2012) - hence the model is fully distributed. As a result, the heterogeneity of soil, land use and the slope in this model is considered through sub-basins, ignoring flow and pollutant routing between HRUs (Glavan & Pintar 2012). The SWAT model also requires modifying numerous parameters during calibration, which may discourage modellers from using the model. Similarly, conducting sensitivity analysis using manual or automatic calibration tools in complex watersheds with multiple HRUs takes a significant time to complete the process in SWAT (Glavan & Pintar 2012).

3.2.2 SWAT Hydrology (Water Balance)

Water balance is essential in accurately predicting water movement in a basin. The water balance in SWAT can be divided into two phases of the hydrologic cycle: the land phase and the water phase. The land phase, depicted in Figure 3.3, controls the amount of water following into each subbasin's main channel. In contrast, water moves through the basin channel to the outlet in the routing phase of the hydrologic cycle (Neitsch et al. 2011).

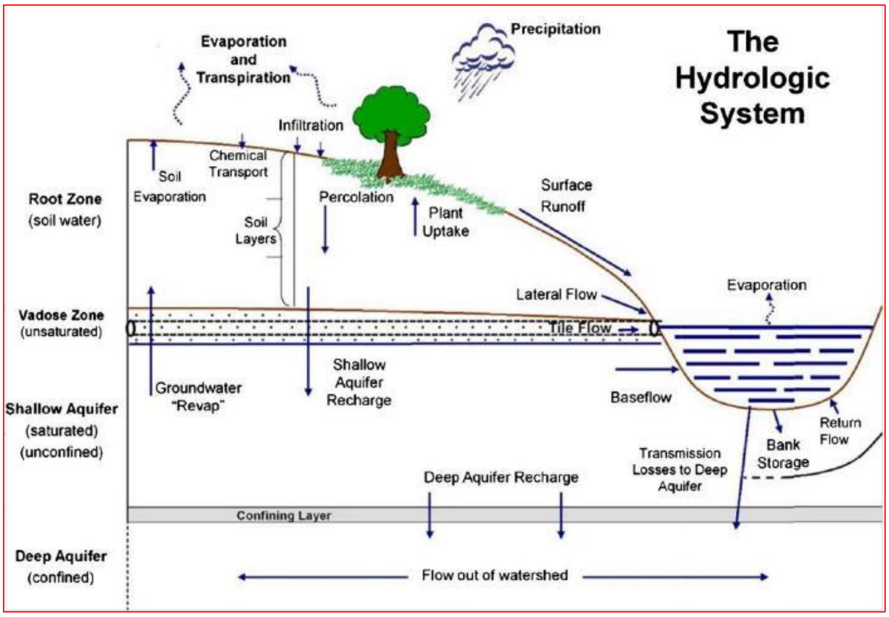


Figure 3.3: SWAT hydrologic system (Source: extracted from Neitsch et al. (2011))

The land phase of water balance can be calculated using either Penman-Monteith, Hargreaves or Priestley-Tylor methods. The Penman-Monteith method gives a better process description, yet it requires a large amount of input data, which is not easy to achieve. Hence, Hargreaves or Priestley-Tylor method was applied in this study because it requires fewer input data; consequently, it may be used under the minimum data available condition (Heuvelmans et al. 2005; Stehr et al. 2008). According to Li et al. (2018), the Hargreaves is the most widely used approach in hydrology to estimate evapotranspiration rate under sufficient soil water availability conditions.

The water balance equation (3.1) (Arnold et al. 2012; Gassman et al. 2007; Neitsch et al. 2011) in SWAT is expressed in terms of soil water content, as shown by

$$SW_t = SW_0 + \sum_{i=1}^{t}\left(R_{day} - Q_{surf} - ET_{days} - w_{day} - Q_{gw}\right) \tag{3.1}$$

SW_t = the soil water content after simulation (mm H_2O),

SW_0 = the soil water content at the beginning of the simulation (mm H_2O)

t = time of simulation (days),

R_{day} = the quantity of rainfall (mm H_2O)

Q_{surf} = the quantity of surface overflow (mm H_2O)

ET_{days} = the total evapotranspiration per day (mm H_2O)

w_{day} = the quantity of infiltration (mm H_2O)

Q_{gw} = the total return flow (mm H_2O) (Koutalakis et al. 2015; Neitsch et al. 2011).

SWAT calculates total runoff for the basin by routing and estimating runoff separately for each HRU. This process improves accuracy and provides a more accurate physical description of water balance. Furthermore, SWAT estimates surface runoff using the SCS-CN (Soil Conservation Service - Curve Number) and the Green and Ampt infiltration method (Johnson 1998). The CSC-CN can be applied in ungauged basins using daily rainfall values. However, the Green and Ampt Infiltration method require finer-than-daily time resolution rainfall data (Johnson 1998), making it difficult to apply in most studies where data is sparse. Thus, the SCS-CN was used to estimate the amount of runoff under various land-use and soil conditions in the study.

The SCS curve number is determined by soil moisture and land use conditions in the watershed area, as shown in equation (3.2).

$$Q_{surf} = \frac{(R_{day} - I_a)^2}{(R_{day} - I_a + S)} \tag{3.2}$$

Where,

Q_{surf} = the accumulated runoff or rainfall excess (mm),

R_{day} = depth of rainfall for a day (mm),

I_a = the initial abstraction, which includes surface storage, interception, and infiltration before runoff (mm),

S = the retention parameter (mm),

The parameter S changes in space and time due to soil, slope, land-use changes and changes in soil water content. The retention value is determined from the following equations (Neitsch et al. 2011).

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \tag{3.3}$$

Where,

CN = the curve numbers

I_a = the function of maximum potential retention S. Therefore,

$$I_a = \lambda S \tag{3.4}$$

Where, λ = 0.2, therefore, the Initial abstraction, I_a is approximately $0.2S$.

Using equations (3.4) in (3.2), we get;

$$Q_{surf} = \frac{(R_{day} - 0.2S\ )^2}{(R_{day} + 0.8S\ )} \tag{3.5}$$

The runoff occurs when $R_{day} > I_a$ (Neitsch et al. 2011).

Equation (3.5) can now be used to estimate surface runoff.

3.2.3 SWAT Model in the Nepalese Context

SWAT model has been successfully used in different watersheds of Nepal for various purposes. For instance, Shrestha et al. (2018) used the SWAT model for river discharge simulation in eleven basins located in different climatic zones of Nepal and other countries such as Vietnam, Myanmar, Cambodia and Laos. Similarly, the effect of climate on water resources for irrigation and hydropower generation was successfully conducted in various watersheds (Bajracharya et al. 2018; Bhatta et al. 2019; Gurung et al. 2013; Siddiqui et al. 2012).

The summary of the SWAT model used in various watersheds and climatic conditions in Nepal is given in Table 3.1.

Using the SWAT model in this study aims to simulate runoff in ungauged basins in Nepal. The country is unable to utilize the vast potential of water resources for hydropower generation, irrigation land, and even to manage the flooding events due to a lack of knowledge to understand the hydrologic behaviour of catchment when adequate hydrologic data are not available. As shown in Table 3.1, not much research has been conducted on runoff simulation in ungauged basins in Nepal. Hence, the findings of this study may play a critical role in understanding basin response and simulating runoff in ungauged basins using the SWAT model. Runoff simulation in ungauged catchments contributes to managing water resources and developing the country's economy.

Table 3.1: Details of SWAT model used in different watersheds for various purposes in Nepal

Study	Study region	Watershed(s) Area	SWAT version	Description of SWAT application
Neupane and White (2010)	Narayani River basin watershed, Nepal	31,986 km^2	SWAT 2005	SWAT was used to simulate runoff, sediment yield, and nutrient loading from the Himalayan headwater watershed because of climate change impacts in the Narayani River basin.
Shakya (2011)	Indrawati River basin, Nepal	1,228 km^2	SWAT2005 SWAT-CUP	The model was used to determine the availability of water resources Indrawati River basin.
Bharati et al. (2012)	The Koshi basin, Nepal	57,760 km^2	SWAT	SWAT was used to calculate water balance and the impact of climate change in the Koshi basin's hydrology.
Siddiqui et al. (2012)	135 watersheds, Nepal	81,484.20 km^2	ArcSWAT	ArcSWAT was used to estimate the climate change vulnerability due to sensitivity, exposure, and adaptive capacity
Gurung and Bharati (2012)	Melamchi river basin, Kathmandu, Nepal	330 km^2	SWAT	Under current and future climate change scenarios, SWAT was used to assess downstream impacts of the Melamchi inter-basin water transfer plan.

Shrestha (2013)	Kulekhani, Nepal		SWAT	SWAT was used to investigate the effect of land-use change on hydrologic processes and hydropower generation in Nepal.
Gurung et al. (2013)	West Seti River basin, Nepal	7,438 km^2	SWAT	SWAT was used to assess water balances and crop yields in response to changing climate scenarios.
Shrestha (2014)	Melamchi river basin, Kathmandu, Nepal	330 km^2	SWAT	SWAT was used to evaluate water supply and demand in the context of climate change.
Pradhan et al. (2015)	Indrawati River basin, Nepal	1,228 km^2	SWAT	SWAT was used to assess the responses of farmers to the impact of climate change on the availability of water resources.
Agarwal et al. (2015)	Koshi River basin, Nepal	57,760 km^2	SWAT (Multi modelled)	The model was set up to predict the effects of temperature and precipitation on hydrology and water resources of the Koshi River basin.
Shrestha et al. (2018)	11 basins located in Nepal, Myanmar, Laos, Vietnam, and Cambodia	330 - 78,529 km^2	SWAT2009	The model was applied to evaluate the sustainability of simulated river flow in Asia’s Himalayan and tropical regions.
Bajracharya et al. (2018)	Kaligandaki basin, Nepal	Approximately 11,830 km^2	ArcSWAT 2012	The model SWAT was utilized to measure climate change impacts on water balance and flow patterns in a snow-dominated watershed.

Bhatta et al. (2019)	Tamor River Basin in the eastern Himalayas of Nepal	4,377km^2, 360-8,385m masl	ArcSWAT SWAT-CUP	The model was applied to examine the impact of climate change on water resources used for hydropower generation and irrigation purposes.
Chinnasamy and Sood (2020)	Kaligandaki basin in Nepal	Approximately 11,830 km^2	SWAT SWAT-CUP	The model estimated sediment loads in the Himalayan rivers.

3.3 Data Acquisition

Data acquisition strategies depend on the application and the available resources ranging from global to local data sets, regional data sources of varying availability and accuracy, and data measured from field observations. Use of local data that describe a specific characteristic and behaviour of catchments play a significant role in obtaining the most accurate runoff prediction results (McGlynn et al. 2013). However, getting local data is not always possible; therefore, a global database was considered a source of data, and it was used in this research. In fact, it is the only source of data freely available.

The necessary SWAT model set-ups data, such as terrain data (land and soil), meteorological data (daily rainfall), temperature (minimum and maximum) and daily discharge data, are analyzed and rearranged before being used as input in ArcSWAT/QSWAT. In addition, the SWAT-CUP was used to calibrate the SWAT model, perform sensitivity analysis, and assess uncertainty.

3.3.1 Topographic Data

The research attempts to use the latest and most comprehensive digital earth's terrain dataset, provided freely by ASTER 1-ARC (approximately 30-meter horizontal positioning at the equator) global digital elevation model (DEM). The seamless mosaic of the dataset consisted of about 1-degree x 1-degree tiles (Abrams et al. 2020). It was freely downloaded from the Earthdata NASA or USGS website (Figure 3.4) (https://earthexplorer.usgs.gov).

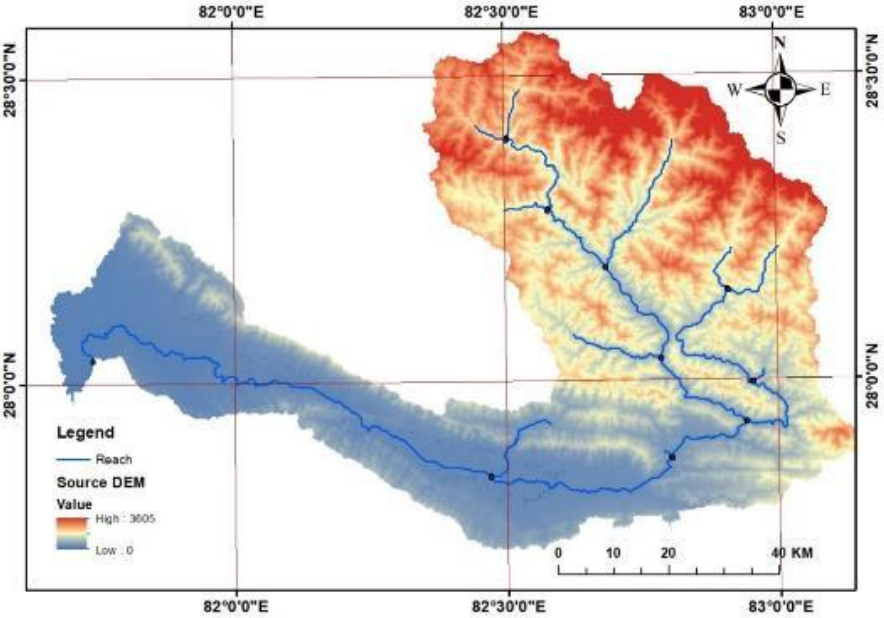


Figure 3.4: DEM and shapefile of the West Rapti river basin

DEMs are useful to obtain most of the characteristics of a basin, for instance, the boundary of watersheds (basin area), drainage patterns, slope, and length of terrain. It is also useful for obtaining physical characteristics of drainage configurations, e.g. slopes, lengths, and widths.

DEMs of all countries are provided in GeoTIFF (raster image file type) format. Thus, it is convenient for users to use ArcGIS, QGIS and other geographic information systems (GIS) tools to process and analyze raster image files. The downloaded mosaic DEM files were merged to obtain single raster data using ArcGIS/ArcMap and then clipped to get the raster image of the selected area.

Applying ArcGIS or QGIS, the DEM data was projected in a rectangular (cylindrical equidistant projection) format and referenced the Geographic Coordinate Systems as World Geodic System 1984 (WGS84) ellipsoid. The WGS 1984 UTM Zone 44 was selected as the Projected Coordinate System for the selected region and the country. Similarly, standard built-in functions of ArcGIS/QGIS were used to fill the sinks and create flow direction and flow accumulation map, as shown in Figure 3.4.

3.3.2 Weather Data

Weather data was downloaded from the Global Weather Data for SWAT webpage https://globalweather.tamu.edu/. The webpage allows obtaining free CFSR (The Climate Forecast System Reanalysis) data, a high-resolution oceanic and atmospheric data, for any geographical region of the world from 1979 to 2014. The CFSR weather data consists of rainfall, temperature, solar radiation, wind speed and relative humidity of any selected region.

Details of stations from which the CFSR data for this research were obtained are shown in Table 3.2

Table 3.2: CFSR weather stations details

Station ID	Location/District	Latitude (°N)	Longitude (°E)	Elevation (m)
W283819	Banke	28.257	81.875	545
W279828	Dhungegadi, Pyuthan	27.944	82.813	637
W283828	Sirpa, Rolpa	28.257	82.813	1348

Source: https://globalweather.tamu.edu/

The study conducted by Tomy and Sumam (2016) and Fuka et al. (2014) showed that CFSR climate data for watershed modelling performed as good as, if not better, than the data obtained from conventional meteorological stations. Furthermore, CFSR climate data also has an advantage over conventional weather because it provides complete climatic data sets that allow the flexibility to apply different functions relating to hydrological models. As a result, when traditional data are not available, the CFSR weather data may be a good choice for the hydrological forecast (Dile & Srinivasan 2014).

3.3.3 Soil Data

Processing the SWAT model needs different soil textures, physical and chemical properties, such as the hydrological group of soil, the hydraulic conductivity, and the bulk density of different layers of each soil type. The soil data used in the study was created by merging and analyzing data from the SOTER (the Soil and Terrain) database for Nepal at a scale of 1:50,000, prepared by the combined effort of Nepal's Survey Department and Food and Agriculture Organization (FAO) (Dijkshoorn & Huting 2009). The dataset can be downloaded freely from https://www.isric.org/ (the International Soil Reference and Information Centre (ISRIC) - World Soil Information website).

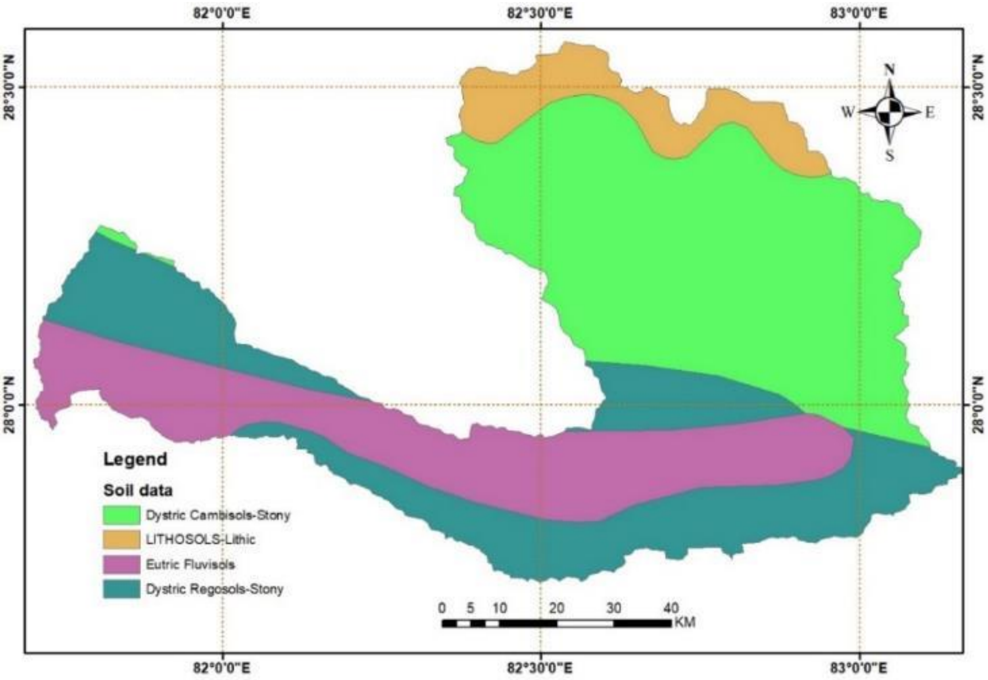


Figure 3.5: Soil map of the study area. (Source: ISRIC)

In the SWAT model, the physical properties of soil texture, water content, hydraulic conductivity, soil bulk density and organic matter content of the soils were evaluated and analyzed for different layers. As a result, four types of soils shown in Figure 3.5 are identified within the study area. Dystric Cambisols, Eutric Fluvisols, and Dystric Regosols soils are sandy clay loam textures belonging to hydrologic soil group (HYDGRP) C. The fourth soil type Lithosols is clay loam texture belonging to HYDGRP D (FAO/IIASA/ISRIC/ISS-CAS/JRC 2009; Neupane & Pandey 2021). Group C soils have moderately high runoff potential when wetted thoroughly (USDA 2009).

3.3.4 Land use and Land Cover (LULC)

The LULC data is considered one of the most critical factors in hydrological modelling because they affect surface runoff, infiltration, evapotranspiration, and soil erosion in the land use type (Dhami et al. 2018).

The LULC dataset for the West Rapti River basin was extracted from Nepal's land cover map developed by ICIMOD (International Centre for Integrated Mountain Development) using ArcGIS (Figure 3.6). The extracted LULC dataset is the first and most complete national land cover dataset prepared by using public domain Landsat TM (Thematic Mapper) data.

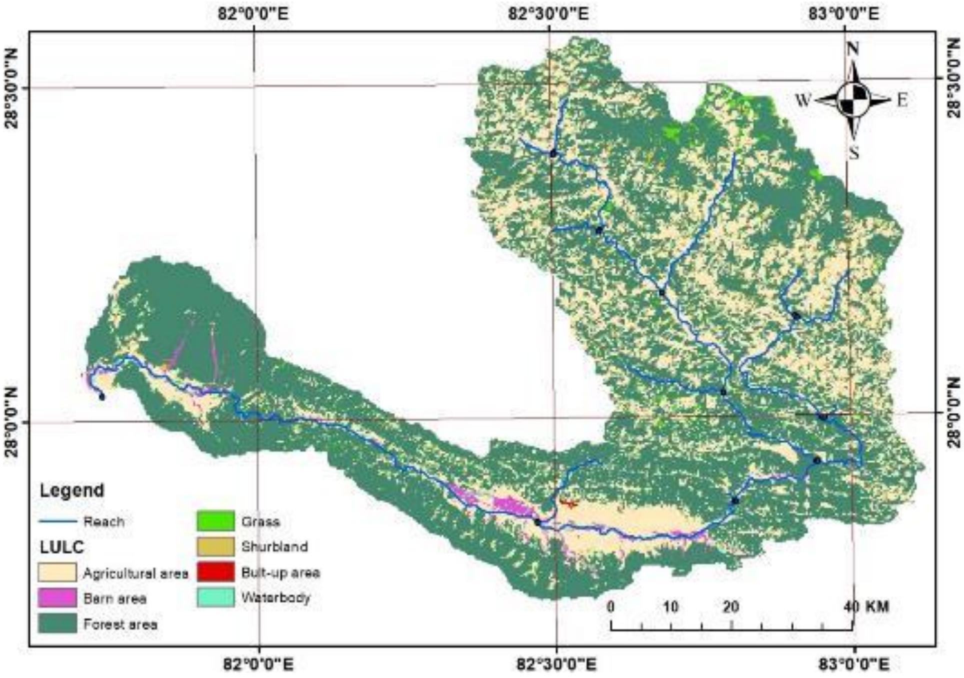


Figure 3.6: LULC map of the West Rapti River basin. (Source: ICIMOD)

3.3.5 Observed river runoff data

Daily recorded observed runoff data is essential for the SWAT model’s calibration and validation. The observed runoff data were downloaded from the GRDC (Global Runoff Data Centre) website https://portal.grdc.bafg.de/. GRDC operates the Global Runoff Database. GRDC collects, stores and disseminates discharge data and associated metadata from rivers around approximately 7,300 stations worldwide. Likewise, the

GRDC provides in-situ river discharge data to scientific research and modelling communities to improve their findings in water and climate-related programs substantially. Moreover, the World Meteorological Organization (WMO) has approved the GRDC as one of the initial datasets in the WMO Climate Data Catalogue.

Details of available GRDC stations in different locations of the West Rapti river basin are presented in Table 3.3.

Table 3.3: Available GRDC stations in the study area

River	Station	Available data series		Latitude (°N)	Longitude (°E)	Altitude (m)
		Daily	Monthly			
Jhimruk Khola	Tigra Gaon	1978-1985	1978-1985	28.05	82.83	634
Mari Khola	Nayagaon	-	1962-1985	28.07	82.80	536
Rapti River	Bagasoti Gaon	-	1976-1985	27.90	82.84	318
Rapti River	Jalkundi	-	1964-1985	27.95	82.23	218

Source: https://www.bafg.de/ (GRDC)

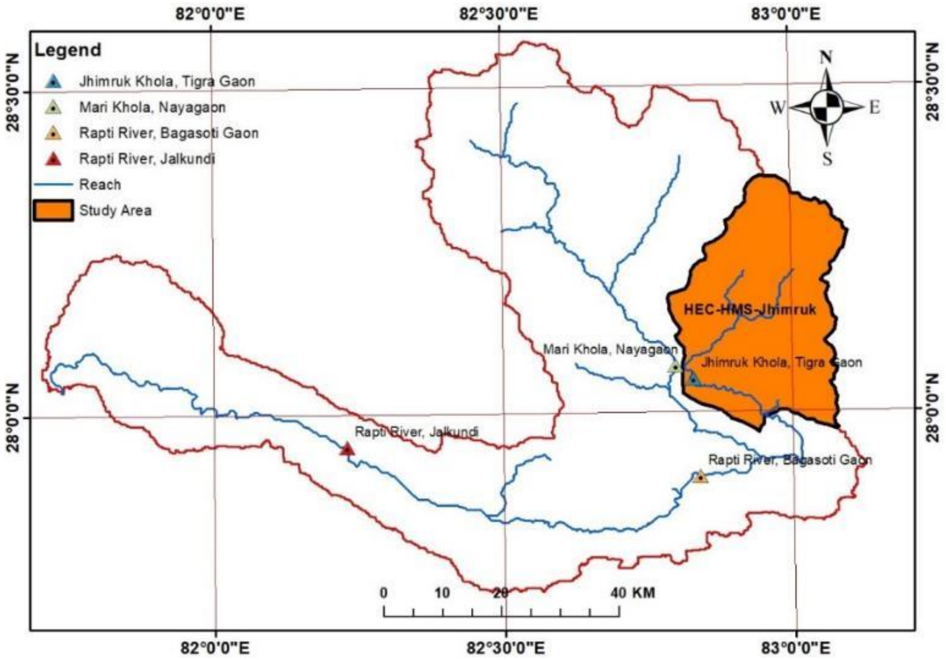


Figure 3.7: Location map of Jhimruk Khola sub-basin

SWAT requires daily runoff data to calibrate and validate the model. However, as shown in Table 3.3, daily observed runoff data is only available in Jhimruk Khola, Tigra Gaon station (Figure 3.7). Therefore, daily runoff data from 1981 to1985 was extracted from the Tigra Gaon station for model calibration and validation purposes.

The majority of the Jhimruk Kola sub-watershed is located in the Pyuthan district, mid-western part of Nepal. Jhimruk Khola is one of the major drainage systems of the West Rapti river basin. The elevation of the sub-basin ranges from 3,000m in the north and 410m in the south. The sub-watershed provides about 60 irrigation systems and possible locations for numerous micro-hydropower projects. In addition, about 68% of the sub-watershed area is covered by forest. Therefore, it is one of the valuable sources of revenue for the communities in the sub-basin area (USAID 2018).

3.4 Input data of SWAT model

Input data such as DEM (digital elevation model), weather data, soil attributes, and land use data (Srinivasan & Arnold 2012) are necessary to simulate runoff in the SWAT model. All the required input data were obtained from the freely available sources, discussed in Section 3.3. Furthermore, additional input parameters such as information on water infrastructure and land management practices can also be integrated into the model. Therefore, the model is useful to predict the impact of water resources due to changes in land-use patterns.

3.4.1 DEM raster data

A DEM dataset is prepared using ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer). DEM is raster data that contains an array of pixels or cells that consist of elevation values. First, the study area's DEM with a resolution of 90m x 90m (Figure 3.4) was obtained from the USGS website (https://earthexplorer.usgs.gov). Then, a Project Coordinate System, World Geodetic System (WGS 1984 UTM Zone 45N), was applied to the downloaded DEM based on the selected region and the country.

3.4.2 Weather data

The SWAT model requires various weather variables data, for instance, rainfall, maximum and minimum temperature, wind, solar and relative humidity of the selected area. The weather data are downloaded from Global Weather Data for SWAT website (https://globalweather.tamu.edu) based on the location of the interest and country. The webpage allows downloading weather data in SWAT format, which can save data preparation time.

Daily weather data for 11-years (1979-1989) was downloaded from different locations within the West Rapti river basin. The detail of the weather stations is discussed in Section 3.3.2. Moreover, a weather lookup table is provided due to data from several weather stations. Therefore, what attributes in the lookup table correspond to the location (station) and climate are defined.

3.4.3 Land use and Soil data

LULC (land use and land cover) data were retrieved from the regional dataset system of the International Centre for Integrated Mountain Development (ICIMOD). The LULC was classified into Agricultural area (AGRL), Barren area (BARR), Built-up area (URBN), forest (FRST), grass (PAST), water body (WATR), and Shrubland (SURB).

Since there was no detailed soil map for the West Rapti basin or Nepal in general (Dijkshoorn & Huting 2009), therefore, digital (FAO) soil data was obtained from the International Soil Reference and Information Centre (ISRIC) - World Soil Information website (https://soil.narc.gov.np/soil/soilmap/). Then, ArcGIS was used to extract the necessary soil map, essential for model setup and calibration processes.

A user lookup table (soil and land-use) was created and loaded in the ArcSWAT/QSWAT interface. It is necessary to define what attributes in the lookup table (***Error! Reference source not found.***) correspond to land and soil types. This allows the interface to recognize codes or names to assign according to categories and reclassify them according to the lookup table.

3.5 SWAT Model setup

ArcGIS 10.7/ QGIS 3.10 platform was used to establish the SWAT model. Both (ArcGIS and QGIS) models store geodatabases consisting of SWAT geographical data, text input data, numeric, and outcomes (Olivera et al. 2006). ArcGIS is an advanced GIS program containing an array of GIS tools that can be used for various purposes. However, some tools may require a software license to use. In addition, Arc-SWAT output visualisation requires an additional program such as SWAT Output Viewer. In contrast, QGIS is public domain software that allows users to visualize the SWAT output in a graphical (linear, column) representation.

There are three main steps involved in the SWAT model set-up; (i) Delineate Watershed, (ii) Build HRUs, and (iii) Create Input files/tables. These are present next.

3.5.1 Watershed Delineation

Partition of the watershed into multiple sub-watersheds is the first step in the watershed delineation process. Subbasins are geographically located in the catchment area, and they are spatially linked to one another. Therefore, the subbasin partition can be performed using subbasin boundaries characterized by surface topography or grid cell boundaries. (Arnold et al. 2013). Subbasin delineation using subbasin boundaries allow water to flow to the outlet of the subbasin. The grid cell may be a suitable method for watershed delineation because most spatial input data (DEM and land use) are grid-based. However, the method does not maintain topographical flow paths and routing reaches (Arnold et al. 2013). Therefore, a process of manual correction may need to be used.

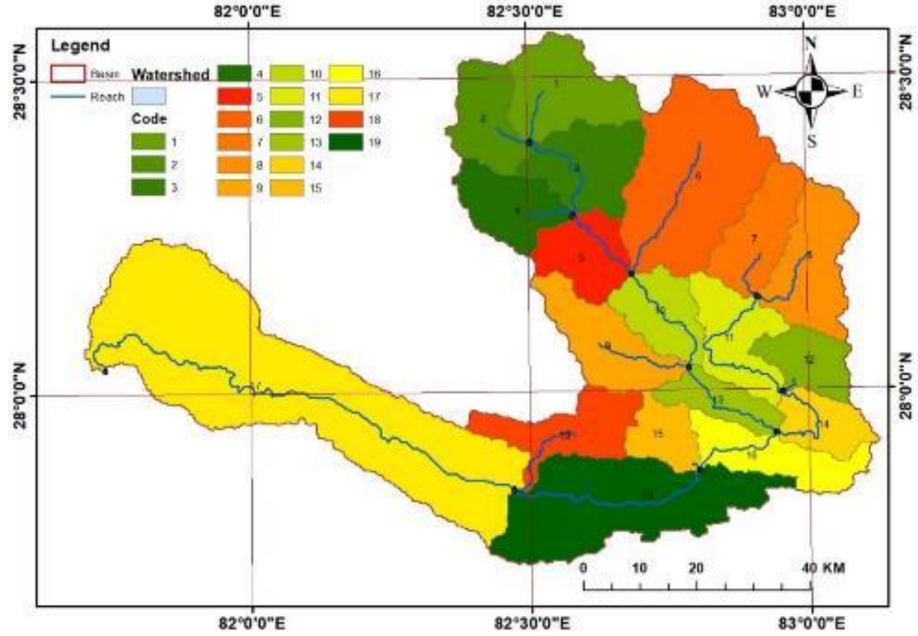


Figure 3.8: Watershed delineation map of the West Rapti river basin

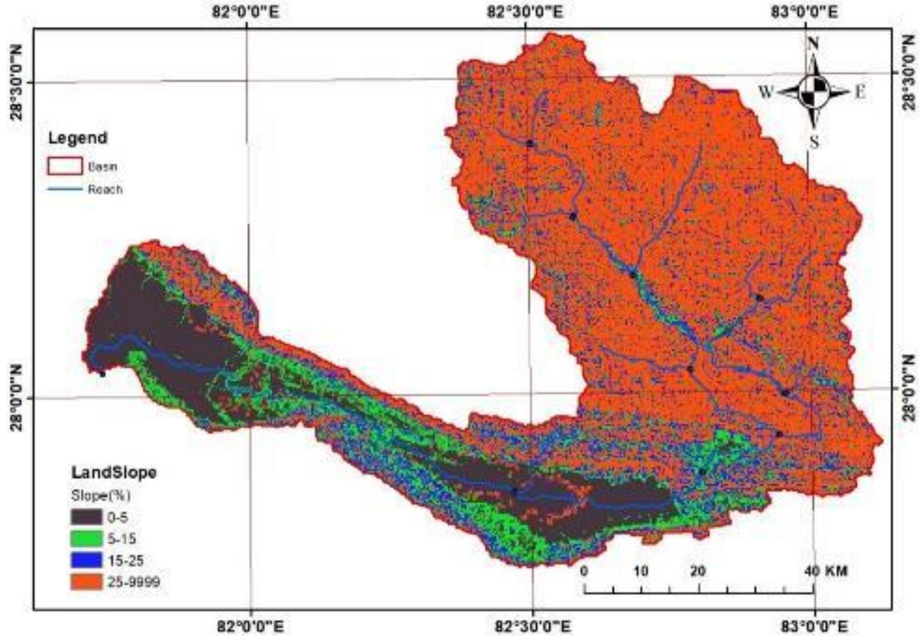


Figure 3.9: Slope map of the West Rapti river basin

The DEM is loaded in the ArcSWAT interface and projected to the UTM Zone 45N projection system. A threshold area is given to identify the source of runoff in ArcSWAT and generate the river network system. Therefore, the density of river networks depends on the given threshold area. For example, the small threshold value produced dense and extensive river systems in the catchment area. Likewise, additional outlet points can be added to the basin as needed. However, no additional outlet point was added to create river networks and subbasins in the West Rapti river basin.

3.5.2 HRU Creation

All-natural catchments are usually not heterogeneous because they are composed of different land uses and soils. SWAT divides the watershed into smaller hydrologic response units (HRU) depending on characteristics of soils, types of land use and classes of slope in the catchment area (Koutalakis et al. 2015) – this maintains homogeneity within each HRU. The SWAT creates a slope depending on DEM information. Therefore various categories of slopes were provided to define HRU (Worku et al. 2017). As shown in Figure 3.9, DEM was divided into four slope categories: i) 0-5%, ii) 5-15%, iii) 15-25% and iv) >25%.

The main purpose for the creation of HRUs is to simplify the model runs; therefore, they were used in most SWAT runs. Similarly, HRU is defined to reduce the heterogeneity of hydrological response due to different climates, soil types, topography and geology within the catchment area (Sisay et al. 2017).

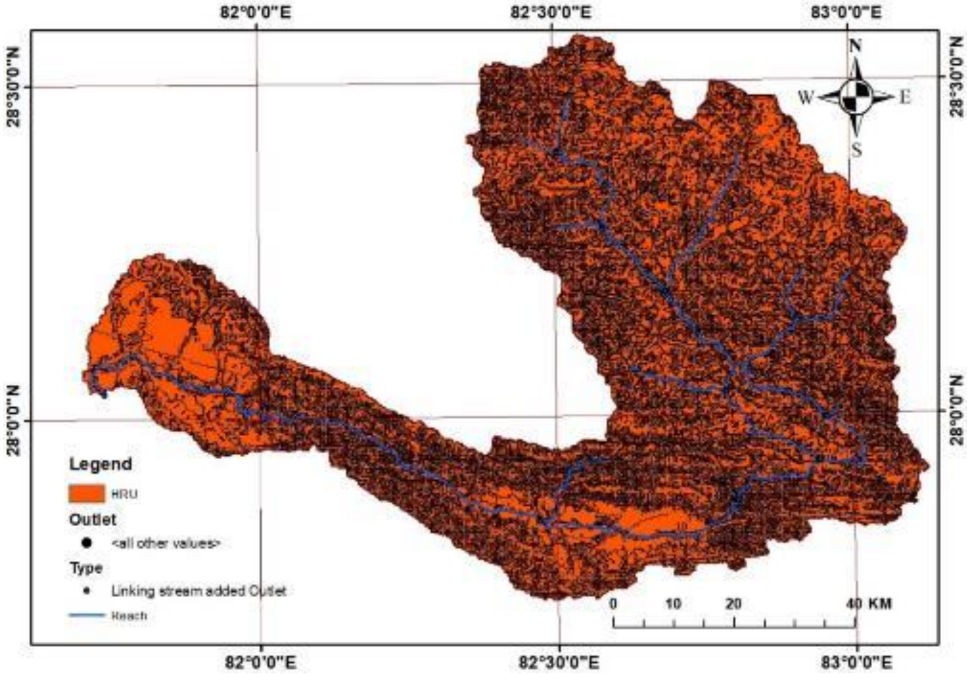


Figure 3.10: HRUs map of the study area

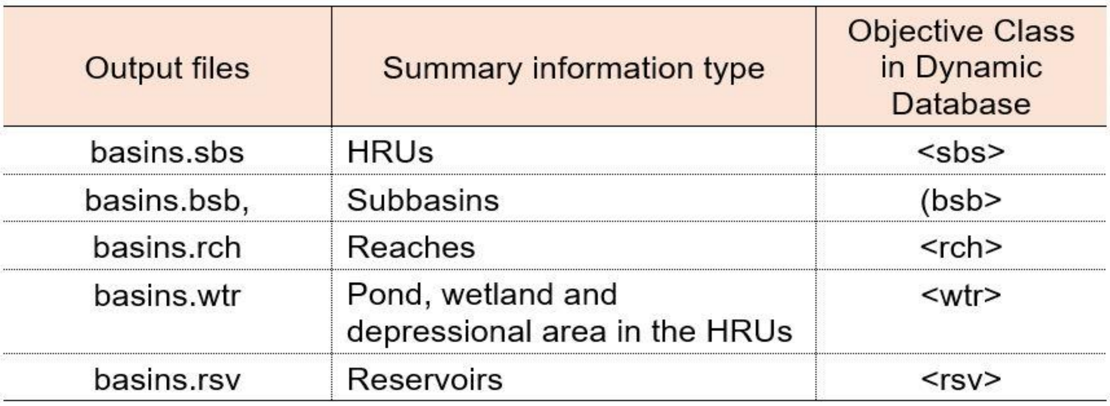
3.5.3 Inputs Files/Tables Creation and Run

The input file defines the watershed attributes, which control various physical processes in the basin. The input file can be created after completing geoprocessing on topographic maps, land and soil data and creation of HRUs. Input files in SWAT can be categorised into different files such as (i) basin, (ii) sub-basin, (iii) HRUs, (iv) reservoir, and (v) point source. These input files are described in Arnold et al. (2013).

The weather data input files were generated by assigning daily rainfall, minimum and maximum temperature, solar radiation, wind speed, and relative humidity data for each sub-watershed depending on the meteorological data for the stations. A lookup table was used to provide statistics of weather stations in the research area. Users can change the statistics and dynamics of lookup tables in ArcGIS-SWAT. After modification, a new set of input files can be created.

A SWAT simulation was conducted after providing input files in ArcGIS-SWAT. Successfully simulation resulted in SWAT generating five different text formatted output files. A summary of SWAT output files is shown in Table 3.4, and details are provided in **Error! Reference source not found.**. In addition, each output file contains detailed information on a particular hydrologic element (Olivera et al. 2006).

Table 3.4: SWAT Output files



Output files	Summary information type	Objective Class in Dynamic Database
basins.sbs	HRUs	<sbs>
basins.bsb,	Subbasins	(bsb>
basins.rch	Reaches	<rch>
basins.wtr	Pond, wetland and depressional area in the HRUs	<wtr>
basins.rsv	Reservoirs	<rsv>

Source: Extracted from Olivera et al. (2006)

Visualizing ArcSWAT output files is not a straightforward process. However, MS Excel helps to visualize the SWAT results. For example, a command <TimeSeries> allows to plot and visualize the desired variables (e.g., rainfall, runoff) and location (e.g., number of sub-catchments, HRU, reach) with Excel in ArcSWAT.

In contrast, QSWAT allowed automatically visualize the time series of one variable with respect to another by choosing SWAT output table (e.g., reach, subbasin, HRU), period (e.g., start date, end date), variables (e.g., precipitation, inflow, outflow, sediment), and summary (e.g., daily, monthly, yearly mean). Therefore, visualizing the time series variables with QSWAT is an easy and time-saving process.

3.6 Model Comparison (SWAT and HEC-HMS)

3.6.1 Introduction

The GRDC data (observed runoff) limited model calibration due to missing values, and it also restricted checking the model's reliability. Therefore, the SWAT model results were compared with those from the HEC-HMS (Hydrologic Engineering Center - Hydrological Modeling System) model to check the model reliability for application in the West Rapti river basin. Hence, the calibrated runoff (volume and depth) and water balance results were analyzed and compared prior to selecting the model.

3.6.2 HEC-HMS model setup

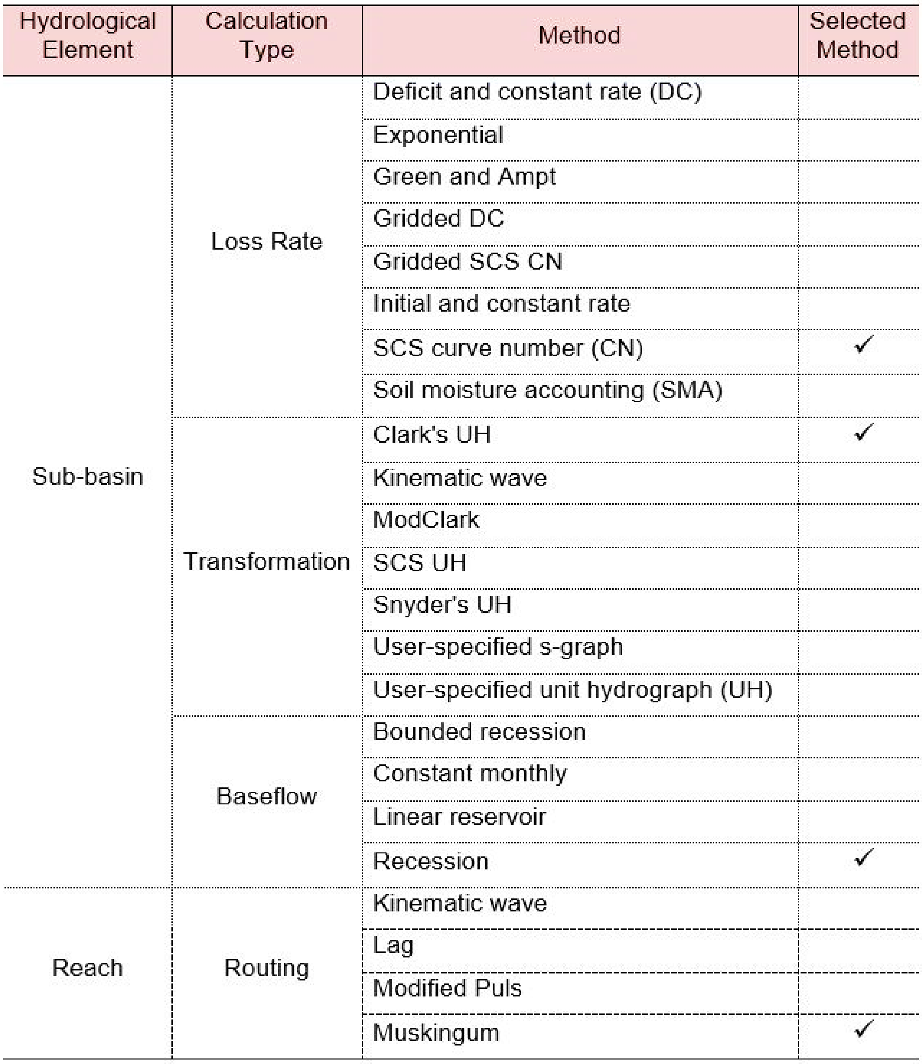
HEC-HMS, a physically based and conceptual lumped parameter hydrologic modelling software, was developed by the US Army Corps of Engineers-Hydrologic Engineering Center (HEC). The model was developed to simulate rainfall-runoff processes in various geographical regions to solve a wide range of hydrological problems (Choudhari et al. 2014). Since its inception over four decades ago, the model has gained wide popularity globally. For example, Deb and Kiem (2020) applied the HEC-HMS model in two different climatic conditions in Western Australia to simulate runoff in catchments with a variable relationship of rainfall and runoff. Similarly, Tassew et al. (2019) used the HEC-HMS model in Ethiopia to study the rainfall and runoff relationship for runoff estimation produced by precipitation.

HEC-HMS has two major model components: Basin Model and Meteorological Model. Control Specification is then used to simulate scenarios. These features are essential to identify sub-basin and hydrologic parameters such as the slope and reach length. In addition, a few specific topography features, such as the elevations and streams, were introduced in the model setup processes in the current study.

The Basin model was set up to calibrate rainfall-runoff in the Jhimruk Khola sub-basin (Figure 3.7). The Basin model includes the hydrological components and their connectivity, representing the movement of water through the drainage system (HEC 2016). The Meteorological model defines characteristics of daily precipitation in any spatial or temporal form. The control specification in the meteorological model specified the starting and ending date, including the input data interval (HEC 2016).

The detailed methods, hydrological elements, and different calculation types, including the selected processes in the HEC-HMS model, are shown in Table 3.5.

Table 3.5: HEC-HMS Model parameters including selected method



Hydrological Element	Calculation Type	Method	Selected Method
Sub-basin	Loss Rate	Deficit and constant rate (DC)	
		Exponential	
		Green and Ampt	
		Gridded DC	
		Gridded SCS CN	
		Initial and constant rate	
		SCS curve number (CN)	✓
		Soil moisture accounting (SMA)	
	Transformation	Clark's UH	✓
		Kinematic wave	
		ModClark	
		SCS UH	
		Snyder's UH	
		User-specified s-graph	
		User-specified unit hydrograph (UH)	
	Baseflow	Bounded recession	
		Constant monthly	
		Linear reservoir	
		Recession	✓
Reach	Routing	Kinematic wave	
		Lag	
		Modified Puls	
		Muskingum	✓

Source: Extracted and modified from HEC (2016)

3.6.3 Data preparation for HEC-HMS

Relevant HEC-HMS model input parameters such as elevation map and SCS curve number (CN) value were taken from the SWAT model. Other input values are either calculated manually or taken as recommended in the literature. For example, the time of concentration (t_c), the time taken by a drop of water to travel from the most hydrologically distant point to the outlet of a basin (Beven 2020), was calculated by using an empirical equation of Bransby-Williams (1977). The empirical equation used for the calculation of t_c is

$$\mathrm{t}_c = \frac{58\ \times L}{A^{0.1}\ \times\ S_e^{0.2}} \tag{3.6}$$

Where,

t_c = time of concentration (min)

L = mainstream length to the catchment divide (km)

A = area of the whole catchment (km^2)

S_e = Equal-Area slope (m/km)

A distance versus elevation graph was developed to calculate the value of S_e, as shown in Table 3.6 and Table 3.7. The data were extracted from ArcGIS.

Table 3.6: Distances and elevation along the most extended reach (point-to-point)

Point-to-point	Distance point-to-point (km)	The elevation difference between point-to-point (m)
0 to 1	104.35	104
1 to 2	43.28	107
2 to 3	18.53	83
3 to 4	23.06	107
4 to 5	24.54	116
5 to 6	18.08	215
6 to 7	23.45	344
7 to 8	10	178

Length of longest reach = 265.29 km. Area of the catchment = 5953.60 km^2

Table 3.7: Distances and elevation along the longest reach (from the outlet)

Point	Distance from point 0 to 8 (km)	Elevation (m)
0	0	134
1	104.35	238
2	147.63	345
3	166.16	428
4	189.22	535
5	213.76	651
6	231.84	866
7	255.29	1210
8	265.29	1388

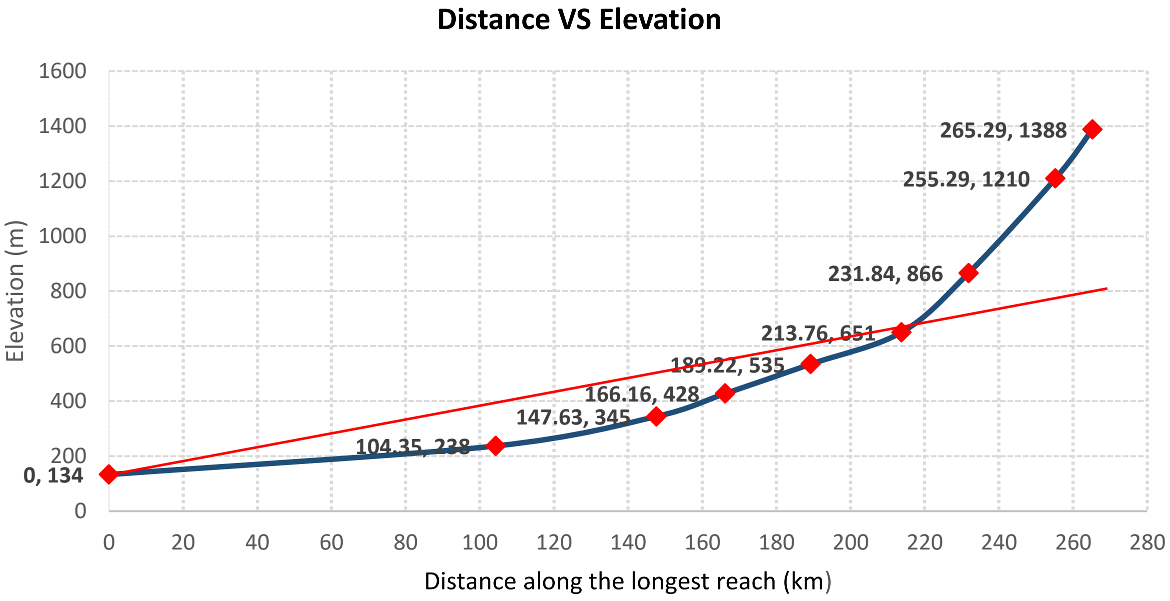


Figure 3.11: Equal-Area slope graph

From Figure 3.11, the Equal-Area Slope (S_e) was taken 20 km/m.

The time of concentration (t_c) was calculated using equation (3.6) and from the known values of S_e, including the basin area (A), and mainstream length to the catchment (L).

After the calculation (t_c) is equal to 3543.76 (min), which is approximately two days (48 hrs). Therefore, t_c = 48 hrs., and the storage coefficient was taken 24 hrs.

3.6.4 Basin Model Creation in HEC-HMS

Terrain pre-processing was carried out after refining and pre-processing the input terrain data (DEM) in HEC-HMS. The process uses the construction of sub-basins and drainage networks by completing different steps, such as filling sinks, creating flow directions and flow accumulation, segmenting streams, delineating catchment grid, and processing polygon drainage lines. As shown in Figure 3.12, a basin model was developed after selecting the outlet point for the entire watershed at the end of the basin.

For the basin model creation, the initial values of loss parameters like curve number (CN) and impervious percentage were estimated from soil data are taken from the SWAT model. The time of concentration was calculated, and details are provided in the Data preparation section. Baseflow initial values such as initial discharge and recession constant were taken from the typical range of daily recession constant value (0.2-0.8) for surface runoff recommended by Nathan and McMahon (1990) and Berhail et al. (2012).

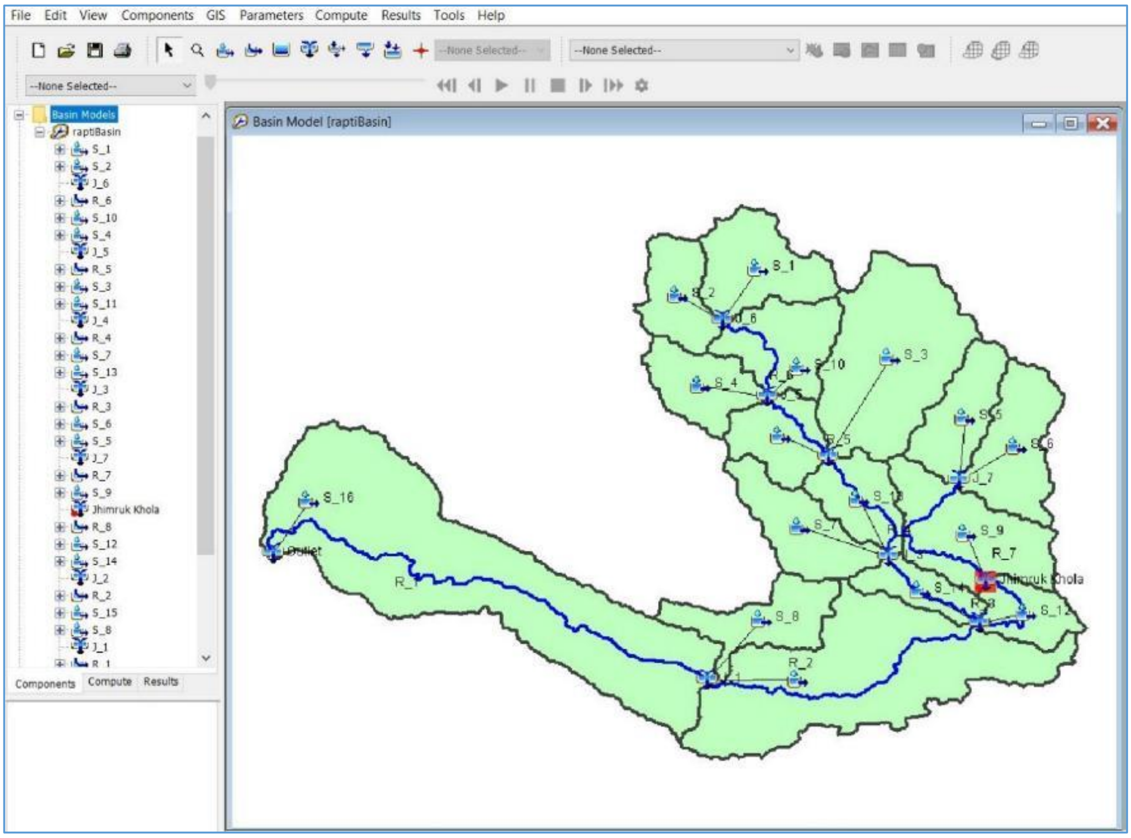


Figure 3.12: Basin model of the West Rapti river basin in HEC-HMS

Some significant characteristics of the basin model for the selected basin are shown in the table below:

Table 3.8: HEC-HMS basin model characteristics

Name of watershed	Basin area (km^2)	Number of sub-basins
West Rapti River basin	5,953.60	16

3.6.5 Basin Model Outputs in HEC-HMS

Simulation runs according to the defined and controlled specifications. The simulations computed in the junction of the Jhimruk Khola sub-basin consists of sub-basins (S_5, S_6 and S_9), the junction (J_7) and reach (R_7), shown in Figure 3.12. The simulation results were produced in the form of graphs and tables. All hydrologic elements are listed in the global summary table, making it possible to observe each hydrologic element, drainage area, peak discharge, time to peak, and volume data individually (HEC 2016).

3.6.6 HEC-HMS Water Balance

Water balance provides a valuable framework for evaluating the hydrological responses of a basin under changed land-use conditions. According to Sangwan (2016), water balance in a basin can be achieved using a simple bucket model technique in a watershed system. According to this method, the changes in water storage capacity of the basin equals the net difference between the inlet and outlet (Sangwan 2016). Therefore, the simple water balance equation can be written as shown below

$$IN - OUT = \varDelta S \tag{3.7}$$

Precipitation (P) is the major input, and Streamflow (Q) and Evapotranspiration (ET) are the major output parameters in a watershed system. Thus, the equation of water balance for a whole catchment can be expressed as:

$$P = ET + Q_{run} + \varDelta S \tag{3.8}$$

Where

P = precipitation (mm),

E = evapotranspiration (mm)

Q_{run} = total runoff (mm), (which is the sum of surface runoff, interflow, and baseflow)

$\varDelta S$ = the change in catchment water storage (Zhang et al. 2004).

The value of $\varDelta S$ is usually considered negligible (equal zero) at an annual scale (Brutsaert 2005; Szilagyi 2020). From the known value of P and Q_{run}, the annual watershed scale Evapotranspiration (ET) rates are generally estimated by the lumped water-balance equation, which is given as:

$$ET = P - Q_{run} - \varDelta S \tag{3.9}$$

According to Sokolov and Chapman (1974), water balance competitions in a region that lack gaging stations or a poorly gauged region, such as the Jhimruk Khola sub-basin, can be expressed as

$$R_{run} = P - \mathrm{E} \tag{3.10}$$

Where

R_{run} = direct runoff (mm)

P = rainfall (mm)

E = Evaporation (mm) (Sokolov & Chapman 1974).

As can be seen, equation (3.10) lumps evaporation and evapotranspiration together and assumes no storage during the simulation period.

3.6.7 Model Comparison

The model comparison was conducted in two stages: (i) runoff volume and depth comparison (ii) model performance evaluation.

The runoff volume, runoff depth, peak discharge and water balance were analyzed in the first instance. Thus, simulated runoff data from SWAT and HEC-HMS were converted into runoff volume (V) and runoff depth (D), which can be calculated as shown below

$$V = Q_{sim} \times (24 * 60 * 60) \tag{3.11}$$

$$D = \frac{Q_{sim}}{A} \tag{3.12}$$

Where

V = runoff volume (m^3) – using daily time step

Q_{sim} = simulated runoff (m^3/s)

D = runoff depth (m)

A = the catchment area (m^2)

In the second step, model performance between SWAT and HEC-HMS model was evaluated by estimating model prediction error in terms of Percentage Error (PE) due to missing daily observed runoff values.

PE is determined by dividing the difference between HEC-HMS and SWAT model simulated runoff by the sum of simulated runoff by HEC-HMS. It is expressed in percentage (%) as shown in the equation (3.13).

$$PE\ (\%) = \left(\frac{\sum Q_H - \sum Q_S}{\sum Q_H}\right) * 100 \tag{3.13}$$

Where

Q_H = HEC-HMS simulated runoff (m^3/s)

Q_S = SWAT simulated runoff (m^3/s)

The reliability of simulated runoff volume and depth in the HEC-HMS and SWAT model was evaluated by estimating the differences (HEC-HMS and SWAT) expressed in percentage (%).

The difference (%) was determined by dividing the difference between HEC-HMS and SWAT simulated runoff volume by the sum of HEC-HMS simulated runoff volume, as shown in equation (3.14).

$$Difference\ (\%) = \left(\frac{V_H - V_S}{V_H}\right) * 100 \tag{3.14}$$

Where

V_H = HEC-HMS simulated runoff volume (m^3)

V_S = SWAT simulated runoff volume (m^3)

3.7 Calibration and Validation of SWAT

SWAT-CUP (SWAT Calibration Uncertainties Program), a program for SWAT calibration (Khalid et al. 2016), was used to calibrate the SWAT model. The SWAT-CUP is a public domain software that can be downloaded freely from https://swat.tamu.edu/. According to Abbaspour (2012), the program is created to analyze the uncertainties of the SWAT model results. The SWAT-CUP also enables sensitivity analysis and uncertainty of SWAT model by using one of the inbuilt algorithms to SWAT models such as SUFI-2 (sequential uncertainty fitting algorithm), PSO (Particle Swarm Optimization), MCMC (Markov Chain Monte Carlo), GLUE (Generalized Likelihood Uncertainty Estimation), and ParaSol (Parameter Solution).

In this study, the SUFI-2 was used to calibrate and analyse the sensitivity and uncertainty of the SWAT model.

3.7.1 SWAT-CUP Model

The SWAT-CUP uses the *'TextInOut'* folder from the SWAT model as input data. Therefore, the successful creation of the SWAT model is essential for setting up the SWAT-CUP. After the successful setup of SWAT-CUP, determination of the most sensitive parameters was carried out.

The SWAT-UP allows local and global sensitivity analysis. The local sensitivity analysis process allows changing a single parameter in the input parameter keeping all other parameters constant. Therefore, the negative aspect of local sensitivity analysis is that the correct values of other fixed parameters will never be known. Whereas the global sensitivity analysis allows changes to several input parameters at the same time; but, it needs a large number of simulations, which may prove to be disadvantageous for global sensitivity analysis (Arnold et al. 2012).

In spite of this, the global sensitivity analysis was used to analyse the sensitivity of parameters in this study, as it was a more robust process. Between 200 and 500 simulations and 5 to 6 iterations were used to get the best results in SWAT-CUP. The parallel processing technology in SWAT-CUP was applied to reduce the model processing time.

3.7.2 Sensitivity Analysis

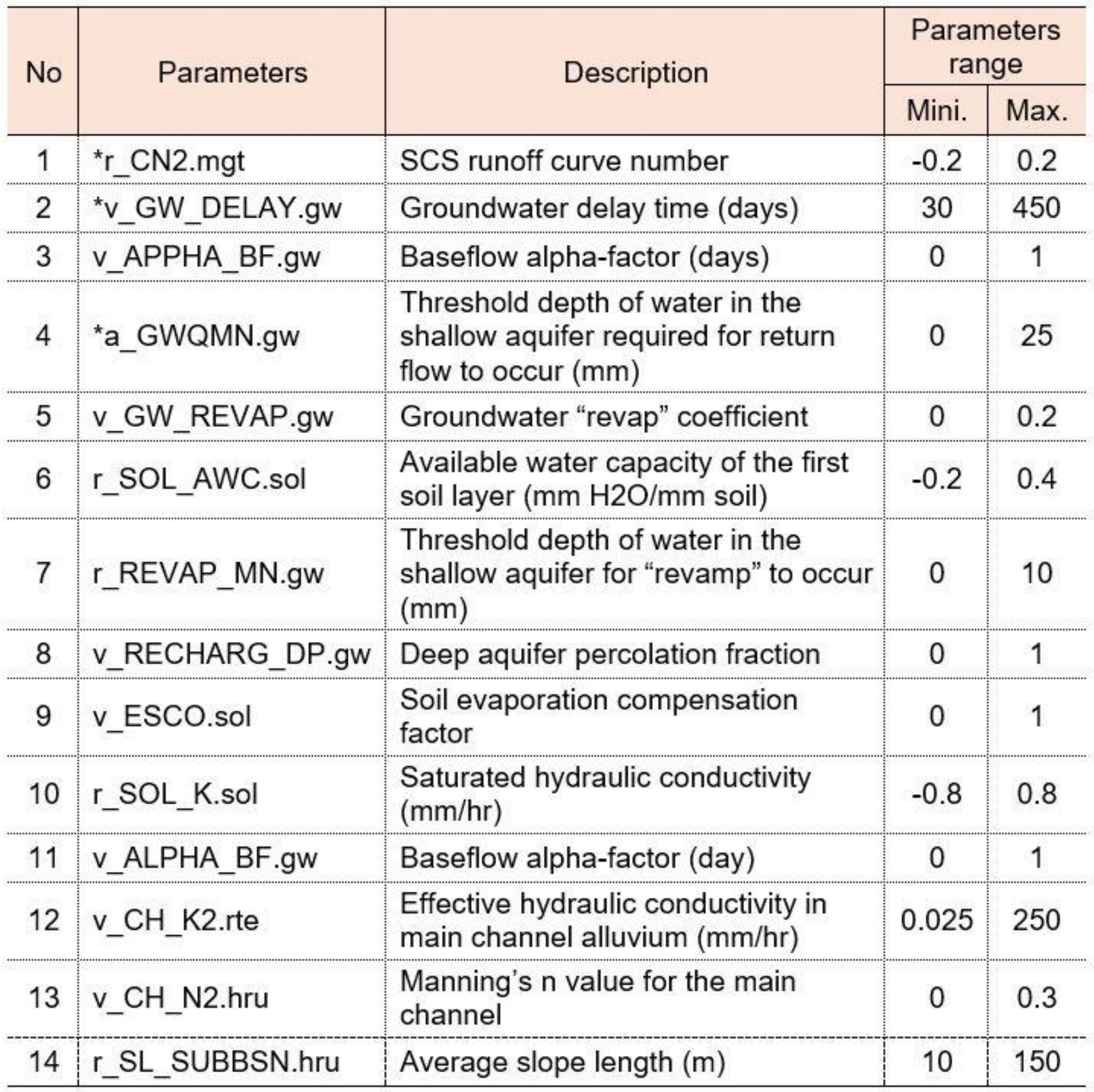
Determining the most sensitive parameters is the first step of the SWAT calibration and validation process (Arnold et al. 2012). Sensitive analysis (SA) is the process that determines the rate of change in model output parameters for changes in model input parameters (Arnold et al. 2012). The sensitive analysis also helps to determine the variable that needs to adjust. The sensitivity of model components and parameters, therefore, is useful in the formulation, calibration and validation of the hydrologic model (McCuen 1973).

SA methods are classified according to their scope, applicability, and characteristics. The most common and the simplest classifications are one-at-a-time (OAT) or local sensitivity analysis and all-at-a-time (AAT) or global sensitivity analysis (Abbaspour et al. 2018; van Griensven et al. 2006). Local SA is a method that changes values individually. In contrast, the global SA allows changing values of all parameters at the same time (Arnold et al. 2012). According to Ma et al. (2000), the independent parameter perturbation (IPP) is the most common form of sensitivity analysis, in which parameters are varied individually by a fixed percentage around an essential value,

The sensitivity analysis procedures involve identifying parameters that dominate model behaviour (Gan et al. 2014), verifying model parameter values (keeping realistic range), and the final stage is running the model under dynamic conditions (Ma et al. 2000). The sensitive parameters, including their rank, were identified through the global sensitivity analysis. Since there is no uniquely defined set of parameters and ranges (Table 3.9), they were selected after analyzing several resources, including the SWAT-CUP user manual.

A list of parameters taken for sensitivity analysis, including their ranges, are shown in Table 3.9.

Table 3.9: Parameters for sensitivity analysis, including their ranges



No	Parameters	Description	Parameters range	
			Mini.	Max.
1	*r_CN2.mgt	SCS runoff curve number	-0.2	0.2
2	*v_GW_DELAY.gw	Groundwater delay time (days)	30	450
3	v_APPHA_BF.gw	Baseflow alpha-factor (days)	0	1
4	*a_GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	0	25
5	v_GW_REVAP.gw	Groundwater “revap” coefficient	0	0.2
6	r_SOL_AWC.sol	Available water capacity of the first soil layer (mm H2O/mm soil)	-0.2	0.4
7	r_REVAP_MN.gw	Threshold depth of water in the shallow aquifer for “revamp” to occur (mm)	0	10
8	v_RECHARG_DP.gw	Deep aquifer percolation fraction	0	1
9	v_ESCO.sol	Soil evaporation compensation factor	0	1
10	r_SOL_K.sol	Saturated hydraulic conductivity (mm/hr)	-0.8	0.8
11	v_ALPHA_BF.gw	Baseflow alpha-factor (day)	0	1
12	v_CH_K2.rte	Effective hydraulic conductivity in main channel alluvium (mm/hr)	0.025	250
13	v_CH_N2.hru	Manning’s n value for the main channel	0	0.3
14	r_SL_SUBBSN.hru	Average slope length (m)	10	150

Source: Extracted from Shivhare et al. (2018)

Note:

*v_ “value” means the existing parameter value is to be replaced by a given value.

*a_ “addition” means the given value is to be added to the existing parameter value.

*r_ “ratio” represents an existing parameter value is multiplied by (1 + the given value)

gw – groundwater parameter

sol – slope parameter

rte – channel parameter

hru – hydraulic response unit

3.7.3 Uncertainty Analysis

Sequential Uncertainty Fitting (SUFI-2) algorithm was selected within SWAT-CUP to verify uncertainty obtained from calibration parameters and model uncertainty.

SUFI-2 quantifies all the uncertainties in terms of two statistics: *p*-factor and *r*-factor. Therefore, the degree of uncertainty and goodness of fit was assessed by the *p*-factor and *r*-factor values (Neupane & Pandey 2021).

The p-factor, the percentage of measured data bracketed by the 95% prediction uncertainties (95PPU), measures the degree of all uncertainties. In contrast, the r-factor measures the strength of a calibration/uncertainty analysis (Khalid et al. 2016). Theoretically, the p-factor and r-factor values range from 0-100% and 0-∞ (infinity), respectively (Khalid et al. 2016).

The value of the *p*-factor equal to 1 and the *r*-factor equal to 0 is considered the ideal simulation condition. However, this is not always possible to achieve. Obtaining reasonable values of these two factors, therefore, is always very important. Moreover, a balance between *p*-factor and *r*-factor allows judging the calibration's strength (Abbaspour 2013). According to Abbaspour et al. (2015), the *P*-factor greater than 0.7 and the *r*-factor around one is recommended for discharge calibration.

3.7.4 Evaluation of Model Performance

The model performance was carried out in SWAT-CUP using three objective functions: i) NSE (Nash-Sutcliffe efficiency), ii) R^2 (coefficient of determination), and iii) PBIAS (percentage of bias). General equations of these functions are given in equations (3.15),(3.16) & (3.17) (Abbaspour 2013).

NSE is the most common objective function for model performance evaluation. The NSE value ranges from -∞ to 1, NSE = 1 is the optimal value, and values between 0 and 1 are generally regarded as acceptable performance levels. The NSE values < 0 indicate the main observed value is a better predictor than the simulated values, indicating undesirable model performance (Moriasi et al. 2007).

$$NSE = 1 - \frac{\sum_i (Q_m - Q_s)_i^2}{\sum_i (Q_{m,i} - \overline{Q}_m)^2} \qquad (3.15)$$

Where, Q is a variable such as discharge, m and s stands for measured and simulated; respectively, the bar stands for the average value.

R^2 describes the proportion of the variance in measured data, ranging from 0 to 1. Higher values indicate less error variance, and values > 0.5 are typically considered acceptable (Kanishka & Eldho 2020). According to Henriksen et al. (2003), R^2 value > 0.85 is considered as excellent for a hydrological models, values between 0.65 and 0.85 is considered very good, 0.5-0.65 good, 0.2-0.5 poor and < 0.2 very poor.

$$R^2 = \frac{\left[\sum_i (Q_{m,i} - \overline{Q}_m)(Q_{s,i} - \overline{Q}_s)\right]^2}{\sum_i (Q_{m,i} - \overline{Q}_m)^2 \ \sum_i (Q_{s,i} - \overline{Q}_s)^2} \tag{3.16}$$

Where R^2 is Coefficient of determination, Q is runoff, m and s are measured and simulated values.

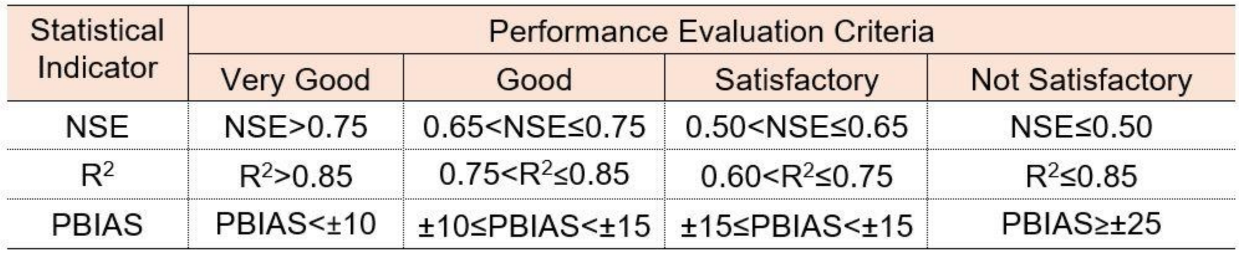
PBIAS measures the simulated data's average tendency to be larger or smaller than the observations. The optimum value of PBIAS is 0. However, a positive (+) value indicates model underestimation, and a negative value (-) indicates model overestimation (Gupta et al. 1999).

$$PBIAS = 100 * \frac{\sum_{i=1}^{n} (Q_m - Q_s)_i}{\sum_{i=1}^{n} Q_{m,i}} \tag{3.17}$$

Where Q is runoff, m and s represent measured and simulated values

A recommended statistic for performance evaluation criteria for a watershed scale is presented in Table 3.10.

Table 3.10: Recommended statistical performance evaluation criteria for a watershed-scale model



Statistical Indicator	Performance Evaluation Criteria			
	Very Good	Good	Satisfactory	Not Satisfactory
NSE	NSE>0.75	0.65<NSE≤0.75	0.50<NSE≤0.65	NSE≤0.50
R^2	R^2>0.85	0.75<R^2≤0.85	0.60<R^2≤0.75	R^2≤0.85
PBIAS	PBIAS<±10	±10≤PBIAS<±15	±15≤PBIAS<±15	PBIAS≥±25

Source: Extracted from Moriasi et al. (2015)

3.8 SWAT-CUP Calibration and Validation

Calibration of the watershed model is challenging due to various factors such as uncertainties of the model, parameter, data and model operation (Tung 2011). The most common uncertainties in SWAT hydrological modelling are associated with the input data, model structure and model parameters (Yen et al. 2014).

The input data such as rainfall, soil type and land use can directly affect the hydrologic modelling procedures and simulation results (e.g., surface runoff). Model structure, on the other hand, is primarily caused by the assumptions and simplification of the hydrological model. In addition, parameter uncertainties are the most common sources of uncertainties; however, they can be controlled easily by applying suitable calibration processes (Zhao et al. 2018).

A warm-up phase (equilibrium time) is necessary to get a fully operational hydrological cycle for the simulation period of interest. Therefore, it is recommended in the calibration process. For example, a warm-up period of 2 to 3 years is recommended for less than five years of simulation. However, the equilibrium period may not be necessary for a 30-years simulation (Arnold et al. 2013). Therefore, two years (1979 - 1980) of the warm-up period was given during the calibration process

3.9 Runoff simulation

Monthly time-series rainfall data for 30 years (1979-2009) were taken to analyze rainfall trends and forecast rainfall in the study area using the linear regression method.

3.9.1 Data and method of rainfall trend analysis

Monthly precipitation data for 30 years (1979-2009) was obtained from the SWAT Global Weather Data website https://globalweather.tamu.edu/ within the vicinity of the West Rapti River basin. In addition, the website provides CFSR global meteorological dataset. The dataset comprises a forecast of hourly weather dataset produced by the National Weather Service’s NCEP Global Forecast System. The weather dataset contains precipitation, temperature, wind, solar, and relative humidity, presenting real-time rainfall estimates and temperature for hydrologic predicting (Fuka et al. 2014).

The CFSR dataset was used to analyze the rainfall trend using simple linear regression analysis. The linear regression equation (3.18) has been used frequently for prediction purposes in hydrology, such as annual or season rainfall-runoff relationships (Diskin 1970). The linear regression method allows predicting the trend of one variable with the help of the values of the other (Altman & Krzywinski 2015) or a model with only one independent variable (Zou et al. 2003).

$$Y = AX + B \tag{3.18}$$

Where the regression parameter B is the Y-intercept and A is the slope of the line (Diskin 1970; Zou et al. 2003). In the equation, X is the independent variable (time) and Y is the dependent variable (rainfall).

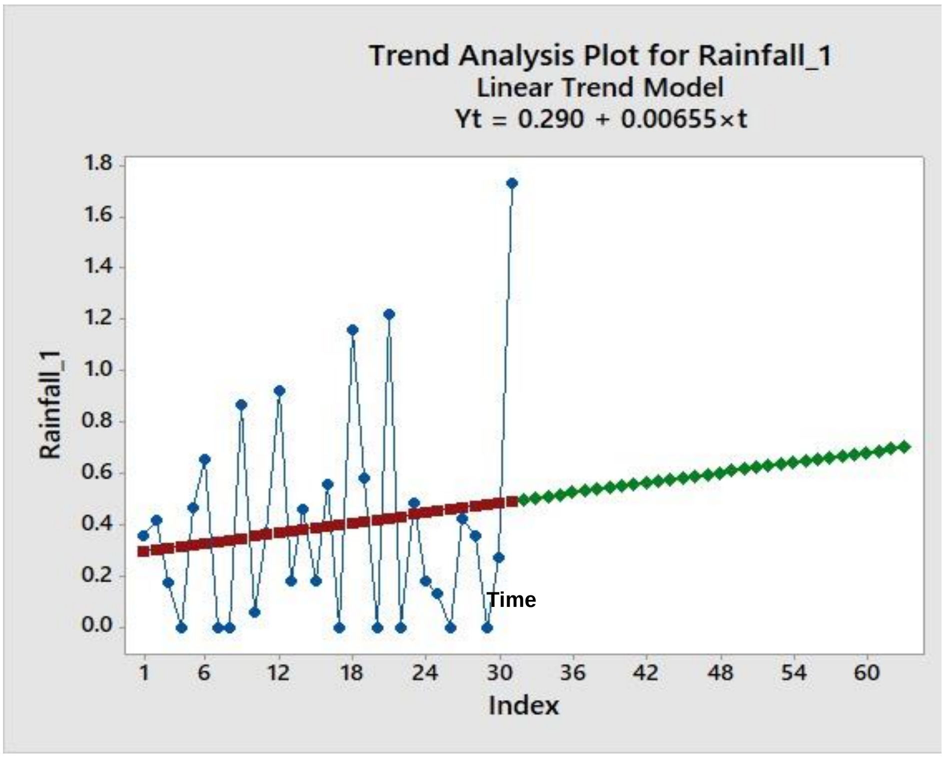


Figure 3.13: Rainfall trend analysis plot in Linear regression model

The linear equation (*3.19*) was used to extract daily rainfall for 2023 to 2026, considering the daily rainfall data of 2013 as a baseline. The extracted rainfall data was used to simulate runoff for 2023 to 2026 in the Jhimruk-Khola sub-basin in Nepal.

$$Yt = 0.290 + 0.00655t \qquad (3.19)$$

3.10 Conclusion

The SWAT model was used for runoff simulation in the West Rapti River basin in Nepal. The model requires topographic, land-use, soil and weather data for model calibration. These data were obtained from freely available resources, and they were processed and used as input data in ArsSWAT/QSWAT. Rainfall data from the GRDC (observed rainfall) limited the SWAT model calibration and validation process. Thus, the SWAT model output and the HEC-HMS model output were compared to identify the reliability of the model runoff simulation.

SWAT is supported by SWAT-CUP, a freely available program for SWAT model calibration. SUFI-2 in SWAT-CUP was used for model calibration, sensitivity analysis and uncertainty analysis. In addition, different objective functions and watershed parameters were selected to assess the SWAT model performance and identify the significance of the parameters.

CFSR data for 31 years (1979-2009) were analyzed using the linear equation to predict rainfall trends in the Jhimruk Khola sub-basin. The trend was later used to extract rainfall and simulate runoff from 2023 to 2026 in SWAT, taking 2013 rainfall as a baseline.

Chapter 4: Study Area

4.1 Introduction

This chapter describes the general characteristics of the study area. It presents general information on Nepal, including the geography, climate, and river systems. In addition, this chapter briefly discusses the West Rapti River basin's location, climate, and type of data available.

4.2 Country Background

Nepal is a relatively small landlocked, and mountainous country located in South Asia. The country borders the Tibet region of the People's Republic of China in the North and the Republic of India in the East, West and the South (Figure 4.1).

Figure 4.1: Map of Nepal (Source: freeworldmaps.net)

The country's total area is 147,181$km^{2,}$ and it extends from 26º 22' to 30º 27' N latitude and 80º 04' to 88º 12' E longitude. The country stretches 885 km from east to west, and the north-south width varies between 130km and 206km. The country's altitude varies from 70m masl in the South to 8884m masl in the North within this range. As a result, Nepal can be divided into five major physiographic regions, as shown in Figure 4.2: Terai plain, Siwalik Hills, Middle Mountains (Middle Hills, Low Mountains) and High Mountains (Gyawali 1989; Kansakar et al. 2004) and seven main climatic and ecological zones (Nepal et al. 2019). As a result, land use and land cover, population density and livelihood patterns, topography, climate, and water availability are highly variable within the country.

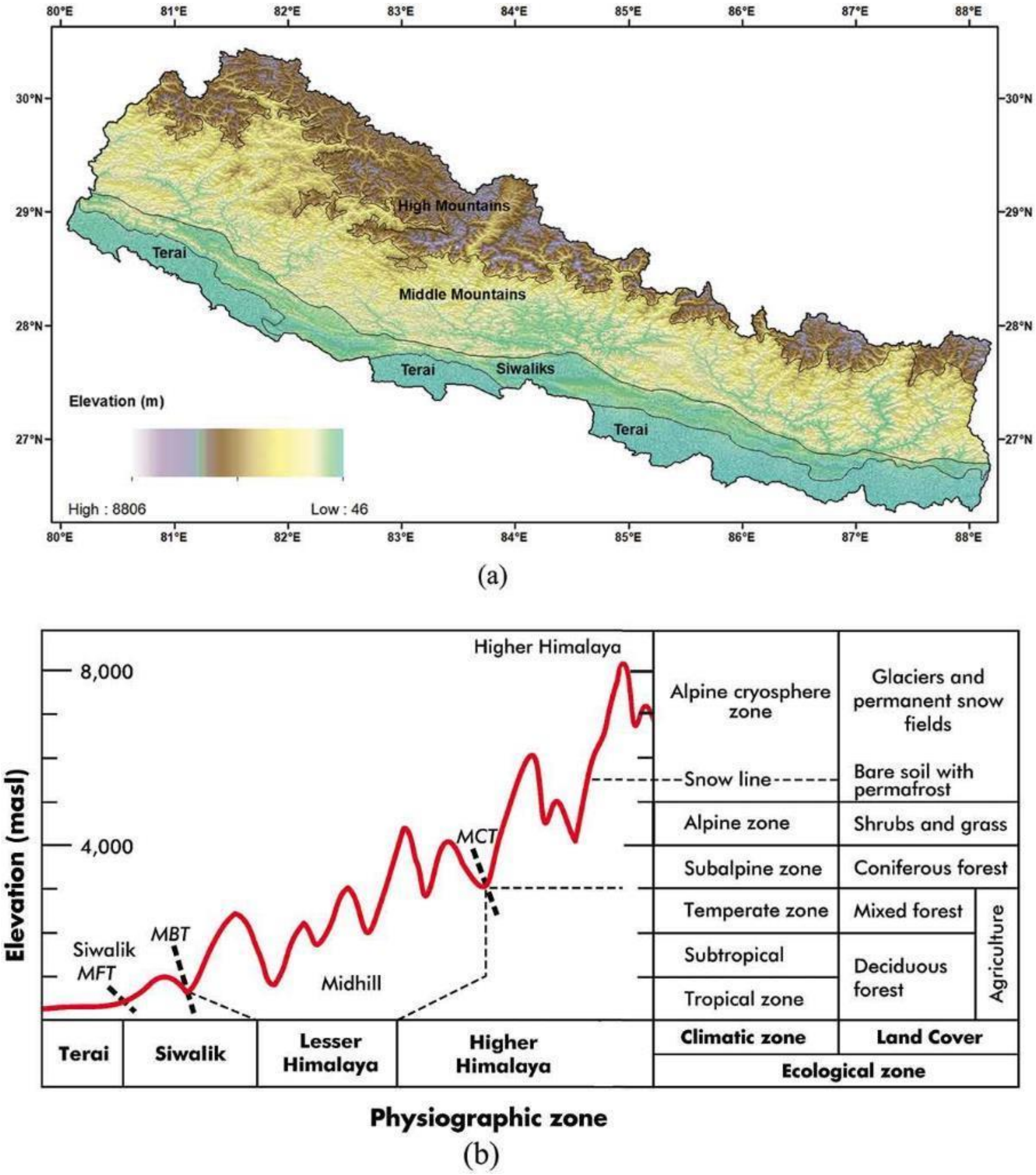


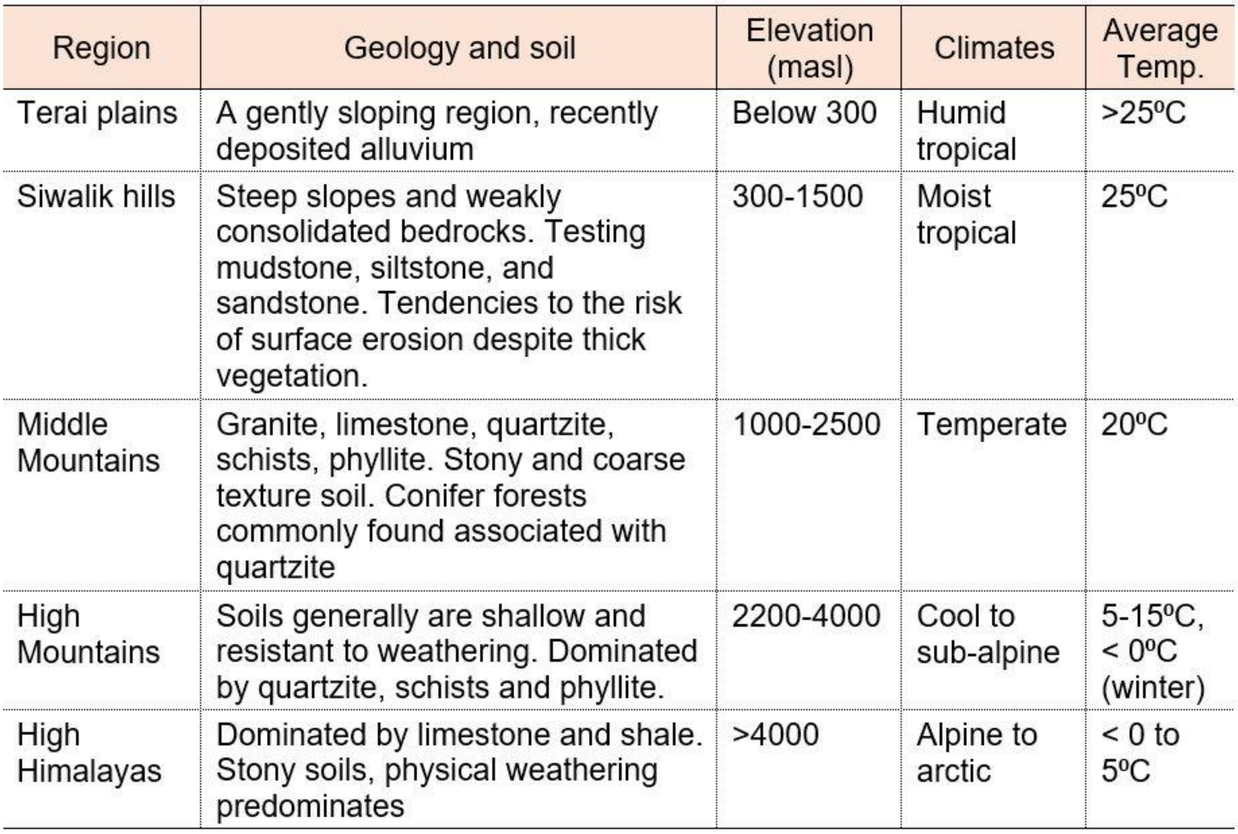
Figure 4.2: Physiographic map of Nepal map including Ecological zones (Source: Nepal et al. (2019))

The Terai zone is relatively flat. The climate ranges from tropical to sub-tropical, with considerable water resources and fertile land with high productivity. As a result, the region has a high density of population. The Terai is surrounded by the low hills of the Siwaliks in the Northern part, followed by the Middle Mountains (also known as Lower Himalaya). Most of the Hydropower in the country is produced in this zone due to favourable physiographic and climatic conditions such as the deep valleys and steep slopes, including subtropical climate.

In the North, the Higher Mountain (also known as Higher Himalaya) is dominated by a sub-alpine to alpine climate, with glaciers and snow peaks (Karki et al. 2016). Thus, this region has a low population density and anthropogenic activities (Nepal et al. 2019).

Approximately 86% of the total area of the country is mountainous (High Himalayas and High Mountains) and hilly regions (Middle Mountains and Siwalik). The remaining 14% is flatland represented by Terai (Karki et al. 2016).

Table 4.1: Geographic regions of Nepal



Region	Geology and soil	Elevation (masl)	Climates	Average Temp.
Terai plains	A gently sloping region, recently deposited alluvium	Below 300	Humid tropical	>25ºC
Siwalik hills	Steep slopes and weakly consolidated bedrocks. Testing mudstone, siltstone, and sandstone. Tendencies to the risk of surface erosion despite thick vegetation.	300-1500	Moist tropical	25ºC
Middle Mountains	Granite, limestone, quartzite, schists, phyllite. Stony and coarse texture soil. Conifer forests commonly found associated with quartzite	1000-2500	Temperate	20ºC
High Mountains	Soils generally are shallow and resistant to weathering. Dominated by quartzite, schists and phyllite.	2200-4000	Cool to sub-alpine	5-15ºC, < 0ºC (winter)
High Himalayas	Dominated by limestone and shale. Stony soils, physical weathering predominates	>4000	Alpine to arctic	< 0 to 5ºC

Source*:* GFDRR (2011) *(GFDRR: Global Facility for Disaster Reduction and Recovery)*

Nepal is categorized as a medium human development country, according to the Human Development Index (a development indicator based on life expectancy, adult literacy, and GDP) (UNDP 2019). However, Nepal is one of the wealthiest countries regarding renewable water resources. A vast amount of water is available in rivers, lakes, snow covers, springs and groundwater. The country holds about 2.7% of the world's freshwater resources (Bhatt 2017; Sapkota & Thapa 2014).

4.3 Climatic Characteristics and River systems

Nepal has two rainy seasons (Shrestha et al. 2000). The most prominent one lasts from June to September, and about 80% of the total annual precipitation occurs due to the southwest monsoon. The remaining rain occurs during the winter and accounts for 20% of the yearly average rainfall. Precipitation occurs higher in the eastern region than in the western part. Pre-monsoon thunderstorms occur from March onwards. As a result, they produce considerable rain in a short period of time in Terai (plain) and hills (Shrestha et al. 2000).

Nepal is endowed with abundant water resources. The available water sources may act as a catalyst for the nation's socio-economic growth. There are more than 6,000 rivers, and many of them originate from the snow-capped Himalayas. The total length of those rivers, including creeks and tributaries, is about 45,000km. The rivers cover a 3,950km^2 land area and offer multiple domestic benefits, irrigation lands and hydropower development (Bhatt 2017).

Rivers in Nepal can be classified into three categories according to their origin. First-class rivers originate from the Himalayas, second or medium class rivers originate from the Midlands, and the third or smaller class rivers originate from Siwalik Range (Devkota 2014).

The first group of rivers is snow-fed; therefore, flow regimes are mainly dominated by the melting snow and glaciers. Examples of these groups of rivers are Koshi, Gandaki, Karnali and Mahakali. Flows in these rivers are perennial and sustainable during the dry seasons. As a result, such rivers are a reliable source of water for hydropower generation and land irrigation (WECS 2011). The second group of rivers originates from middle mountains and hills; therefore, monsoon rainfall and groundwater are the primary contributors to the flow regimes. The Bagmati, Rapti, Mechi, Kanaki, and Babia rivers are examples of this rivers group. Finally, the third group of rivers originates from Siwalik. The flow in these rivers primarily depends on monsoon rainfall; therefore, the flow level could reduce substantially during the non-monsoon season (WECS 2011).

Table 4.2: Main river basin and discharge details

River Basin	Catchment area in Nepal (Estimated) (km^2)	Average discharge (m^3/s)	Annual discharge (km^3/year)
Rivers originated from the Himalayas			
Koshi	27,863	1,409	45
Gandaki/Narayani	31,464	1,600	50
Karnali	41,058	1,397	44
Mahakali	5,188	573	18

Rivers originated from the Middle Mountains and Hills	17,000	461	14.5
Rivers originated from Siwalik	23,150	1,682	53
Total	145,723	7,122	224.5

Source: Extracted from Pradhanang et al. (2017)

There are three substantial rivers systems in the country: Karnali in the west, Gandaki in the central, and Koshi, also known as Sapta Koshi in the east (Alam et al. 2017; Gyawali 1989; Sapkota & Thapa 2014) divide the country into approximately three equal areas. This division, along with the physiographic regions, is used to organize data to examine regional precipitation variations (Kansakar et al. 2004). Of these, Koshi is the most extensive river system, followed by Karnali and Gandaki (Figure 4.3).

The Koshi (Sapta Koshi) stretches 17,720km long, and the catchment area is 66,400km^2. The average flow rate of the river is 1409m^3/s. The main tributaries are Sunkoshi, Indrawati, Likhu, Dudhkoshi, Tamakoshi, Tamor and Arun.

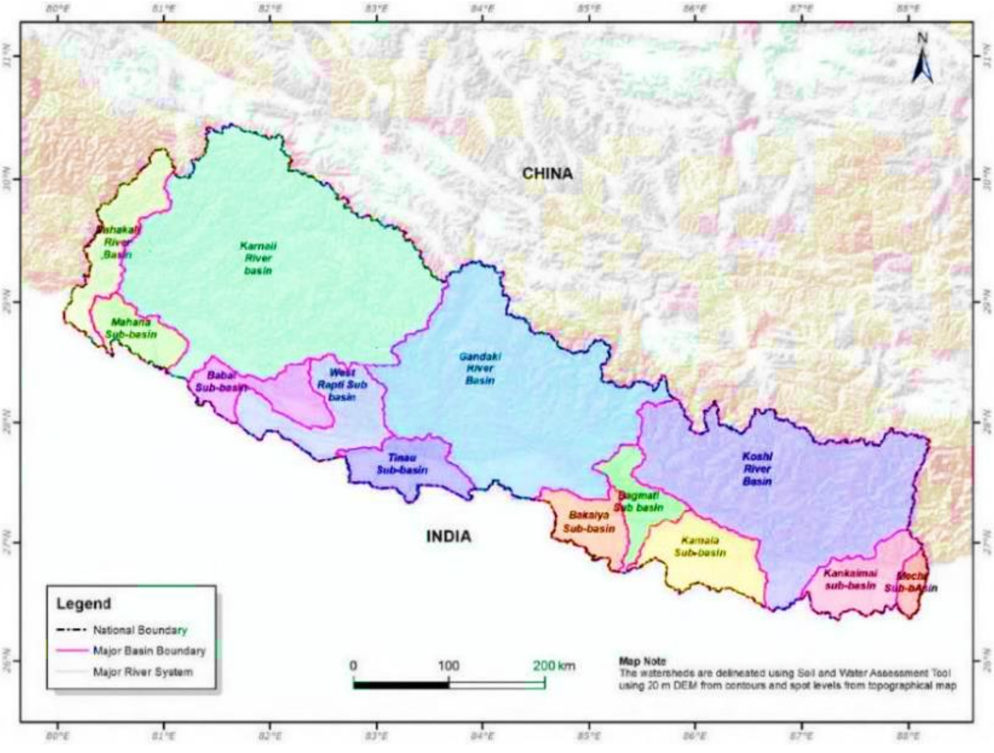


Figure 4.3: River basins of Nepal (Source: Siddiqui et al. (2012))

The mainstream length of the Karnali river is 338km. The catchment area of the Karnali river basin is 43,679km^{2,} and the average discharge is 1397m^3/s. The main tributaries of the river are Bheri, Budi Ganga, Western Seti, Humla Karnali, Mugu Karnali, Thuli Bheri, Tila (Alam et al. 2017; Sapkota & Thapa 2014).

The catchment area of the Gandaki river basin is 34,960km^2. The average flow rate is 1600m^3/s, and the length of the main channel is 338km. The main tributaries of the river are Kaligandaki, Seti, Marsyangadi, Budigandaki, Daraudi, Madi and Trishuli. Other major river basins include Mahakali, West Rapti, Bagmati, Babia and Kankai (Table 4.3)

Table 4.3: Characteristics of major river basins in Nepal

River basin	Area (km^2)	Streamflow source	Remarks
Koshi	60,400	Monsoon rain and snowmelt	In Nepal: 27,863 km^2 In China: 32,537 km^2
Karnali	43,679	Monsoon rain and snowmelt	In Nepal: 41,058 km^2 In China: 2,621 km^2
Gandaki	34,960	Monsoon rain and snowmelt	In Nepal: 29,626 km^2 In China: 5,334 km^2
Mahakali	15,260	Monsoon rain and snowmelt	In Nepal: 5,317 km^2 In India: 9,943 km^2
West Rapti	6,500	Monsoon rain	Whole catchment in Nepal
Bagmati	3,700	Monsoon rain	Whole catchment in Nepal
Babai	3,400	Monsoon rain	Whole catchment in Nepal
Kankai	1,329	Monsoon rain	Whole catchment in Nepal

Source: Extracted from (WECS 2002) Gautam and Acharya (2012)

Hydrological and meteorological activities in Nepal is monitored by the Department of Hydrology and Meteorology (DHM). The hydrometric network consists of 170 gauging stations, of which 54 were established in 1999. Daily flow time series data are available only for 36 river basins across the country. The hydrologic data records range from 5 to 31 years, with an average length of 17 years. More than 80% of gauging stations possess more than ten years of data. These data span the period of 1963-1995. The large numbers of gauging stations are located in the Middle Mountains and High Mountains, and a few in the Siwalik hills area (Hannah et al. 2005).

4.4 West Rapti River basin

4.4.1 Location and main features

West Rapti River basin (Figure 4.4) is a transboundary river basin. The basin originates in the mid-western region near the Nepal-India border area. It is one of the major tributaries of the River Ganga, located in the Republic of India.

The river basin extends from 27˚56'50" to 28˚02'30" North and 81˚45'00" to 81˚40'00" East (Talchabhadel et al. 2015), and the area of the basin is 5,953.60km^2. The elevation varies from about 131m (at the Indian border) to 3,620m masl. The river originates in the middle mountain and has no contribution from melting snow and glaciers. About 60% of the West Rapti River catchment area is in the northern mountain region, which is further divided into middle and high mountain zones. The basin's remaining area (about 40%) is situated in the low southern part within the Siwalik and Terai (plain) zones. The northern and southern zones are separated by a famous thrust fault known as Main Boundary Thrust (MBT) (Pathak et al. 2007).

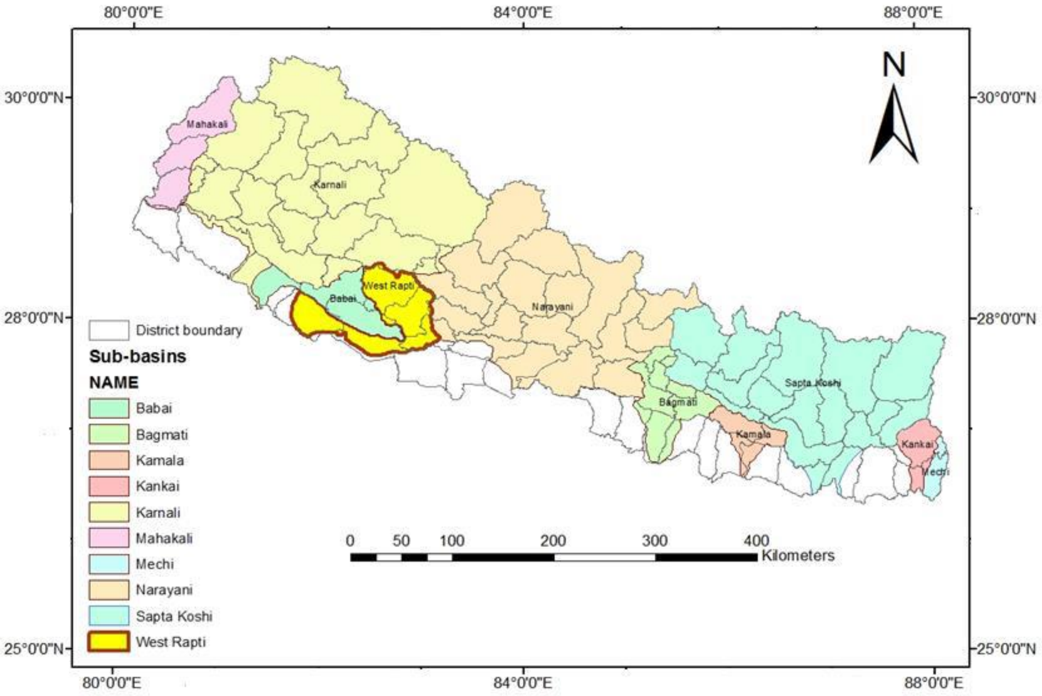


Figure 4.4: Location map of the study area (Source: Devkota (2014))

West Rapti basin is considered to be one of Nepal's flood-prone rivers (Gautam & Phaiju 2013; Talchabhadel & Sharma 2014). The basin area receives about 80% of total yearly precipitation during summer monsoons (June to September). The annual average rainfall varies between 1151mm to 2489mm **(**(Devkota & Bhattarai 2018). The river's mainstream channel is 257km long, and the average slope of the basin is relatively steep at 16.8% (Talchabhadel et al. 2015).

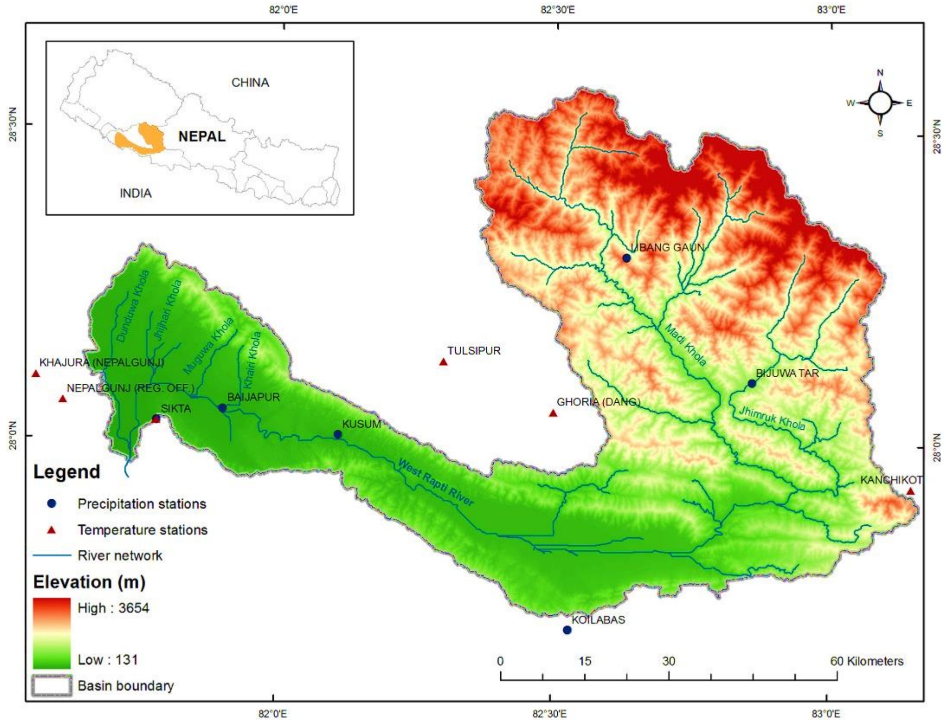


Figure 4.5: River network and DEM of the study area (Source: Devkota (2014))

According to the Hydrology Department of Nepal, four hydrological and seven meteorological stations are located within the basin. The details of hydrological and meteorological stations are presented in Table 4.4

Table 4.4: Hydro-Meteorological stations of West Rapti River basin

SN	Station numbers	Station name	Purposes / Remarks
Meteorological stations			
1	530	Swargdwari	Rainfall
2	527	Sulichour	Rainfall
3	504	Libang Gaun	Rainfall & Temperature
4	505	Bijuwartar	Rainfall & Temperature
5	537	Lamahi	Rainfall
6	438	Dhakeri	Rainfall
7	420	Nepalgunj	All parameters
Hydrological stations			
1	339.3	Jhimruk at Cherneta	Water level

2	330	Mari at Nayagaon	Rainfall & Water level
3	350	West Rapti at Bagasoti	Rainfall
4	365	West Rapti at Kusum	Rainfall & Water level

Source: www.hydrology.gov.nep

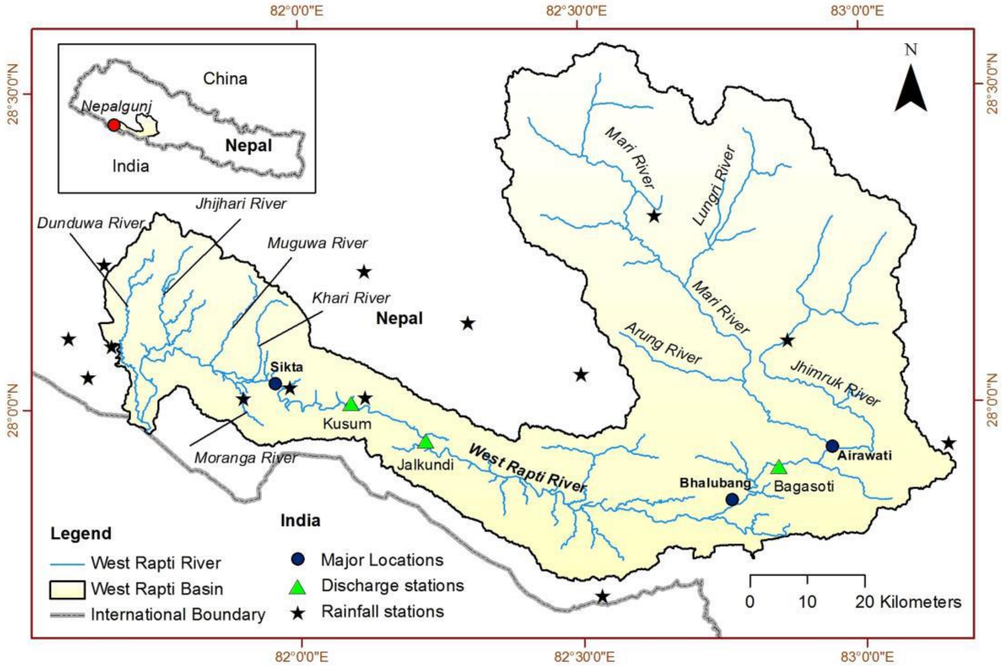


Figure 4.6: Major tributaries of the West Rapti river basin (Source: Devkota (2014))

4.4.2 Geography and Geomorphology

The physiographic region of the West Rapti River consists of Terai (plain), Siwalik, Mahabharat ranges and Lesser Himalayan range. Like other parts of the country, the significant changes in weather, geography and hydrology can be seen within a short distance from the south to the northern parts of the basin.

Terai is primarily composed of sediments from the Gangetic plain such as sand, silt, and clay. The groundwater level in the Terai area is shallow, located approximately 3m below the surface level. However, water availability is limited in these aquifers (District Profile 2007). The Siwalik hills are the southernmost mountain range of the Himalayas (Devkota 2014). The region is usually characterized as rugged terrain with high peaks, steep slopes, and thin soil cover. Lower Siwalik, however, has gentler topographic characteristics with low terraces and alluvial fans backed by the considerable amounts of silt carried by the rivers and creeks in the watershed area. Most rivers originate from lower Siwalik discharge water only during the monsoon period (Devkota 2014).

The riverbed materials in the watershed comprise a few medium-size boulders, different sizes of coarse gravel and sediment at upper reach. In contrast, lower reach is dominated by fine sediment. Round boulders and coarse gravel predominate the steep reach, and coarse to medium-grained sand is also found throughout this reach (Devkota 2014).

The upper part of the river basin consists of hills and grasslands; hence, the area has less settlement and agricultural land. However, the lower part is flat; thus, most of the land is used for agriculture and settlement. As a result, the settlement is dense in this watershed section (Devkota 2014).

4.4.3 Climate, Rainfall and Runoff

The climate varies significantly within the basin, dominated by the temperate and subtropical climatic conditions. The northern part of the catchment has a temperate climate. In contrast, the climate in the southern part ranges from tropical to sub-tropical. The temperature along the basin varies from 46ºC during summer in the southern region to 2ºC during winter in the northern mountain region (Gautam & Phaiju 2013). The average annual temperature is 25ºC; however, temperatures vary from 15ºC in the winter to 32ºC in the summer. The temperature increases from March to June/July and decreases from October to January (DHM 2008).

Rainfall varies considerably within the basin. The dry period extends from October to May, and the rainy season extends from June to September. Precipitation is highly influenced by the monsoons in the Rapti basin; therefore, more than 80% of rainfall occurs during June-September. Figure 4.7 shows the monthly average rainfall and discharge of Nayagaon (left) and Jalkundi (right) gauging stations. It shows that discharge and precipitation significantly varied within the year.

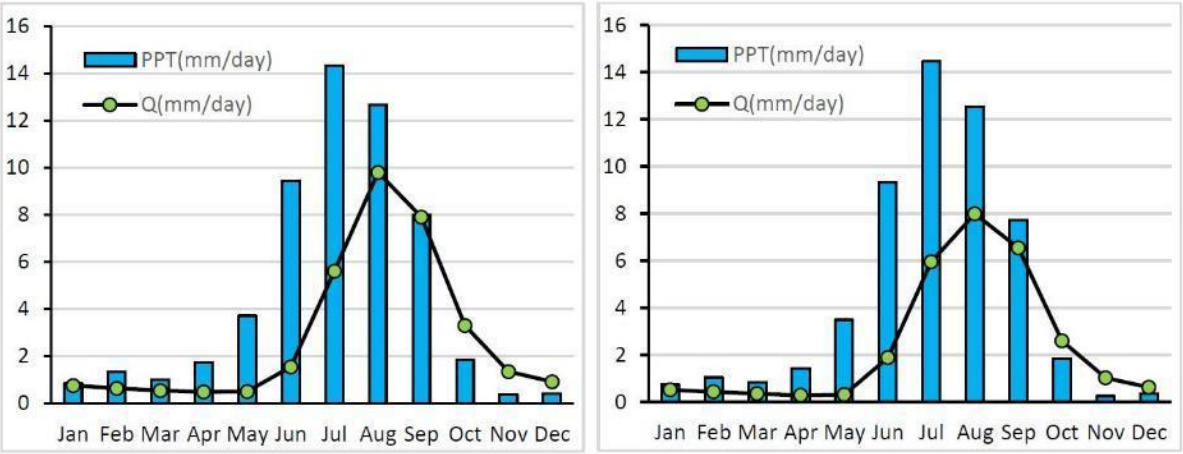


Figure 4.7: Average monthly precipitation and discharge (Source: DHM)

Rainfall and groundwater are the primary water resource of the West Rapti river basin. Snowmelt contribution is negligible; only a small portion of the basin lies above 3000m masl (Sharma 1993).

Water in the West Rapti river is mainly used for irrigation purposes. Traditional farmers have utilized water in the main Rapti river and its tributaries for irrigation systems since historical times (Shrestha 2016). According to the preliminary study of the West Rapti's multipurpose project, farmers built 26 irrigation systems that help irrigate around 10,680 ha (106.80 km^2) of land.

4.5 Conclusion

Nepal is a small mountainous landlock country in South Asia, covering an area of 147,181 km^2. Despite its small size, the country can be divided into five physiographic zones and seven climatic and ecological zones. As a result, the climate varies from alpine in the Mountainous region to humid tropical in the plain area of the Terai zone. The mountainous zone covers about 86%, and the plain area covers about 14% of the nation's total area. Similarly, monsoon and winter monsoon are two distinct rainy seasons. About 80% of the total annual rainfall occurs in the monsoon and lasts from June to September, and 20% of total annual rainfall accounts for the winter monsoon. According to the origin, river systems are divided into first-class (from mountains), second-class (from midlands), and third-class (from Siwaliks).

West Rapti river originates in the middle mountain; therefore, rainfall and groundwater are the river's primary water sources, with no melting snow and glacier contribution. The river's mainstream length is 257km, and the average slope is 18.6%. Rainfall varies within the basin, and the annual average temperature is 25°C. West Rapti river is regarded as one of the flood-affected rivers basins in the country. The West Rapti river water is largely used for irrigation purposes, and the river contributes to irrigating about 106.80 km^2 of land.

Chapter 5: Results and Discussions

This chapter evaluates the reliability of the SWAT model for runoff simulation. The chapter has four sections. The first section assesses the GRDC data for model calibration. In the second section, SWAT model results were compared with that of the results from HEC-HMS. In the third section, model calibration and validation are presented using SWAT-CUP. The final section discusses the runoff simulation approaches.

5.1 SWAT Model Results

5.1.1 Watershed Delineation, land and soil types

Land use and soil data are processed and reclassified to match the SWAT model with the land use and soil data code, and they were calibrated in ArcSWAT/QSWAT. The basin is divided into 19 subbasins and 35 HRUs (Figure 3.8), the smallest spatial unit of the hydrological model containing similar land use, soil and slope (Kalcic et al. 2015) based on provided topography, land and soil data in ArcSWAT 2012.

The land and soil types, including the coverage area, obtained from the HRUs analysis report in SWAT output files, are shown in Table 5.1 and Table 5.2.

Table 5.1: LULC types details including covered area different land-use type

Values	LULC code	Description	Computed area (km^2)	Watershed (%)
1	FRST	Forest -Mixed	3,668.65	61.62
4	AGRL	Agricultural Land -Generic	1,935.00	32.50
2	SHRB	Shrubland	117.42	1.97
3	GRAS	Grassland	113.11	1.90
5	BARR	Barren area	84.34	1.42
6	WATR	Waterbodies	33.25	0.56
8	URLD	Residential – Low density	1.83	0.03

As shown in Table 5.1, the total watershed area is 5,953.60 km^2. The current land use data shows that the forest (mixed type) is the most dominant land use type, covering 61.62% of the total watershed area. The agricultural land is the second dominant land-use type, covering 32.5%, followed by shrubland, which covers 1.97%. The residential area covers only 0.03% of the total watershed area.

According to Neupane and Pandey (2021), Dystric Cambiosols, Dystric Rogosols, Eutric Fluvisols and Lithosols (Table 5.2) are the main soil types in the West Rapti River basin.

Table 5.2: Soil types detail including covered area

Soil type	Computed area (km^2)	Watershed (%)
Dystric Cambisols	2,567.00	43.12
Dystric Regosols	1,542.00	25.90
Eutric Fluvisols	1,408.40	23.66
Lithosols - Lithic	436.23	7.33

The most dominant soil type in the study area is Dystric Cambisols, which covers about 43% of the watershed area. This is followed by Dystric Regosols 26%, Eutric Fluvisols 24%, and Lithosols - Lithic covers 7% of the watershed area.

5.1.2 GRDC (observed) data calibration

A relationship between simulated and observed discharge at the Jhimruk Khoal sub-basin outlet point was established to check the reliability of GRDC (observed) data for model calibration. Details of the Jhimruk Khola sub-basin in the West Rapti river basin is given in Table 5.3.

Table 5.3: Details of Jhimruk Khola sub-basin

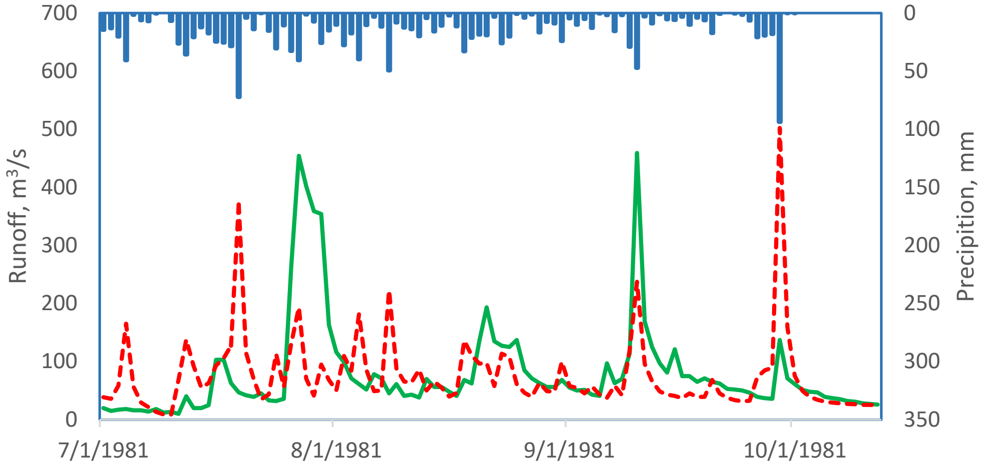
GRDS station no.	River	Station	Country	Latitude	Longitude	Area, km^2	Year start	Year end	No. Yrs
2548310	Jhimruk Khola	Tigra Gaon	Nepal	28.05	82.83	885	1978	1985	8

Source: GRDC

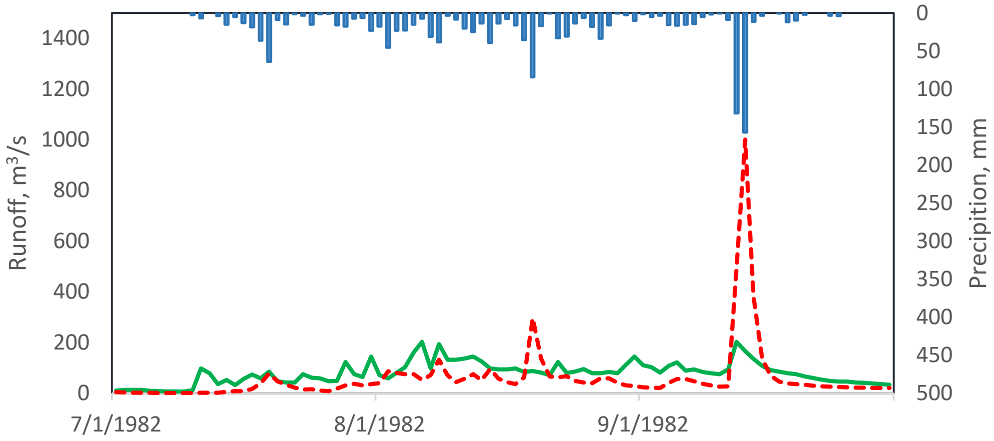
The area of the Jhimruk Khola sub-basin is 885 km^2. Daily observed data from 1978 to 1985 are available in the sub-basin area. Four years (1981-1985) daily GRDC (observed) data are taken for the SWAT calibration in this research. The outcomes of the SWAT calibration are presented below.

Figure 5.1 shows a series plot of rainfall and runoff (simulated and observed). It illustrates that the precipitation and simulated runoff trends perfectly matched for all years (1981-1985). However, the simulated and observed runoff trend varies significantly. Similarly, there were considerable variances in peak flow and time to peak in simulated and observed runoff graphs.

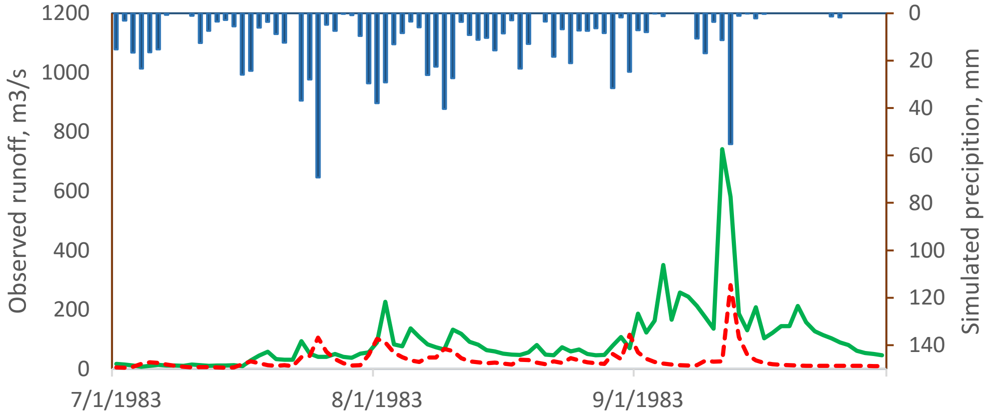
(a)


Runoff, m3/s
Precipition, mm
700
600
500
400
300
200
100
0
0
50
100
150
200
250
300
350
7/1/1981
8/1/1981
9/1/1981
10/1/1981

(b)


Runoff, m3/s
Precipition, mm
1400
1200
1000
800
600
400
200
0
0
50
100
150
200
250
300
350
400
450
500
7/1/1982
8/1/1982
9/1/1982

(c)


Observed runoff, m3/s
Simulated precipition, mm
1200
1000
800
600
400
200
0
0
20
40
60
80
100
120
140
7/1/1983
8/1/1983
9/1/1983

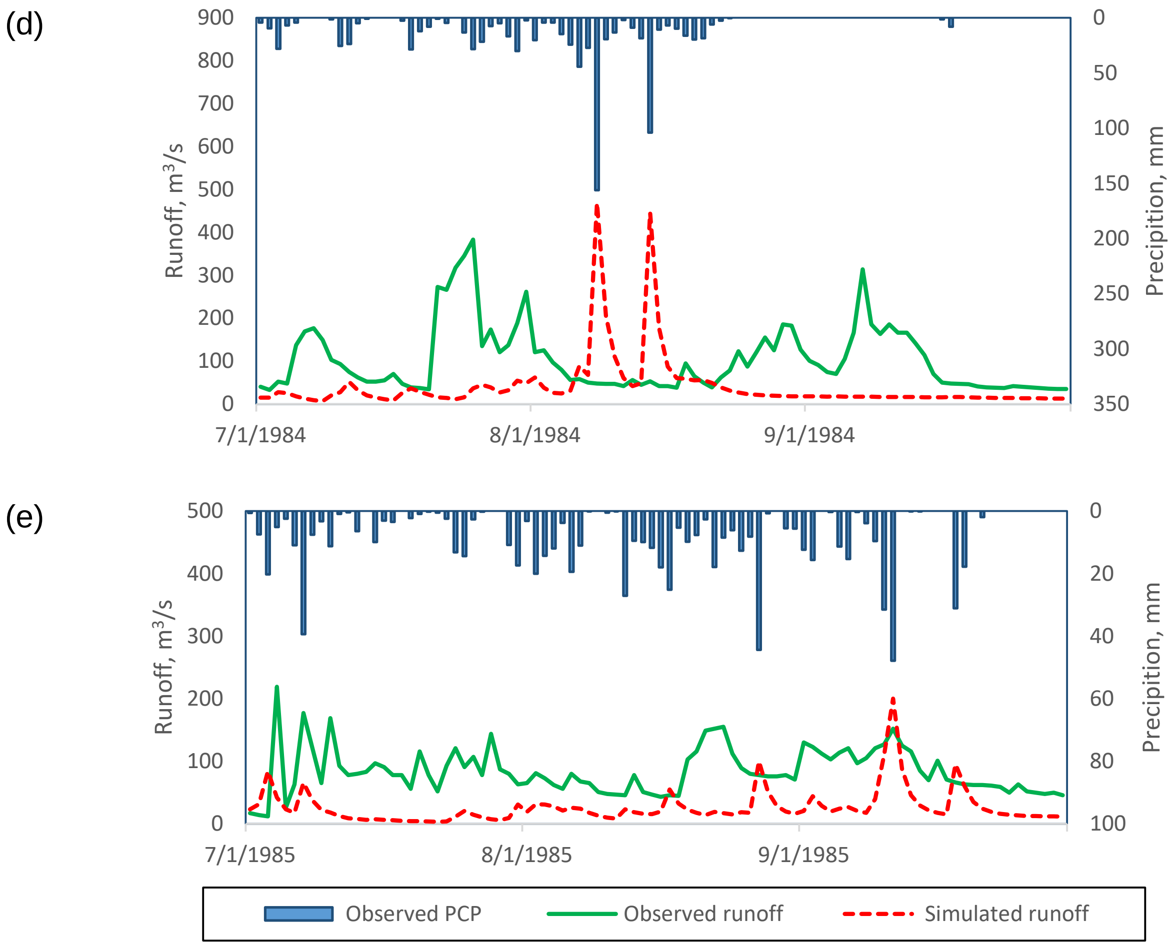


Figure 5.1: A series of rainfall, daily simulated and observed runoff pot in Jhimruk Khola sub-basin. (a) 1981, (b) 1982, (c) 1983, (d) 1984, (e) 1985.

Note: Graphs are shown only for the monsoon season (July-September).

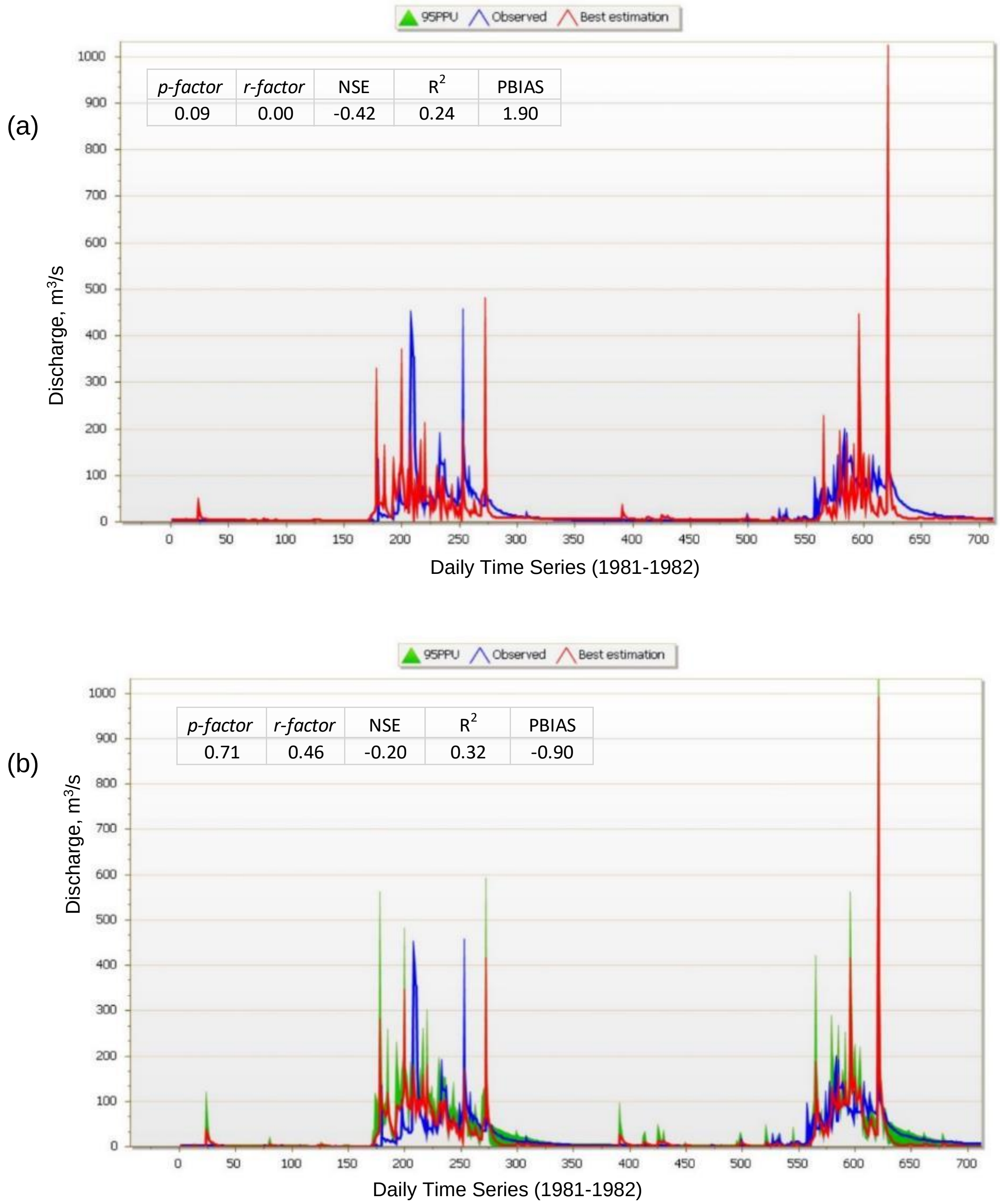
The initial SWAT calibration results showed that the GRDC data are not reliable for the SWAT model calibration and validation. Therefore, the GRDC data was used in the SWAT-CUP to verify the reliability and authenticity of SWAT results.

5.2 SWAT-CUP Model to validate observed runoff data

The SWAT calibration was limited due to missing values of GRDC observed data. Therefore, the reliability of observed data was verified in the SWAT-CUP Sequential Uncertainty Fitting Version 2 (SUFI-2). Four years (1979-1982) of GRDC daily data were utilized, including the first two years (1979-1980) for model warm-up in the calibration process.

5.2.1 SWAT-CUP model calibration and validation

The SWAT-CUP calibration results with 95PPU are presented in Figure 5.2. The model evaluation statistics showed unacceptable model performance as per given objective functions, NSE and R^2 ($NSE<0$, $R^2 < 0.5$), but as per the PBIAS, it was acceptable (PBIAS± 2.5) (Ref. Table 3.10, performance evaluation criteria). Similarly, the fitted values between simulation results and observation expressed in *p-factor* (the percentage of observed data) and *r-factor* (thickness of the 95PPU envelope*)* showed the acceptable simulation result. p-factor greater than 70% and r-factor around 1 as recommended by Khalid et al. (2016).



p-factor	*r-factor*	NSE	R^2	PBIAS
0.09	0.00	-0.42	0.24	1.90

p-factor	*r-factor*	NSE	R^2	PBIAS
0.71	0.46	-0.20	0.32	-0.90

Figure 5.2: Illustration of model output uncertainty as 95PPU generated by SWAT-CUP. (a) before calibration, (b) after calibration

Note: 95PPU = 95% prediction uncertainties

However, significant variances in simulated (best estimation) and observed runoff trends have been shown in the 95PPU graph. The findings showed that the GRDC observed daily runoff data are considered unreliable to calibrate and validate the SWAT model. Both the SWAT-CUP and SWAT calibration results showed that the GRDC data is unreliable for calibration and validation.

According to Arnold et al. (2012), model validation shows the capability of the model to make sufficiently accurate simulation results based on project goals. The model validation in SWAT-CUP involves running the model with the same parameters used in the calibration and comparing the prediction to observed data not used in calibration. However, the SWAT model validation was not performed in this study due to missing values of GRDC observed data.

Since observed data proved unreliable for model validation, the SWAT model was compared with the Hydrologic Engineering Centre’s Hydrologic Modeling System (HEC-HMS). The outcomes of model comparison (volume and depth, peak flow, time to peak and water balance) are presented in Section 5.3.

5.2.2 Sensitivity Analysis

Sensitivity analysis aims to determine the critical parameters that significantly affect the model performance. Thus, it plays a crucial role in model parameterization (McCuen 1973; Song et al. 2015). It also reduces the number of parameters that need to be calibrated, thereby saving time and effort.

Twelve parameters associated with groundwater, surface runoff, HRUs and soil were investigated, as shown in Table 5.4, regarding their sensitivity to streamflow by reviewing the appropriate literature. The sensitivity of parameters was obtained by running between 200 to 500 simulations and from 5 to 10 iterations in SWAT-CUP using SUFI-2.

Table 5.4: Selected parameters for sensitivity analysis with range and fitted values

Parameter	Description	Rank	Range	Fitted Value
CN2.mgt	SCS runoff curve number	1	(0, 50)	4.69
ALPHA_BF.gw	Baseflow alpha factor (days)	2	(0, 1)	0.78
GW_DELAY.gw	Groundwater delay time (days)	3	(30, 450)	331.88

GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	4	(0, 2)	0.31
GW_REVAP.gw	Groundwater “revap” coefficient	5	(0, 0.2)	0.01
ESCO.hru	Soil evaporation compensation factor	6	(0.8, 1)	0.98
CH_N2.rte	Manning’s “n" value for the main channel	7	(0, 0.3)	0.22
CH_K2.rte	Effective hydraulic conductivity in main channel alluvium (mm/hr)	8	(5, 130)	102.66
ALPHA_BNK.rte	Baseflow alpha factor for bank storage (days)	9	(0, 1)	0.28
SOL_AWC.sol	Available water capacity of the first soil layer (mm/mm)	10	(0.2, 0.4)	0.28
SOL_K.sol	Saturated hydraulic conductivity (mm/hr)	11	(0, 0.8)	0.33
SOL_BD.sol	Moist bulk density (Mg/m^3)	12	(0, 0.6)	0.36

The ranking of the most sensitive parameters was determined based on the *t-test* and *p-test* values (Abbaspour 2012). The t-test and p-test values are necessary to measure and identify the relative significance of the sensitivity. The larger absolute values indicate more sensitivity than the lower one, while a value closer to zero indicates more significance (Narsimlu et al. 2015).

Based on the global sensitivity analysis results (Table 5.5), the SCS runoff curve numbers (CN) was among the most sensitive parameters. Similarly, parameters such as a base flow alpha-factor (ALPHA_BF), groundwater delay time (GW_DELAY), threshold depth of water required for return flow to occur in the aquifer (GWQMN), and groundwater revap coefficient (GW_REVAP) also showed higher sensitivity.

Table 5.5: p-stat and t-state values of most sensitivity parameter

Parameters	t-stat	p-value	Sensitivity ranking	Classification
CN2	-1.81	0.32	1	Surface runoff

ALPHA_BF	0.43	0.74	2	Groundwater
GW_DELAY	-0.73	0.60	3	Groundwater
GWQMN	0.68	0.62	4	Groundwater
GW_REVAP	-0.03	0.98	5	Groundwater
ESCO	0.79	0.57	6	Hydrologic Response Unit
CH_N2	0.79	0.79	7	Channel
CH_K2	3.41	0.18	8	Channel
ALPHA_BNK	0.61	0.61	9	Channel
SOL_AWC	-0.27	0.83	10	Soil
SOL_K	1.71	0.34	11	Soil
SOL_BD	-0.08	0.95	12	Soil

5.3 Model Comparison (SWAT and HEC-HMS)

HEC-HMS, a physically based and conceptual lumped parameter model, was developed by the US Army Corps of Engineers- at the Hydrologic Engineering Center (HEC) in Davis, California. The model was designed to simulate the rainfall-runoff processes in a wide range of geographic areas to solve the broadest possible hydrological problems (Choudhari et al. 2014).

5.3.1 HEC-HMS model setup

A basin model was created in HEC-HMS, as shown in Figure 5.3. The model divided the basin into16 subbasins and seven junctions, and it also created reaches and drainage networks.

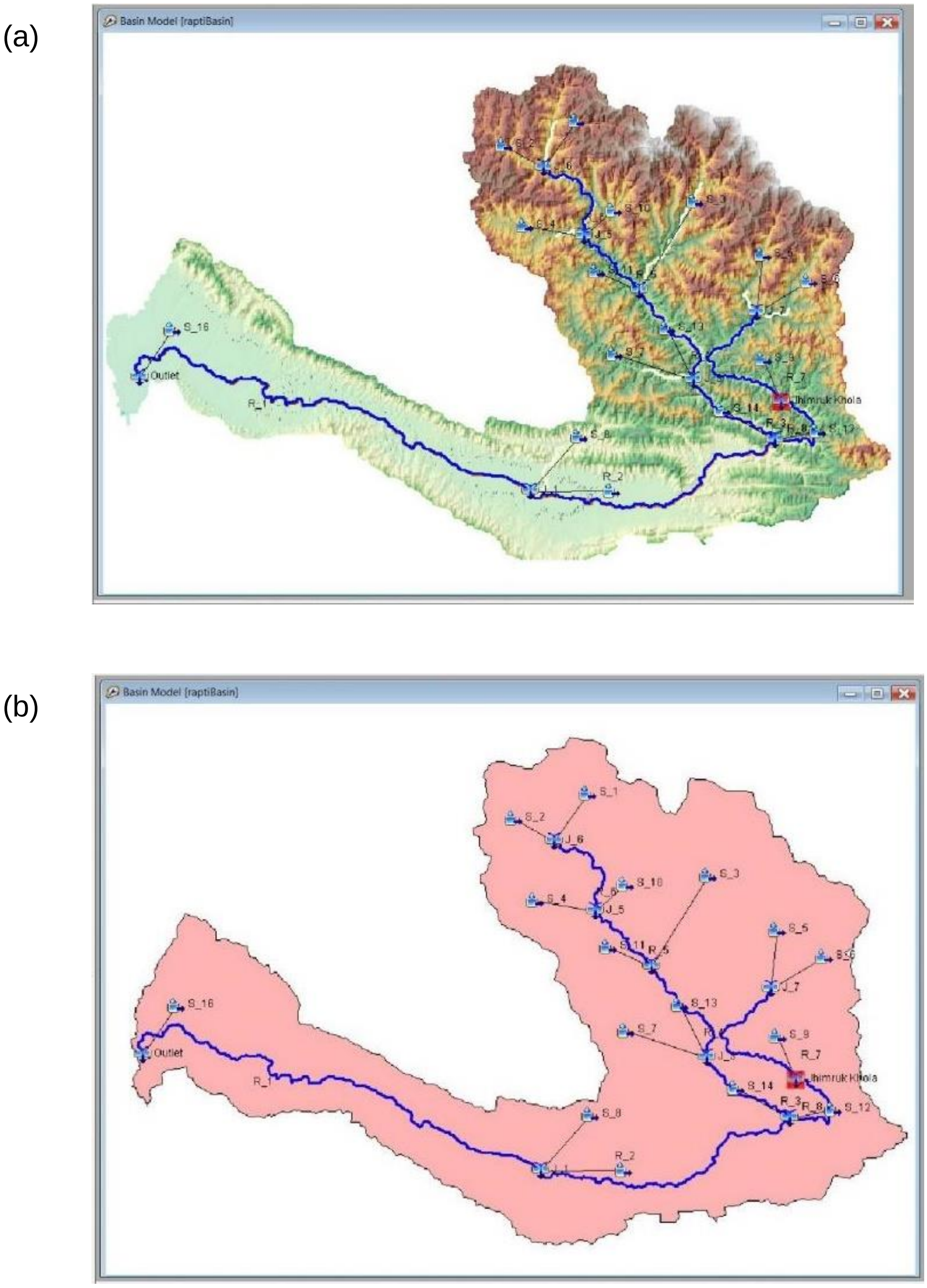


Figure 5.3: HEC-HMS model for the West Rapti river basin, (a) DEM and watershed delineation, (b) basin model

5.3.2 Runoff depth comparison in SWAT and HEC-HMS

In this study, the Jhimruk Khola sub-catchment outlet, as shown in Figure 5.4, was selected to obtain simulated runoff volume, runoff depth, peak flow, time to peak and water balance reports from SWAT and HEC-HMS models. The area of the sub-catchment is 885 km^2.

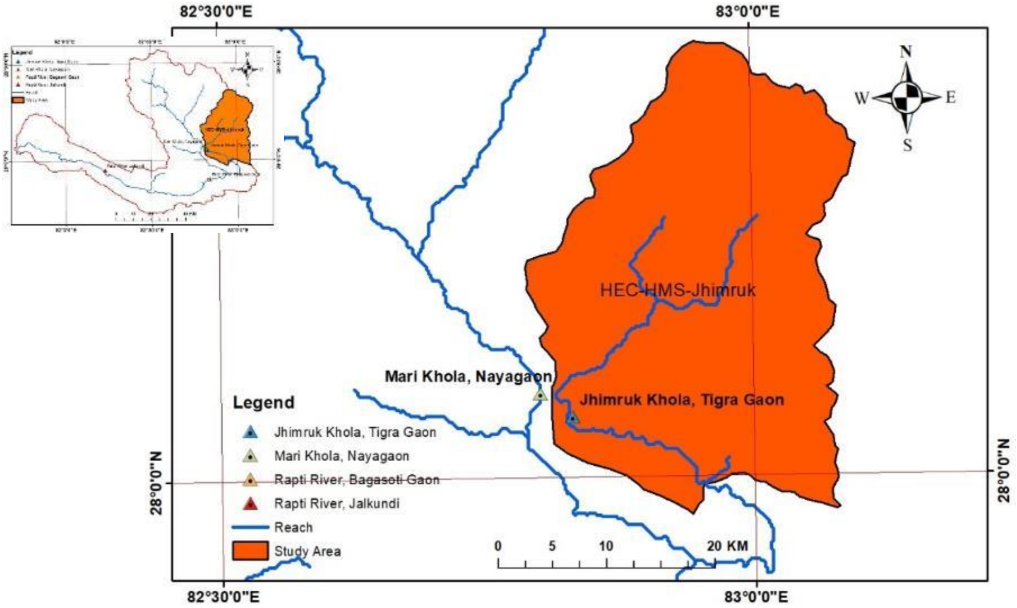
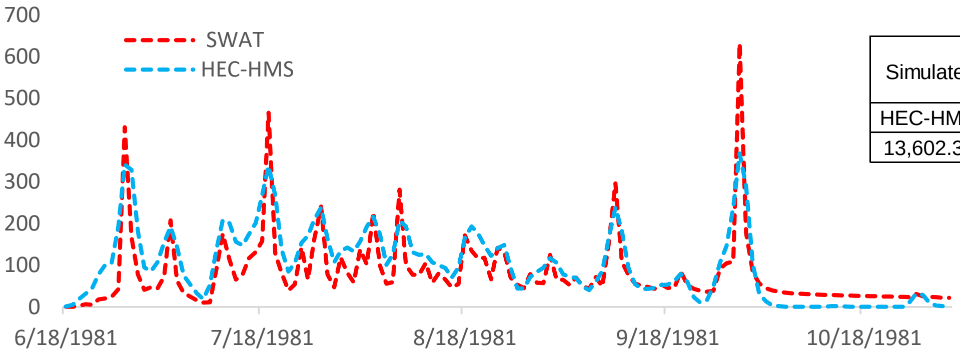
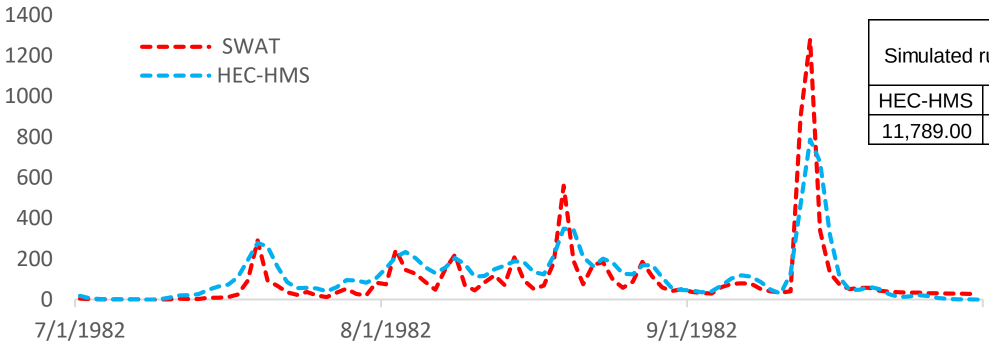


Figure 5.4: Location map of Jhimruk Khola sub-basin

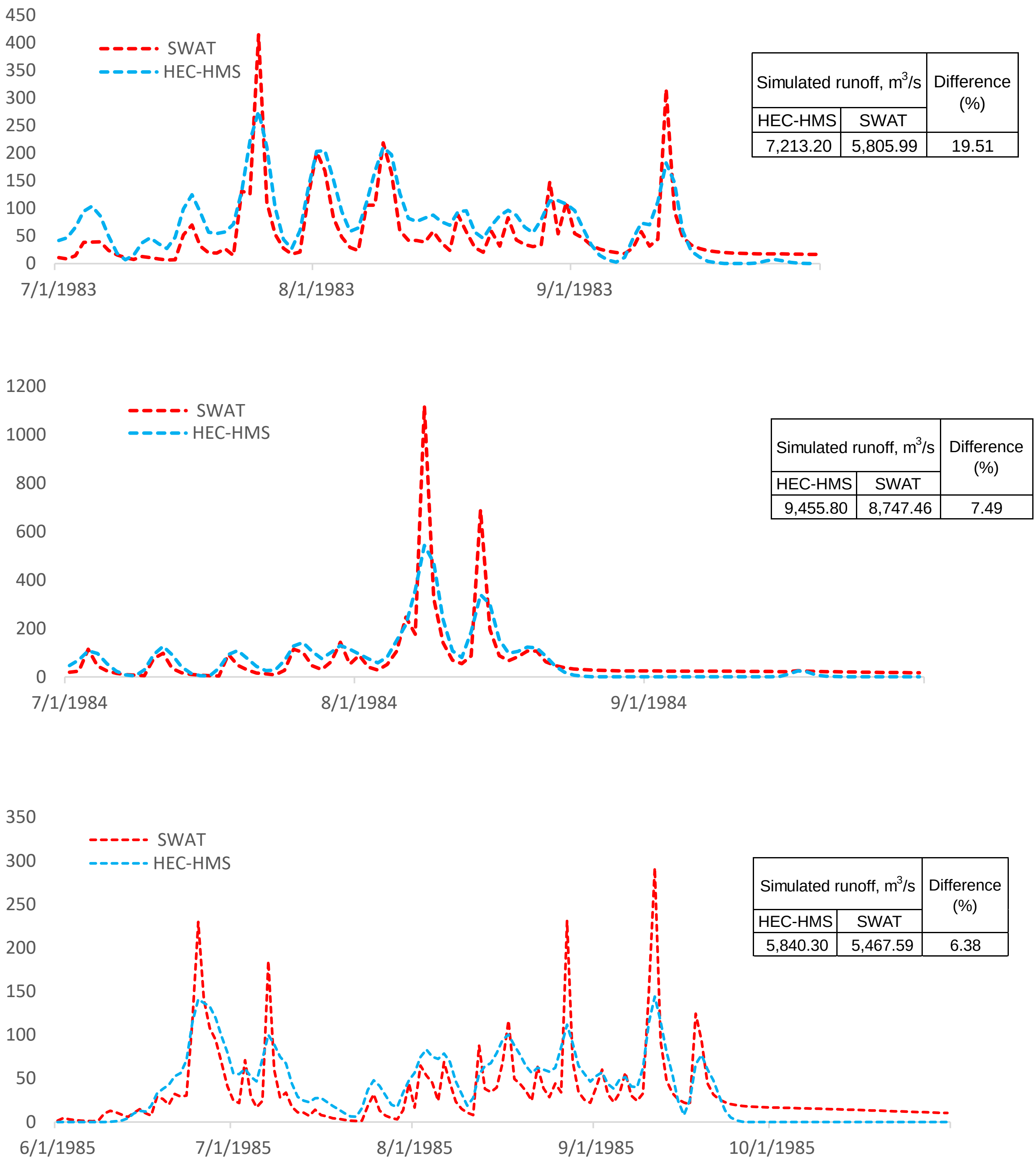
The simulated runoff comparison results between HEC-HMS and SWAT, including their differences, are shown in Figure 5.5. The simulated runoff trends perfectly matched in both SWAT and HEC-HMS models.



Simulated runoff, m^3/s		Difference (%)
HEC-HMS	SWAT	
13,602.30	11,629.30	14.50



Simulated runoff, m^3/s		Difference (%)
HEC-HMS	SWAT	
11,789.00	10,250.38	13.05



Simulated runoff, m^3/s		Difference (%)
HEC-HMS	SWAT	
7,213.20	5,805.99	19.51

Simulated runoff, m^3/s		Difference (%)
HEC-HMS	SWAT	
9,455.80	8,747.46	7.49

Simulated runoff, m^3/s		Difference (%)
HEC-HMS	SWAT	
5,840.30	5,467.59	6.38

Figure 5.5: Simulated daily streamflow using SWAT and HEC-HMS for the calibration period (1981-1985)

However, the HEC-HMS model overestimated runoff in all cases, differences ranging from 6.38 - 9.51%. The highest difference is shown in 1985 (19.51%) and lowest in 1985 (6.38%).

Details of peak discharge and time to peak is shown in Table 5.6. It shows that the SWAT overestimated the peak discharge in all years (1981-1985). For example, the peak discharge difference between SWAT and HEC-HMS is ranges from 33-51%. The highest peak discharge difference was shown in 1984 (51.55%) and the lowest in 1983 (33%).

Table 5.6: Details of peak discharge and time to peak comparison

Year	Rainfall (mm)	Peak Discharge (m^3/s)		Time to Peak (d-m-y)		Peak runoff diff. (%)
		SWAT	HEC-HMS	SWAT	HEC-HMS	
1981	1,750.2	631.55	364.8	29-09-81	29-09-81	42.24
1982	1,612.7	1,279.18	786.70	23-09-82	23-09-82	38.50
1983	1,129.7	414.55	276.30	25-07-83	25-07-83	33.35
1984	1,435.0	1,120.46	542.9	09-08-84	09-08-84	51.55
1985	1,076.9	291.84	144.1	11-09-85	11-09-85	50.62

The time to peak occurrences was similar in the SWAT and HEC-HMS models. But it varies each year. For example, the peak occurred in the same month (September) in 1981, 1982 and 1985. However, in 1983 and 1984, the peak occurred one month apart, in July and August respectively. As the peak flow rate and time-to-peak provide more information about flood estimation and forecasting (Ramírez 2000), the SWAT results are crucial for flood management in the study area.

The model performance was evaluated in terms of percentage error (%). The percentage error (PE) was highest in 1983 (19.51%) and lowest in 1985 (3.38%). PE in other years ranged from 7-14%. Therefore, the range of PE below 20% is considered acceptable in hydrology to evaluate the model performance.

The runoff volume and depth comparison results (Figure 5.6) showed the HEC-HMS overestimated the runoff depth in all years.

Table 5.7: Summary of runoff volume and depth comparisons in SWAT and HEC-HMS

Year	Rainfall (mm)	Runoff volume (m^3)		Runoff depth (mm)		Difference (%)
		HEC-HMS	SWAT	HEC-HMS	SWAT	
1981	1,750.2	1,175,238,720	1,004,771,520	1,327.92	1,135.34	14.50
1982	1,612.7	1,018,569,600	885,632,832	1,150.90	1,000.72	13.05
1983	1,129.7	623,220,480	501,637,536	704.19	566.82	19.51
1984	1,435.0	816,981,120	755,780,544	923.12	853.99	7.49
1985	1,076.9	504,601,920	472,399,776	570.16	533.79	6.38

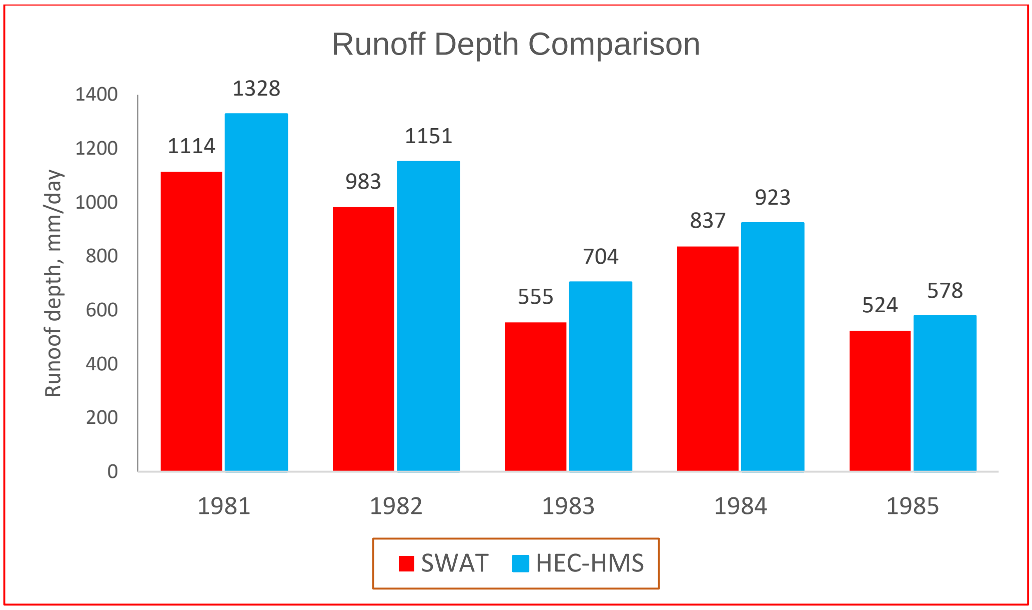


Figure 5.6: Simulated streamflow depth comparison using SWAT and HEC-HMS for the calibration period (1981-1985).

The simulated runoff depth differences in SWAT and HEC-HMS range from 7-20%. For example, the difference was 20% in 1983 and 7% in 1984. Overall, SWAT and HEC-HMS models produced comparative results in runoff volume, depth, and peak discharge aspects.

5.3.3 Water balance analysis - SWAT Model

Different water balance components of the Jhimruk Khola sub-basin were determined from the calibration of the SWAT model. The most crucial water balance components in the SWAT model are surface runoff (SURQ), lateral flow (LATQ), percolation (PERCO) and evapotranspiration (ET) (Sandra & Sathian 2016).

Table 5.8: Water balance results in SWAT model

Sub-Basin	Area (km^2)	Year	PREC (mm)	SURQ (mm)	PERCO (mm)	LATQ (mm)	ET (mm)	Error (%)
Jhimruk Khola,	885	1981	1,750.20	395.21	495.25	420.3	438.60	0.01
		1982	1,612.70	449.95	361.99	337.64	456.48	0.07
		1983	1,129.70	190.37	266.75	263.55	400.61	0.08
		1984	1,435.00	376.64	314.54	300.31	441.65	0.02
		1985	1,076.90	154.60	290.00	272.40	359.88	0.00

Note: *PREC - Precipitation, SURQ- Surface runoff, PERCO-Percolation, LATQ- Lateral flow, ET – Evapotranspiration, Water Yield = SURQ + LATQ + GWQ - T Loss - Pond abstraction.*

The average monthly distribution of water balance components and average annual yield are presented in Table 5.8. The average yearly rainfall of the basin ranges from 1750mm to 1076mm between 1981 and 1985. Approximately 25-35% of rainfall goes to annual evapotranspiration from the basin. Therefore, the value of evapotranspiration is significantly high. The highest surface runoff from the basin was 450 mm in 1982 and ranges about 15-30%, lateral sub-surface flow accounts 21-25 %, percolation is 22-28% of total rainfall, and total annual water yield ranges from 1,293mm to 684mm, which is 74-62% of the total precipitation.

5.3.4 Water balance analysis - HEC-HMS Model

Different water balance components were determined from the calibration of the HEC-HMS model. The most critical water balance components are direct runoff (Q) and Loss which includes ET (Evapotranspiration) and infiltration.

Table 5.9: Water balance results in HEC-HMS model

Sub-Basin	Area (km^2)	Year	IN	Out		Error (%)
			Perception (mm)	Direct runoff (mm)	Loss (mm)	
Jhimruk Khola,	885	1981	1,750.20	1,592.35	157.85	0.00
		1982	1,612.70	1,447.16	162.12	0.21
		1983	1,129.70	970.28	159.42	0.00
		1984	1,435.00	1,273.67	161.33	0.00
		1985	1,076.90	941.02	135.76	0.01

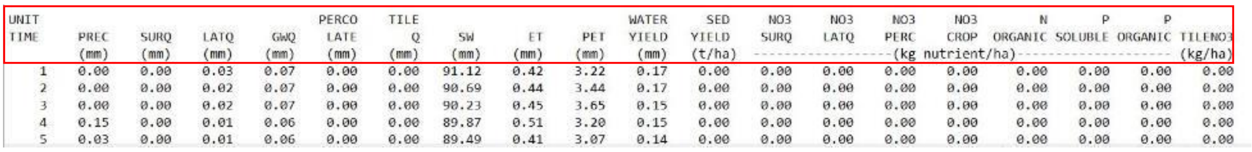
Table 5.9 shows the water balance outcomes of the HEC-HMS model. Annual precipitation was highest (1,750mm) in 1981 and lowest (1,076.90mm) in 1985. The direct runoff ranged from 85-90% of rainfall which looks very high. For example, the direct runoff was 1,592.35mm in 1981 and 970.28mm in 1983. This may be due to the lack of detailed land use data. Loss ranges from 135mm to 162mm, representing 9-14% of precipitation. The percentage of error in inflows and outflows is negligible, which shows that the HEC-HMS model satisfied the water balance equation.

Overall, both models produced comparative results in runoff volume and water balance analysis aspects, making it difficult to choose the most reliable model for this study.

5.3.5 Selection of Hydrologic model

The SWAT model overestimated the peak discharge, the most essential value for estimating flooding events. Thus, obtaining comprehensive information on flood events is critical to managing flooding events. The West Rapti River basin has a long history of devastating flood events (Devkota et al. 2013). Therefore, obtaining information about the flood event is essential for flood management that saves people’s lives and properties in the watershed area.

The SWAT model also produced additional output data that can be applied to evaluate the environmental effect on land use, land management practice, and watershed management. All this output information is saved in the *output.STD* file inside the *TextInOut* folder of SWAT, shown in Figure 5.7.



```
UNIT                                 PERCO    TILE                               WATER     SED      NO3      NO3      NO3      NO3        N        P        P
TIME     PREC     SURQ     LATQ     GWQ   LATE       Q       SW       ET      PET   YIELD   YIELD     SURQ     LATQ     PERC     CROP  ORGANIC  SOLUBLE  ORGANIC  TILENO3
         (mm)     (mm)     (mm)    (mm)   (mm)    (mm)     (mm)     (mm)     (mm)    (mm)   (t/ha)  -----------------(kg nutrient/ha)-------------------       (kg/ha)
   1     0.00     0.00     0.03    0.07   0.00    0.00    91.12     0.42     3.22    0.17    0.00     0.00     0.00     0.00     0.00     0.00     0.00     0.00     0.00
   2     0.00     0.00     0.02    0.07   0.00    0.00    90.69     0.44     3.44    0.17    0.00     0.00     0.00     0.00     0.00     0.00     0.00     0.00     0.00
   3     0.00     0.00     0.02    0.07   0.00    0.00    90.23     0.45     3.65    0.15    0.00     0.00     0.00     0.00     0.00     0.00     0.00     0.00     0.00
   4     0.15     0.00     0.01    0.06   0.00    0.00    89.87     0.51     3.20    0.15    0.00     0.00     0.00     0.00     0.00     0.00     0.00     0.00     0.00
   5     0.03     0.00     0.01    0.06   0.00    0.00    89.49     0.41     3.07    0.14    0.00     0.00     0.00     0.00     0.00     0.00     0.00     0.00     0.00
```

Figure 5.7: SWAT Output.STD files and basin components.

Note: PREC - Precipitation, SURQ - Surface runoff, LATQ - Lateral discharge, GWQ - Groundwater discharge, PERCO - Percolation, SW-Soil water, ET – Evapotranspiration, LATQ - Lateral flow, ET - Evapotranspiration, Water Yield, SED YIELD - Sediment yield.

Overall, the SWAT model performed better in flood estimation and management. The model also produced additional useful information about the study area. Eventually, the SWAT model was selected for the runoff simulation in the study area in Nepal.

5.4 Runoff simulation

The rainfall trend was estimated using a simple linear regression method in statistical analysis software. It produced the linear equation of $Y=0.29+0.00655t$, as shown in Figure 5.8. The graph illustrates an increasing rainfall trend in the West Rapti river basin.

Unfortunately, the obtained rainfall trend was unable to verify due to the lack of long-term precipitation trends in Nepal. However, Shrestha et al. (2000) suggested that the monsoon precipitation has increased by 5-15% due to increased global temperature. According to Shrestha et al. (1999), Nepal's annual temperature in most mountainous and Himalayan areas is rising at the rates between 0.06 to 0.12°C per year. In Siwalik and plain Terai, it is less than 0.03°C per year. The rise in temperature will alter the hydrological cycle, which in return impacts water availability, rainfall and runoff patterns of rivers (Sayari et al. 2011).

An increase in atmospheric GHG (GreenHouse Gas) is the primary cause of increased precipitation in Nepal, especially in the west of the country. As a result, the runoff trends in the West Rapti River basin showed a statistically significant upward trend and are compatible with increased flooding events in the region. Therefore, the obtained rainfall trend equation was considered acceptable for estimating rainfall for runoff simulation.

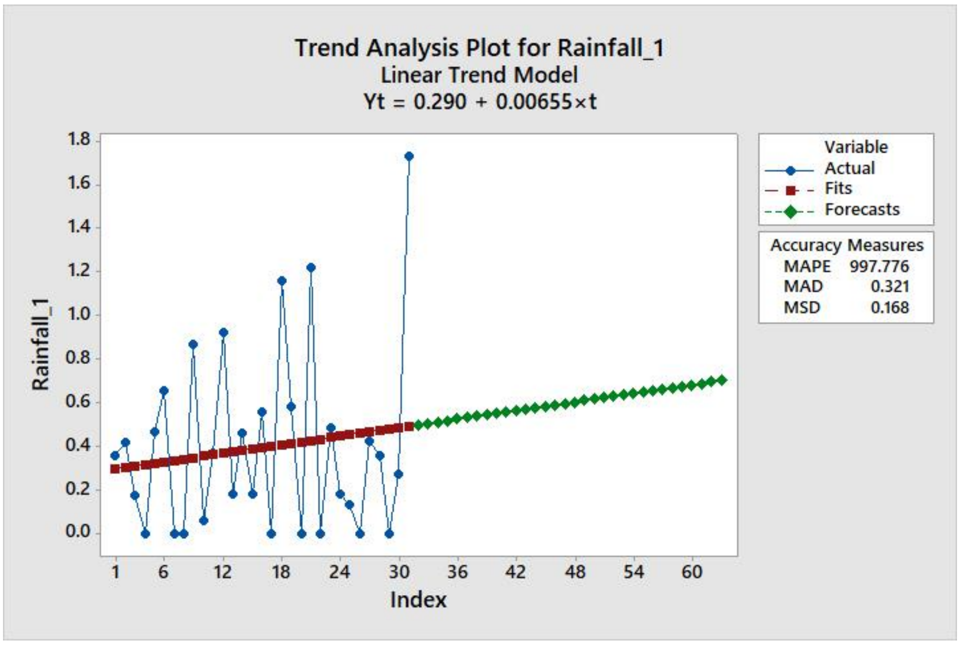


Figure 5.8: Rainfall trend analysis results of the study area

Note: MAPE = Mean Absolute Percentage Error, MAD = Mean Absolute Deviation, MSD = Mean Square Deviation

The linear equation (Y=0.29+0.00655t) was used to estimate rainfall for 2023-2026, considering the rainfall of 2013 as a baseline. These rainfall data were further used to simulate runoff for 2023-2026, and the results are shown in Figure 5.9.

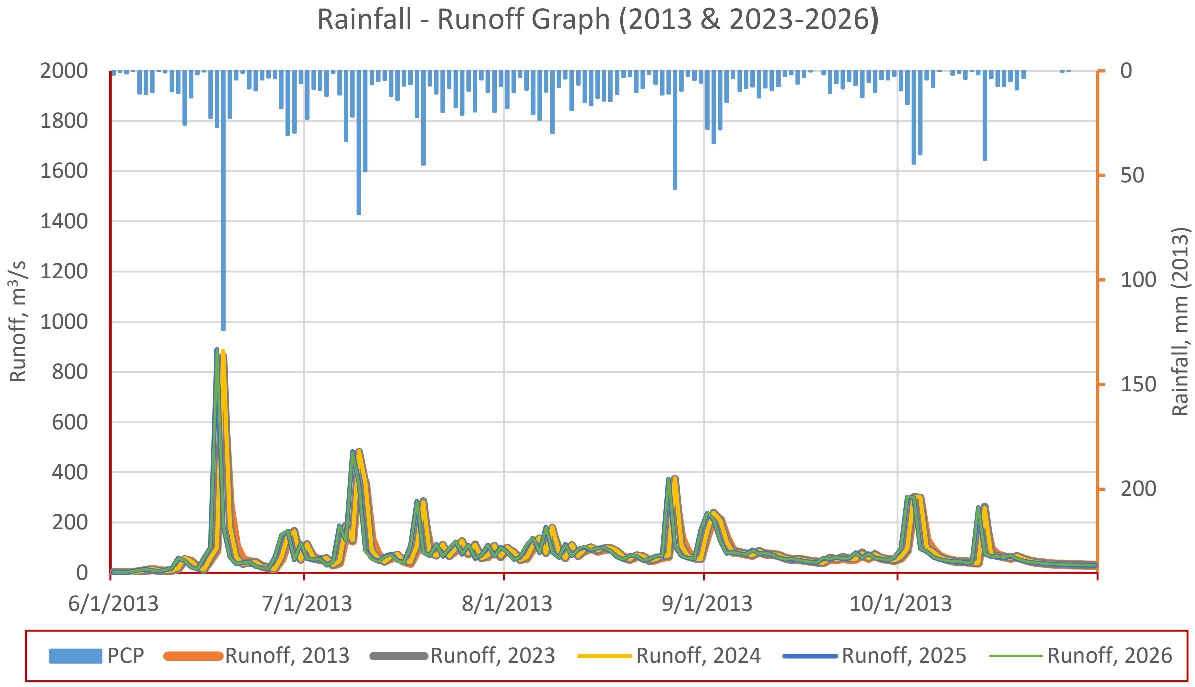


Figure 5.9: Simulated runoff details of the study area (2013 & 2023-2026).

The runoff simulation showed that the runoff patterns (2023-2026) perfectly matched the rainfall baseline (2013). Similarly, the simulated runoff trends also perfectly matched with the runoff baseline in all years.

Table 5.10 illustrates that the peak discharge is increased by about 17% from 2013 to 2023 and approximately 3% from 2023 to 2026. It shows that the time to peak is similar from 2023 to 2024, but it shifted one day earlier in 2025 and 2026, which may be due to increased rainfall.

Table 5.10: Summary of peak discharge simulation (2023-2026)

Date	Peak Discharge, m^3/s	Time of peak discharge
2013	718.00	18-Jun
2023	863.03	18-Jun
2024	884.49	18-Jun
2025	889.73	17-Jun
2026	890.71	17-Jun

The rainfall, simulated volume, and runoff depth, as shown in Table 5.11, illustrate that the rainfall increased by about 0.3%. In comparison, the runoff depth increased approximately 3% from 2023 to 2026.

Table 5.11: Summary of simulated volume and flow depth (2023 - 2026)

Date	PCP, mm	Out-flow, m^3/s	Flow depth, mm
2013	1,975.40	14,702.94	1,435.41
2023	2,043.48	14,968.54	1,461.34
2024	2,047.33	15,309.27	1,494.60
2025	2,047.53	15,373.54	1,500.87
2026	2,049.18	14,414.85	1,504.91

Overall, the SWAT model produced satisfactory simulation results despite limited input data. These findings can be used for flood estimation and management in the study area. Thus, it is concluded that the SWAT is reliable for runoff estimation in ungauged catchments in Nepal.

5.5 Conclusion

The SWAT model was set up for runoff simulation in the West Rapti River basin. The SWAT model calibration and validation process were limited due to missing GRDC runoff values. Therefore, the SWAT model results were compared with HEC-HMS results as a way to calibrate the model. The purpose was for the SWAT model to be used confidently in runoff simulation in poorly gauged basins in Nepal. Both models produced satisfactory results in volume comparison and water balance analysis. However, the SWAT model resulted in a conservative estimate in the peak discharge scenario, essential for flood management. The model also produced additional hydrological information about the study area. This supported selection of the SWAT model for runoff simulation.

Rainfall in the study area showed an increasing trend. The runoff simulation based on rainfall of 2013 showed good results. The runoff pattern matched the rainfall trend for all years. A minor shift of the time to peak was observed in 2025 and 2026. Overall, the results of the SWAT model are found to be acceptable, arriving at the conclusion that the model can be used confidently to simulate runoff in an ungauged basin in Nepal.

Chapter 6: Conclusion and Recommendations

6.1 Conclusion and Recommendations

Nepal, a South Asian country, is extremely rich in water resources availability and is one of the important natural resources of the country. The available water resources provide hydropower generation and irrigation opportunities because of perennial river flow during the dry season. However, the utilization of water resources depends on the availability and use of hydrological data that many river basins lack due to sparse hydrological gauging stations. Therefore, water resources in Nepal remain unexploited. It affects the power and irrigation sectors.

Understanding the hydrological processes, including frequencies and magnitudes of streamflow in data lacked basins (ungauged basins), is essential to manage water resources for hydropower generation, land irrigation, and even control natural disasters (e.g. flood and drought). However, predicting the system behaviour of these basins needs hydrological data. This provides challenges in calibrating simulation models that are reliable predictors. This study is an attempt to address this void by emphasizing on selection and calibration (to the extent possible) of a hydrological model that can be reliably used to simulate runoff in ungauged or poorly gauged catchments in Nepal.

A hydrological model is indispensable to understand a watershed's behaviour and responses to any changes, which are crucial for water management and flood forecasting. However, selecting a specific model is challenging at the best of times due to the absence of a specific model selection methodology. SWAT (Soil & Water Assessment Tool), a physically based distributed hydrological model selected for runoff simulation in the West Rapti River basin, is based on research objectives and personal interest to advance knowledge on hydrologic modelling.

The SWAT model is a public domain watershed scale model, which requires various input data to run. The primary data consists of DEM, land use, soil data, and weather data (precipitation, temperature, wind speed, solar radiation, and relative humidity). These data were extracted from various freely available resources such as USGS (topography), Global Weather Data for SWAT (weather database), GRDC (runoff database) and ISRIC (Soil and Terrain database). In addition, the built-in stochastic weather generator model (WXGEN) generates and fills climate data in the SWAT; therefore, the model is useful for simulating hydrology in ungauged or poorly gauged catchments.

The SWAT model was successfully set up in the ArcSWAT/QSWAT interface with a combination of input data (topographic, land use, soil, and weather data) and relevant literature. ArcSWAT created the West Rapti river networks divided the watershed into 16 sub-watersheds and 35 small HRUs (hydrologic response units) based on provided DEM, land and soil data. The study considered that the most physical attributes that influence runoff production are similar within the watershed.

The SWAT model calibration process was limited due to the missing observed data values from the GRDC. The data also restricted the verification and reliability of the SWAT model for the simulated condition. Thus, the SWAT model performance was compared with that of another popular hydrologic model, HEC-HMS (Hydrologic Engineering Center-Hydrologic Modeling System). The basin model was created in HEC-HMS by taking input values and data from the SWAT, such as SCS curve number (CN) and topographic data (DEM). Other input values, such as the time of concentration (t_c), was manually calculated using the Bransby-Willams (1977) method. The values of initial discharge and recession constant for surface runoff were taken as recommended by the literature. The HEC-HMS basin model created river networks, including seven junctions and divided the West Rapti River basin into 16 sub-basins.

The study compared and analyzed runoff volume, runoff depth and water balance results from both models (SWAT and HEC-HMS) to determine a reliable hydrological model for runoff simulation in the West Rapti River basins. Daily time-series rainfall data from 1981 to 1985 (5 years) were taken to simulate and analyze discharge in both models. Water balance is an essential factor in predicting the water movement in a watershed. Thus, the land phase of the hydrologic cycle, which controls the amount of water to the main channel, was taken in SWAT model water balance analysis. The primary water balance components included PREC (Precipitation), SURQ (Surface runoff), PERCO (Percolation), LATQ (Lateral flow), and ET (Evapotranspiration). Water balance analysis in the HEC-HMS model was performed by considering that the change in watershed storage is equal to the net difference in inflow and outflow of water in the system. The primary water balance parameters of the HEC-HMS model included Precipitation, Q (Runoff) and Loss (Evapotranspiration + Infiltration).

Both models produced comparative results in volume (runoff volume and runoff depth) and water balance analysis. However, the HEC-HMS overestimated runoff volume and depth by about 7-20%. On the other hand, the SWAT overestimated peak discharge about 30-50% more than HEC-HMS – this provided a conservative estimate, useful for flood analysis. Since the West Rapti River basin is one of the flood-affected areas in the country, obtaining additional flood event information is crucial for flood risk management. Likewise, the SWAT model produced additional data which can be used for the ecology, agriculture, and water quality management in the watershed. Therefore, SWAT was selected for runoff simulation in the Jhimruk Khola sub-basin. The sub-basin is one of the major drainage systems of the West Rapti river basin that provides water for irrigation and possible locations for small hydropower projects.

A companion program, SWAT-CUP (SWAT Calibration Uncertainty Procedure), supports the SWAT model calibration and validation. The SWAT model must be accurate for a successful calibration because the SWAT-CUP uses the SWAT output data as the input data source in the model creation process. The observed runoff data from 1979 to 1982 from GRDC were used for model calibration in SWAT-CUP, considering two years (1979-1980) as a model warm-up period. The warm-up period (equilibrium period) is necessary for the calibration process to get a fully operational hydrological cycle for the simulation period. Therefore, 2-3 years is recommended if the simulation period is five years or less.

The SUFI-2 (Sequential Uncertainty Fitting 2) approach with SWAT-CUP was used for model calibration, validation, sensitivity, and uncertainty analysis. The global sensitivity analysis method in SUFI-2 was chosen to capture the range of parameter values that significantly affect the model performance in the calibration process. Several parameters (surface runoff, groundwater, soil and HRUs) were investigated according to their sensitivity to streamflow suggested by relevant literature. The t-test and the p-values were used to determine the sensitivity and the significance of the parameters. The runoff parameter (CN2) was found to be the most sensitive parameter, followed by the groundwater parameters, the baseflow alpha-factor (APLHA_BF) and the groundwater delay time (GW_DELAY) also found the sensitive parameters.

Three different objective functions, such as NSE, R^2 and PBIAS, were used to estimate model performance according to the given GRDC observed data. The model evaluation statistics showed unacceptable model performance as per given objective functions, NSE and R^2 ($NSE<0$, $R^2 \neq 0.5$), but PBIAS showed acceptable ($PBIAS \pm 2.5$). Similarly, the fitted values between simulation result and observation expressed in p-factor and r-factor showed the satisfactory simulation result. However, the 95PPU graph showed significant variances in simulated (best estimation) and observed runoff trends and values. As a result, it was concluded that the observed data from GRDC are unsuitable for model calibration and validation in SWAT-CUP.

The daily rainfall data for 31 years (1979-2009) was used to estimate the rainfall trend using the linear regression method. The statistics showed an increasing rainfall trend in the West Rapti River basin. However, the rainfall trend was unable to be compared due to the unavailability of long-term rainfall records in Nepal. A previous study showed that monsoon rainfall increased by 5-15% due to increased global temperature. After completing a rainfall trend analysis, rainfall data for four years (2023-2026) was extracted to simulate runoff in SWAT, considering rainfall of 2013 as a baseline. The simulation results showed baseline rainfall trends perfectly matched with the simulated runoff in all years. The runoff volume, depth, and peak discharge increased by approximately 3% from 2023 to 2026. In addition, a minor shift (one day) to peak discharge was shown in 2025 and 2026.

This research implemented several theories related to the model setup, water balance analysis, trend analysis, and calibration processes. These procedures provided a basis for monitoring the reliability of data generated by the SWAT model and making a necessary decision to achieve the aims and objectives of the research. In the technical part, the percentage of error (%) and difference (%) were estimated to evaluate the reliability of data and performance of selected models (SWAT and HEC-HMS).

The overall conclusion of this research is that the SWAT model is a reliable tool for runoff simulation even though the model requires many input data. It is experienced that the model simulation under the conditions of limited data availability was tremendously difficult. However, the SWAT model produced satisfactory results by providing the available technology on model calibration and the freely available data. Thus, the SWAT model is a reliable tool for the runoff simulation in an ungauged basin in Nepal.

Based on overall findings and discussions, some recommendations for further research related to hydrology modelling for runoff simulation are proposed as mentioned below:

i. More detailed rainfall trend analysis using an advanced and reliable method is recommended to estimate more accurate runoff in the study area.
ii. The establishment of rain gauge stations for data collection is recommended because these are not as expensive as flow gauging stations.
iii. Detailed land use management analysis of the study area due to anthropogenic activities is recommended to estimate accurate surface runoff.
iv. Applying a similar method in other catchments with different sizes and climatic conditions is recommended to examine the reliability of the SWAT model.

This study attempted to answer the research questions by overviewing some popular hydrologic models and providing their advantages and disadvantages. Preferrable model selection depends on the objective of research and personal interest. Therefore, the SWAT model was selected to simulate runoff in the ungauged basin in Nepal. Furthermore, the model was compared with another hydrologic model, HEC-HMS, to select the reliable model in this study. The comparison results showed that the SWAT is more reliable than HEC-HMS regarding flood estimation and water resource management. Therefore, the SWAT model was successfully used for runoff simulation in the West Rapti river basin, one of the flood-affected watersheds in the country.

6.2 Future Work

This study did not consider the effect of climate change on streamflow for runoff simulation in the ungauged basin located in Nepal. Increasing greenhouse gas concentration leads to global warming that affects temperature, rainfall patterns, river flow regimes, and water resources (Arnell & Reynard 1996). Many developing countries like Nepal are vulnerable to climate change impacts due to low adaptive capability. In addition, agriculture which is highly dependent on climate change is the primary income source for most populations in the country (Manandhar et al. 2011). As a result, the impact of climate change on flood events and drought, including some measures to cope with climate change, is necessary for future study.

One of the possible solutions to study climate change impacts on flood and drought events is selecting and calibrating an appropriate rainfall-runoff model using historical records of rainfall, temperature, and flow data. For example, researchers successfully evaluated the impact of climate change on flood and drought events in different climatic and geographic conditions through the SWAT (Soil and Water Assessment Tools) model. Thus, the SWAT model could be the possible hydrologic model for this study. However, along with the hydrological model, other norms and regulations recommended by literature need to be considered to estimate climate change impacts and adopt reliable prevention measures accurately.

In addition, understanding the GCMs (Global Climate Models) information is essential for evaluating past and future changes in climate scenarios and climate change impacts for hydrologic analysis (Oo et al. 2020). The GCM is the primary tool that provides global, hemispheric, and continental-scale climate information, which can be applied to comprehend current and future climate scenarios in the presence of increased greenhouse gas concentrations (Nakicenovic et al. 2000). Above all, climate change is a pressing event that is dynamic and complex to predict; therefore, expert assistance and guidance are inevitable for completing the study successfully.

References

Abbaspour, KC 2012, 'SWAT-CUP5: SWAT calibration and uncertainty programs–a user manual', *Swiss Federal Institute of Aquatic Science and Technology, Eawag, Duebendorf*.

Abbaspour, KC 2013, 'SWAT-CUP: SWAT calibration and uncertainty program - a user manual', *Swiss Federal Institue of Aquatic Science and Technology*.

Abbaspour, KC, Rouholahnejad, E, Vaghefi, S, Srinivasan, R, Yang, H & Kløve, B 2015, 'A continental-scale hydrology and water quality model for Europe: Calibration and uncertainty of a high-resolution large-scale SWAT model', *Journal of Hydrology*, vol. 524, pp. 733-752, DOI https://doi.org/10.1016/j.jhydrol.2015.03.027, <http://www.sciencedirect.com/science/article/pii/S0022169415001985>.

Abbaspour, KC, Saeid Ashraf, V & Srinivasan, R 2018, 'A Guideline for successful calibration and uncertainty analysis for Soil and Water Assessment: A review of papers from the 2016 International SWAT conference', *Water*, vol. 10, no. 1, p. 6, ProQuest Central; SciTech Premium Collection, DOI http://dx.doi.org/10.3390/w10010006.

Abbaspour, KC, Vaghefi, SA, Yang, H & Srinivasan, R 2019, 'Global soil, landuse, evapotranspiration, historical and future weather databases for SWAT applications', *Scientific Data*, vol. 6, no. 1, p. 263, DOI 10.1038/s41597-019-0282-4, <https://doi.org/10.1038/s41597-019-0282-4>.

Abrams, M, Crippen, R & Fujisada, H 2020, 'ASTER Global Digital Elevation Model (GDEM) and ASTER Global Water Body Dataset (ASTWBD)', *Remote Sensing*, vol. 12, no. 7, p. 1156.

ADB & ICIMOD 2006, 'Environment assessment of Nepal: Emerging issues and challenges', *Kathmandu: ICIMOD*, <https://www.unisdr.org/files/2728_icimod59a59ac8a15f18ff0fa133fb193b0b50.pdf>.

Addor, N & Melsen, LA 2019, 'Legacy, Rather Than Adequacy, Drives the Selection of Hydrological Models', *Water Resources Research*, vol. 55, no. 1, pp. 378-390, DOI https://doi.org/10.1029/2018WR022958, <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2018WR022958>.

Agarwal, A, Babel, MS & Maskey, S 2015, 'Estimating the impacts and uncertainty of climate change on the Hydrology and Water Resources of the Koshi River Basin', in *Managing Water Resources under Climate Uncertainty*, Springer, pp. 105-126.

Alam, Q, Reza, S, Khurshid-ul-Alam, SM, Saleque, K & Chowdhury, H 2017, 'A review of hydropower projects in Nepal', *Energy Procedia*, vol. 110, pp. 581-585, DOI 10.1016/j.egypro.2017.03.188.

Alford, D 1992, *Hydrological aspects of the Himalayan region*, ICIMOD Occasional Paper No. 18, Kathmandu.

Altman, N & Krzywinski, M 2015, 'Points of Significance: Simple linear regression', *Nature Methods*, vol. 12, no. 11, pp. 999-1000, ProQuest Central; SciTech Premium Collection, DOI http://dx.doi.org/10.1038/nmeth.3627.

Arnell, NW & Reynard, NS 1996, 'The effects of climate change due to global warming on river flows in Great Britain', *Journal of Hydrology*, vol. 183, no. 3, pp. 397-424, DOI https://doi.org/10.1016/0022-1694(95)02950-8, <https://www.sciencedirect.com/science/article/pii/0022169495029508>.

Arnold, J, Kiniry, J, Srinivasan, R, Williams, J, Haney, E & Neitsch, S 2013, *Soil & Water Assessment Tool 2012 input/output documentation*, Texas Water Resources Institute.

Arnold, JG, Moriasi, DN, Gassman, PW, Abbaspour, KC, White, MJ, Srinivasan, R et al. 2012, 'SWAT: Model use, calibration, and validation', *Transactions of the ASABE*, vol. 55, no. 4, pp. 1491-1508.

Arsenault, R, Breton-Dufour, M, Poulin, A, Dallaire, G & Romero-Lopez, R 2019, 'Streamflow prediction in ungauged basins: analysis of regionalization methods in a hydrologically heterogeneous region of Mexico', *Hydrological sciences journal*, vol. 64, no. 11, pp. 1297-1311, <https://www-tandfonline-com.ezproxy.uws.edu.au/doi/pdf/10.1080/02626667.2019.1639716>.

Arsenault, R & Brissette, FP 2014, 'Continuous streamflow prediction in ungauged basins: The effects of equifinality and parameter set selection on uncertainty in regionalization approaches', *Water Resources Research*, vol. 50, no. 7, pp. 6135-6153, viewed 2021/01/12, DOI https://doi.org/10.1002/2013WR014898, <https://doi.org/10.1002/2013WR014898>.

Bajracharya, AR, Bajracharya, SR, Shrestha, AB & Maharjan, SB 2018, 'Climate change impact assessment on the hydrological regime of the Kaligandaki Basin, Nepal', *Science of The Total Environment*, vol. 625, pp. 837-848, DOI https://doi.org/10.1016/j.scitotenv.2017.12.332, <http://www.sciencedirect.com/science/article/pii/S0048969717337658>.

Bárdossy, A & Singh, S 2008, 'Robust estimation of hydrological model parameters', *Hydrology and Earth System Sciences*, vol. 12, no. 6, pp. 1273-1283.

Bera, A, Mukhopadhyay, PB & Biswas, S 2019, 'Assessment of gully erosion and estimation of sediment yield in Siddheswari River Basin, Eastern India, using SWAT model', in, Gully Erosion Studies from India and Surrounding Regions., pp. 279-293.

Berhail, S, Ouerdachi, L & Boutaghane, H 2012, 'The Use of the Recession Index as Indicator for Components of Flow', *Energy Procedia*, vol. 18, pp. 741-750, DOI https://doi.org/10.1016/j.egypro.2012.05.090, <https://www.sciencedirect.com/science/article/pii/S1876610212008600>.

Beven, KJ 2020, 'A history of the concept of time of concentration', *Hydrology and Earth System Sciences*, vol. 24, no. 5, pp. 2655-2670, ProQuest Central; SciTech Premium Collection, DOI http://dx.doi.org/10.5194/hess-24-2655-2020.

Bharati, L, Gurung, P & Jayakody, P 2012, 'Hydrologic characterization of the Koshi Basin and the impact of climate change', *Hydro Nepal: Journal of Water, Energy and Environment*, pp. 18-22.

Bhatt, RP 2017, 'Hydropower development in Nepal-climate change, impacts and implications', *Renewable Hydropower Technologies*, pp. 75-98.

Bhatta, B, Shrestha, S, Shrestha, PK & Talchabhadel, R 2019, 'Evaluation and application of a SWAT model to assess the climate change impact on the hydrology of the Himalayan River Basin', *Catena*, vol. 181, p. 104082.

Blöschl, G 2006, 'Rainfall-runoff modeling of ungauged catchments', *Encyclopedia of hydrological sciences*, < https://doi.org/10.1002/0470848944.hsa140>.

Blöschl, G, Bloschl, G, Sivapalan, M, Savenije, H, Wagener, T & Viglione, A 2013, *Runoff prediction in ungauged basins: synthesis across processes, places and scales*, Cambridge University Press.

Blöschl, G & Sivapalan, M 1995, 'Scale issues in hydrological modelling: a review', *Hydrological Processes*, vol. 9, no. 3-4, pp. 251-290.

Bonacci, O 2004, 'On the role of hydrology in water resources management', *IAHS PUBLICATION*, vol. 286, pp. 88-94.

Bras, RL 1999, 'A brief history of hydrology* The Robert E. Horton Lecture', *Bulletin of the American Meteorological Society*, vol. 80, no. 6, pp. 1151-1164.

Brutsaert, W 2005, *Hydrology: An introduction*, Cambridge University Press.

Burek, P, Satoh, Y, Fischer, G, Kahil, M, Scherzer, A, Tramberend, S et al. 2016, 'Water futures and solution-fast track initiative', *International Institute for Applied Systems Analysis (IIASA)*, <http://pure.iiasa.ac.at/id/eprint/13008/>.

Caracciolo, D, Arnone, E & Noto, LV 2014, 'Influence of spatial precipitation sampling on hydrological response at the catchment scale', *Journal of Hydrologic Engineering*, vol. 19, no. 3, pp. 544-553.

Castellarin, A, Camorani, G & Brath, A 2007, 'Predicting annual and long-term flow-duration curves in ungauged basins', *Advances in Water Resources*, vol. 30, no. 4, pp. 937-953, DOI https://doi.org/10.1016/j.advwatres.2006.08.006, <http://www.sciencedirect.com/science/article/pii/S0309170806001503>.

Chalise, SR 2002, 'Management of water resources for poverty alleviation in the Hindu-Kush Himalayas', *FRIEND 2002- Regional Hydrology: Bridging the Gap Between Research and Practice*, no. 274, pp. 27-34.

Chinnasamy, P & Sood, A 2020, 'Estimation of sediment load for Himalayan Rivers: Case study of Kaligandaki in Nepal', *Journal of Earth System Science*, vol. 129, no. 1, pp. 1-18.

Choudhari, K, Panigrahi, B & Paul, JC 2014, 'Simulation of rainfall-runoff process using HEC-HMS model for Balijore Nala watershed, Odisha, India', *International Journal of Geomatics and Geosciences*, vol. 5, no. 2, p. 253.

Deb, P & Kiem, AS 2020, 'Evaluation of rainfall–runoff model performance under non-stationary hydroclimatic conditions', *Hydrological Sciences Journal*, vol. 65, no. 10, pp. 1667-1684, DOI 10.1080/02626667.2020.1754420, <https://doi.org/10.1080/02626667.2020.1754420>.

Devia, GK, Ganasri, B & Dwarakish, G 2015, 'A review on hydrological models', *Aquatic Procedia*, vol. 4, no. 1, pp. 1001-1007.

Devkota, RP 2014, *Flood adaptation strategies under climate change in Nepal: S socio-hydrological analysis*, University of Southern Queensland.

Devkota, RP & Bhattarai, U 2018, 'Assessment of climate change impact on floods from a techno-social perspective', *Journal of Flood Risk Management*, vol. 11, no. S1, pp. S186-S196, DOI https://doi.org/10.1111/jfr3.12192, <https://onlinelibrary.wiley.com/doi/abs/10.1111/jfr3.12192>.

Devkota, RP, Maraseni, TN, Cockfield, G & Devkota, LP 2013, 'Flood vulnerability through the eyes of vulnerable people in mid-western Terai of Nepal', *Journal of Earth Science and Climatic Change*, vol. 4, no. 1, pp. 1-7.

Dhami, B, Himanshu, SK, Pandey, A & Gautam, AK 2018, 'Evaluation of the SWAT model for water balance study of a mountainous snowfed river basin of Nepal', *Environmental earth sciences*, vol. 77, no. 1, p. 21.

Dijkshoorn, J & Huting, J 2009, *Soil and terrain database for Nepal (1.1 million)*, ISRIC-World Soil Information.

Dile, YT & Srinivasan, R 2014, 'Evaluation of CFSR climate data for hydrologic prediction in data-scarce watersheds: an application in the Blue Nile River Basin', *JAWRA Journal of the American Water Resources Association*, vol. 50, no. 5, pp. 1226-1241.

Diskin, MH 1970, 'Definition and uses of the linear regression model', *Water Resources Research*, vol. 6, no. 6, pp. 1668-1673, DOI https://doi.org/10.1029/WR006i006p01668, <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/WR006i006p01668>.

District Profile, 2007, District Development Committee, Government of Nepal, Banke.

Easton, ZM, Fuka, DR, White, ED, Collick, AS, Ashagre, BB, McCartney, M et al. 2010, 'A multi basin SWAT model analysis of runoff and sedimentation in the Blue Nile, Ethiopia', *Hydrology and Earth System Sciences*, vol. 14, no. 10, p. 1827, ProQuest Central; SciTech Premium Collection.

Emmerik, Tv, Mulder, G, Eilander, D, Piet, M & Savenije, H 2015, 'Predicting the ungauged basin: Model validation and realism assessment', vol. 3, no. 62, DOI 10.3389/feart.2015.00062, <https://www.frontiersin.org/article/10.3389/feart.2015.00062>.

FAO/IIASA/ISRIC/ISS-CAS/JRC 2009, 'Harmonized world soil database (version 1.1)', *FAO, Rome, Italy and IIASA, Laxenburg, Austria.*

Fuka, DR, Walter, MT, MacAlister, C, Degaetano, AT, Steenhuis, TS & Easton, ZM 2014, 'Using the Climate Forecast System Reanalysis as weather input data for watershed models', *Hydrological Processes*, vol. 28, no. 22, pp. 5613-5623.

Gan, Y, Duan, Q, Gong, W, Tong, C, Sun, Y, Chu, W et al. 2014, 'A comprehensive evaluation of various sensitivity analysis methods: A case study with a hydrological model', *Environmental Modelling & Software*, vol. 51, pp. 269-285, DOI https://doi.org/10.1016/j.envsoft.2013.09.031, <http://www.sciencedirect.com/science/article/pii/S1364815213002338>.

Gao, H, Ding, Y, Zhao, Q, Hrachowitz, M & Savenije, H 2017, 'The importance of aspect for modelling the hydrological response in a glacier catchment in Central Asia', *Hydrological Processes*, vol. 31, DOI 10.1002/hyp.11224.

Gassman, PW, Reyes, MR, Green, CH & Arnold, JG 2007, 'The soil and water assessment tool: historical development, applications, and future research directions', *Transactions of the ASABE*, vol. 50, no. 4, pp. 1211-1250.

Gassman, PW, Sadeghi, AM & Srinivasan, R 2014, 'Applications of the SWAT model special section: Overview and insights', *Journal of Environmental Quality*, vol. 43, no. 1, pp. 1-8, DOI 10.2134/jeq2013.11.0466, <https://acsess.onlinelibrary.wiley.com/doi/abs/10.2134/jeq2013.11.0466>.

Gautam, DK & Phaiju, AG 2013, 'Community based approach to flood early warning in West Rapti river basin of Nepal', *IDRiM Journal*, vol. 3, no. 1, pp. 155-169.

Gautam, MR & Acharya, K 2012, 'Streamflow trends in Nepal', *Hydrological sciences journal*, vol. 57, pp. 344-357, DOI 10.1080/02626667.2011.637042, <https://www.researchgate.net/publication/254241444>.

GFDRR 2011, 'Climate risk and adaptation country profile, Nepal: Vulnerability, risk reduction, and adaptation to climate change', *Washington, DC: World Bank Group*.

Glavan, M & Pintar, M 2012, 'Strengths, weaknesses, opportunities and threats of catchment modelling with Soil and Water Assessment Tool (SWAT) model', *Water Resources Management and Modeling*, pp. 39-64.

Gohar, AA & Cashman, A 2016, 'A methodology to assess the impact of climate variability and change on water resources, food security and economic welfare', *Agricultural Systems*, vol. 147, pp. 51-64, DOI https://doi.org/10.1016/j.agsy.2016.05.008, <http://www.sciencedirect.com/science/article/pii/S0308521X16301299>.

Goodarzi, M 2019, 'A Brief Survey of Regionalization Modeling; A Bonus from Gauged to Ungauged Basins', *Advancements in Civil Engineering & Technology*, vol. 3, DOI 10.31031/ACET.2019.03.000566.

Goswami, M, O'Connor, KM & Bhattarai, KP 2007, 'Development of regionalisation procedures using a multi-model approach for flow simulation in an ungauged catchment', *Journal of Hydrology*, vol. 333, no. 2-4, pp. 517-531, DOI 10.1016/j.jhydrol.2006.09.018, <https://www.scopus.com/inward/record.uri?eid=2-s2.0-33845967871&doi=10.1016%2fj.jhydrol.2006.09.018&partnerID=40&md5=057259ed83601ea90d49722f1047de9b>.

Guo, Y, Zhang, Y, Zhang, L & Wang, Z 2020, 'Regionalization of hydrological modeling for predicting streamflow in ungauged catchments: A comprehensive review', *Wiley Interdisciplinary Reviews: Water*, p. e1487.

Gupta, HV, Sorooshian, S & Yapo, PO 1999, 'Status of automatic calibration for hydrologic models: Comparison with multilevel expert calibration', *Journal of hydrologic engineering*, vol. 4, no. 2, pp. 135-143.

Gurung, A, Adhikari, S, Chauhan, R, Thakuri, S, Nakarmi, S, Ghale, S et al. 2019, 'Water crises in a water-rich country: case studies from rural watersheds of Nepal's mid-hills', *Water Policy*, vol. 21, no. 4, pp. 826-847, viewed 5/12/2021, DOI 10.2166/wp.2019.245, <https://doi.org/10.2166/wp.2019.245>.

Gurung, P & Bharati, L 2012, 'Downstream impacts of the Melamchi Inter-Basin Water Transfer Plan (MIWTP) under current and future climate change projections', *Hydro Nepal: Journal of Water, Energy and Environment*, pp. 23-29.

Gurung, P, Bharati, L & Karki, S 2013, 'Application of the SWAT model to assess climate change impacts on water balances and crop yields in the West Seti River Basin'.

Gyawali, D 1989, 'Water in Nepal: an interdisciplinary look at resource uncertainties, evolving problems, and future prospects', *East-West Center*, vol. 8.

Hannah, D, Kansakar, S, Gerrard, AJ & Rees, G 2005, 'Flow regimes of Himalayan rivers of Nepal: Nature and spatial patterns', *Journal of Hydrology*, vol. 308, pp. 18-32, DOI 10.1016/j.jhydrol.2004.10.018.

He, Y, Bárdossy, A & Zehe, E 2011, 'A review of regionalisation for continuous streamflow simulation', *Hydrology and Earth System Sciences*, vol. 15, no. 11, pp. 3539-3553.

HEC 2016, 'Hydrological Modelling (HEC-HMS) user`s Manual', *US Army Corps of Engineers.*

Henriksen, HJ, Troldborg, L, Nyegaard, P, Sonnenborg, TO, Refsgaard, JC & Madsen, B 2003, 'Methodology for construction, calibration and validation of a national hydrological model for Denmark', *Journal of Hydrology*, vol. 280, no. 1, pp. 52-71, DOI https://doi.org/10.1016/S0022-1694(03)00186-0, <https://www.sciencedirect.com/science/article/pii/S0022169403001860>.

Heuvelmans, G, Garcia-Qujano, JF, Muys, B, Feyen, J & Coppin, P 2005, 'Modelling the water balance with SWAT as part of the land use impact evaluation in a life cycle study of CO2 emission reduction scenarios', *Hydrological Processes*, vol. 19, no. 3, pp. 729-748, DOI https://doi.org/10.1002/hyp.5620, <https://onlinelibrary.wiley.com/doi/abs/10.1002/hyp.5620>.

Hirsch, RM & Costa, JE 2004, 'U.S. stream flow measurement and data dissemination improve', *Eos, Transactions American Geophysical Union*, vol. 85, no. 20, pp. 197-203, <https://doi.org/10.1029/2004EO200002>.

Hrachowitz, M, Savenije, HHG, Blöschl, G, McDonnell, JJ, Sivapalan, M, Pomeroy, JW et al. 2013, 'A decade of Predictions in Ungauged Basins (PUB)—a review', *Hydrological sciences journal*, vol. 58, no. 6, pp. 1198-1255, DOI 10.1080/02626667.2013.803183, <https://doi.org/10.1080/02626667.2013.803183>.

Jain, SK & Singh, VP 2003, *Water resources systems planning and management*, Elsevier.

Jajarmizadeh, M, Harun, Sb, Shahid, S, Akib, S & Salarpour, M 2014, 'Impact of Direct Soil Moisture and Revised Soil Moisture Index Methods on Hydrologic Predictions in an Arid Climate', *Advances in Meteorology*, vol. 2014, p. 156172, DOI 10.1155/2014/156172, <https://doi.org/10.1155/2014/156172>.

Johnson, R 1998, 'An investigation of curve number applicability to watersheds in excess of 25000 hectares (250 km2)', *Jornal of Environmental Hydrology*, vol. 6.

Kalcic, MM, Chaubey, I & Frankenberger, J 2015, 'Defining Soil and Water Assessment Tool (SWAT) hydrologic response units (HRUs) by field boundaries', *International Journal of Agricultural and Biological Engineering*, vol. 8, no. 3, pp. 69-80.

Kanishka, G & Eldho, TI 2020, 'Streamflow estimation in ungauged basins using watershed classification and regionalization techniques', *Journal of Earth System*

Science, vol. 129, no. 1, p. 186, DOI 10.1007/s12040-020-01451-8, <https://doi.org/10.1007/s12040-020-01451-8>.

Kansakar, S, Hannah, D, Gerrard, J & Rees, G 2002, 'Flow regime characteristics of Himalayan river basins in Nepal', *International Association of Hydrological Sciences, Publication*, no. 274, pp. 425-432.

Kansakar, S, Hannah, D, Gerrard, J & Rees, G 2004, 'Spatial pattern in the precipitation regime of Nepal', *International Journal of Climatology: A Journal of the Royal Meteorological Society*, vol. 24, no. 13, pp. 1645-1659.

Karki, R, Talchabhadel, R, Aalto, J & Baidya, SK 2016, 'New climatic classification of Nepal', *Theoretical and applied climatology*, vol. 125, no. 3-4, pp. 799-808, <https://www.researchgate.net/profile/Juha_Aalto/publication/280034906_New_climatic_classification_of_Nepal/links/5707be4008ae2eb9421bd6cf.pdf>.

KC, S, Khanal, SK, Shrestha, P & Lamsal, B 2011, 'Current status of renewable energy in Nepal: Opportunities and challenges', *Renewable and Sustainable Energy Reviews*, vol. 15, no. 8, pp. 4107-4117, DOI https://doi.org/10.1016/j.rser.2011.07.022, <http://www.sciencedirect.com/science/article/pii/S1364032111002619>.

Khalid, K, Ali, MF, Rahman, NFA, Mispan, MR, Haron, SH, Othman, Z et al. 2016, 'Sensitivity Analysis in Watershed Model Using SUFI-2 Algorithm', *Procedia Engineering*, vol. 162, pp. 441-447, DOI https://doi.org/10.1016/j.proeng.2016.11.086, <http://www.sciencedirect.com/science/article/pii/S1877705816333951>.

Koutalakis, P, Zaimes, GN, Emmanouloudis, D, Ioannou, K & Iakovoglou, V 2015, 'Using ArcSWAT to Predict Discharge in Ungauge Torrents of Thasos Island', pp. 154-162, <http://ceur-ws.org/Vol-1498/HAICTA_2015_paper21.pdf>.

Krysanova, V & Arnold, JG 2008, 'Advances in ecohydrological modelling with SWAT—a review', *Hydrological Sciences Journal*, vol. 53, no. 5, pp. 939-947.

Krysanova, V & White, M 2015, 'Advances in water resources assessment with SWAT—an overview', *Hydrological Sciences Journal*, vol. 60, no. 5, pp. 771-783.

Li, Q, Peng, Y, Wang, G, Wang, H, Xue, B & Hu, X 2019, 'A combined method for estimating continuous runoff by parameter transfer and drainage area ratio method in ungauged catchments', *Water*, vol. 11, no. 5, p. 1104, DOI 10.3390/w11051104, <https://www.scopus.com/inward/record.uri?eid=2s2.085066316096&doi=10.3390%2fw11051104&partnerID=40&md5=bff810f6251c5eec55834fb95b8a15eb >.

Li, Z, Yang, Y, Kan, G & Hong, Y 2018, 'Study on the applicability of the Hargreaves potential evapotranspiration estimation method in CREST distributed hydrological model (version 3.0) applications', *Water*, vol. 10, no. 12, p. 1882.

Ma, L, Ascough Ii, J, Ahuja, L, Shaffer, M, Hanson, J & Rojas, K 2000, 'Root zone water quality model sensitivity analysis using Monte Carlo simulation', *Transactions of the ASAE*, vol. 43, no. 4, p. 883.

Magaju, D 2018, *Hydropower potential assessment using an analytical hydrological model: Case study of West Rapti Basin, Nepal*, UNESCO-IHE Institute for Water Education.

Makungo, R, Odiyo, JO, Ndiritu, JG & Mwaka, B 2010, 'Rainfall–runoff modelling approach for ungauged catchments: A case study of Nzhelele River sub-quaternary catchment', *Physics and Chemistry of the Earth, Parts A/B/C*, vol. 35, no. 13, pp. 596-607, DOI https://doi.org/10.1016/j.pce.2010.08.001, <http://www.sciencedirect.com/science/article/pii/S1474706510001683>.

Manandhar, S, Vogt, DS, Perret, SR & Kazama, F 2011, 'Adapting cropping systems to climate change in Nepal: a cross-regional study of farmers' perception and practices', *Regional Environmental Change*, vol. 11, no. 2, pp. 335-348.

Marshall, L, Nott, D & Sharma, A 2005, 'Hydrological model selection: A Bayesian alternative', *Water Resources Research*, vol. 41, no. 10.

McCuen, RH 1973, 'The role of sensitivity analysis in hydrologic modeling', *Journal of Hydrology*, vol. 18, no. 1, pp. 37-53, DOI https://doi.org/10.1016/0022-1694(73)90024-3, <http://www.sciencedirect.com/science/article/pii/0022169473900243>.

McGlynn, B, Blöschl, G, Borga, M, Bormann, H, Hurkmans, R, Komma, J et al. 2013, 'A data acquisition framework for prediction of runoff in ungauged basins', in *Run-off Prediction in Ungauged Basins: Synthesis Across Processes, Places and Scales*, pp. 29-51.

Meins, FM 2013, *Evaluation of spatial scale alternatives for hydrological modelling of the Lake Naivasha basin, Kenya*, University of Twente.

Merwade, V, Olivera, F, Arabi, M & Edleman, S 2008, 'Uncertainty in flood inundation mapping: Current issues and future directions', *Journal of hydrologic engineering*, vol. 13, no. 7, pp. 608-620, Environment Complete, EBSCOhost, DOI 10.1061/(ASCE)1084-0699(2008)13:7(608), <http://ezproxy.uws.edu.au/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=eih&AN=32634856&site=ehost-live&scope=site>.

Merz, R & Blöschl, G 2004, 'Regionalisation of catchment model parameters', *Journal of Hydrology*, vol. 287, no. 1-4, pp. 95-123, <https://www.hydro.tuwien.ac.at/fileadmin/mediapool-hydro/Publikationen/bloeschl/2004_Merz_JH.pdf>.

Mishra, B, Takara, K & Tachikawa, Y 2008, 'REGIONALIZATION OF NEPALESE RIVER BASINS FOR FLOOD FREQUENCY ANALYSIS', vol. 52.

Moriasi, DN, Arnold, JG, Van Liew, MW, Bingner, RL, Harmel, RD & Veith, TL 2007, 'Model evaluation guidelines for systematic quantification of accuracy in watershed simulations', *Transactions of the ASABE*, vol. 50, no. 3, pp. 885-900.

Moriasi, DN, Gitau, MW, Pai, N & Daggupati, P 2015, 'Hydrologic and water quality models: Performance measures and evaluation criteria', *Transactions of the ASABE*, vol. 58, no. 6, pp. 1763-1785.

Nakicenovic, N, Alcamo, J, Davis, G, Vries, Bd, Fenhann, J, Gaffin, S et al. 2000, 'Special report on emissions scenarios'.

Narsimlu, B, Gosain, AK, Chahar, BR, Singh, SK & Srivastava, PK 2015, 'SWAT Model Calibration and Uncertainty Analysis for Streamflow Prediction in the Kunwari River Basin, India, Using Sequential Uncertainty Fitting', *Environmental Processes*, vol. 2, no. 1, pp. 79-95, DOI 10.1007/s40710-015-0064-8, <https://doi.org/10.1007/s40710-015-0064-8>.

Nathan, RJ & McMahon, TA 1990, 'Evaluation of automated techniques for base flow and recession analyses', *Water Resources Research*, vol. 26, no. 7, pp. 1465-1473, DOI https://doi.org/10.1029/WR026i007p01465, <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/WR026i007p01465>.

National Research Council 1991, *Opportunities in the hydrologic sciences*, National Academies Press, Washington, DC.

Neitsch, SL, Arnold, JG, Kiniry, JR & Williams, JR 2011, *Soil and water assessment tool theoretical documentation version 2009*, Texas Water Resources Institute.

Nepal, S, Neupane, N, Belbase, D, Pandey, VP & Mukherji, A 2019, 'Achieving water security in Nepal through unravelling the water-energy-agriculture nexus', *International Journal of Water Resources Development*, pp. 1-27.

Neupane, RP & White, JD 2010, 'Simulation of climate change impacts on Himalayan headwater watershed snowmelt hydrology: discharge, sediment load, and nutrient shifts', *AGUFM*, vol. 2010, pp. H43F-1318, <https://ui.adsabs.harvard.edu/abs/2010AGUFM.H43F1318N/abstract>.

Neupane, SN & Pandey, A 2021, 'Hydrological modeling of West Rapti River Basin of Nepal using SWAT model', in *Water Management and Water Governance*, Springer, pp. 279-302.

Olivera, F, Valenzuela, M, Srinivasan, R, Choi, J, Cho, H, Koka, S et al. 2006, 'ArcGIS-SWAT: A Geodata Model and GIS Interface for SWAT', *JAWRA Journal of the American Water Resources Association*, vol. 42, pp. 295-309, DOI 10.1111/j.1752-1688.2006.tb03839.x.

Oo, H, Zin, W & Kyi, C 2020, 'Analysis of Streamflow Response to Changing Climate Conditions Using SWAT Model', *Civil Engineering Journal*, vol. 6, pp. 194-209, DOI 10.28991/cej-2020-03091464.

Oudin, L, Andréassian, V, Perrin, C, Michel, C & Le Moine, N 2008, 'Spatial proximity, physical similarity, regression and ungaged catchments: A comparison of regionalization approaches based on 913 French catchments', *Water Resources Research*, vol. 44, no. 3, DOI 10.1029/2007WR006240.

Oudin, L, Kay, A, Andréassian, V & Perrin, C 2010, 'Are seemingly physically similar catchments truly hydrologically similar?', *Water Resources Research*, vol. 46, no. 11.

Pagliero, L, Bouraoui, F, Diels, J, Willems, P & McIntyre, N 2019, 'Investigating regionalization techniques for large-scale hydrological modelling', *Journal of Hydrology*, vol. 570, pp. 220-235, PubMed, DOI 10.1016/j.jhydrol.2018.12.071, <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6472599/>.

Parajka, J, Blöschl, G & Merz, R 2007, 'Regional calibration of catchment models: Potential for ungauged catchments', *Water Resources Research*, vol. 43, no. 6.

Parajka, J, Merz, R & Blöschl, G 2005, 'A comparison of regionalisation methods for catchment model parameters', *Hydrology And Earth System Sciences Discussions*, vol. 9, no. 3, pp. 157-171, <https://hal.archives-ouvertes.fr/hal-00304814/document>.

Parajka, J, Viglione, A, Rogger, M, Salinas, JL, Sivapalan, M & Blöschl, G 2013, 'Comparative assessment of predictions in ungauged basins – Part 1: Runoff-hydrograph studies', *Hydrol. Earth Syst. Sci.*, vol. 17, no. 5, pp. 1783-1795, DOI 10.5194/hess-17-1783-2013, <https://hess.copernicus.org/articles/17/1783/2013/>.

Pathak, D, Gajurel, AP & Shrestha, GB 2007, 'GIS-based landslide hazard mapping in Jhimruk River basin, west Nepal', *Journal of Nepal Geological Society*, vol. 36, p. 25.

Patil, S & Stieglitz, M 2012, 'Controls on hydrologic similarity: role of nearby gauged catchments for prediction at an ungauged catchment', *Hydrol. Earth Syst. Sci.*, vol. 16, no. 2, pp. 551-562, DOI 10.5194/hess-16-551-2012, <https://www.hydrol-earth-syst-sci.net/16/551/2012/>.

Peters, NE 1994, 'Hydrologic processes', *Biogeochemistry of Small Watersheds: A Tool for Environmental Research, Scope*, vol. 51, pp. 189-206.

Pokharel, S 2001, 'Hydropower for Energy in Nepal', *Mountain Research and Development*, vol. 21, pp. 4-9, DOI 10.2307/3674124, <https://www-jstor-org.ezproxy.uws.edu.au/stable/pdf/3674124.pdf?refreqid=excelsior%3A4c5c44c5fc2c1dd3216b8f1863ea60ca>.

Poudel, K & Sharma, S 2012, *Small Irrigation Systems in Nepal: An Analytical preview from Irrigated Agricultural Development Perspective of Batch I Irrigation Sub-projects under Community Managed Irrigated Agriculture Sector Project*.

Pradhan, NR, Ogden, F, Tachikawa, Y & Takara, K 2008, 'Scaling of slope, upslope area, and soil water deficit: Implications for transferability and regionalization in topographic index modeling', *Water Resources Research*, vol. 44, DOI 10.1029/2007WR006667.

Pradhan, NS, Sijapati, S & Bajracharya, SR 2015, 'Farmers' responses to climate change impact on water availability: insights from the Indrawati Basin in Nepal', *International Journal of Water Resources Development*, vol. 31, no. 2, pp. 269-283, DOI 10.1080/07900627.2015.1033514, <https://doi.org/10.1080/07900627.2015.1033514>.

Pradhanang, S, Khadka, UR & Thakuri, S 2017, 'Fresh water resources of Nepal: Prespectives and issues', in, ResourceBook-ICIMOD, pp. 133-153.

Rai, PJ, Pokharel, GR, Samrat, K & Pokharel, GC 2020, 'Current Status of Hydropower Development in Nepal: Generation, Transmission, Distribution, and Electrification'.

Ramírez, JA 2000, 'Prediction and modeling of flood hydrology and hydraulics', *Inland flood hazards: Human, riparian and aquatic communities*, p. 498.

Razavi, T & Coulibaly, P 2013, 'Streamflow prediction in ungauged basins: Review of regionalization methods', *Journal of hydrologic engineering*, vol. 18, no. 8, pp. 958-975, DOI 10.1061/(ASCE)HE.1943-5584.0000690, <https://www.scopus.com/inward/record.uri?eid=2-s2.0-84881365698&doi=10.1061%2f%28ASCE%29HE.1943-5584.0000690&partnerID=40&md5=d7fc01a8eeff99da81789d210d1de41f>.

Rees, G, Croker, K, Zaidman, M, Cole, G, Kansakar, S, Chalise, S et al. 2002, 'Application of the regional flow estimation method in the Himalayan region', *International Association of Hydrological Sciences*, vol. 274, pp. 433-440.

Rui, X-f, Liu, N-n, Li, Q-l & Liang, X 2013, 'Present and future of hydrology', *Water Science and Engineering*, vol. 6, no. 3, pp. 241-249, DOI https://doi.org/10.3882/j.issn.1674-2370.2013.03.001, <http://www.sciencedirect.com/science/article/pii/S1674237015302404>.

Samuel, J, Coulibaly, P & Metcalfe, RA 2011, 'Estimation of continuous streamflow in Ontario ungauged basins: comparison of regionalization methods', *Journal of hydrologic engineering*, vol. 16, no. 5, pp. 447-459, <https://www.researchgate.net/profile/Jos_Samuel/publication/259821269_Estimation_of_Continuous_Streamflow_in_Ontario_Ungauged_Basins_Comparison_of_Regionalization_Methods/links/56bb880a08ae3f9793153542.pdf>.

Sandra, G & Sathian, K 2016, 'Assessment of water balance of a watershed using swat model for water resources management', *Int. J. Eng. Sci. Res. Technol*, vol. 5, pp. 177-184.

Sangwan, N 2016, 'Estimating the Total Annual Evapotranspiration depth using the Annual Watershed Balance concept', *The Science Education Resource Center*, <https://serc.carleton.edu/hydromodules/steps/114224.html>.

Sapkota, N & Thapa, K 2014, 'Integrated water resource management in Nepal', DOI 10.13140/RG.2.1.1476.4249, <https://www.researchgate.net/publication/282976233_Integrated_water_Resource_Management_in_Nepal>.

Sayari, N, Bannayan, M, Farid, A, Alizadeh, A & Kermani, MRH 2011, 'Crop water consumption and crop yield prediction under climate change conditions at northeast of Iran', pp. 16-18.

Seibert, J & Beven, K 2009, 'Gauging the ungauged basin: How many discharge measurements are needed?', *Hydrology Earth System Sciences*, vol. 13, no. 6, pp. 883-892.

Shakya, MK 2011, 'Assessing water resources availability in Indrawati river basin in Nepal: application of SWAT model for hydrologic simulation', *UNESCO-IHE Institute for Water Education*.

Sharma, K 1993, 'Role of meltwater in major river systems of Nepal', *IAHS Publications-Publications of the International Association of Hydrological Sciences*, vol. 218, pp. 113-122.

Shivhare, N, Dikshit, PKS & Dwivedi, SB 2018, 'A Comparison of SWAT Model Calibration Techniques for Hydrological Modeling in the Ganga River Watershed', *Engineering*, vol. 4, no. 5, pp. 643-652, DOI https://doi.org/10.1016/j.eng.2018.08.012, <http://www.sciencedirect.com/science/article/pii/S2095809917306586>.

Shrestha, AB, Wake, CP, Dibb, JE & Mayewski, PA 2000, 'Precipitation fluctuations in the Nepal Himalaya and its vicinity and relationship with some large scale climatological parameters', *International Journal of Climatology: A Journal of the Royal Meteorological Society*, vol. 20, no. 3, pp. 317-327.

Shrestha, AB, Wake, CP, Mayewski, PA & Dibb, JE 1999, 'Maximum temperature trends in the Himalaya and its vicinity: an analysis based on temperature records from Nepal for the period 1971–94', *Journal of climate*, vol. 12, no. 9, pp. 2775-2786.

Shrestha, H 2013, *Impact of land use change on hydrology and hydropower production: A case of Kulekhani Project, Nepal*, Doctoral dissertation. Thailand: Asian Institute of Technology, School of Engineering and Technology.

Shrestha, HM 2016, 'Naumore storage project should be the last resort of development on the main course of Rapti (West), Nepal', *Hydro Nepal: Journal of Water, Energy and Environment*, vol. 18, pp. 1-5.

Shrestha, M 2014, 'Evaluation of water supply and demand under climate change scenarios in Kathmandu valley, Nepal', *Thailand: Asian Institute of Technology*.

Shrestha, M, Chaudhary, S, Maskey, R & Rajkarnikar, G 2010, 'Comparison of the anomaly of hydrological analysis tools used in Nepal', *Journal of Hydrology and Meteorology*, vol. 7, no. 1, pp. 30-39.

Shrestha, S, Shrestha, M & Babel, MS 2016, 'Modelling the potential impacts of climate change on hydrology and water resources in the Indrawati River Basin, Nepal', *Environmental earth sciences*, vol. 75, no. 4, p. 280, DOI 10.1007/s12665-015-5150-8, <https://doi.org/10.1007/s12665-015-5150-8>.

Shrestha, S, Shrestha, M & Shrestha, PK 2018, 'Evaluation of the SWAT model performance for simulating river discharge in the Himalayan and tropical basins of Asia', *Hydrology Research*, vol. 49, no. 3, pp. 846-860, DOI 10.2166/nh.2017.189.

Shu, C & Burn, D 2003, 'Spatial patterns of homogeneous pooling groups for flood frequency analysis', *Hydrological sciences journal*, vol. 48, pp. 601-618, DOI 10.1623/hysj.48.4.601.51417.

Siddiqui, S, Bharati, L, Pant, M, Gurung, P, Rakhal, B & Maharjan, LD 2012, *Nepal: building climate resilience of watersheds in mountain eco-regions climate change and vulnerability mapping in watersheds in middle and high mountains of Nepal*, International Water Management Institute (IWMI), Kathmandu, Nepal.

Singh, L & Saravanan, S 2020, 'Simulation of monthly streamflow using the SWAT model of the Ib River watershed, India', *HydroResearch*, vol. 3, pp. 95-105, DOI https://doi.org/10.1016/j.hydres.2020.09.001, <https://www.sciencedirect.com/science/article/pii/S2589757820300159>.

Singh, T 2005, 'Water resources development of Nepal: Assessment and recommendations ', *NDC E-JOURNAL*, vol. 4, no. 1, pp. 93-130.

Singh, VP 2018, 'Hydrologic modeling: progress and future directions', *Geoscience Letters*, vol. 5, no. 1, p. 15, DOI 10.1186/s40562-018-0113-z, <https://doi.org/10.1186/s40562-018-0113-z>.

Sisay, E, Halefom, A, Khare, D, Singh, L & Worku, T 2017, 'Hydrological modelling of ungauged urban watershed using SWAT model', *Modeling Earth Systems and Environment*, vol. 3, no. 2, pp. 693-702.

Sivapalan, M 2003a, 'Prediction in ungauged basins: A grand challenge for theoretical hydrology', *Hydrological Processes*, vol. 17, no. 15, pp. 3163-3170, <https://www.researchgate.net/profile/Murugesu_Sivapalan/publication/229739643_Prediction_in_Ungauged_Basins_A_Grand_Challenge_for_Theoretical_Hydrology/links/59e3590c0f7e9b97fbeaf828/Prediction-in-Ungauged-Basins-A-Grand-Challenge-for-Theoretical-Hydrology.pdf>.

Sivapalan, M 2003b, 'Process complexity at hillslope scale, process simplicity at watershed scale: Is there a connection?', p. 7973.

Sivapalan, M, Takeuchi, K, Franks, S, Gupta, V, Karambiri, H, Lakshmi, V et al. 2003, 'IAHS decade on predictions in ungauged basins (PUB), 2003–2012: shaping an exciting future for the hydrological sciences', *Hydrological sciences journal*, vol. 48, no. 6, pp. 857-880.

Sokolov, AA & Chapman, TG 1974, 'Methods for water balance computations'.

Song, X, Zhang, J, Zhan, C, Xuan, Y, Ye, M & Xu, C 2015, 'Global sensitivity analysis in hydrological modeling: Review of concepts, methods, theoretical framework, and applications', *Journal of Hydrology*, vol. 523, pp. 739-757.

Srinivasan, R & Arnold, JG 1994, 'Integration of a basin-scale water quality model with GIS', *JAWRA Journal of the American Water Resources Association*, vol. 30, no. 3, pp. 453-462.

Stehr, A, Debels, P, Romero, F & Alcayaga, H 2008, 'Hydrological modelling with SWAT under conditions of limited data availability: evaluation of results from a Chilean case study', *Hydrological Sciences Journal*, vol. 53, no. 3, pp. 588-601.

Stoll, S & Weiler, M 2010, 'Explicit simulations of stream networks to guide hydrological modelling in ungauged basins', *Hydrology and Earth System Sciences*, vol. 14, no. 8, pp. 1435-1448, <https://www.hydrol-earth-syst-sci.net/14/1435/2010/hess-14-1435-2010.pdf>.

Swain, JB & Patra, KC 2017, 'Streamflow estimation in ungauged catchments using regionalization techniques', *Journal of Hydrology*, vol. 554, pp. 420-433, DOI https://doi.org/10.1016/j.jhydrol.2017.08.054, <http://www.sciencedirect.com/science/article/pii/S0022169417305802>.

Szilagyi, J 2020, 'Water Balance Backward: Estimation of Annual Watershed Precipitation and Its Long-Term Trend with the Help of the Calibration-Free Generalized Complementary Relationship of Evaporation', *Water*, vol. 12, no. 6, p. 1775, ProQuest Central; SciTech Premium Collection, DOI http://dx.doi.org/10.3390/w12061775.

Talchabhadel, R, Shakya, NM, Dahal, V & Eslamian, S 2015, 'Rainfall runoff modelling for flood forecasting (A case study on West Rapti watershed)', *Journal of Flood Engineering*, vol. 6, no. 1, pp. 53-61, <https://www.researchgate.net/profile/Rocky_Talchabhadel4/publication/271585048_RAINFALL_RUNOFF_MODELLING_FOR_FLOOD_FORECASTING/links/54ccbcd40cf29ca810f58105.pdf>.

Talchabhadel, R & Sharma, R 2014, 'Real time data analysis of west Rapti River basin of Nepal', *Journal of Geoscience and Environment Protection*, vol. 2, no. 05, <https://www.researchgate.net/profile/Rocky_Talchabhadel4/publication/269764691_Real_Time_Data_Analysis_of_West_Rapti_River_Basin_of_Nepal/links/549643ca0cf20f487d2f5a7e.pdf>.

Tamalew, C & Kemal, A 2016, 'Estimation of discharge for ungauged catchments using rainfall-runoff model in Didessa sub-basin: The case of Blue Nile River', *International Journal of Innovations in Engineering Research and Technology (IJIERT)*, vol. 3, no. 9, pp. 62-72, DOI 10.1177/154193120605001782.

Tassew, BG, Belete, MA & Miegel, K 2019, 'Application of HEC-HMS Model for Flow Simulation in the Lake Tana Basin: The Case of Gilgel Abay Catchment, Upper Blue Nile Basin, Ethiopia', *Hydrology*, vol. 6, no. 1, p. 21, <https://www.mdpi.com/2306-5338/6/1/21>.

Tegegne, G & Kim, YO 2018, 'Modelling ungauged catchments using the catchment runoff response similarity', *Journal of Hydrology*, vol. 564, pp. 452-466, DOI 10.1016/j.jhydrol.2018.07.042, <https://www.scopus.com/inward/record.uri?eid=2-s2.0-85050183424&doi=10.1016%2fj.jhydrol.2018.07.042&partnerID=40&md5=1daefd2bb018b4ca341fd2b44f1c332f>.

Tomy, T & Sumam, KS 2016, 'Determining the adequacy of CFSR data for rainfall-runoff modeling using SWAT', *Procedia Technology*, vol. 24, pp. 309-316, DOI https://doi.org/10.1016/j.protcy.2016.05.041, <http://www.sciencedirect.com/science/article/pii/S2212017316301256>.

Tung, Y-K 2011, 'Uncertainty and reliability analysis in water resources engineering', *Journal of Contemporary Water Research and Education*, vol. 103, no. 1, p. 4.

UNDP 2019, *Human development report 2019: Inequalities in human development in the 21st century*, United Nations Development Programme.

Uniyal, B, Jha, MK & Verma, AK 2015, 'Parameter identification and uncertainty analysis for simulating streamflow in a river basin of Eastern India', *Hydrological Processes*, vol. 29, no. 17, pp. 3744-3766, DOI https://doi.org/10.1002/hyp.10446, <https://onlinelibrary.wiley.com/doi/abs/10.1002/hyp.10446>.

USAID 2018, *Jhimruk Khola watershed profile: Status, challanges, opportunities for improved water resource management*, USAID/Nepal, Nepal.

USDA 2009, 'Hydrologic soil groups', in *National Engineering Handbook*, Part 630 - Hydrology.

van Griensven, A, Meixner, T, Grunwald, S, Bishop, T, Diluzio, M & Srinivasan, R 2006, 'A global sensitivity analysis tool for the parameters of multi-variable catchment models', *Journal of Hydrology*, vol. 324, no. 1, pp. 10-23, DOI https://doi.org/10.1016/j.jhydrol.2005.09.008, <http://www.sciencedirect.com/science/article/pii/S0022169405004488>.

Wagener, T & Wheater, HS 2006, 'Parameter estimation and regionalization for continuous rainfall-runoff models including uncertainty', *Journal of Hydrology*, vol. 320, no. 1-2, pp. 132-154, DOI 10.1016/j.jhydrol.2005.07.015, <https://www.scopus.com/inward/record.uri?eid=2-s2.0-33644505802&doi=10.1016%2fj.jhydrol.2005.07.015&partnerID=40&md5=6ae21b8d60ba8c53ea1b8ee0cacd9f33>.

WECS 1982, *Hydrological studies of Nepal*, His Majesty's Government of Nepal, Ministry of Water Resources Wanter and Energy Commission Secretariat and Department of Hydrology and Meteorology, Kathmandu, Nepal.

WECS 1990, *Methodology for estimating hydrological characteristics of ungauged locations in Nepal*, His Majesty's Government of Nepal, Kathmandu, Nepal.

WECS 1994, *Perspective energy plan: Energy synopsis report*, Water and Energy Commission Secretariat (WECS), Kathmandu, Nepal.

WECS 2005a, *National Water Plan (NWP)*, Water and Energy Commission Secretariat, Government of Nepal.

WECS 2005b, *National water plan Nepal (2002-2027)*, Water and Energy Commission Secretariat (WECS), Singhadurbar Kathmandu, Nepal.

WECS 2011, *Water resources of Nepal in the context of climate change*, Water and Energy Commission Secretariat (WECS), Singhadurbar Kathmandu, Nepal.

Worku, T, Khare, D & Tripathi, SK 2017, 'Modeling runoff–sediment response to land use/land cover changes using integrated GIS and SWAT model in the Beressa watershed', *Environmental earth sciences*, vol. 76, no. 16, p. 550, DOI 10.1007/s12665-017-6883-3, <https://doi.org/10.1007/s12665-017-6883-3>.

Yang, X, Magnusson, J, Rizzi, J & Xu, C-Y 2017, 'Runoff prediction in ungauged catchments in Norway: Comparison of regionalization approaches', *Hydrology Research*, vol. 49, no. 2, pp. 487-505, DOI 10.2166/nh.2017.071.

Yen, H, Wang, X, Fontane, DG, Harmel, RD & Arabi, M 2014, 'A framework for propagation of uncertainty contributed by parameterization, input data, model structure, and calibration/validation data in watershed modeling', *Environmental Modelling & Software*, vol. 54, pp. 211-221, DOI https://doi.org/10.1016/j.envsoft.2014.01.004, <http://www.sciencedirect.com/science/article/pii/S1364815214000139>.

Zhang, L, Hickel, K, Dawes, WR, Chiew, FHS, Western, AW & Briggs, PR 2004, 'A rational function approach for estimating mean annual evapotranspiration', *Water Resources Research*, vol. 40, no. 2, DOI https://doi.org/10.1029/2003WR002710, <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2003WR002710>.

Zhang, Y & Chiew, F 2009a, 'Evaluation of regionalisation methods for predicting runoff in ungauged catchments in southeast Australia', *18th World IMACS Congress and MODSIM09 International Congress on Modelling and Simulation, eds. RS Anderssen, RD Braddock & LTH Newham, Modelling and Simulation Society of Australia and New Zealand and International Association for Mathematics, Cairns, July*.

Zhang, Y & Chiew, F 2009b, 'Relative merits of different methods for runoff predictions in ungauged catchments', *Water Resources Research* vol. 45, DOI 10.1029/2008WR007504.

Zhao, F, Wu, Y, Qiu, L, Sun, Y, Sun, L, Li, Q et al. 2018, 'Parameter uncertainty analysis of the SWAT model in a mountain-loess transitional watershed on the Chinese loess plateau', *Water*, vol. 10, no. 6, pp. 690-706, ProQuest Central; SciTech Premium Collection, DOI 10.3390/w10060690, <http://dx.doi.org/10.3390/w10060690>.

Zou, KH, Tuncali, K & Silverman, SG 2003, 'Correlation and simple linear regression', *Radiology*, vol. 227, no. 3, pp. 617-628.