Glacio-Hydrological Modelling of Dudh Koshi River Basin, Nepal

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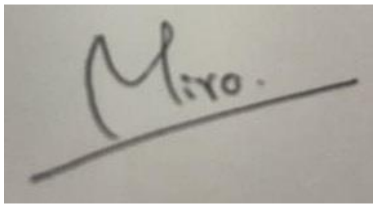
Author's declaration

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.



Mira KHADKA

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Abstract

This study analyzed the hydrological regime of a glaciated alpine catchment; Dudh Koshi River Basin, Nepal using SWAT, a process based hydrological model and a degree-day model, T-index. Temperature and Precipitation trends were also studied based on past time-series hydro-meteorological datasets. The simulated runoffs from both models were compared against the observed discharge and the temperature and precipitation trends were analyzed statistically. The results indicated that Dudh Koshi catchment is very sensitive to increase in temperature and precipitation changes and the overall runoff is most likely to increase in the future for a certain period of time along with extreme changes in glacier areas and higher frequency of climate-induced disasters.

Keywords: Dudh Koshi River Basin, SWAT, T-index, Climate Change, Rainfall Runoff, Snowmelt Runoff, Glacier melt Runoff

Acknowledgement

Working with hydrological models without prior experience in this field was very challenging for me. However, after completing this research, I feel more confident about my research skills and this study was a great learning experience for me in developing a better understanding of hydrological and cryospheric regimes in Nepal Himalayas.

I would like to thank my supervisor Dr. Stephen Boult and my advisor Dr. Andrew Lowe for supporting me with technical difficulties throughout the research. This research would not have been possible without their constant motivation and valuable feedbacks.

I would also like to thank Mr. Binod Parajuli, hydrologist at Department of Hydrology and Meteorology, Government of Nepal, for helping me to collect the secondary data used in this research and for his insightful suggestions based on the previous study conducted in river basins in Nepal.

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List of Abbreviations

SRTM Shuttle Radar Topographic Mission

DEM Digital Elevation Model

ICIMOD International Centre for Integrated Mountain Development

SWAT Soil and Water Assessment Tool

RCM Regional Climate Model

GCM Global Climate Model

HKH Hindu Kush Himalayan Region

1. Introduction

The Hindu Kush Himalayan (HKH) region, also known as “the freshwater tower of South-Asia” and sometimes as “the third pole”, extends over 3,500 kilometers passing through Pakistan, Afghanistan, India, China, Nepal, Bhutan, Myanmar and Bangladesh and it is the largest mountain system in the world. HKH region has the highest concentration of snow and ice including glaciers outside the polar regions and it provides water to ten major river basins of Asia; Amu Darya, Brahmaputra, Ganges, Indus, Irrawaddy, Mekong, Salween, Tarim, Yangtze and Yellow (Figure 1). The Himalayas provide water for agriculture, hydropower generation, industry, drinking and sanitation purposes and supports livelihood of 210 million people living in the mountains and over 1.3 billion people living downstream (Dixit et al., 2009). The region has high ecological significance as it is home to four global biodiversity hotspots, 488 protected areas (Pas), 330 important bird areas (IBAs), 29 Ramsar sites, and 60 ecoregions (Shrestha et al., 2016). HKH region has been playing a significant role in influencing global climate regulation as it forms an ecological buffer and separates the Tibetan Plateau from South Asia (Shrestha et al., 2016).

Figure 1 The Hindu Kush Himalayan Region and its major river basins (Source: ICIMOD)

The application of hydrological models in sustainable water resources management is equally important for scientific studies as well as policy formulations and decision-making. Hydrological models have been proven very helpful in understanding the water balance, availability and distribution in the river basin and when climate models are integrated in the hydrological models, future climate scenarios for the watershed can be predicted and this information can be further used in minimizing the possible uncertainties due to climate change. The physically based models (like SWAT) provide in depth understanding of physical characteristics of a watershed and every important parameter influencing the water quality and quantity are taken into consideration. Conceptual models like T-index represent the watershed at a conceptual level. Despite the differences in model processes, all hydrological models have their own strengths in analyzing the hydrological regime of watershed. However, all models are prone to certain limitations and such factors should be taken into account while estimating and analyzing the results. While working in the mountain ecosystem, hydrological models can help in developing a better understanding of the physiographic features of the areas that are inaccessible due to complex topography. IPCC (2007) identified the Himalayan region as an area that lacks scientific information on climate change impacts and hydrological regime and it is crucial to apply hydrological models in this region to expand the available scientific information. Past studies especially related to climate change prediction of hydrological systems in this region don't seem to have same conclusions and this shows that uncertainty exists here due to climate change. IPCC (2013) suggested that the variation in model projections mainly occur when the research is carried out in a smaller scale.

The temperature in the HKH region has been rising faster than the global average and scientific studies have shown that the temperature of the region will increase by 2.5 to 5 C by 2100 and the precipitation is also likely to increase in the coming decades (Immerzeel et al., 2012). Kumar et al. (2011) projected that the Indian summer monsoon rainfall will increase by 20% by the end of this century. These climate scenarios are very likely to influence the cryospheric dynamics and hydrological regimes of the region eventually affecting the water balance, availability and distribution in the mountain and downstream areas. It has been reported that with increase in precipitation along with net glacier melt (due to the rise in temperature), the annual runoff of the region will increase and the total water availability will be maintained until mid-century, however, with rapid glacier retreats and low snowfall in the region due to rising temperature, the region will be facing severe water shortages after mid-century (Immerzeel et al., 2013; Lutz et al., 2014). A scientific study carried out by Bohner and Lehmkuhl (2005) predicted that the snow cover area might decrease by 43-81% by 2100 with an increase in temperature by 1-6 C at higher altitude in Asia. The changing climate is also likely to increase the climate induced hazards like Glacier Lake Outburst Floods (GLOFs), flash floods, landslides, avalanches, droughts and soil erosion in the region that might affect the seasonal water availability in the region and can cause loss and damage of lives and properties in a large extent (IPCC, 2007). Most of the countries in HKH region are poor and developing nations with limited capacity to adapt to such disasters. It is also essential to sustainably manage the water resources for the socio economic growth of these countries. However, in this region, it is very challenging to formulate and implement policies and management strategies on water management because of the current scenarios of Climate Change. According to Bharati et al. (2016) the impacts of Climate Change are very uncertain in this region.

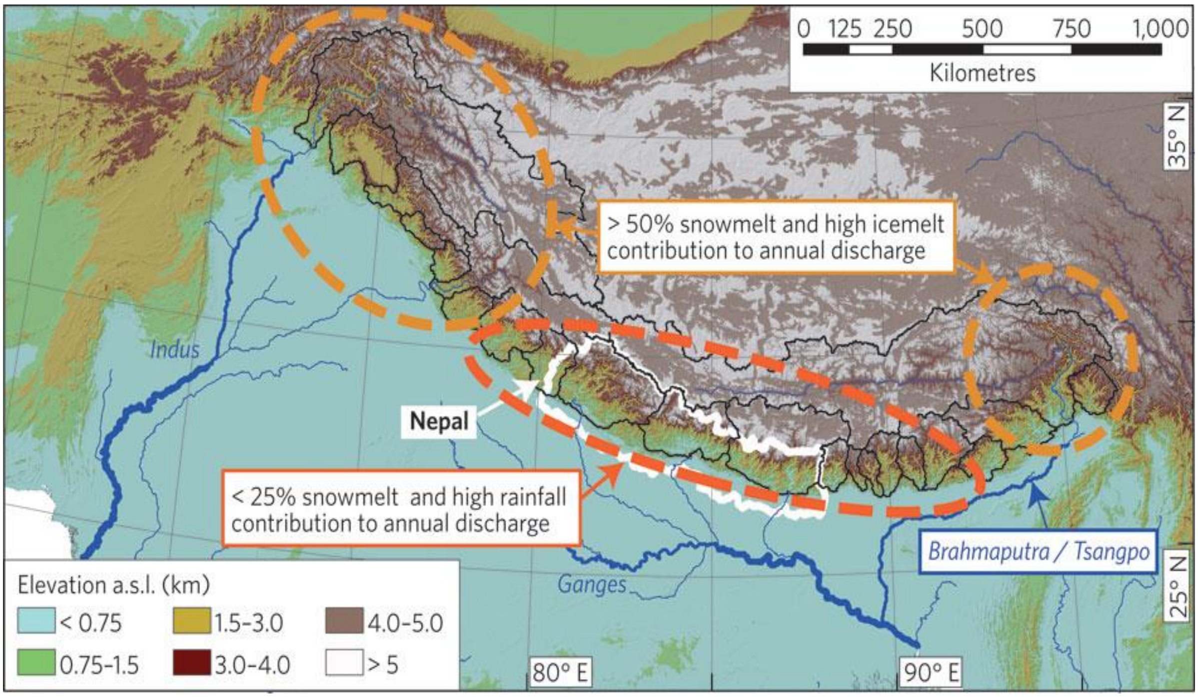

Figure 2 Contribution of different runoff components in HKH region (Source: Nature.com)

Several researches have been carried out in this region to study the impact of changing climate in the hydrological regime, but the complexity of hydrological and glacier systems, unavailability of data and inaccessible topography have been causing difficulties in significant scientific study of the region. These factors are also responsible for the uncertainties in the results (Nepal, 2015). The scientific studies in Himalayas are mostly done in a larger scale, however, the geology, topography and climate vary within different watershed and it is crucial to conduct researches at a smaller catchment scale to develop in depth understanding of the watershed system and its changing nature under climate change scenarios.

The main motivation for conducting this research is to understand how a small glacierized alpine catchment (Dudh Koshi River Basin) in the Himalayas has been changing under the past and present climate scenarios especially the runoff components (rainfall runoff, snowmelt and glacier melt runoff) of the river basin.

The major objectives of this research are:

i. To analyze the temperature and precipitation trends in Dudh Koshi watershed based on the historical time series climate datasets.
ii. To analyze the runoff pattern of Dudh Koshi River using SWAT and T-index models.

1.1 Study Area

Dudh Koshi River Basin (3712 km^2), one of the major sub-basins of Koshi River Basin in eastern Nepal (Figure 3) was used as the study area for the research. The selected study area has steep topography with elevation ranging from 400 m to 8848m (height of Mt. Everest). The climate varies from temperate (with deciduous forests) in the lower elevation to sub-alpine/alpine (with coniferous forests) in the higher elevation (Nepal et al., 2015). The physiography of the basin ranges from the high Himalayas above 3000 masl with glaciers and permafrost to the lesser Himalayas below 3000 masl and most of the anthropogenic activities like agriculture and urban settlements occur in the lesser Himalayan region. Dudh Koshi River Basin is a glacier-dominated river basin with 13% of the catchment covered by glaciers in the higher elevation. Data from one temperature station and four precipitation stations located within the study area was used as the input data for models. In Dudh Koshi sub basin, almost 82% of the rainfall occurs during the monsoon season (June – September) and about 77% of the runoff occurs during the same period (Nepal et al., 2015).

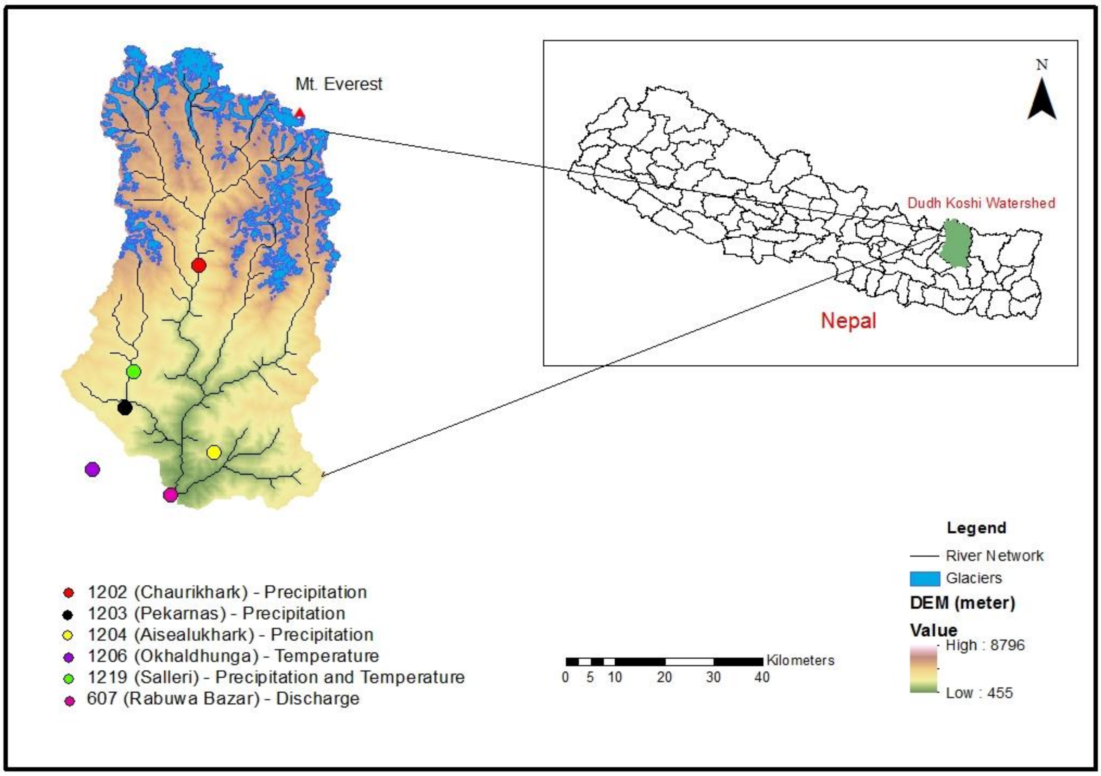

Figure 3 Location of Dudh Koshi Watershed and climate and discharge stations (Created in ArcGIS)

1.2 Model Description

1.2.1. Soil and Water Assessment Tool (SWAT)

SWAT (Arnold et al., 1998) is a process based, semi-distributed and time continuous watershed model that is mostly used for rainfall-runoff modelling. In this research, Arc-SWAT has been used which is an ArcGIS/ArcView extension of SWAT. Theoretically, Arc-SWAT divides the catchment to sub-basins and sub basins are further divided into Hydrological Response Units (HRUs). Each HRU (functional unit) represents a part of the catchment with similar land use, soil type and topography and these factors are essential components affecting runoff significantly. This feature of Arc-SWAT is a significant advantage for this research considering the spatial heterogeneity of the catchment. SWAT estimates the hydrological parameters and runoff at the HRU scale and in order to simulate the runoff at the catchment scale (the outlet of the watershed), a weighted average of HRU results is taken and the runoff is routed. The detailed description of SWAT model can be found in Arnold et al. (1998) and Srinivasan et al. (1998).

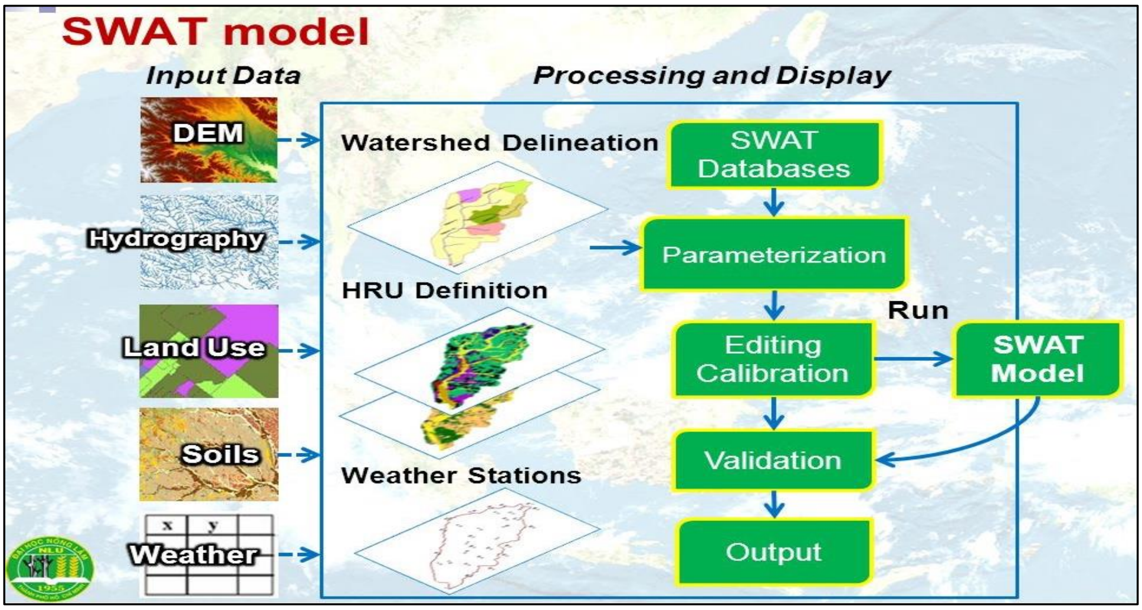

Figure 4 Conceptual framework of SWAT model (Source: SlidePlayer.com)

1.2.2. Temperature index or T-index (Degree – day Model)

Temperature index (Braithwaite and Olesen, 1989) is one of the simplest yet powerful model that uses air temperature data to simulate ice and snow melt and in this research this model has been used for hydrological modelling (melt modelling) although it has wide range of other applications from study of ice dynamics, flood forecasting to climate sensitivity. Generally, there are two types of melt models, a. Energy Balance Model that estimates runoff/melt as a residue of heat balance equation and b. Temperature Index Model that assumes an empirical relationship between air temperatures and melt rates. T – index models are often thought to perform better than energy balance models on a catchment scale (Hock, 2003). The empirical formula used in the T-index model is given below.

$$At(z) = DDF snow/ice \sum_{t=1}^{t=n} \gamma \, Tair(z)$$

Where A = Ablation rate for a given elevation zone at time interval t

DDF= Degree factor for snow or ice

T air = Air temperature for a given elevation zone

2. Data and Methodology

2.1 Hydro – Meteorological Data

Hydrological (Discharge) and meteorological (Temperature and Precipitation) data was collected from Department of Hydrology and Meteorology (DHM), Government of Nepal for one discharge station, one temperature station and three precipitation stations within Dudh Koshi watershed. As Dudh Koshi River Basin is a glaciated alpine catchment with few of the world's highest peaks, the topography of the region makes it difficult for the installation of climate and hydrological stations for government and private sectors.

The station number and location are given in Table 1.

Station	**Index No.**	**Data type***	**Data Period (Year)**	**Latitude (degree)**	**Longitude (degree)**	**Elevation (masl)**
Rabuwa Bazar	670	D	1964-2014	27.27	86.66	670
Salleri**	1219	P,T	1948-2015	27.5	86.58	2378
Chaurikhark	1202	P	2008-2015	27.7	86.71	2619
Pekarnas	1203	P	2008-2015	27.43	86.56	1982
Aisealukhark	1204	P	2008-2015	27.35	86.75	2143
Okhaldhunga***	1206	T,P	1962-2015	27.31667	86.5	1720

Table 1 Details of hydro-meteorological stations

*D=Discharge, P=Precipitation, T=Temperature

**Precipitation data from 1948-2015 from this station was used for precipitation trend analysis and data from 2008-2015 was used as model input data for both models

*** Temperature data from this station was used for temperature trend analysis and both precipitation and temperature data were used to fill the missing values for some months in stations 1219, 1202, 1203 and 1204. Data from this station (1206) was not used as model input as it lies outside the watershed region but it is very closer to the watershed, hence the data from this station was used to fill the missing values.

2.2. Geo - spatial Data

DEM, Land use map and soil map were used to run Arc-SWAT and glacier map and clean ice and debris map were used in T-index model.

2.2.1. Digital Elevation Model (DEM)

The NASA Shuttle Radar Topographic Mission (SRTM) DEM data with 90m resolution was downloaded from the CGIAR Consortium for Spatial Information (CGIAR-CSI) website. Initially, the DEM data was downloaded for Nepal and using the clip function for raster data in ArcGIS, the DEM data for Dudh Koshi catchment was obtained.

2.2.2. Land Use Map

Land use data for Dudh Koshi watershed was extracted (using clip function in ArcGIS) from Land Cover of Nepal 2010 raster dataset (30 m resolution) downloaded from Regional Database System (RDS) of International Centre for Integrated Mountain Development (ICIMOD) website.

2.2.3. Soil Map

The soil map for Dudh Koshi catchment was extracted (using clip function in ArcGIS) from Digital Soil Map of the World provided by Food and Agriculture Organization (FAO).

2.2.4. Glacier Map

The glacier map for Dudh Koshi watershed was extracted (using clip function in ArcGIS) from digital polygon data of Status of Glaciers in Koshi Basin, Nepal during the period of 2002-2008 which was provided by

ICIMOD. The dataset was created using Landsat ETM+ imageries of respective years and 90m resolution SRTM DEM.

2.2.5. Clean ice and Debris Map

The clean ice and debris map for the glaciers in HKH region (excluding China) was provided by ICIMOD and the dataset for Dudh Koshi watershed was extracted in ArcGIS. ICIMOD had created the dataset using 200 Landsat 7 ETM+ images of 2002-2008 and 90m resolution SRTM DEM.

2.2 Methods

While starting the research, the initial idea was to obtain snowmelt/rainfall runoff from Arc-SWAT and glacier-melt runoff from T - index and combine both simulated runoff results to estimate the total runoff of the watershed and analyze the contribution of rainfall, snow/ice melt and glacier melt in the total runoff of the watershed. However, combining both model results required programming through Python, MATLAB, etc. and due to the limited time availability for this research, that process couldn't be carried out and the results were analyzed and discussed separately.

The selection of appropriate hydrological model was one of the most challenging aspects of this research due to the unavailability of data in the region and the complex topography of the watershed. SWAT, a process based model used in this research, has a default module for snowmelt and rainfall runoff; however, it lacks a module for glacier melt. Hence, a glacier runoff model or melt model (T - index) was used to simulate the glacier melt runoff of the watershed. It was very essential to study the glacier melt factor as Dudh Koshi River Basin is a glaciated catchment and glacier melt runoff contributes significantly in the total runoff especially in the pre and post-monsoon season.

The methodology for both models is discussed below in detail.

2.2.1 Arc-SWAT

The SWAT Model was used as Arc-SWAT, an Arc-GIS/Arc-View interface where a new project was set up as an initial step and the next step was to delineate the chosen watershed. DEM data and river network shapefile was provided as the input data and after selecting the outlet of the watershed, the model delineated the watershed area from the DEM with reach, monitoring points, outlet and longest path incorporated in the watershed area.

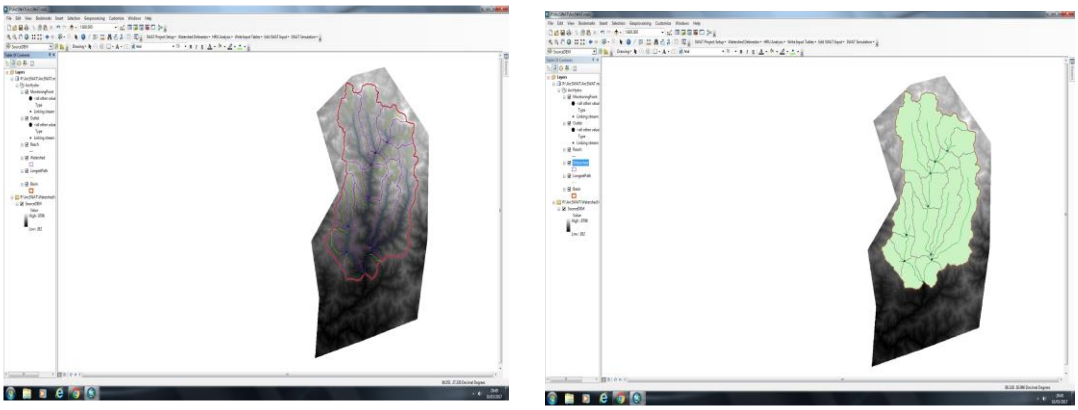

Figure 5 and 6 Watershed Delineation processes in Arc-SWAT

The third step was HRU definition where land use and soil data were provided to the model along with values for slope and elevation bands. The model divided the watershed into 3 sub basins and 50 HRUs based on the land use and soil types of the region. The HRU analysis report gave detailed physiographic information of each sub basin and HRU and this information was very valuable in understanding the physical nature of watershed and analyzing the possible runoff scenarios. After HRU definition, the locations of weather stations were added to the model database and then the weather files (.txt) were provided to the models. In this study, temperature (one station) and precipitation (four stations) data from 2008-2015 were used as weather input data and the model simulated the wind, solar and humidity parameters. The final step was to run the model and runoff values were obtained from output.rch file that provided runoff for each sub basin. The weighted average of the sub basin runoffs (Flow Out) was taken the model was routed to estimate the overall runoff the watershed.

2.2.2 T – index

The average daily temperature of maximum and minimum temperatures from 2008-2015 was calculated and it was integrated in the model along with the rainfall data for the same period of time. The climate data from Salleri station (1219) was used to run the model. 0.3 and 0.7 were used as Degree Day Factor (DDF) for snow and ice respectively. A research study done by Tiwari et al. (2015) estimated that the annual precipitation in the Himalayas remain in the form of snow in a significant proportion at high altitudes above 3000m in both summer and winter and the snowmelt rate varies spatially all over the region due to the disparity in surface temperatures and accumulated snow amount. The snowmelt rate in the Himalayas lies between 0.02 to 0.6 cm/C/day and in the region with height over 4000m; the melt coefficient is usually 0.5 cm/C/day or higher (Tiwari et al., 2015). The climate station elevation (2378 m), snowline elevation (4480m) and lapse rate (0.3 C per 100 m; 4.5 C per elevation zone) were used in the model. Using lapse rate in this model was very helpful as the temperature data for higher elevation zones were not available and lapse rate minimized certain errors that would have occurred due to the unavailability of temperature data. The glacier region of the watershed was divided into three elevation zones and the glacier areas were estimated for respective elevation zone using glacier map (2002-2008) from ICIMOD.

The table below shows three elevation zones with respective glacier area.

Elevation zone (z)	Zone interval (m)	Elevation (m)	Elevation (m)	Total Area (Km2)	Glacier Area (Km2)	Non-Glacier Area (Km2)	% glacier
	1500	**Min**	**Max**				
zi	4000-5500	4000	5500	1301	147	1154	11
zii	5501-7000	5501	7000	434	267	167	62
ziii	7001-8500	7001	8500	25	1	24	4

Table 2 Elevation zones and glacier area in Dudh Koshi catchment

The model estimated the ice melt runoff, rain runoff and snow melt runoff for each elevation zone and the averages of all those runoff components were taken for each elevation zone. The storage coefficient (k) was used to calculate the quick flow and slow flow in the area and later a time lag of four hours was used and the storage factor was integrated to calculate the final glacier melt runoff (Lag 4 hr per z + store).

3. Results and Discussion

The models used in this research are susceptible to uncertainties and have certain limitations due to the conceptualization of hydrological processes and those factors are well considered in the simulated results. Comparison of simulated results from different models is crucial to minimize the uncertainties that occur due to the conceptualization of hydrological processes in the model (Nepal et al., 2015). The simulated runoffs were compared with the observed discharge data to study the performance of the used models. Same input data and time period were used in both models to make the comparison between two models easier and for an effective statistical analysis of the results.

3.1. Temperature/Precipitation Trend Analysis

3.1.1. Temperature Trend Analysis

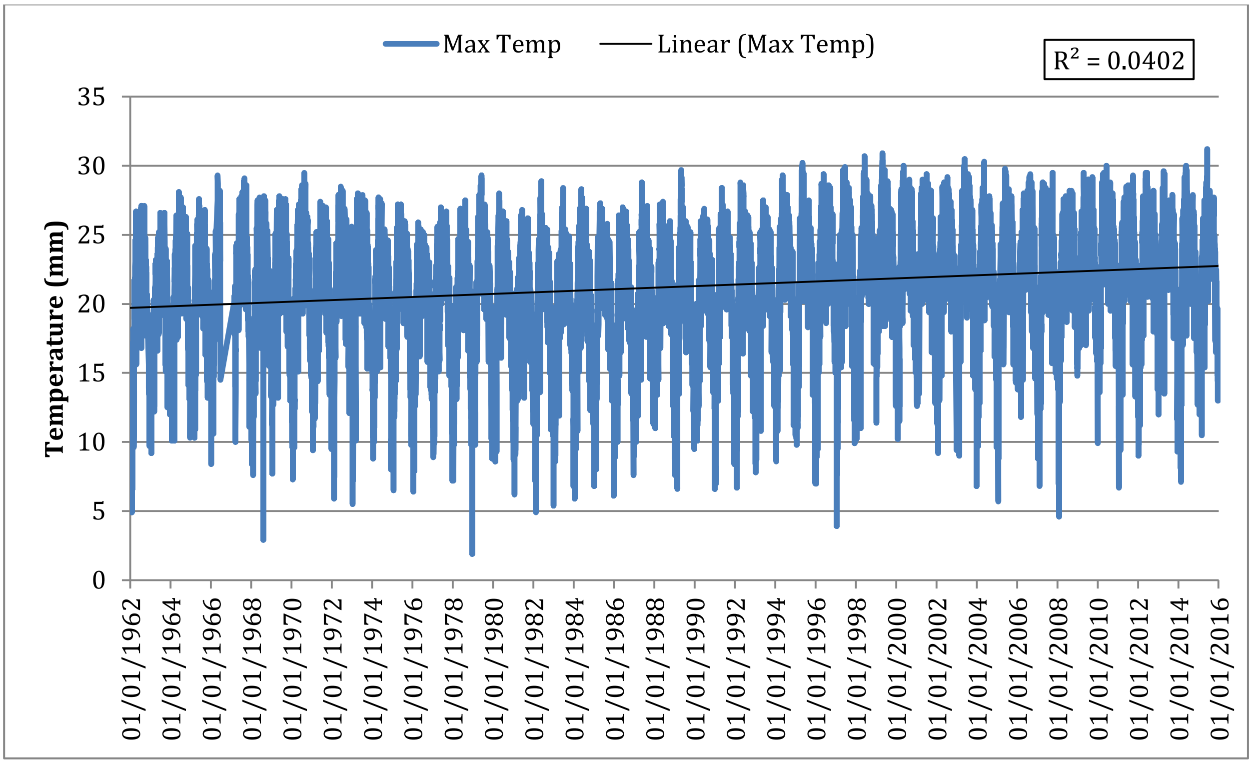

Figure 7 Maximum temperature from 1962 – 2015 (Station: Okhaldhunga)

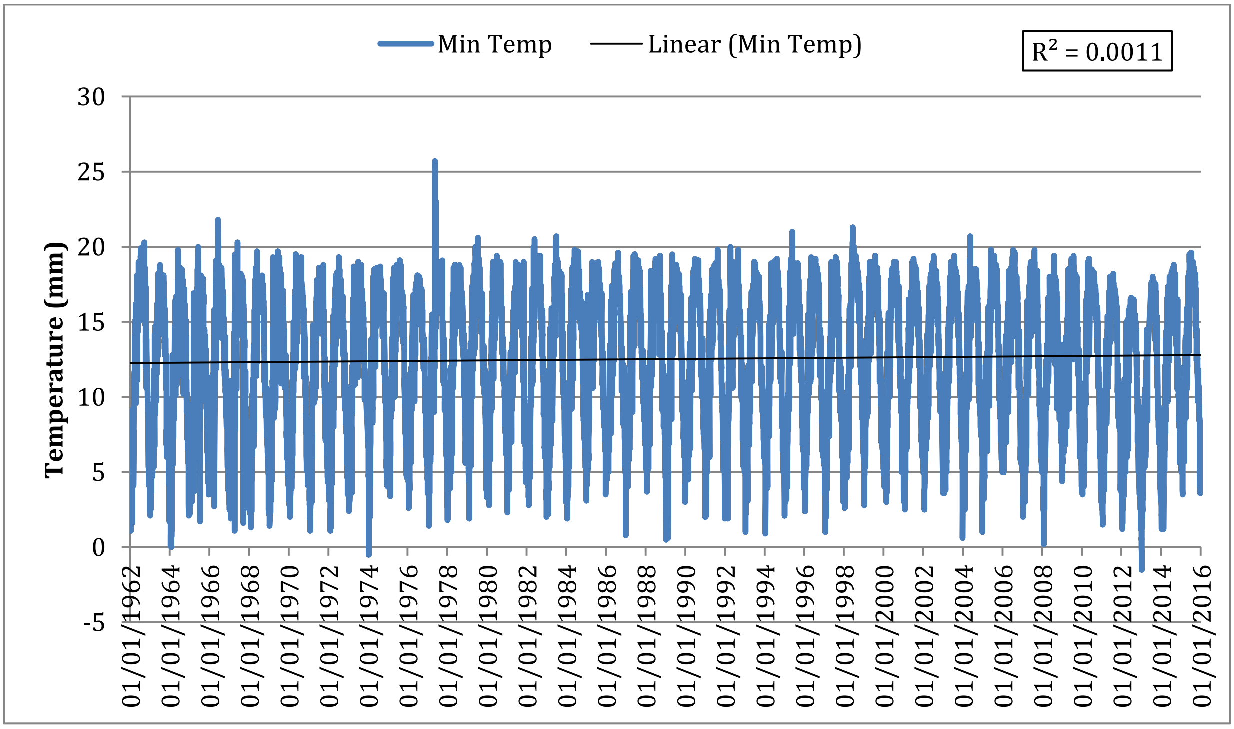

Figure 8 Minimum temperature from 1962 – 2015 (Station: Okhaldhunga)

As shown in Figure 7 and 8, the maximum and minimum temperatures in the Dudh Koshi watershed have been showing an increasing trend. The temperature analysis done in this region by other researchers (Bharati et al., 2016; Nepal 2016; Rajbhandari et al., 2016) show a similar increasing trend and this changing temperature pattern has already started affecting the glaciers of the Himalayas. Temperature directly affects the snowfall, evapotranspiration and both of these components are essential in determining water availability in terms of timing and quantity. Snowfall plays a vital role in maintaining the glaciers in higher altitude and when the snowfall decreases due to increase in temperature, it accelerates the glacier retreat processes. A study done by (Rajbhandari et al., 2016) projected that the highest increase in temperature in this region will be over the high Himalayan areas. This temperature change will shift the snowline upwards causing a significant decrease in the snow storage capacity in the watershed (Nepal, 2016).

The lower elevation region of Dudh Koshi watershed is mainly covered with forests and agricultural areas and increase in temperature will increase the moisture holding capacity of the atmosphere and when there is more moisture in the atmosphere, it changes the rainfall pattern in the region significantly affecting the vegetation. The moisture holding capacity of the atmosphere increases by 7% with every 1 °C rise in global temperature (NERC).

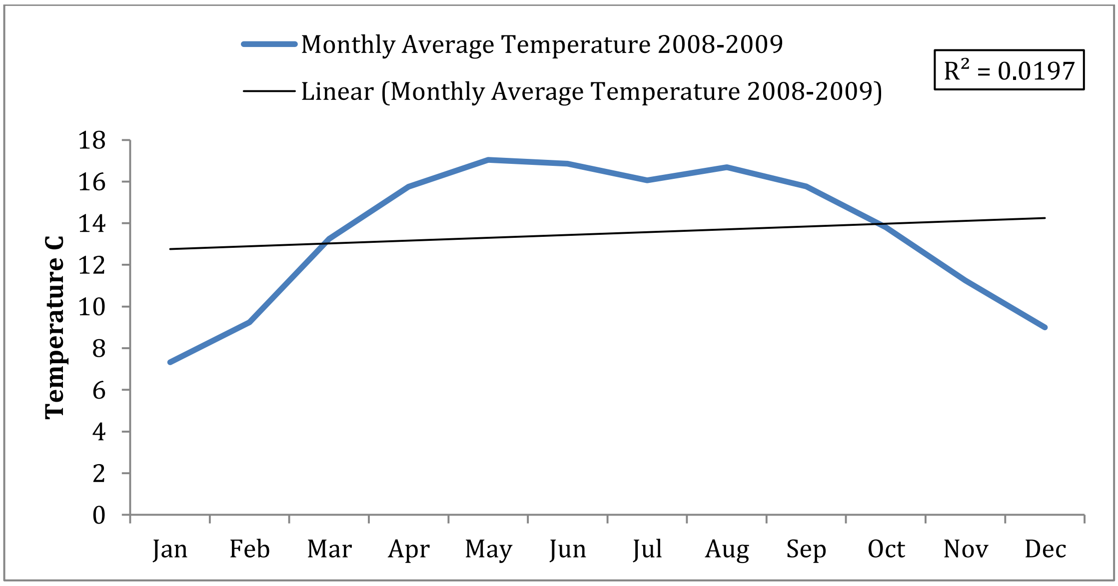

Figure 9 Monthly average temperatures over a period of 2008-2009

Understanding the seasonal variation of temperature is important because this region is monsoon dominated and hence most of the precipitation and runoff occur in the summer season and extreme variation of temperature seasonally can bring significant changes in the hydrological regime of the region.

3.1.2. Precipitation Trend Analysis

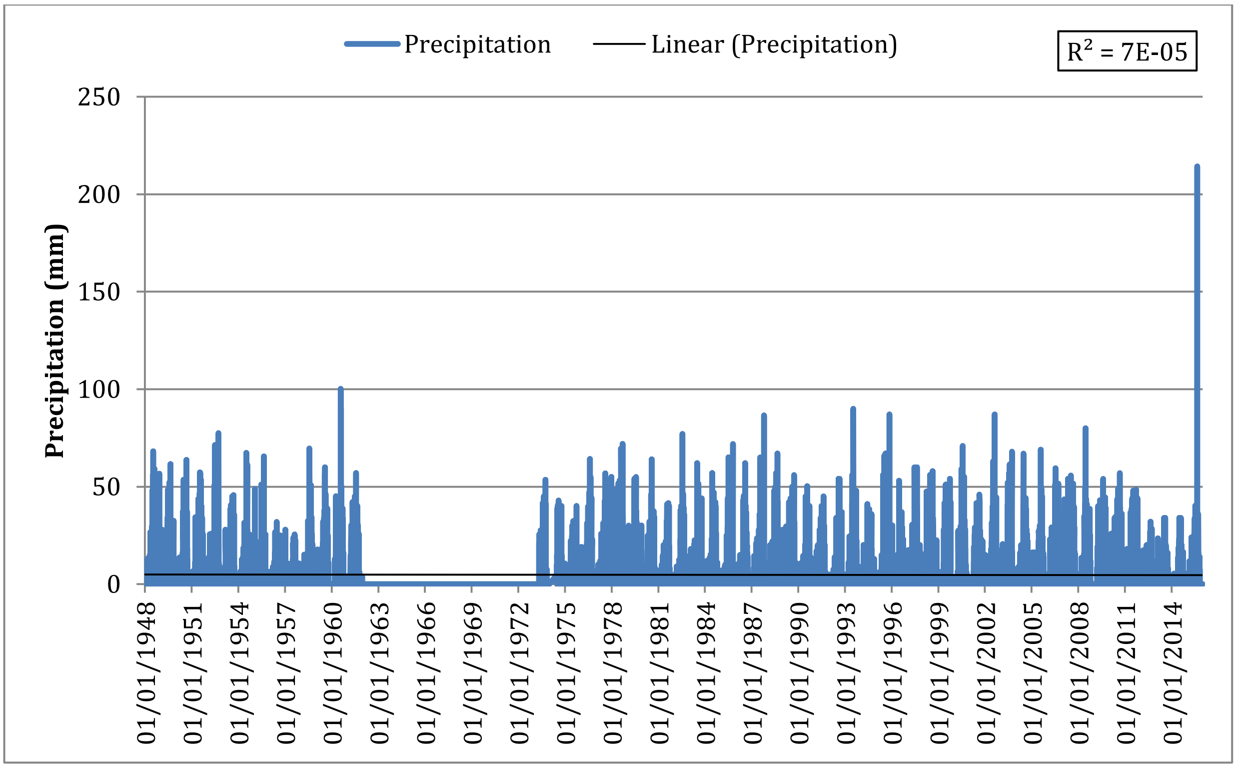

Figure 10 Precipitation data from 1948 – 2015 (Station: Salieri)

The past and current precipitation trends in the region are very fluctuating but looking at the Figure above, it seems clear that there have been some extreme precipitation events in the past and such events contribute significantly to river runoff. Dudh Koshi Watershed lies within a wide range of elevation zone (400-8848 m) with land surface changing from hills to mountains and climate varying from temperate to alpine. As a result of these factors, the spatial distribution of the precipitation in this region varies significantly. Moreover, due to the Monsoon influence, there is also seasonal variation in the precipitation intensity. Almost 82% of the precipitation takes place during the monsoon season (June to September) and during this season the precipitation pattern shows a significant temporal variation. However, the distribution of precipitation is similar during the winter season (December to February) when there is lesser amount of precipitation. The winter rainfall along with pre-monsoon (March to May) and post-monsoon (October and November) rainfall is quite deficient as compared to the monsoon rainfall. During winter season, the river runoff mainly depends on glacier melt and snowmelt runoff from higher altitudes and this available water in the river basin is crucial for irrigation in the low-lying areas. Hence, a seasonal analysis of precipitation distribution in this region is important under different climate change scenarios.

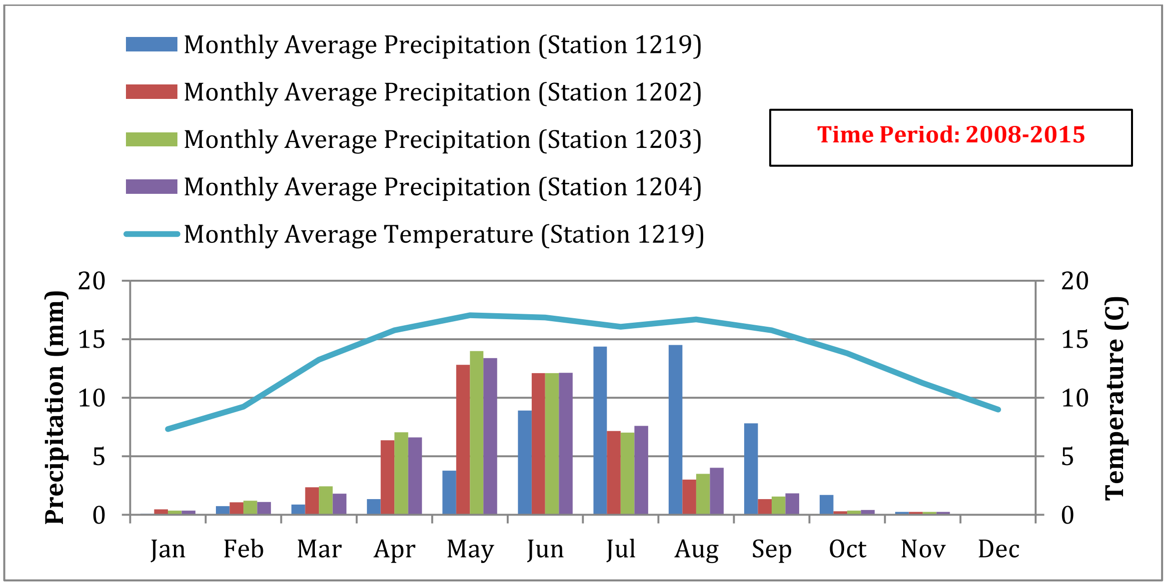

Figure 11 Monthly average precipitation and temperature over a period of 20085-2015 for different climate stations

A climate projection study conducted in this region by (Rajbhandari et al., 2016) based on CMIP5 GCMs for RCP4.5 scenario estimated that the rainfalls will most likely increase by 5 – 25% until mid-century and it shows that the overall water availability will slightly increase in future. However, the author has also highlighted that the monsoon season might get wetter and winter drier, which can cause intense flood events in the summer and droughts in the winter and it will directly affect the livelihood of thousands of people living in the river basin. This seasonal variation in rainfall changing the runoff of the river is more likely to affect the hydropower generation of mountain rivers.

Considering the scenario of increasing temperature rise, the precipitation in higher altitude that falls as snow will change to rainfall and that will affect the glacier retreat processes and snow accumulation in the mountains.

3.2. Runoff Analysis

3.2.1. Observed Discharge

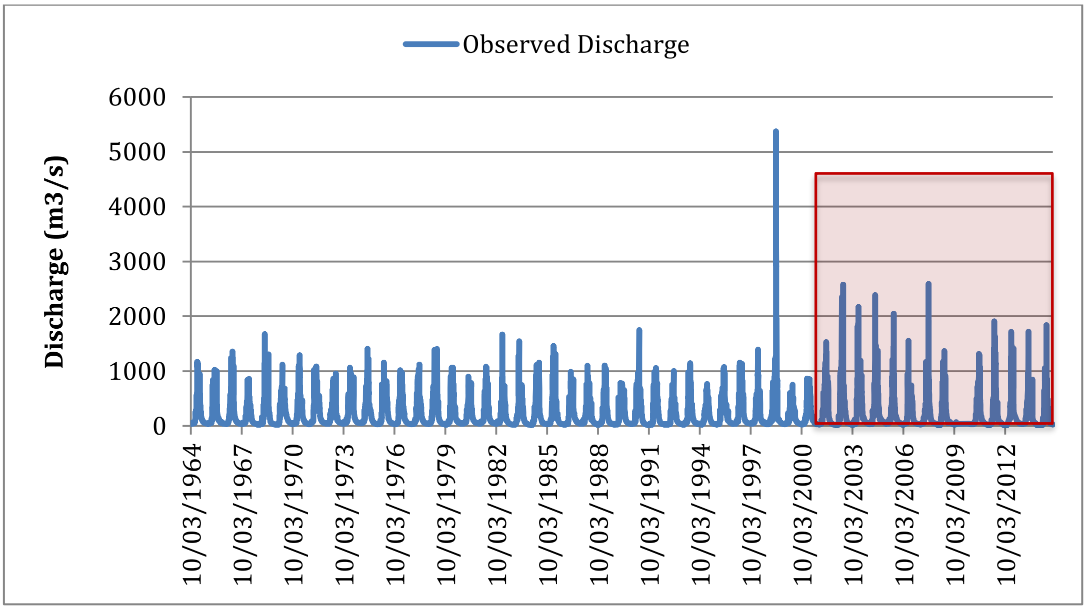

Figure 12 Daily observed discharge during the period of 1964-2014 (Station: Rabuwa Bazar)

Figure 12 clearly demonstrates that the discharge has been increasing in the Dudh Koshi watershed and the recent increase in discharge has been highlighted in the figure. The discharge (particularly surface runoff) is generally very high in this watershed because of its steep topography, the fan-shaped catchment and large number of tributaries in the lower elevation region. It is a glaciated sub basin and hence the contribution of glacier melt to overall runoff is very significant and the rocky surface in glaciated region increases the surface runoff unlike lower elevation region which has sandy soil and therefore more infiltration and less surface runoff. Most importantly, the increasing discharge has raised concerns over the uncertainty due to changing climate. Increase in discharge is most likely to intensify the climate-induced disasters like Glacier Lake Outburst Floods (GLOFs), floods and landslides and it is crucial to study the past, present and future discharge pattern of climate sensitive catchments.

Hydrological models have been extensively used to study the role of physical characteristics of a watershed and temperature and precipitation changes on river runoff. Such models can also integrate the results from Global Climate Models (GCMs) and Regional Climate Models (RCMs) and effectively predict the future runoff trends in the basin. Similar approach has been adopted in this study; however, the climate change scenario analysis has not been performed. The runoff results from models used in this study will be discussed in further sections.

Nepal (2016) conducted a related research in the same sub basin using J2000 hydrological model and in that research, the climate change scenarios were incorporated in the hydrological model using Providing REgional Climates for Impact Studies Regional Climate Model (PRECIS RCM). The author suggested that the future projected climate change scenarios is most likely to affect the surface runoff in the region which will increase by 27% in mid-century and 25% in late century with respect to baseline (2000-2010). This increase in surface runoff can be explained by the increased precipitation in the monsoon season when the soil is saturated and the rainfall-runoff coefficient is high. Also, the rise in extreme precipitation events can cause higher runoff. The interflow is expected to increase by 5% for both 2050 and 2100 study periods; however, the base flow is predicted to decrease by 2 and 5% in 2050 and 2100 respectively. The increase in surface runoff will decrease the infiltration and hence the decrease in base flows. Khadka et al. (2015) estimated that the magnitude and frequency of peak flows will mostly likely increase under the climate change scenarios and there will also be a significant increase in the contribution of the snowmelt to total river runoff.

3.2.2. Rainfall/Snowmelt Runoff (Arc-SWAT)

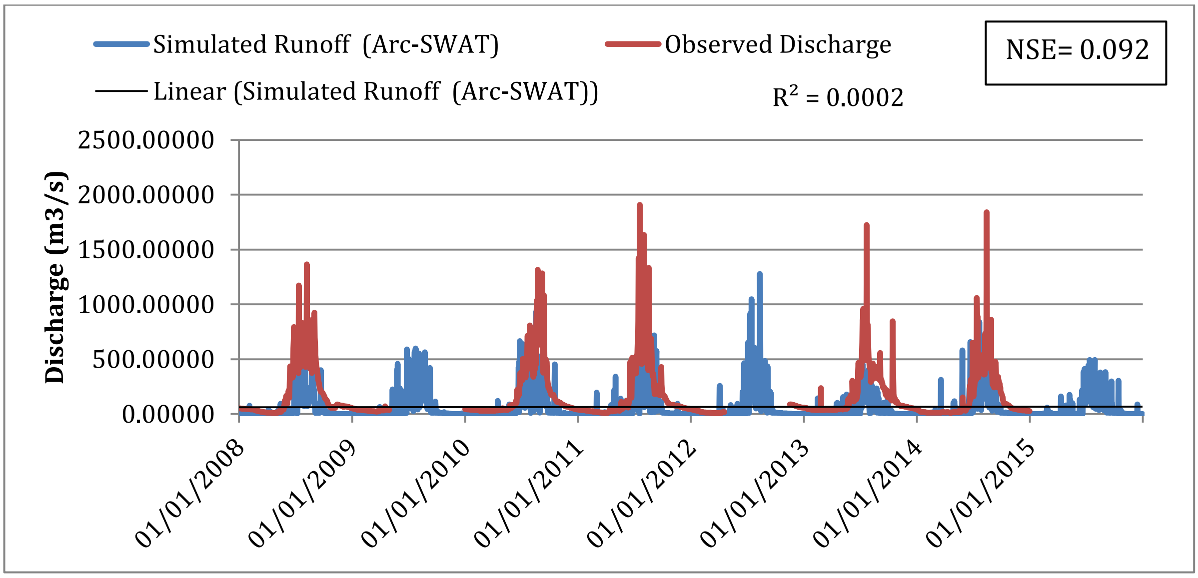

Figure 13 Daily Observed and Simulated Runoff (Arc-SWAT) during the period of 2008-2015

Arc-SWAT estimates the runoff for every sub basin and the weighted average is taken in order to calculate the runoff for overall catchment. The simulated runoff from Arc-SWAT seems low compared to the observed discharge. However, while looking at the individual sub basin created by Arc-SWAT, Sub basin 1 and 2 are located in the low elevation areas with mostly dense vegetation and sandy soil and surface runoff is reduced largely due to the loss of water through interflow and base flow. Sub basin 3 lies in the high elevation zone with rocky and steep topography and also has large number of glaciers.

The table below shows a detailed description of the annual observed discharge for a period of 2008-2015 and annual simulated runoff of three different sub basins of Dudh Koshi watershed created by Arc-SWAT for the same time period.

Year	Average Annual Observed Discharge (m3/s)	Average Annual Simulated Runoff (Sub basin 1) (m3/s)	Average Annual Simulated Runoff (Sub basin 2) (m3/s)	Average Annual Simulated Runoff (Sub basin 3) (m3/s)
2008	185.2762	7.97	6.966	135.5
2009	35.24583*	7.132	6.233	192.4
2010	194.1005	7.279	6.362	200.9
2011	181.1304	6.348	5.548	213.1
2012	34.60006*	3.832	3.349	213.1
2013	173.2145	6.324	5.527	135.6
2014	146.3586	5.643	4.931	205.5
2015		11.39	9.959	152.9

Table 2 Average annual observed discharge and average simulated annual runoff of three sub basins of Dudh Koshi catchment generated by Arc-SWAT

*The observed discharge data for the year 2009 (May-Dec) and 2012 (19 Apr – 15 Nov) were missing and the missing gaps were not filled due to the lack of nearby discharge stations.

3.2.3. Glacier-melt Runoff (T-index)

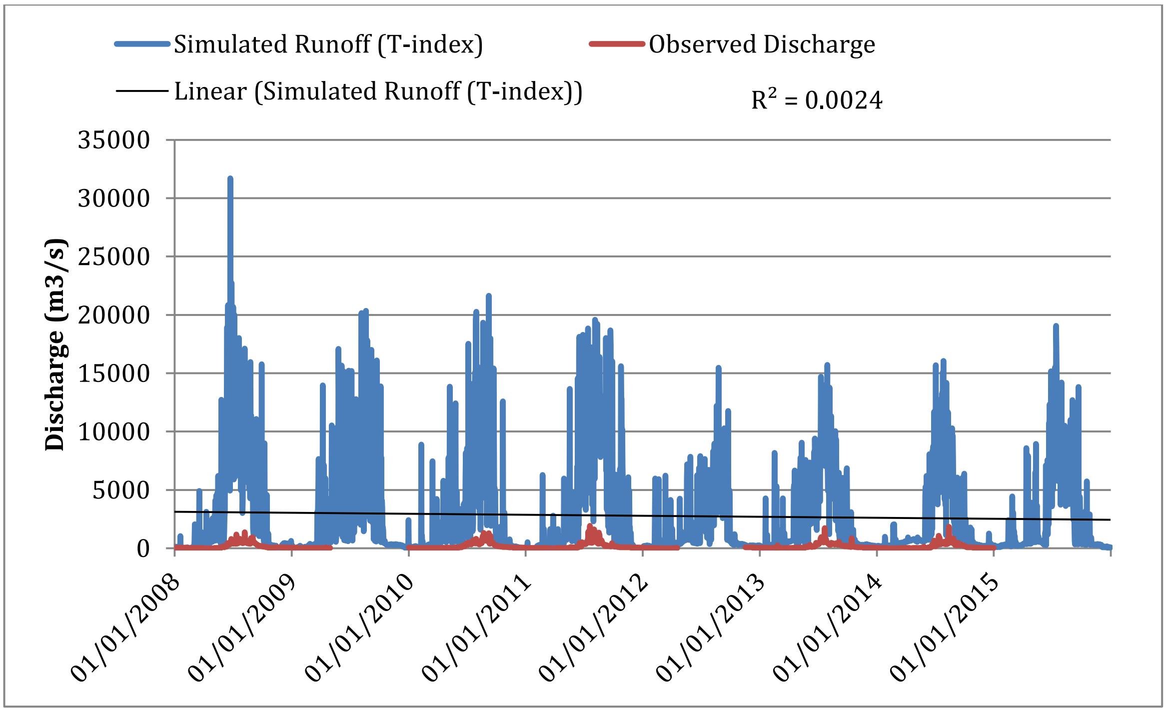

Figure 14 Daily observed and simulated (T-index) discharge

In this model, while estimating the runoff, only that section of the watershed was considered that has glaciers (above 4000m). The glaciated part of the watershed was further divided into three elevation zones and the glacier area was calculated for each elevation zone using the glacier map from ICIMOD. The glacier melt runoff estimated from this model includes the glacier snowmelt, glacier ice melt and runoff from rainfall on the glacier and an average of all these components was taken into account to calculate the total glacier runoff. Further, a time period of four hours was incorporated in the model as lag time. Lag time signifies the amount of time taken by glacier melt runoff to reach the river network.

In this model, the clean ice and debris characteristics of the glacier wasn't taken into account however it is well known that those factors hugely influence the glacier melt. The melt is lower in the debris-covered glaciers compared to clean ice covered glaciers because debris decreases the ablation rate in the glaciers. The clean ice and debris map prepared by ICIMOD for a period of 2002 -2008 for the Himalayas showed that 12.8% of glaciers in the Dudh Koshi catchment are covered with debris and 87.2% of the glaciers are covered with clean ice. As the number of clean ice covered glaciers is higher in the Dudh Koshi catchment, the glacier melt runoff is expected to be higher.

Previous researches have indicated that the exact future of glaciers and changes in amount of glacier melt runoff from Dudh Koshi catchment are unknown and the uncertainties due to current climate scenarios will make the situation worse as cryospheric regions are more sensitive to changing climate. As mentioned in the introduction section, the glacier melt will most likely increase until mid-century and then decrease toward the end of the century due to reducing number of glaciers and snowfall.

Hock (2005) mentioned that the variations in glacier runoff under climate change scenarios are complex and hence it is very challenging to simulate the response in a model system. Hock (2005) indicated that timescale is an important factor in understanding the response of glacier runoff to climate change. Rees and Collins (2006) predicted that the runoff for most glaciated sub basins of the Himalayan region may increase up to 150 and 170% of initial flow until 2050 and 2070 in the west and east respectively, later there will be a decrease in the flow and the respective glaciers might disappear in 2086 and 2109.

Assumptions and Limitations

While working with hydrological models, one of the most important factors influencing the result is the quality of input data. In this research, filling the missing gap for temperature data minimized certain errors in input data; however, it was not possible to evaluate the quality of input data statistically due to the time limitation for this research. Also, the calibration and validation of hydrological models is crucial in order to verify the quality of output results. In previous researches, for calibration and validation, the simulated results were compared to results from nearby watershed and the models were calibrated and validated for a certain period of time. In this research, the results were compared with the observed data to analyze the results.

Arc-SWAT was very helpful in understanding the physical characteristics of selected watershed and mainly the role of runoff factors (land use, soil types and shape of the catchment) in influencing the overall runoff of the river. However, Arc-SWAT can be more accurately used in analyzing the water quality of river basin and it showed lesser efficiency while estimating the runoff the watershed.

T-index model significantly estimated the glacier melt runoff considering all runoff components like glacier snowmelt, glacier ice melt and rainfall runoff, however, the changes in glacier area over a certain time period was not included in the model. The changes in glacier area largely affect the glacier melt runoff especially in the region like Dudh Koshi watershed whose glaciers are sensitive to climate change. As mentioned in the results and discussion chapter, this model has not integrated the clean ice and debris factor and this could be another major limitation of the model.

Conclusion

The study of hydrological and cryospheric dynamics in the Hindu Kush Himalayan region is a very challenging task considering the inaccessible topography, unavailability of data and uncertainties due to climate change. In order to use results from scientific studies for decision-making, more advanced studies should be carried out in both smaller and larger scales with higher resolution of climate and spatial data. Comparing the results from different hydrological and climate models is crucial to minimize uncertainties that occur due to the conceptualization of model processes. As Nepal is a poor country with limited financial and human resources, the adaption strategies to cope with the uncertainty due to changing climate and climate-induced disasters should be strategically planned based on reliable scientific information. Although it is quite challenging to appropriately assess the changes in hydrological regimes in the Himalayas, the scientific community can develop a network for sharing information and can agree on certain conclusions to develop effective adaptation and mitigation strategies. As mentioned in the methodology section, there is a possibility of further analysis of this research through data correction and combining simulated results from both models to study the runoff contribution from rainfall, snow/ice melt and glacier melt. This future research will be helpful in understanding the water balance of the region and its influence on water availability and distribution.

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