Impact of Climate Change on Snow melt in Marshyangdi River Basin of Nepal

A Dissertation submitted to the Central Department of Hydrology and Meteorology in Partial fulfillment of the Master's Degree of Science in Meteorology

Submitted by
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Letter of Recommendation

This is to certify that Miss Anita Tuitui has prepared the dissertation entitled **"Impact of climate change on snow melt in Marshyangdi River Basin of Nepal"** to fulfill the partial requirement for the award of the Degree of Master of Science in Meteorology of the Tribhuvan University. It is the record of the candidate's own work carried by her under my supervision and guidance.

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Letter of Approval

The dissertation entitled, **"Impact of climate change on snow melt in Marshyangdi River Basin of Nepal"** Submitted by Ms. Anita Tuitui has been approved as a partial fulfillment for the Masters of Science in Meteorology to the Central Department of Hydrology and Meteorology, Tribhuvan University is hereby accepted.

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ABSTRACT

The climate change in general is the change in precipitation and temperature pattern which has potential impacts on economy, ecology and environment of Himalayas. Most of the studies of glacier melting and retreating are the main focus in Himalayas. Most of the study of glacier of Nepal shows that the glacier is undergoing rapid deglaciation. Snow and glacier melt contribution in Marshyangdi River have not been studied. Hence this study implemented the process-oriented distributed hydrological model J2000 model to investigate the contribution of snow and glacier melt in snow fed stream. The J2000 model able to distinguish between different runoff components including snow and glacier melt contribution. Hydrological modelling plays an important role in understanding hydrological process of a basin. The dynamically downscaled precipitation and temperature data were used for the future climate scenarios prediction for period of 2020-2050s, under the Representative Concentration Pathway's scenarios RCP4.5 and RCP8.5 scenarios. The downscaled RCPs data was used to run the distributed hydrological J2000 to study the climate change impacts on snowmelt of Marshyangdi River basin. Increase temperature in future scenarios results the increase snowmelt contribution. The result of the model show there was total 20% contribution of snow melt to stream flow which will increase by 29% and 38% in RCP4.5 and RCP8.5 scenarios respectively which shows the shifting of snowline to higher altitude in future due to the increase temperature.

The study shows that 5.4% increase of rain precipitation increases 14% of discharge in RCP4.5 scenario and 3.9% increase of rain precipitation increases 13% of discharge in RCP8.5 scenario. High snowmelt contribution in future scenarios increases the river discharge of study basin. The analysis shows the contribution of base flow will decrease whereas the overland flow will increase by 30% and 23% in RCP4.5 and RCP8.5 respectively. Actual evapotranspiration is highly affected by the climate change.

The non-parametric Mann Kendall and Sen's slope estimator for the trend analysis shows warming of the basin. And precipitation trend at northern part of basin is decreasing whereas the lower part of basin show increasing trend. With respect to the result of various runoff components, the overland flow RD1 will increase in future scenarios which conclude there will be increase of flood event in future.

Keywords: Climate Change, J2000 hydrological model, Snow melt, Runoff component.

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ACRONYMS AND ABBREVIATIONS

^{0}C	Degree centigrade
Act ET	Actual Evapotranspiration
CFC	Chlorofloro carbon
DEM	Digital Elevation Model
DHM	Department of Hydrology and Meteorology
GCMS	Global Climate Models
HRU	Hydrological Response Units
HWSD	Harmonized World Soil Database
ICIMOD	International Centre for Integrated Mountain Development
IPCC	Intergovernmental Panel on Climate Change
J2000	As a part of JAMS (Jena Adaptable Modeling System)
JAMS	Jena Adaptable Modelling System
LAI	Leaf Area Index
LPS	Large pore storages
m.a.s.l	meter above sea level
m^3/s	cubic meter per second
mm	Millimeter
MPS	Middle pore storages
PET	Potential Evapotranspiration
RCP	Representative Concentration Pathways
SRTM	Shuttle Radar Topography Mission
UGB	Upper Ganges Basin
UNFCC	United Nation Framework Conventions on Climate Change
WRF	Weather Research and Forecasting Model

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CHAPTER 1: INTRODUCTION

1.1 Background and Motivation

Nepal is a land-locked country located in South Asia between India and China. There is spatial climate variation from a subtropical to arctic climate from south to north. Nepal is divided into five geographic regions: Terai plan, Siwalik hills, Middle Mountains, High Mountains (consisting of the Main Himalayas and the Inner Himalayan Valleys), and the High Himalayas. It forms a barrier between the Tibetan plateau and the Gangetic plain along the southern slope of the Himalaya. Rainfall estimation in Nepal is very difficult because of steep slopes and rugged topography. The country is rich in water resources. There are more than 6000 rivers from the Himalayan Mountains to the hills and plains (Dixit, 1995). There are three major river systems in Nepal – the Koshi in the east, Gandaki in the centre, and Karnali in the west. All of them drain into the Ganges River basin, flowing through northern India and emptying in the Bay of Bengal. The hydrology of these rivers is largely dependent on the climatic conditions of the region, which in turn is a part of global climate. Most of the rivers are fed by melt water from over three thousands glaciers and provide sustained flows during dry seasons to fulfill the water requirements of hydropower plants, irrigation canals and water supply schemes downstream (Shrestha,2009).

Most of the rivers derive water from snow and glacier melt, spring and ground water recession for about eight months (October- May) (Pradhananga,2010). During this period the flow is in tranquil state. In the four months of the rainy season (June to September) all the rivers turn into a violent mass of water and sediment. Department of Hydrology and Meteorology (DHM) Nepal, has recorded that about 1500mm rainfall receives in a year (Dixit, 1995). The mean temperature of nation is around 15°C, which increase from north to south with the exception of mountain valleys. In the mid-hills, temperatures are between 12-16^{o}C, and in Terai region, winter temperatures are between 22-27^{o}C, while summer temperatures exceed 37^{o}C (Dhakal K., et al., 2010). In monsoon period more than 80% of the rainfall is occurs. Although annual rainfall is abundant, its distribution is of great concern: flooding is frequent in the monsoon season during the summer, while droughts are not uncommon in certain regions in other parts of the year. The glacier retreat; and changes in timing and intensity of precipitation contribute to increased variability of river runoff. In addition, decreased winter snowfall means less precipitation would be stored on the glaciers, so this would in turn decrease the spring and summer runoff. Winter runoff, on the other hand, would increase due to earlier snowmelt and a greater proportion of precipitation falling as rain.

Any systematic change in the long term statistics of climate elements (such as temperature, precipitation, pressure or winds) sustained over several decades or longer time periods is called Climate change. It is caused by factors such as biotic processes, variations in solar radiation received by earth, plate tectonics and volcanic eruptions. Certain human activities have also been identified as significant causes of recent climate change, often referred as global warming. According to IPCC, the increase in mean surface air temperature of the Northern Hemisphere was larger in 20th century than in any other period of the last 1000 years. United Nation Framework Conventions on Climate Change (UNFCCC) in its Article 1 defines climate change as a change of climate, which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods.

The temperature of earth is determined by balance between incoming solar radiation and outgoing terrestrial radiation of earth. The energy from solar radiation passes through atmosphere so some of the energy absorbed by various gases present in atmosphere as a result its heat the earth surface. Those gases are known as green house gases. Without this natural greenhouse gases the temperature of earth surface would be less than 30°C than it is, which would not be habitable. This natural phenomenon is disturbed by the addition of unnatural greenhouse gases such as CFCs and other toxic gases result of human activities which increase the temperature of the earth surface.

With respect to hydrology, climate change directly effects on the water resources resulting by change on hydrological cycles. The change in temperature and precipitation directly effects on runoff component. Snow and glaciers are very sensitive to temperature so increase temperature cause fast melting of snow and glacier as a result runoff in stream flow increases but later decreases the runoff as deglaciation.

The increase temperature may effects on the form of precipitation. Precipitation occurs only in liquid form so the snowfall reduces so that there will be decrease in snow cover land. Since the late 19th century, the global average surface temperature has increased by 0.6^{0}C ± 0.2^{0}C and it is projected to rise by 1.4 - 5.8^{0}C by 2100 (IPCC 2001). Decreasing snow cover and land-ice extent continue to be positively correlated with increasing land-surface temperatures. With increase of 1^{o}C air temperature, results 20 % of the present glaciated areas above 5000 meter altitude are likely to be snow and glacier free area. Similarly, 3^{o}C and 4^{o}C rise in temperature could result into the loss of 58 % and 70 % of snow and glaciated areas respectively (MoPE, 2004). Satellite data show that it is very likely that there have been decreases of about 10% in the extent of snow cover since the late 1960s.

1.2 Rationale of the study

The mountainous areas play a key role in hydrology because they usually receive high amounts of precipitation, which may be stored in the form of snow and glaciers. These areas provide essential freshwater for populations living in both upstream and downstream areas. The global increment of trends of climate change has become a serious issue. Climate change can greatly alter the water resources in mountain environments. Warmer conditions would most likely increase water withdrawals which in turn may alter the water supply demand balance in different regions of the world.

Warmer climate would initially increase the runoff due to glaciers melt and then decrease later as deglaciation processes. Water resources are inextricably linked with climate, so the prospect of global climate change has serious implications for water resources and regional development. If there is no balance between water supply and demand it affects a large area on agriculture. Agriculture water demand is considerably more sensitive to climate change. Climate change induced natural hazards such as floods landslide and droughts will impose significant stress on the livelihood of the mountain people and downstream populations.

Since glaciers are very sensitive to the temperature and precipitation changes associated with climate change, the rate of glacier growth or decline can serve as an indicator of regional and global climate change. Rising temperatures have caused glacier to melt and retreat faster and receding glacier means an increased risk of sudden flooding following glacier lake outburst. Nepalese river basins are spread over such diverse and extreme geographical and climatic condition that the potential benefits of water are accompanied by risks and hazard.

1.3 Objectives

The main objective of this study is to identify the possible impacts of the climate change on snow and glacier melt contribution in Marshyangdi river basin of Nepal. To analyze the impact of climate change on precipitation pattern and river discharge of Marshyangdi River Basin. Some of the specific objectives are as follows:

- To determine the yearly trend of meteorological (temperature and precipitation) information of Marshyangdi river basin.
- To analyze the impacts of climate change on discharge in the Marshyangdi river Basin.
- To determine different runoff components (surface, subsurface, base flow) including snow and glacier melt.
- To analyze the impacts of climate change on water balance component including snow melt contribution in river runoff.

1.4 Limitations

There are very few meteorological stations in high altitudes. Long term temperature, precipitation, and river flow data were available only at the lower levels. Thus, the trends of weather parameters at lower and higher altitudes for the longer period might not be the same. Furthermore, here inside the study basin the weather parameters like solar radiation, wind speed, relative humidity, and evaporation and transpiration data were not analyzed due to study limitations and unavailability of relevant data.

Following are the limitations taken into consideration in this study

- Uncertainties associated with the data.
- Limited resources.
- Lack of station density at Himalayan region of the basin.
- Due to lack of advance techniques, equipments and accountability on data collection, the stream flow data and meteorological data do not show consistency.
- Lack of sufficient number of temperature and precipitation station inside the basin.
- The J2000 model considers the static glacier area which considers the glacier area only. The glacier ice storage is unknown and therefore, ice melt occurs all the time. In the applied climate change scenario also, the increasing temperature cause higher ice melt and therefore not consider in the analysis.

CHAPTER II: LITERATURE REVIEW

2.1 Climate change

Himalayan snow and glaciers plays a major role for the stream flow in South Asia. Snow and Glacier melting is an important indicator for climate change in context of Nepal. Rapidly melting glaciers are resulting initial increase in river runoff, which will reduce after certain time period below a critical threshold and formation merging and expansion of glacial lakes in the stage of glacial lake outburst floods (Bajracharya, et.al, 2008). The global temperature rise continue to the 21 century and depending on the climate model and green house gases emission scenarios, the global mean temperature increases by 2100 could amount anything from 1.4 to 5.8^{o}C (IPCC report, 2001). The over proportional increase of surface temperature in Central Europe over the last 100 years in comparison to the global mean value of +0.6±0.2 K (IPCC, 2001; Mu¨ller-Westermeier and Kreis, 2002). There is decreasing trend in snow cover areas. The snow line is also found to be retreating and the glaciers in Himalaya are in retreat condition (Shrestha and Joshi, 2009). The annual snow-cover extent (SCE) has decreased by about 10% since 1966 over both the Eurasian and American continents of Northern Hemisphere. The increases temperature in snow covered areas resulting reduction in snow cover during the mid- to late 1980s (Shrestha and Joshi, 2009).

The increased temperature can change the form of precipitation. Higher temperature will increase the ratio of rain to snow. It accelerates the rate of snow and glacier melt. Also shorten the snowfall season. Rainfall gives high runoff than the snowfall. There is increased variability of river runoff due to changes in timing and intensity of precipitation as well as melting of snow and glaciers (Agrawala et al., 2003). Climate change incidence of extreme weather events such as droughts, storms, floods and avalanches is expected to increase.

The Himalayan Rivers are expected to be very vulnerable to climate change because snow and glacier melt water make a substantial contribution of their runoff. The Himalayan glaciers are melting faster in recent years than before (IPCC 2007).

Regional climate projections by the Intergovernmental Panel on Climate Change (IPCC, 2007) indicate by the end of the 21st century the Central Asia may warm by a median temperature of 3.7 °C. There is large variation in the glacier contribution and snow melt to total runoff over high Asia’s river basins, which is poorly quantified (Lutz A.F., et al., 2014).

2.2 Study based on impact of climate change on snow and glacier melt

Tanguang Gao, et al. (2011) analyzed the sensitivity of temperature and precipitation to the climate change. The study used the J2000 model for study of climate change impact. In this study, incremental climatic scenarios were used to assess climate change impacts. In this study, a ± 20% change in precipitation and a ±1^{o}C change in air temperature, in total, eight climate scenarios of J2000 model were used to assess the response of the river runoff and glacier melt to climate change. An increase in air temperature by 1^{o}C resulted in the increase of 14 and 41% in stream flow and glacier melt, respectively. Another interesting feature was that an increase in precipitation not only resulted in an increase in stream flow, but also caused a decrease in glacier melt. An increase in air temperature by 1^{o}C and in precipitation by 20% resulted in the highest increase (23%) in simulated stream flow. The highest increase (54%) in simulated glacier melt was due to the combination of 1^{o}C increase in air temperature and 20% decrease in precipitation. Decreased precipitation resulted in decreased stream flow in most scenarios in the Qugaqie catchment. However, the combination of decreased precipitation and increased temperature caused the increase of glacier melt in two out of three scenarios.

Vicuña Sebastian, et al., 2010 analyzed the direct impact of climate change on the hydrology of the snowmelt driven Limari river basin of range from 1000-5500m above sea level. The study used the meteorological and discharge data and also the baseline and two climate change projections (A2, B2) for the calibration of climate driven hydrology and water resources model. The result of this study shows the increased temperature decrease the precipitation with respect to baseline. The decrease of projected rainfall results the decrease of mean flow because of the increasing temperature which enhances water losses to evapotranspiration. The result shows that the increase in temperature during spring/summer and the lower snow accumulation in winter, there is maximum seasonal flow tend to occur earlier in future climate than in current conditions.

Julian M. M., et al., 2015 implemented the J2000 hydrological model to assess the impact of land use change and climate change on the hydrological dynamics of the upper Citarum River basin (UCB). The study used realistic based three scenarios such as land use change, precipitation change with keeping temperature constant and temperature variability with keeping precipitation constant. The result shows that the land use change increases the stream discharge whereas decrease of evaporation. As the forest land changes into residential land increases the overland flow. The study concluded that the increase temperature has less effect than the increase precipitation to the stream flow. The application of the J2000 hydrological model proved that the land use change has greater impacts on hydrological dynamics than the impact of climate change.

Welderufael W.A. 2010 conducted the stream flow analysis by using four base flow separation methods in quaternary catchment of Modder River. The stream flow is initially recharged by ground water. The used four methods are Nathan and McMahon (N &M) method, the Chapman method, the Smakhtin and Watkins (S&W) method, and the frequency duration analysis. The result showed that all method gives high percentage of the base flow except S&W method. The analysis concluded that the semi-arid catchment like Modder River with an average runoff coefficient of approximately 6%, there is negligible annual contribution of rainfall to direct runoff. The large contribution of ground water to the stream flow results the stream flow during long non-rainy periods. With the significance expansion of urban area, the amount of overland flow was estimated to be increased (Bugan R. D. H., et al.)

Pandey P. and Venkataraman (2012) studied the effect of climate change on the change in the length of Chhota Shigri glacier of Indian Himalayan Mountains. This studied used the remote sensing data and toposheet map of 1962 for study the change in glacier length from 1962-2008. The glacier has reduced an area of 0.19 square kilometers from 1962- 2008, with a standard deviation of 0.065046. From 1999-2008, the glacier retreated by about 190 meters. The analysis result that the glacier has retreated at a rate of 15 meters per year from 1999-2008. The study conducted the glacier area is in decreasing trend with $r^2 = 0.95$. The study purposed the important of the glacier length change for the melt and runoff modeling.

Nepal is highly vulnerable to the effects of climate change due to presence of climate-sensitive sectors such as glaciers, agriculture and forestry, and its low financial adaptive capacity (Karki, 2007). Shrestha and Joshi, (2009) concluded that there is decreasing trend in snow cover or glacier area in khumbu and langtang basin. The analysis concluded that the general lowering trend in the snowline elevation from east to west of the country. By the analysis of MODIS data, the snow cover extent over the country is highest during late winter and spring and lowest during summer monsoon season. The snow cover area shows dynamic nature and the variability during late winter and spring is quite large. The maximum snow cover areas is 53,000km2 (36%) and the minimum is 3,000 km2 (3.4%) in the six years of MODIS data. By using the remote sensing at Parbati glacier in Himachal Pradesh found that the glacier had retreated by 578m between 1990 and 2001, about 52m per year (kulkarni et.al, 2005).

Sharma, (1993), studied the important role of range of altitude in the contribution of melt water to the rivers downstream by analyzing the long term data. The melt water contribution to the stream is highest in the month before onset of monsoon. The snowmelt contribution is low in the post monsoon and winter when snow accumulation processes in the high mountains. The study concluded that the base flow of all major rivers in Nepal is maintenance from the groundwater. Himalayas contributes only 4% of the total annual stream flow volume of the rivers of Nepal (Alford D. and Armstrong R., 2010).

Bajracharya S.R., et al. (2008), analyzed the impact of climate change on Himalayan glaciers with past data. The study investigated the Himalayan glacier are retreating rapidly with range 10-60 meters per year and many small glaciers are disappeared because of increased temperature. There is increase size and number of glacier lakes due to glacier retreat in Himalayas. The rapidly growing and merging of several supraglacial on Thorthomi glaciers form larger lakes. Further the increase temperature expands the glacier lakes which results the glacier lake outburst floods (GLOF) events in Himalayas region.

Nepal S., et al., 2012 investigated the impact of land use change on Himalayan hydrology by using spatially distributed J2000 hydrological model. The study used land use change scenarios in order to study the impact of its on hydrological regime and different runoff components. The result showed that there is minimum impact on hydrology from vegetation change. Infiltration helps to understand the impact of land use change on hydrology. The study concluded that flood events will increase by deforestation however intense rainfall overshadows a vegetation role in the Himalayan region.

Chaulagain N.P., 2009 investigated the impacts of climate change on water resources of Nepal with reference to snow and glacier. The study analyzed the sensitivity of all glaciers upstream of Kyangjing hydrological station in the Langtang Valley in the Nepal Himalayas to the increases in temperature. The analysis has concluded that if the current glacier melting rate continues, the glaciers may disappear within less than two centuries in the study area of the Nepal Himalayas. The result showed most of the glaciers will disappear within 3-4 decades. About only 24% of glacier ice will left in the study basin of Nepal Himalayas by 2100AD even without any further increase of temperature. Due to the increased temperature increase proportion of the liquid precipitation which results decrease of seasonal storage. There is increasing temperature trends in the higher elevation in the northern part of the country compare to the lower elevation in the south and show the warming trends of 0.06^0C per year (Shrestha et al., 1999).

Bhattarai, 2011, has investigated the snow melt contribution in the stream flow of snow fed stream in order to understand the climate change on the water resources. The study used the positive degree day index integrated with snowmelt runoff model (SRM) to estimate the snowmelt from the catchment. The average snow melt contribution to the stream flow during summer is increased by 5% by increasing the temperature value 1^0C. The study concluded that the snowmelt contribution was increased during all seasons by projection of positive temperature rise.

Adhikari, et al. studied impact of climate change on water resources of Langtang Khola basin, Nepal by using the hydrological model HBV *Light 3 .0* and GCMs using SRES A2 and A1B Scenarios. The model has been projected on annual precipitation of 2050s for the both A2 and A1B scenario are 613.5 mm and 620.0 mm respectively. The study concluded the annual precipitation will increase 3.3% for A2 scenario and increase by 2.0 % for A1B emission scenarios. The study concluded the future precipitation will increase during all seasons except in autumn by precipitation projections. There is increase of maximum and minimum temperature in every seasons of 21st century for both A2 and A1B emission scenarios in GCMs projections. The simulated projects of the study gave there is increase maximum discharge for A1B scenarios. Whereas discharge decreases from 2050s to 2080s and again increases from 2080s in 21 century for both A2 and A1B scenarios.

Shrestha, (2009) studied the climate change impact on water resources and food production over Langtang valley. Also identify the adaptation strategies to reduce vulnerability due to environmental and climate change. The study includes the temperature and precipitation data analysis to identify the climate change trend and pattern during the time period 1987 to 2007. The study analyzed the increasing trend of warm days and cool nights in recent years. The study also analyzed number of extreme precipitation events (> 20mm/day) and heavy events (10-20 mm/day) are found higher in the latest decade (1997-2007) as compare with previous decade (1987-1996). The study analyzed the decrease of glacier from 45% to 35% for the year 1988 to 2000 with highest glacier cover in 1988 and lowest cover in 2000.

Menzel Lucas, et al., 2004 studied the impact analysis of global climate change on regional hydrology with special emphasis on discharge conditions and floods. The study simulated the runoff components for present climate by using a hydrological model HBV-D. Two different global circulation model and emission scenarios are used for the large scale atmospheric study.

The study focused on the impact of climate change on future runoff conditions. The result of the study shows there is increase in precipitation, mean runoff and flood discharge for small return periods.

Parajuli, et.al, used the HBV light model to simulate the discharge of Marshyangdi river basin by use three different scenarios. The model was run without glacier component, with glacier component and by increasing the temperature by 5% which results the decrease in stream flow in both with glacier component and without glacier component whereas the discharge was increased with respect to increased temperature. It was concluded that the Marshyangdi river basin is highly sensitive toward climate change.

2.3 Hydrological Models

The hydrology of the basin is governed by the type of basin where rivers originate. The hydrological models are simplified, conceptual representation of a part of the hydrologic cycle. They are primarily used for hydrologic prediction and for understanding hydrologic processes. Hydrological models conceptualize and investigate the relationship between climate and water resource. Such hydrological models are also used as means of extrapolation from those available measurements in both space and time into the future to assess the likely impact of future hydrological change. Changes in global climate have significant impacts on local hydrological regimes, such as in stream flows which support aquatic ecosystem, navigation, hydropower, irrigation system etc. Several hydrological models are presents in below but few major types of hydrologic models are famous which describe here under.

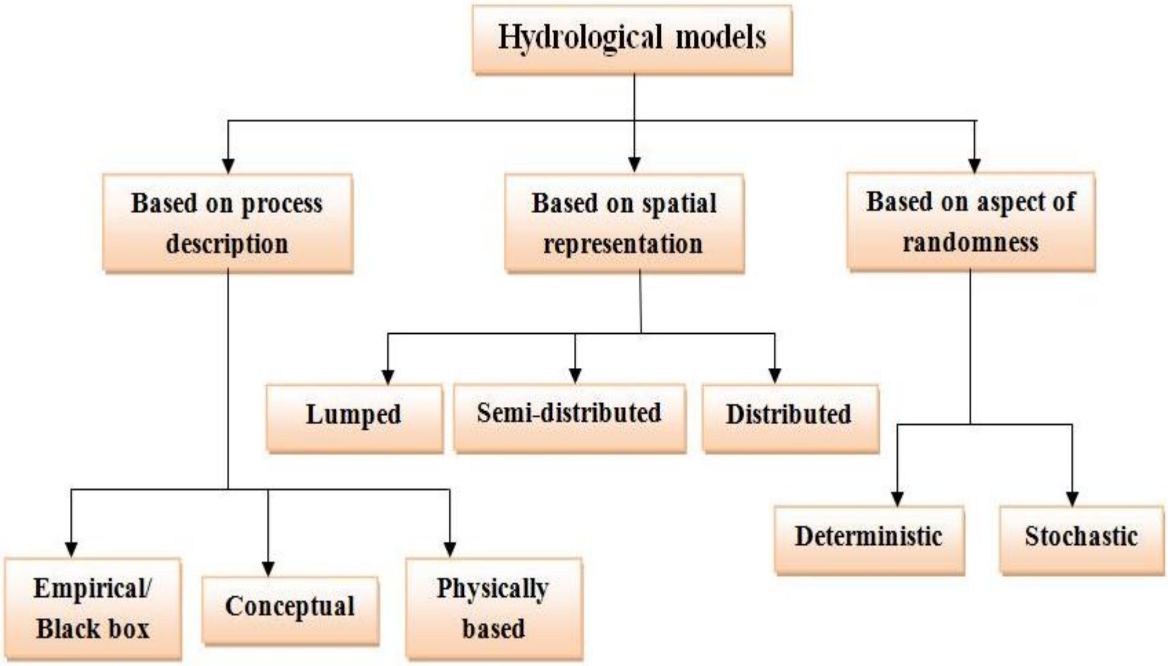


Figure2. 1 Type of Hydrological models

There are mainly three kinds of models ***based on process description*** as follows

Physically-based models, also known as "white"-box models, are fully based on laws of physics. They consist of a complex set of mathematical equations to represent the hydrological processes in a catchment. This approach can be used with some degree of confidence even when there is little data. Examples of such models are: the MIKE-SHE model (Jayatilaka et al. 1998), the PRMS/MMS model (Leavesley et al. 1983), the J2000 model (Krause 2002, 2001), and the HSPF (Bicknell et al. 1997).

Conceptual models, also known as "gray"-box models, are a combination of an empirical approach and simple functions of physical processes. Generally, this category of models considers physical laws with simplified form. The requirements of input data are less extensive than that of physically based models. Due to this nature, conceptual models are often preferred over physically-based models. Examples of conceptual models are SWAT (Arnold et al. 1993), HBV (Bergstroem 1976), QUAL-2K (Chapra and Pelletier 2003) and J2000g (Krause et al. 2009).

Empirical models, also known as “black”-box models or input-output model, do not take into account any physical processes. They consist of functions used to approximate or fit available data. Examples include simple regression models or water-balance/water-quality spreadsheet models.

Another classification is ***based on the spatial variability*** of system variables and parameters. Under this classification, the models are categorized into: distributed, semi-distributed and lumped models.

Lumped models, the whole catchment is considered as one unit and a relationship between observed inputs and outputs determined without accounting any physics and spatial variability in the catchment. The lumped approach is often implemented in conceptual models. Parameters of lumped models often do not represent physical features of hydrologic process and usually involve certain degree of empiricism. This model is capable for modeling the potential climate change impact on river basin, water balance or seasonal snow accumulation and melt. For example: IHACRES (Identification of unit Hydrograph and Component flows from Rainfalls, Evaporation and Stream flow data), SRM (Snow Melt Runoff), etc.

Semi-distributed models have a more physically-based structure than lumped models have. They are a composition between the lumped and distributed model and demand less input data than distributed models do. Generally, the small sub-catchments are lumped so that the whole catchment has more than one lumped basins. There are two main types of semi-distributed models a) Kinematic wave theory models (KW models) and b) Probability distributed models (PD models). The KW models are simplified versions of the surface and/or subsurface flow equation of physically based hydrologic models. In PD models spatial resolution is accounted for by using probability distributions of input parameters across the basin. Some of this type of model is SWAT (Soil and water assessment tool), PRMS (precipitation runoff modeling system), SWMM (storm water management model), etc.

Distributed models, the catchment are divided into small segments called grid cell and consider all spatial and temporal variability in catchment as well as accounting physically consistent formulation and parameters. These models need a large amount of data for parameterization in each grid cell. Because the physical process of a catchment is simulated in detail, they provide the highest degree of accuracy. They have become more common in recent years. Examples of distributed models are the PRMS/MMS (Leavesley et al. 1983) and the J2000 (Krause 2002, 2001). Flügel (1995), the distributed model are applied to catchments with complex channel network, varying spatial distribution of land use, soil type and vegetation cover, with complex aquifer system below the soil surface etc.

Another classification is ***based on aspect of randomness***. There are mainly two kinds of model in such a category.

Stochastic Model is a model involving random variables having a probability distribution. These models are black box systems, based on data and using mathematical and statistical concepts to link a certain input (for instance rainfall) to the model output (for instance runoff). Commonly used techniques are regression, transfer functions, neural networks and system identification.

Deterministic Model is a model with no random variables is called a deterministic model. The given input always produces the same output. Such model expresses the domain (physics) of system by equations. Deterministic models can be split into different combinations of lumped or distributed and empirical, conceptual, or physically based.

CHAPTER III: STUDY AREA

3. General Description of study area

3.1 Topography

Marshyangdi river is a mountain river located in Central Nepal approximate length is 150km as shown in Figure 3.1 Which covers four districts of Nepal viz. Manang, Lumjung, Gorkha and Tanahu. Marshyangdi starts from a confluence of two mountain rivers Khangsar Khola and Jharsang Khola. Marshyangdi River drains through the northern slope of the Annapurna Mountain. The river flows eastward through the territory of Manang district and then southward through the territory of Lamjung district. This river flows from high himalayan range to mid hill of Nepal and finally converges to Trisuli River at Muglin which further joined with the Gandaki River. The study area extends from latitude 27.95^{O}N to 28.92 ^{O}N and longitude 83.83 ^{O}E to 85.68 ^{O}E with covering area of about 4063 square kilometers and the elevation ranges from 358m.a.s.l. to 8124 m.a.s.l. Marshyangdi river basin have 525square kilometers of glacier area, which is about 13% of the total basin area.

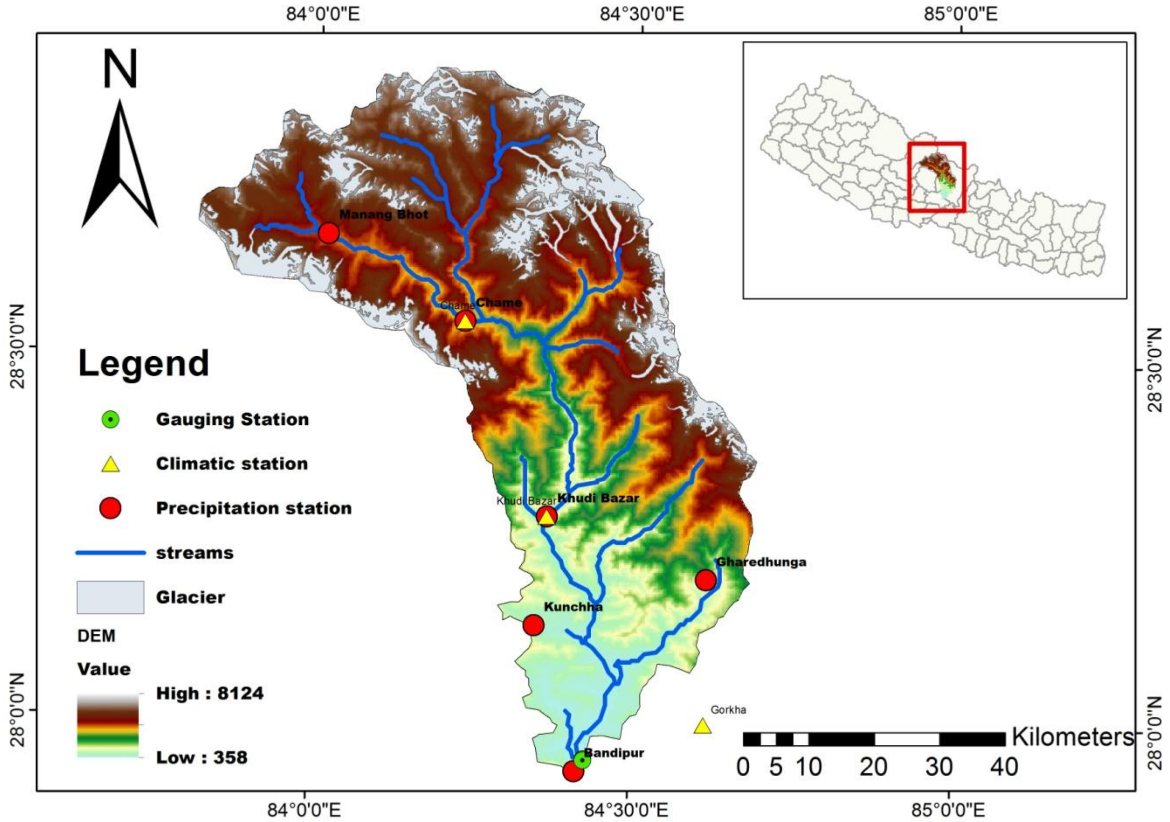


Figure 3.1 Study area (Marshyangdi river basin) (Source of DEM: SRTM)

Marshyangdi River is one of the hydropower potential rivers owing its gradient topography that extends from Himalayas region to Terai region.

3.2 Climate

The climate of this basin is cool temperate (low altitude) to alpine climate (in high altitude) affected by the rain shadow of the Himalayas at North. The seasonal climate is dominated by southeasterly monsoon, which occurs between June to September. Altitudinal difference from 358 to 8124 m.a.s.l. also plays important role in shaping up the differential climatic regime in this basin. Moving from North to South we find increase in air temperature. Monsoon and westerly disturbance is the predominant factor influencing the climate of this basin.

In summer, snow accumulates only above 5000m. In autumn, it accumulates down to 4000m and during the winter precipitation is generally in the form of snow and it starts accumulating from 3000m. In general, north and west facing slopes tend to be more protected allowing snow to accumulate.

3.3 Temperature

Temperature varies widely with aspect, altitude and cloud cover. Figure 3.2 shows the mean monthly maximum and minimum temperature of the basin from the station located at the elevation at 823 m.a.s.l to 2680 m.a.s.l. There is gradual increase in temperature form March to July and after July the air temperature declines. The days become hottest in June to September (summer season) while coldest in December to February (winter season). Humidity and cloud cover increases with the onset of the monsoon. According to data available in this basin, the seasonal average temperature of this basin is 18.85°C in pre-monsoon season, 21.9°C in monsoon season, 16.55°C in post monsoon season and 11.27°C during winter monsoon season. The below figure shows the Monthly average temperature form year 1979-2012 of study area. The long term annual mean air temperature is 17.60 ^{0}C from 1979 to 2012. This area receives most of the rain during summer season. Snow fall mostly occurs between Novembers to March.

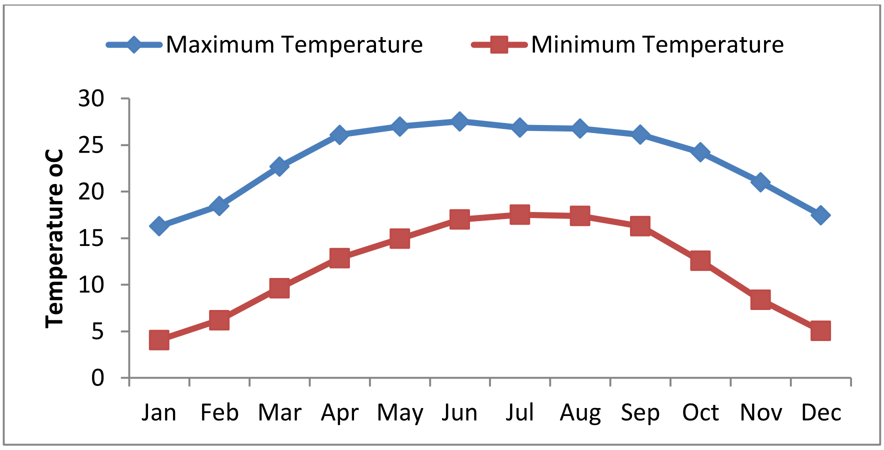


Figure 3.2 Monthly maximum and minimum Temperature from 1979-2012 of Marshyangdi Basin (823-2680 m.a.s.l.)

3.4 Precipitation

Precipitation of the basin also affected by the summer monsoon. During this period nearly 80% of the precipitation falls. There are extremely large gradients in rainfall over small spatial scales (10–20 km), on the timescales of both the monsoon season as well as individual weather events. During each monsoon onset, 2-day rainfall reached as high as 462 mm, corresponding to 10%–20% of the monsoon rainfall (Timothy J. Lang AND Ana P. Barros, 2001) in this basin. Figure 3.3 shows the monthly precipitation from 1979 to 2012 of Marshyangdi river basin. Highest precipitation occurs in the monsoon season (June to September) which accounts for 77.58% in the period from 1979-2012. The pre-monsoon season (March-May) accounts for 14.72% precipitation of the total precipitation from year 1979-2012. The winter monsoon (December-February) influenced by the westerly disturbances accounts only 3.82% while 3.88% for post monsoon season (October-November).

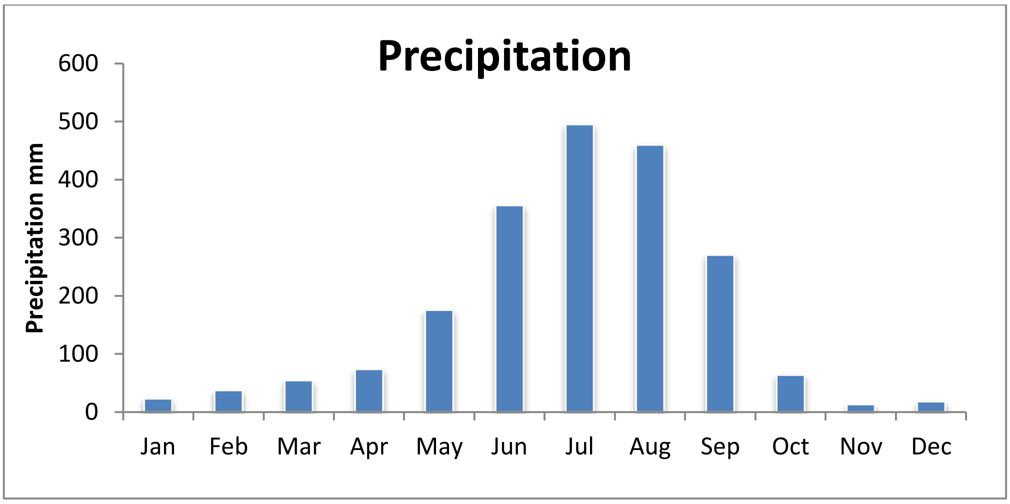


Figure 3.3 Monthly precipitation from 1979-2012 of Marshyangdi River basin

3.5 Soil

In the high Himalayas, the soil texture is relatively very thin because of the topography (rocky landscape and steep slope). Soil is found with significant variation in terms of texture, mineral, depth, content and other components. Mostly shallow and loose type of soil with sandy gavel and cobbles is found in these areas. Areas higher than the 5500m contains rocks. In middle mountains regions, dark brown color and silt loam soil is found. In the upper Marshyangdi valley, the most textural component is silt loam with a large proportion of rocks.

3.6 Land

Figure 3.4 shows the land use of the study basin. Forest, bare land and grassland area dominates the study area as 20.77%, 35.86% and 17.25% share for forest, bare land and grassland respectively. The most important factor bringing change in the discharge pattern the snow and glacier cover was also 13.12% which was mostly in the Northern part of the study area while agricultural land in the south covered 12.43% of total study area. Urban areas covered small area sharing 0.58%.

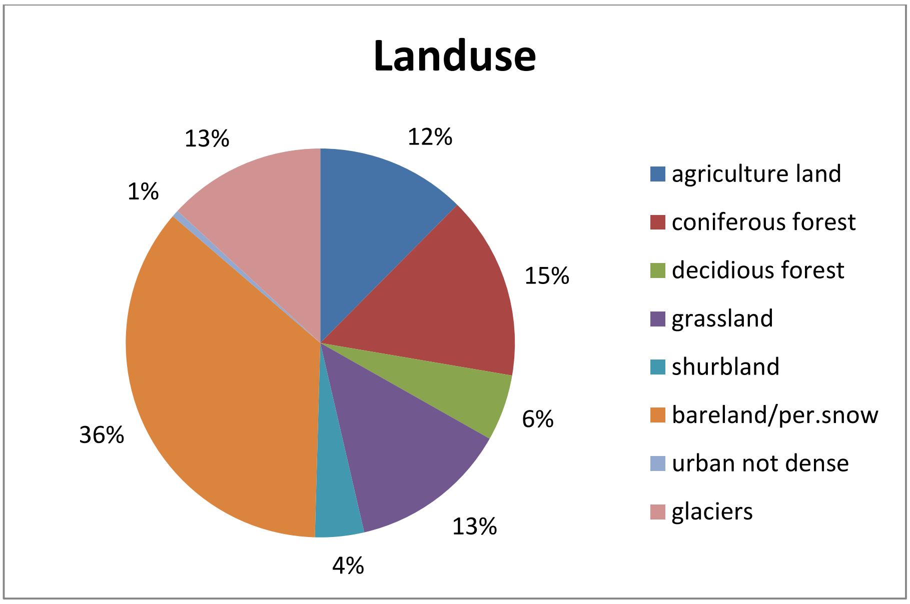


Figure 3.4 Land use type occurred in Marshyangdi Basin (source: Globe cover data)

3.7 Snow and Glacier

Upper Marsyangdi River basin is generated from the Thulagi glacier which is one out of the two moraine-dammed lakes (supra-glacial lakes), identified as a potentially dangerous lake. The glacier cover of Marshyangdi river basin is 525.44 square kilometer which is about 13 percent of the total basin area.

CHAPTER IV: METHODOLOGY

This chapter includes the description of different tools and techniques of research process such as methods and selection of data collection and analysis.

4.1 Meteorological and Hydrological data

The required meteorological and hydrological data for the Marshyangdi river basin has been collected from DHM (Department of Hydrology and Meteorology, Nepal). From this source the Meteorological data (precipitation, minimum and maximum temperature, sunshine hours, relative humidity, wind) has been collected from 1979-2012 and Hydrological data from 1987-2008. For the model calibration and validation discharge data is essential. The discharge data of Marshyangdi river basin at Bimalnagar has been collected.

The 90m resolution Digital Elevation Model (DEM) data has been collected for the Marshyangdi river basin from the Shuttle Radar Topography Mission (SRTM). The required soil data for this study is collected from the Harmonized world soil database and the required land use data is collected from the globe cover data. Also the required glacier covered data is collected from the ICIMOD.

4.2 Climate Projected Data

To quantify the relative change of climatic variables between the current and future time, the climate scenario data is required. This is used as the input to the hydrological model for study of hydrological impacts. Fifth Assessment Report of IPCC has developed new concentrations scenarios termed as Representative Concentration Pathways (RCPs). The RCPs scenarios are based on the pathways of radiative forcing. There are four RCPs scenarios namely RCP 2.6, RCP4.5, RCP 6.0 and RCP 8.5. The description of these RCPs scenarios are given in Table 4.1 below. These RCPs represent a larger set of mitigation scenarios and were selected to have different targets in terms of radiative forcing at 2100 (about 2.6, 4.5, 6.0 and 8.5 Wm–2). The RCPs were developed using Integrated Assessment Models (IAMs) that typically include economic, demographic, energy, and simple climate components.

For the future climatic projection, the study used the RCPs 4.5 and RCPs8.5 scenarios of 12 km by 12 km resolution gridded data which was downscaled from WRF (weather research and forecasting model) model. The projected data was use for analysis of the climate change impacts on snow and glacier melt contribution of Marshyangdi river basin. The projected RCP data was downloaded from 1996-2050 for RCPs 4.5 and from 2006-2050 for RCPs 8.5.

Table 4.1 Description of representative concentration pathway (RCP) scenarios

RCP	Description	Developed by
RCP 2.6	Its radiative forcing level first reaches a value around 3.1 W/m2 mid-centuries, returning to 2.6 W/m2 by 2100. Under this scenario greenhouse gas emissions and emissions of air pollutants are reduced substantially over time.	IMAGE modelling team of the Netherlands Environmental Assessment Agency
RCP4.5	It is a stabilization scenario where total radiative forcing is stabilized before 2100 by employing a range of technologies and strategies for reducing greenhouse gas emissions.	MiniCAM modelling team at the Pacific Northwest National Laboratory's Joint Global Change Research Institute
RCP 6.0	It is a stabilization scenario where total radiative forcing is stabilized after 2100 without overshoot by employing a range of technologies and strategies for reducing greenhouse gas emissions.	AIM modelling team at the National Institute for Environmental Studies, Japan
RCP 8.5	It is characterized by increasing greenhouse gas emissions over time representative of scenarios in the literature leading to high greenhouse gas concentration levels.	MESSAGE modelling team and the IIASA Integrated Assessment Framework at the International Institute for Applied Systems Analysis (IIASA), Austria

The study used the RCPs scenarios data from 2020 to 2030 for the study of climate change impacts on the various hydrological components.

4.3 Bias correction methodology for the projected data

Future climate GCM data for RCP4.5 and RCP8.5 Scenarios was used. Daily temperature and precipitation from 1996-2050 for RCP4.5 and from 2006- 2050 for RCP8.5 were downloaded for future projection of climatic parameters. The RCPs data downscale from WRF model further extracted in Grads then the data was de-biased.

The results from GCMs and RCMs always show some degree of biases for both temperature and precipitation data. The reasons for such biases include systematic model errors cause by imperfect conceptualization, discretization and spatial averaging within the grids. The bias correction approach is used to eliminate the biases from the daily time series of downscaled data (Salzmann et al. 2007). In this study, the following equations are used to de-bias daily temperature and precipitation data (Mahmood et.al. 2012) respectively.

$$T_{deb=}T_{SCEN} - \overline{(T_{CONT}} - \overline{T_{obs}})$$

$$P_{deb} = P_{SCEN} \times \left(\frac{\overline{\boldsymbol{P_{obs}}}}{\overline{\boldsymbol{P_{CONT}}}}\right)$$

Where, $\boldsymbol{T_{deb}}$ and $\boldsymbol{P_{deb}}$ are bias corrected daily temperature and precipitation respectively. **TSCEN** and **PSCEN** are daily temperature and precipitation obtained from downscale data (WRF). $\overline{\boldsymbol{T_{obs}}}$ and $\overline{\boldsymbol{P_{obs}}}$ are long term monthly mean of observed temperature and precipitation respectively, while $\overline{\boldsymbol{T_{CONT}}}$ and $\overline{\boldsymbol{P_{CONT}}}$ are long term monthly mean of temperature and precipitation simulated using WRF for observed period.

Several methods of bias corrections have been proposed to improve the quality of **GCM** data for hydrological analysis purposes, such as linear scaling of precipitation and temperature, local intensity scaling (**LOCI**) of precipitation, power transformation of precipitation, variance scaling of temperature, distribution mapping of precipitation and temperature and delta-change correction of precipitation & temperature. Both precipitation and temperature output obtained by statistical downscaling WRF data were bias corrected for the calibration period 1988 to 1996 and validation period 1996 to 2003.

4.4 Data Quality

In this study the only one hydrological station data used from the gauging station at Bimalnagar which is quite good. The discharge data is available from 1987-2008. There are six precipitation stations inside basin which are used for the study. In the study basin there is lack of sunshine, humidity and wind data so that these data are collected from the nearest station of the study area. Here the Sunshine, Relative humidity and Wind data is collected from the Pokhara Airport station and Lumle station.

The stations data have gaps ranging from a days to few months. To fill the missing data of temperature the nearby stations was choose. The temperature data gaps less than 4 days were filled by linear interpolation by taking average from days before and after the gaps. And the gaps more than 4 days were filled by using linear regression from nearby stations. The coefficients of determination (r^2) of nearby station for maximum temperature were range from 0.63 to 0.69 and for minimum temperature were range from 0.8 to 0.9. The missing data of discharge and precipitation were filled up with value -9999 to run the J2000 model.

4.5 Trend analysis

The study used MAKESENS model for Mann Kendall trend test and Sen's Slope estimation. The non-parametric Mann Kendall Trend test gives the increasing and decreasing trend of the time series data whereas the Sen's slope estimator for magnitude of the trend. The advantage of this Mann Kendall (MK) Trend test is that it could be operated with the missing data. For time series data (n) analysis with less than 10 points, the S test is used, and with more than 10 values or points, the Z test is used.

MK Trend Test on the basis of S statistic is given as

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(x_j - x_k)$$

Where x_j and x_k are the annual values in years *j* and *k*, *j* > *k*, respectively, and

$$sign(x_j - x_k) = \begin{cases} +1 \text{ if } (x_j - x_k) > 0 \\ 0 \quad \text{if } (x_j - x_k) = 0 \\ -1 \text{ if } (x_j - x_k) < 0 \end{cases}$$

The value of ***S*** indicates the direction of trend. The positive value of S indicates increasing and negative value gives decreasing trend.

If the time series data size n >10, the test statistics ***S*** is approximately normally distributed and the variance is given as follows:

$$Var(S) = \frac{[(2n(n-1)n+5)] - \sum_{i=1}^{m} t_i(t_i-1)(2t_i+5)}{18}$$

Where, *m* is the number of tied groups i.e. having equal value in time series and t_i is the size of the *ith* tie group. Then the values of *S* and *VAR(S)* are used to compute the test statistic *Z* as follows:

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{Var(S)}}, \text{for } S > 0 \\ 0, \text{for } S = 0 \\ \dfrac{S+1}{\sqrt{Var(S)}}, \text{for } S < 0 \end{cases}$$

The positive value of Z indicates the upward or increasing trend and the negative value indicates the downward or decreasing trend of the time series data. In MAKESENS model the tested significance levels (α) are 0.001, 0.01, 0.05 and 0.1.

Sen (1968) non-parametric approach is used to estimate the true slope of an existing trend (as change per unit time) where it is assumed to be linear. The estimation of slope of N pairs of data is expressed as:

$$Q_i = \frac{x_i - x_k}{j - k}$$

Where, x_i and x_k are the data values at times j and k $(J > k)$ respectively.

When the number of time series data N is odd, the Sen's estimator of slope is given by the median slope as:

$$Q_{med} = Q_{[(N+1)/2]}$$

When the value of N is even the Sen's estimator is given as

$$Q_{med} = \frac{1}{2}\left(Q_{(N/2)} + Q_{[(N+2)/2]}\right)$$

Finally, ***Q*** is estimated by the nonparametric Sen's slope method based on the normal distribution.

4.6 The J2000 Model

The study used the J2000 hydrological model to simulate hydrologic conditions; impacts of climate on snow and glacier melt of this basin. The J2000 is a distributed, process oriented framework system JAMS (Jena Adaptable Modelling System) (Kralisch and Krause 2006, Kralisch et al. 2007) developed at the University of Jena. Generally this model used for hydrological simulation of meso- and macro scale catchment (Krause 2001). The model describes the hydrological processes as encapsulated process modules. The principal layout of the model components is shown as below figure.

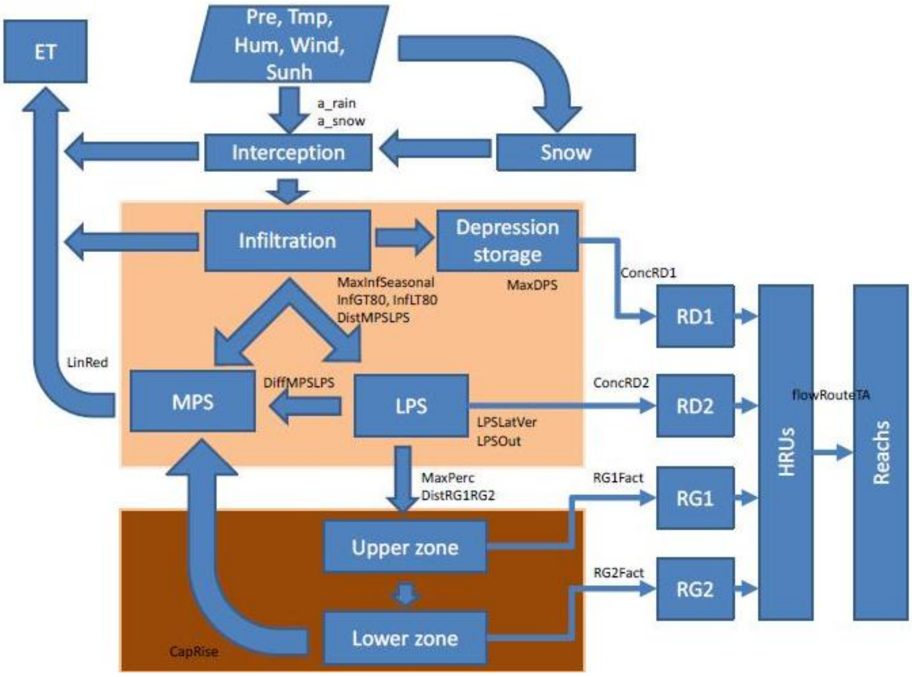


Figure 4.1 The principal Layout of the J2000 model (source: Krause, 2001)

4.6.1 Modules within the J2000 modeling system

The J2000 model describes the modules to represent the important hydrological processes. Depending upon the objective of the study and data availability for simulation the J2000 model can be used different modules. Here are short descriptions of the modules which contain a number of calibration parameters.

- Precipitation module
- Interception module
- Snow module
- Glacier module
- Soil module
- Groundwater module
- Routing module

The important processes within the modules are described below in the respective section of the module.

4.6.1.1 Precipitation module

In general precipitation is distributed between liquid rain and solid snow, depending upon the air temperature. The amount of rain and snow is determine by assuming the temperatures below a certain threshold results in total snow precipitation and exceeding a second threshold results in rainfall. Between this threshold temperature range the mixed precipitation occurs.

4.6.1.2 Interception module

Interception refers to precipitation that does not reach the soil, but is instead intercepted by the leaves and branches of plants and other open spaces of vegetation. Interception can be identified as important components of a hydrological cycle which can affect on water balance components. The interception module uses a simple storage approach according to Dickinson (1984). The interception module calculates the maximum interception storage capacity, on the basis of the Leaf Area Index (LAI) of the respective land cover. The exceeded precipitation passed on to the next module after the maximum interception storage capacity of the vegetation is reached. The J2000 model assumed that the interception storage is lost by evaporation only.

The maximum interception capacity (Int_{max}) is calculated according to the following formula:

$$Int_{max} = \alpha \,.\, LAI \text{ [mm]}$$

Where, α = storage capacity per m^2 leaf area against the precipitation type [mm]

LAI = LAI of the particular land use class provided in the land use parameter file.

4.6.1.3 Snow module

The snow module mainly describes different phases of snow accumulation, metamorphosis and snowmelt. The snow module is purposed by Knauf (1980). The snow module calculates two different types of Snow Water Equivalent (SWE). The first one describes the SWE of ‘dry’ snow, which is actually frozen, and the related density .The second one is total SWE including the liquid water stored in a snowpack and the related density. In this way, the total SWE, which is the product of stored liquid water and dry SWE, is known. The potential snowmelt is calculated by providing energy associated with air temperature (temperature factor), soil heat flux (ground factor), and rainfall (rain factor) in the form of calibration parameters. In the model, the snowmelt runoff from snowpack then is passed to the soil water module. The accumulation and melt temperatures can be calculated according to:

$$T_{acc} = \frac{T_{min} + T_{avg}}{2} \quad [^{o}C]$$

$$T_{melt} = \frac{T_{max} + T_{avg}}{2} \quad [^{o}C]$$

The sum of all energy inputs gives the potential snowmelt rate (Mp). The calculation of Mp is carried out according to:

$$Mp = t\_factor \ \_ \ T_{melt} + r\_factor.netRain.T_{melt} + g\_factor \ [mm]$$

Mp is initially used to balance out the cold content of the snow cover and is then also used to generate snowmelt.

The snow pack can store liquid water in its pores up to a certain critical density (snowCritDens). This storage capacity is lost nearly completely and irreversibly when a certain amount of liquid water in relation to the total SWE (between 40 and 45 percent) is reached according to (Bertle 1966, Herrmann 1976, Lang 2005). In the model, this process is simulated by using the calculation of a maximum water content of the snow pack (SWEmax) according to:

$$WS_{max} = snowCritDens \ . \ SD \ [mm]$$

4.6.1.4 Glacier module

The glacier module is developed and adapted as a part of the PhD research (Nepal, 2012) carried out in the Dudh Kosi River. A glacier module helps to understand the glacier melt runoff in the basin. In J2000 model, the glacier module is treated as a separate module where snow and ice melt (SIM) runoff directly provided to a stream as overland flow (RD1). The glacier module calculate ice melt by using an enhanced degree day factor (Hock 1999) and has been further modified by taking into consideration the radiation, slope aspect and debris covered factors.

The glacier area for this module is provided as a GIS layer which is generated during HRU delineation which separately treated based on the unique ID. First the seasonal snow occurs on top of the glacier (or glacier HRU). The model first treats the snow as described earlier and produces snow runoff. In order to make sure that ice melt occurs, two conditions have to be met. First, the entire snow cover of a glacier HRU has to be melted (i.e. storage is zero), and second, the base temperature (tbase), as defined by users, has to be less than meltTemp. Only under these circumstances, does the ice melt occur as a model process.

$$meltTemp = \frac{Tmax + Tmean}{2} \quad [^oC]$$

The melt rate (ice Melt) (mm/day) is obtained by the following equation:

$$iceMelt = \frac{1}{n} \cdot meltFactorIce + alphaIce \cdot radiation \cdot (meltTemp - tbase) \quad [mm]$$

Where:

Radiation = actual global radiation

MeltFactIce = generalized melt factor for ice as a calibration parameter

alphaIce = melt coefficient for ice

n = time step (i.e. for daily model, n=1)

The presence of debris affects the ablation process. Supra-glacial debris cover, with thickness exceeding a few centimeters, leads to considerable reduction in melt rates (Oestrem 1959, Mattson et al. 1993). According to Oestrem (1959) when the thickness of the debris cover was more than about 0.5 cm thick the melt rate will decrease. There is not only the melting will be slower under the moraine cover, but also the ablation period will be shorter for the covered ice. When a glacier is covered by debris, the ice melt is reduced. Using the calibration parameter, the effects of debris cover on melt is controlled as follows.

$$iceMelt' = icemelt - \left(icemelt \cdot \frac{debrisFactor}{10} \right)$$

The glacier melt runoff is the product of snowmelt, ice melt and rain on top of glaciers. The glacier runoff directly contributes to stream flow and is regarded as an overland flow (RD1) component. However, for the long-term estimation of glacier runoff in the context of climate change, the module is less suitable because it does not account for the changing spatial extent of glacier areas.

4.6.1.5 Soil module

The soil module is central and most complex part of the J2000 model, which controls the regulation and distribution of water movement and interacts with most of the other modules, except the glacier module. The major input for the soil module is snowmelt and precipitation in the form of rain through infiltration. The infiltrated water is distributed to both soil storage components (MPS and LPS) in each response unit (HRU). The Middle pore storage represents the pores with diameter 0.2-50 µm in which water is hold against gravity but can reduced by plant transpiration. The pores with diameter greater than 50µm called Large pore storage (LPS) which cannot hold water against gravity. The LPS is emptied by generating the interflow and recharging the ground water. The water holding capacity is provided in a soil parameter file.

Any surplus water, if it exceeds the maximum infiltration capacity of the corresponding soil or saturation of the LPS, is stored as depression storage (DPS). Emptying the depression storage component is done through evaporation, and the generation of overland flow surface runoff and routed to the next HRU. The principal layout of the soil module is as below.

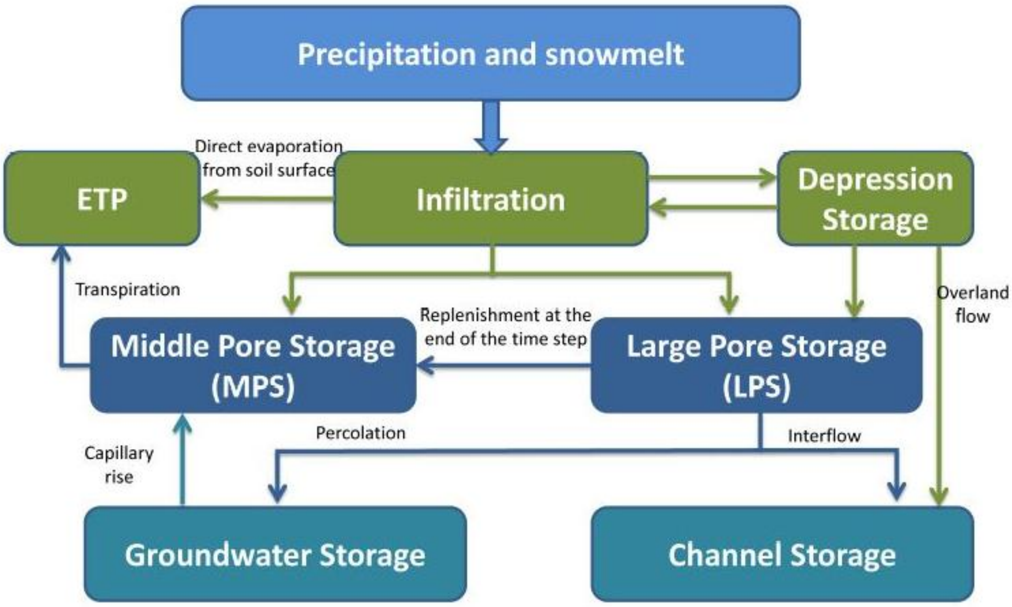


Figure4.2 Principal Layout of J2000 soil module. Source (Krause 2002)

4.6.1.6 Ground water module

The ground water module presents the simple storage concept of ground water storage for each hydrological response unit. The input water from the soil water module distributed in two storage zones. First the upper ground water zone (RG1) considered as weathered layer on top of bedrock. The RG1 is highly permeable and short retention time. Second the lower groundwater storage

(RG2) represented as saturated groundwater aquifers with low permeability and long retention time (Figure). The lower groundwater storage (RG2) is similar to base flow. The ground water module emptying can be done by the lateral underground runoff component and the capillary rise on the unsaturated zone. The maximum storage capacity can be estimated by multiplying the part of the underground chamber by the thickness of the individual storages per m^2 standard area. The glacier area does not have any infiltration and groundwater storage. The upstream areas with high-mountain slope and low elevation with relatively flat areas distinguished. The former has less groundwater storage compared to the latter one as the flat areas can have higher groundwater storage.

The water discharge from the two different storages RG1 and RG2 are made according to the current storage amount in the form of a linear-outflow function. The storage retention coefficients (kRG1, kRG2), which are considered as the time water rests in the specific storage, are factors of the current storage volume (actRG1, actRG2) used for the calculation of the groundwater outflow (outRG1 and outRG2) as follows:

$$outRG1 = \frac{1}{gwRG1Fact \cdot kRG1} \cdot actRG1 \quad [mm]$$

$$outRG2 = \frac{1}{gwRG2Fact \cdot kRG2} \cdot actRG2 \quad [mm]$$

4.6.1.7 Routing module

Reach routing and the HRU routing are the two routing components of J2000 model. The HRU routing is applied for the simulation of lateral water transport from one HRU to the next HRU until the water finally reaches a stream network. The reach routing implemented the flow process in the stream network by using kinematic wave approach and the calculation of velocity according to Manning and Stricker. The individual reaches receive water from neighboring HRU and upstream reaches (Krause, 2001).The only model parameter that has to be estimated by the user is a routing coefficient, which influences the ‘run time’ of the runoff waves that move in the channel until it reaches the catchment outlet after precipitation. Its value is required for the calculation of the restraint coefficient (*Rk*) together with the velocity of the river (*v*) and flow length (*fl*):

$$RK = \frac{v}{fl} . TA .3600$$

4.7 Model Entity HRU delineation

The Hydrological Response Units (HRUs) are applied as model entities for the J2000 hydrological model. HRUs are distributed, heterogeneously structured generates from the DEM, land cover, soil types and underlying pedo-topogeological associations controlling their hydrological dynamics.

In this study, HRUs were delineated from the spatially distributed information of land cover, soil type and physiographic data. The 90m resolution Digital Elevation Model data were collected from the Shuttle Radar Topographical Mission (SRTM). The soil information was derived from the Harmonized World Soil Database (HWSD) and Globe Cover data was used for the land use information and glacier data was collected from the ICIMOD. The physiographic data was collected from the Survey Department of Nepal. All these collected maps were reclassified at 250m resolution.

The HRUS were delineated by overlaying the maps in GRASS –HRU in QGIS environment. The total 2566 HRUs and 21 reaches were delineated. To preserve the heterogeneity of some specific land use types and distinct from neighboring land use types, the land use (eg. glacier) is merged with nearby areas of the same land use (glacier) in delineating the HRUs. These HRUs were topologically connected for lateral routing of flows to simulate lateral water transport processes between HRUs. These HRUs were further connected to the nearby reach for reach routing. The information about each HRUs is stored in HRU parameter file, which is created at the end of the HRU delineation process. The information about reach is stored in reach parameter file, which is also created at the end of the HRU delineation process.

The J2000 model has separate parameter files for land use, soil type, geology, HRU and reach. The required information is stored in each parameter files.

4.8 Model Calibration and Validation

Calibration is the initial testing of model in which parameter adjustment are made to obtain a better fit between observed and simulated variables. The calibration based on observed hydrological behaviors of the target basin is necessary for obtaining suitable estimates of model parameters. It defines the model parameter accurately until get satisfactory result between simulated and observed variables to apply the hydrological model successfully. The main objective of the calibration process is to minimize the errors due to non- optimal parameters values to obtain best possible results. The calibration of the model is adjusted in a trial and error process corresponds to match the simulated to observed values.

The distributed J2000 hydrological model involves large number of calibration parameters to optimize during model setup. For model calibration, all 40 parameters were used. The calibration was done by trial and error method. By varying the value of every single parameter the trial and error method was applied. The calibration tried to match initially the simulated and observed runoff (such as high peaks and base flow) of the study basin.

Sensitivity analysis was conducted as a part of automatic calibration. From this process, information about higher and moderate sensitive parameters was obtained. After that effort, a finer adjustment of those calibration parameters was made in order to attain the best fit between observed and simulated values. The higher and moderate sensitive parameters were responsible for visible and prominent variation in the model results.

For this study, the model was first applied in the Marshyangdi river basin using input data from 1987 through 2008 on a daily basis. However, the entire time series data for this period was split up into 1987-1999 for the calibration and 2000-2008 for the validation period. Model quality was quantified by the data from the validation period which were not used for the model calibration. After a successful application in the Marshyangdi river basin, the parameters were used for climatic scenarios data.

The simple outline of the research methodology given below

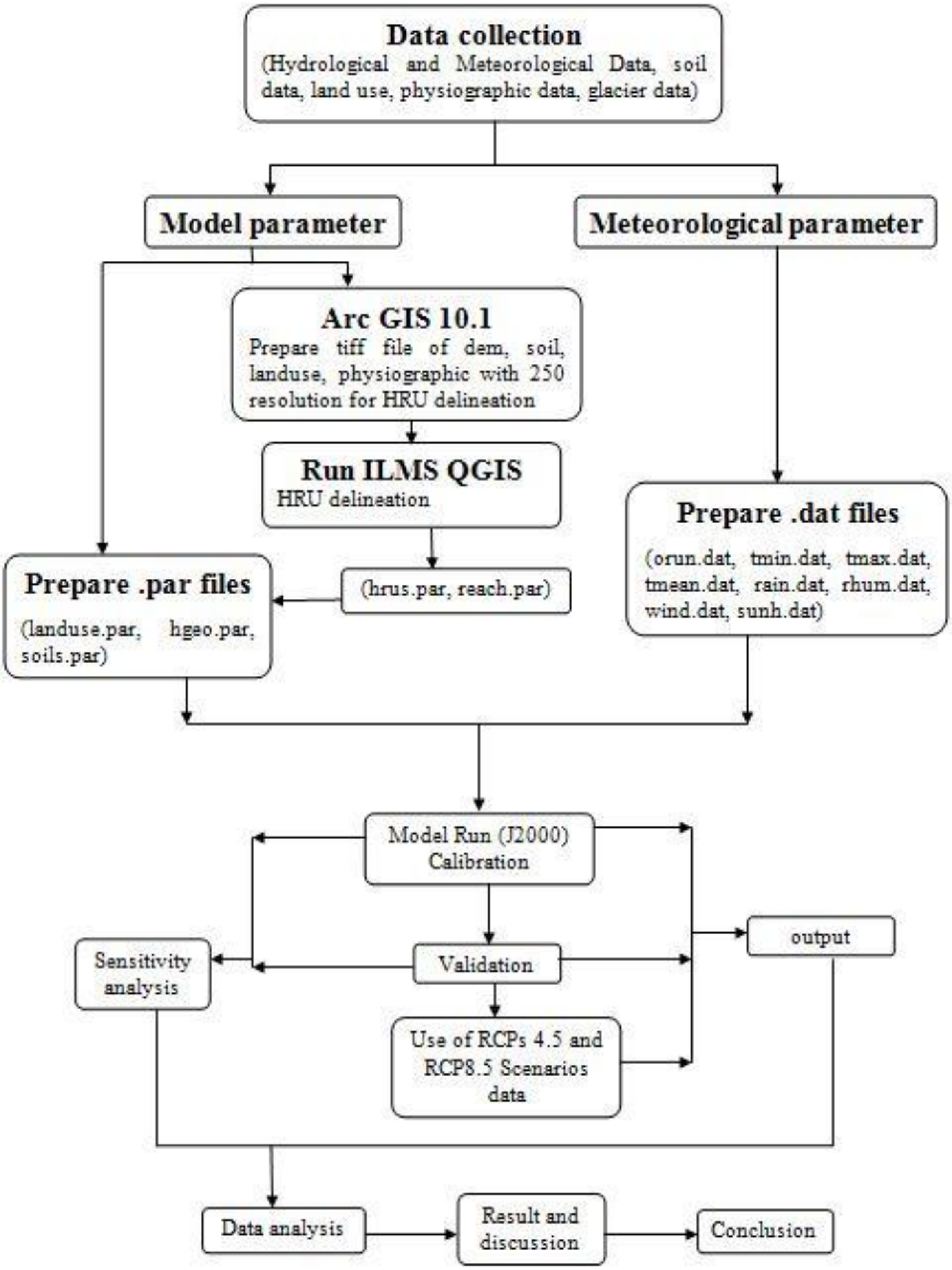


Figure 4.3 Research methodology of the study

CHAPTER V: RESULT AND DISCUSSION

5.1 Analysis of Temperature

The analysis of the temperature is based on the data recorded from 1979-2012 by DHM. There are two stations inside the Marshyangdi river basin and one near the basin for trend analysis of temperature. The monthly maximum temperature recorded from 1979-2012 for the Marshyangdi river basin is 27.44^0C whereas the minimum temperature is 4.06^0C. The highest temperature is recorded during the summer season (June-August) and the lowest temperature is recorded during the winter season (December-February).

Over the last 34 years temperature data of Marshyangdi basin the highest maximum temperature was 28.7 ^{0}C, which was recorded at khudibazar (823 masl) in the year 2010 A.D. And the highest minimum temperature ever recorded inside the basin was 6.5^0C at Chame station (2680masl) in the year 1999A.D.

5.1.1 Temperature trend analysis by using Mann Kendall and Sen's slope

For the trend analysis three stations was choose. Figure 5.1 shows the temperature stations provided for trend analysis. The study used non-parametric Mann Kendall and Sen's slope method to analyze the trend of maximum and minimum temperature. The analysis used 34 years of recorded data of DHM from 1979 to 2012. Table 5.1 shows that there is a high confidence in warming. The majority of the stations indicated a rising temperature trend (both maximum and minimum). Only the exception is the station Chame which showed a decreasing trend for minimum temperature. The maximum temperature of all three stations shows a high rate of increasing trend.

Table 5.1 Temperature trend in the Marshyangdi river basin (□C/year).

Station ID	Station Name	Elevation	Data Period	SS: MT// NT	Trend(^{o}C): MT// NT
802	Khudibazar	823	1979-2012	***//**	+0.057// +0.043
809	Gorkha	1097	1979-2012	***//	+0.097 // +0.023
816	Chame	2680	1979-2012	***//***	+0.085// -0.070

*** 0.001 level of significance, ** 0.01 level of significance, *0.05 level of significance

SS: Statistically significant; MT: Maximum Temperature; NT: Minimum Temperature

Figure 5.2 and Figure 5.3 show the trend of maximum and minimum temperature. All three stations (Khudibazar, Gorkha and Chame) indicated general rise in temperature for which level

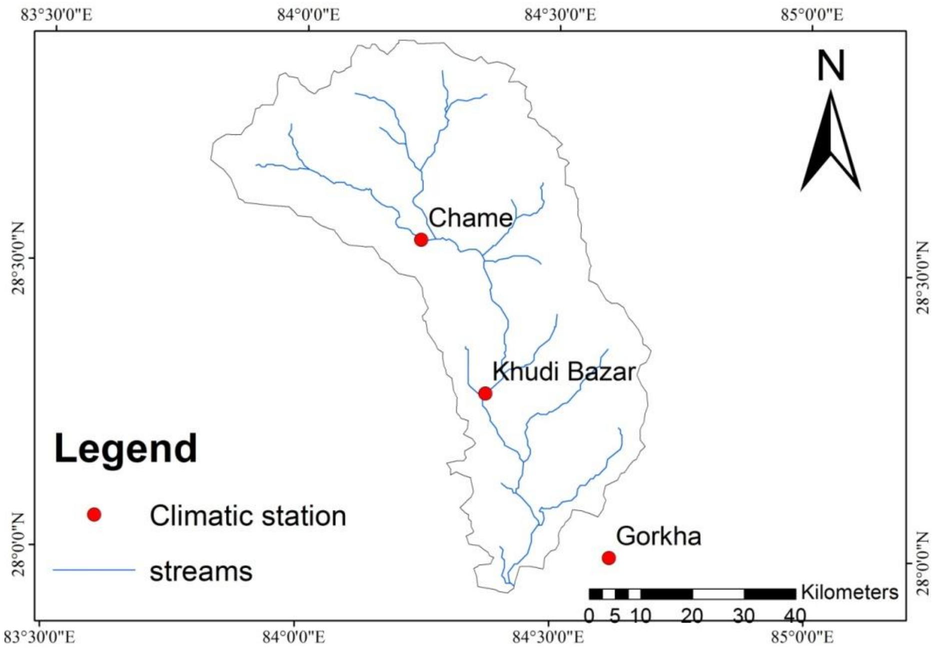


Figure 5.1 Temperature Station for Trend analysis

of significance is 0.001 (99.9 % confidence level). From this analysis, the increasing trend of temperature at high elevation station (Chame) was higher than low elevation station (Khudibazar) inside the basin. The analysis shows that there was sudden increase and decrease in both maximum and minimum temperature in Chame station in year 2003. On average the maximum temperature trend of Marshyangdi river basin (based on the average of all three stations) was 0.08 ^{o} C/ year and the minimum temperature was - 0.001^{O}C/year. The result shows there was higher confidence level of increasing maximum temperature than the minimum temperature.

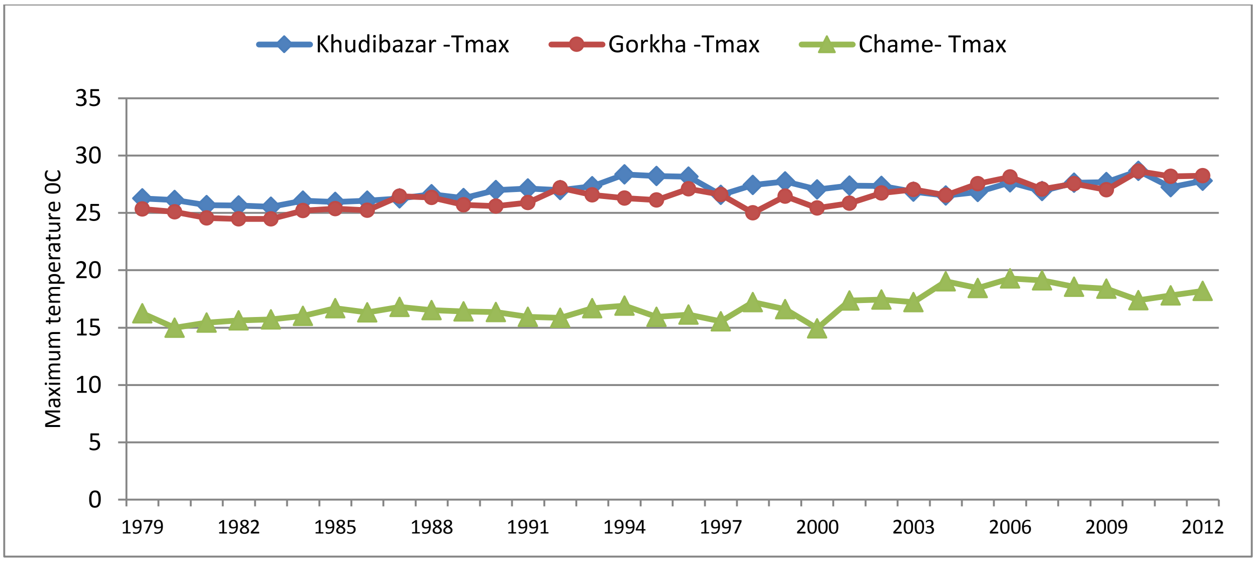


Figure 5.2 Maximum Temperature trend in Marshyangdi river basin

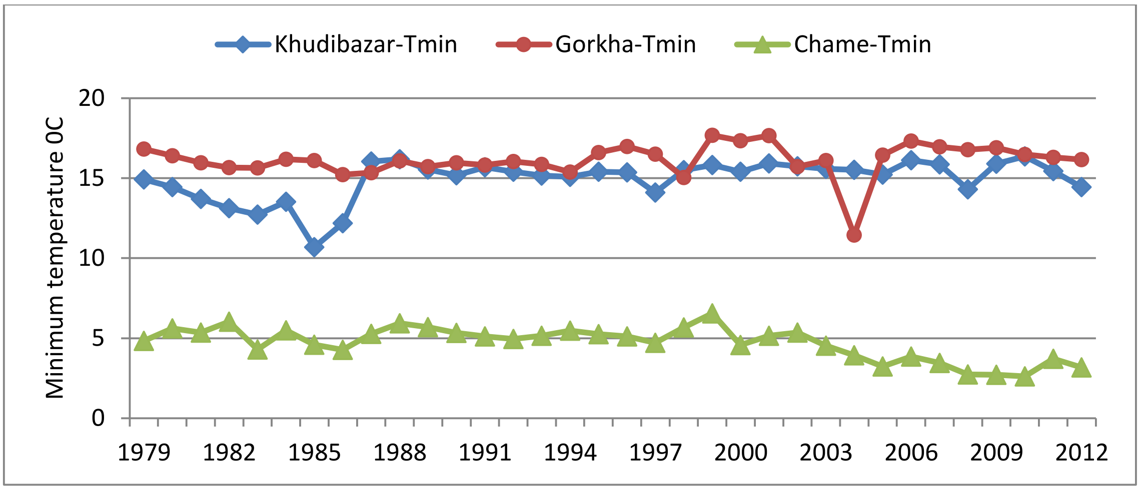


Figure 5.3 Minimum Temperature trend in Marshyangdi river basin

5.2 Analysis of precipitation

The study analyzed the six precipitation stations inside the Marshyangdi river basin. The rainfall data from 1979-2012 has been obtained from DHM. According to the data obtained by DHM the study area receives 77.38% of the annual precipitation in monsoon season (June - September). Among the monsoon months, July is the wettest month which receives nearly 495 mm (i.e. 24% of the total annual precipitation). Likewise, November is the driest month which receives 13mm (i.e. 0.63% of the total annual precipitation). The figure 5.4 shows the monthly precipitation from 1979 to 2012.

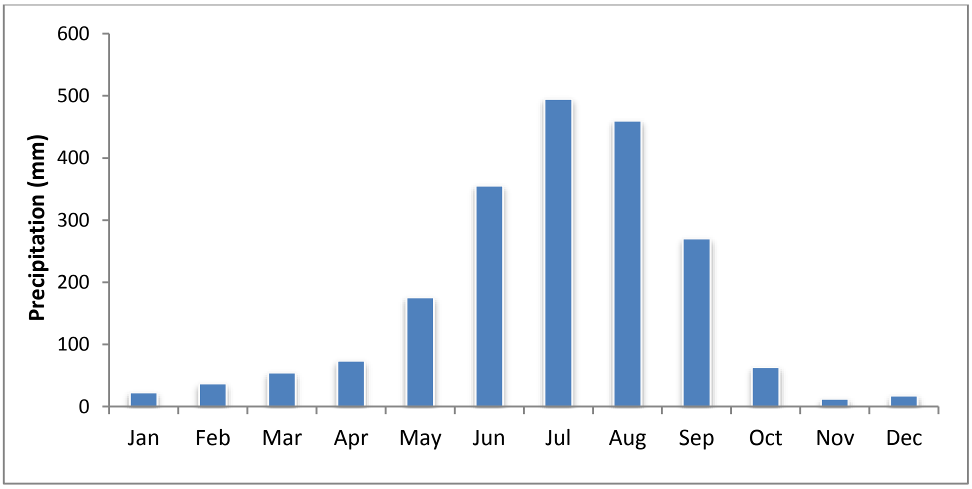


Figure 5.4 Monthly precipitation of Marshyangdi river basin from 1979-2012

5.2.1 Trend analysis of precipitation

The study used 34 year precipitation data of six precipitation station inside the Marshyangdi river basin. The precipitation data from 1979-2012 collected from DHM is used for the trend analysis. The Mann Kendall method used for monotonic increasing and decreasing trend of precipitation whereas Sen's slope method is used for slope (magnitude) of the linear trend analysis. The trend of each station is carried out and plotted in Figure 5.5. The three stations out of six stations inside the basin showed increasing trend, while other three stations showed decreasing trend. Figure5.5 showed increasing and decreasing trend of precipitation inside the study basin. Three station showed increasing trend. Those were: Kuncha (4.5mm/year), Bandipur (3.9mm/year) and Gharedhunga (3.4mm/year). Three stations showed decreasing trend. Those were: Khudibazar (-1.9mm/year), Chame (-2.1mm/year) and ManangBhot (-6.2mm/year). Only one station indicated a statistically significant trend in precipitation. Only the Manang Bhot station showed an decreasing trend which are statistically significant at 0.01 level of significance.

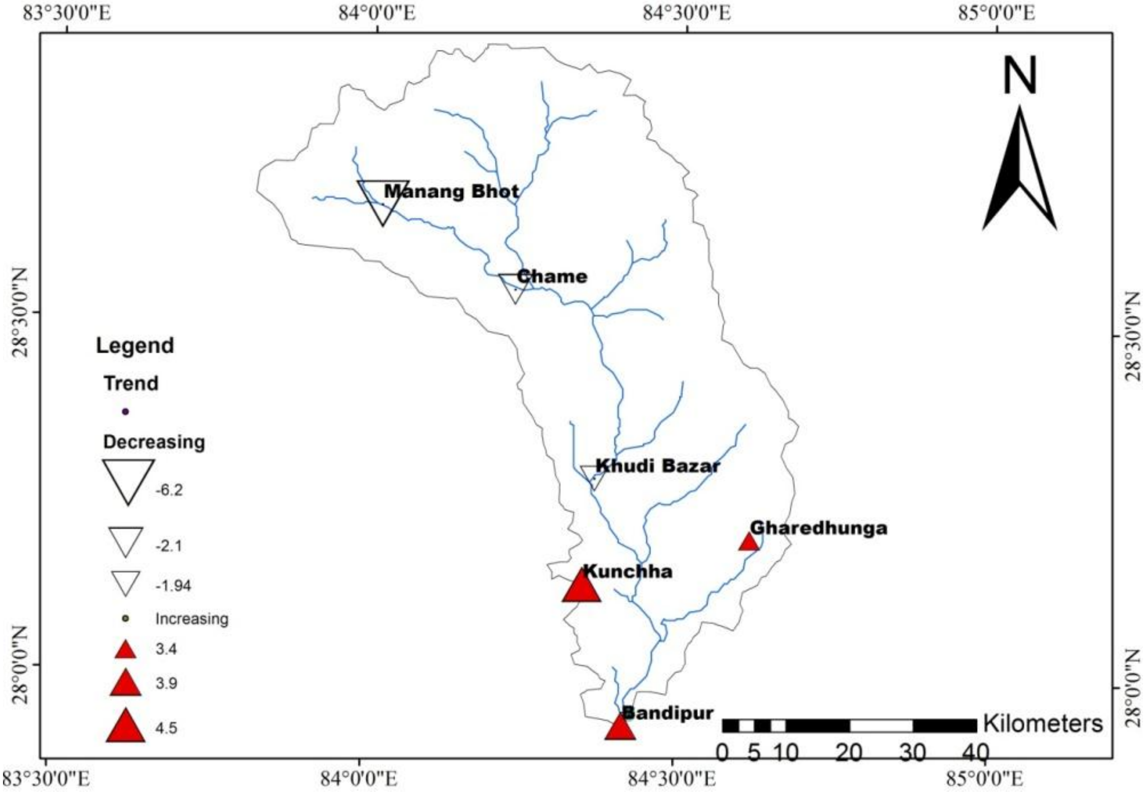


Figure5. 5 Annual precipitation trends in the Marshyangdi river basin.

The upward and downward pointing triangles indicate increasing and decreasing trends in Figure5.5. The precipitation at higher elevation was in the form of snow which contributes the stream flow in dry season if the trend decrease the snow accumulation also will be affected.

5.3 Discharge and precipitation relation

In the Marshyangdi river basin, about 78% of the precipitation and 71% discharge occur during the monsoon season. This shows that the about 7% precipitation is stored during the monsoon season. Figure 5.6 shows the monthly plots of observed precipitation and discharge of the

Marshyangdi river basin from 1987 to 2008. The maximum precipitation occurs in the month July and the stream flows begin to increase from June and reach their peak flow in August. With increase of the precipitation, increases the discharge. During the pre-monsoon season (March-May) the temperature start increasing which helps for the snow and glacier melt in high Himalaya which contribute to the stream flow. During the high precipitation seasons the discharge shows lower value than precipitation it may due to the contribution of precipitation to the ground water. As the soil moisture becomes saturated the overland flow gives the high stream flow in middle of the monsoon season. In the post monsoon (Oct-Nov) and winter season (Dec-Jan) the stream flow is higher than the precipitation (Figure 5.6)which shows, the stream flows based on the base flow contribution.

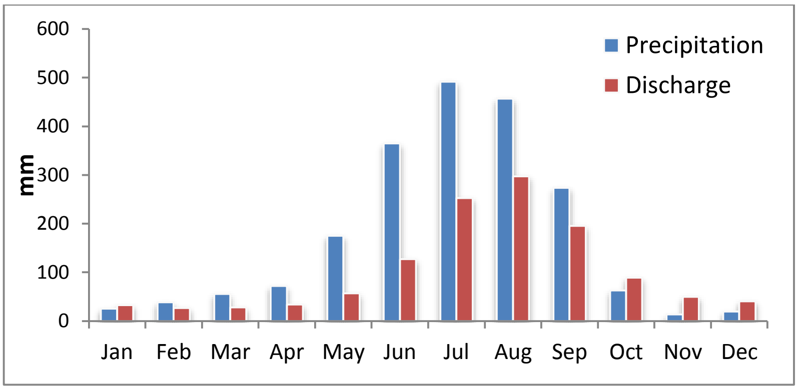


Figure 5.6 Monthly observed precipitation and discharge of the Marshyangdi basin from 1987 to 2008

5.4 Calibration and Validation

Calibration is the process by which the model parameters values are identified to use in the future application. After calibration the identified parameters are used in the validation process by using independent time series data. Validation checked the calibrated parameter sets. If the calibrated parameters value is matched the results from the validation results should be same as calibrated results.

In this study the J2000 model has been calibrated the data at Bimalnagar for the Marshyangdi river basin. The model has been calibrated during 1987 to 1999 and validated during 2000 to 2008 against daily discharge data. The actual values of the parameters of J2000 hydrological model for calibration are shown in Table 5.2 below. For the calibration, daily precipitation, temperature, relative humidity, sunshine hours, wind speed and stream flow data, observed at various stations inside and outside of the basin are used, considering the calibration period from 1987-1999, meanwhile the validation period is defined from 2000-2008.

Table 5.2 Calibration parameters for J2000 hydrological model

Parameters	**Descriptions**	**Actual value**	**Range**
Interception MODULE			
a_rain	Interception storage for rain	1.0	0-5
a_snow	Interception storage for snow	1.28	0-5
SNOW MODULE			
snowCritDens	Critical density of Snow	0.39	0-1
snowColdContent	Cold content of snow pack	0.091	0-1
baseTemp	***Threshold temperature for snowmelt***	***0***	***-5 to+ 5***
t_factor	***Melt factor by sensible heat***	***3***	***0 - 5***
r_factor	Melt factor by liquid precipitation	1	0-5
g_factor	Melt factor by soil heat flow	1	0-5
GLACIER MODULE			
meltFactorIce	***Melt factor for ice melt***	***4***	***0 - 10***
alphaIce	***Radiation melt factor for ice***	***0.2***	***0 - 1***
kIce	Routing co-efficient for ice melt	10	0-100
kSnow	Routing co-efficient for snowmelt	5	0-50
kRain	Routing co-efficient for rain runoff	5	0-50
debrisFactor	Debris factor for ice melt	3	0-10
tbase	***Threshold temperature for snowmelt***	***-0.5***	***-5 to +5***
SOIL MODULE			
soilMaxDPS	Maximum depression storage	1	0-10
soilLinRed	***Linear reduction co-efficient for AET***	***2.5***	***0 - 10***
soilMaxInfSummer	***Maximum infiltration in summer***	***80***	***0 - 100***
soilMaxInfWinter	***Maximum infiltration in winter***	***95***	***0 - 100***
soilMaxInfSnow	Maximum infiltration in snow cover areas	60	0-200
Soil IMPGT80	Infiltration for areas greater than 80% sealing	0.09	0-1
soilImpLT80	Infiltration for areas lesser than 80% sealing	0.09	0-1
SoilDistMPSLPS	MPS-LPS distribution coefficient	0.1	0-10
SoilDiffMPSLPS	MPS-LPS diffusion coefficient	0.09	0-10
soilOutLPS	***Outflow coefficient for LPS***	***0.1***	***0 - 10***
soilLatVertLPS	***Lateral vertical distribution coefficient***	***0.3***	***0 - 5***
soilMaxPerc	***Maximum percolation rate to groundwater***	***30***	***0 - 100***
soilConcRD1Flood	Recession coefficient for flood event	1.4	0-10
soilConcRD1Floodthreshold	Threshold value for soilConcRD1flood	300	0-500
soilConcRD1	***Recession coefficient for overland flow***	***2.5***	***0 - 5***
soilConcRD2	***Recession coefficient for Interflow***	***3.5***	***0 - 5***
GROUNDWATER MODULE			
gwRG1RG2dist	***RG1-RG2 distribution coefficient***	***5***	***0 - 20***
gwRG1Fact	***Adaptation for RG1 flow***	***0.1***	***0 - 1***
gwRG2Fact	***Adaptation for RG2 flow***	***0.1***	***0 - 1***
gwCapRise	Capillary rise coefficient	0.1	0-1
REACH ROUTING			
flowRouteTA	***Flood routing coefficient***	***10***	***0 - 50***

Figure 5.7 and Figure 5.8 presents the visual comparison of simulated flow and observed flow for calibration and validation periods respectively. The red, blue and gray lines represent the simulated, observed stream flow discharges and precipitations respectively. The manual calibration was focused on the low flow periods. The low flow was represented reasonably well. The simulated hydrograph for higher flows (flood) periods are well captured but in some cases are under predicted (eg. in 1995) (Figure 5.7). The well matched simulated and observed hydrograph during the rising limb shows the role of snow and glacier melt in early monsoon period.

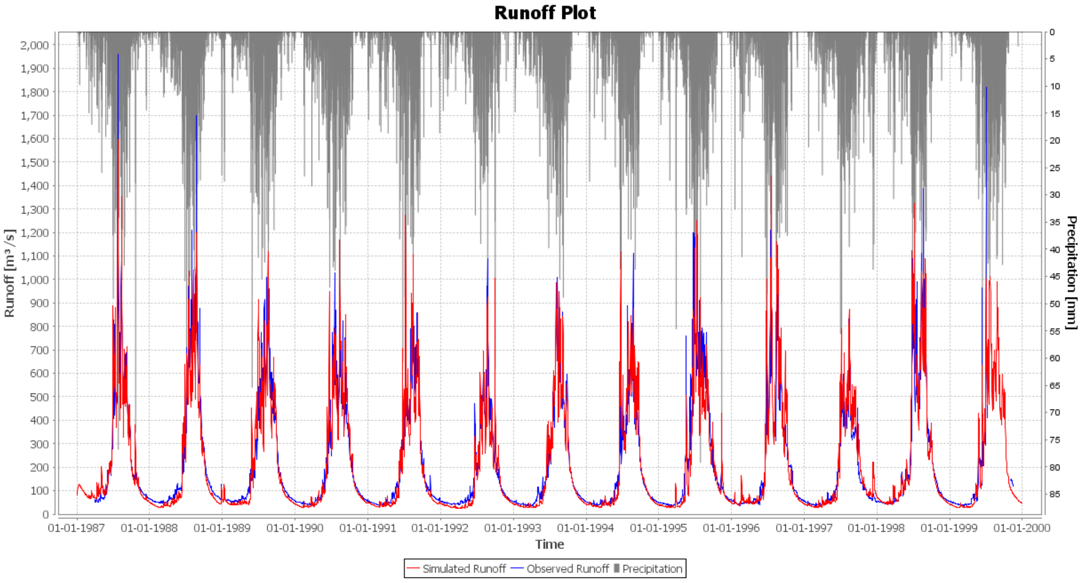


Figure 5.7 Observed and simulated discharge during the calibration period (1987-1999) in the Marshyangdi river basin

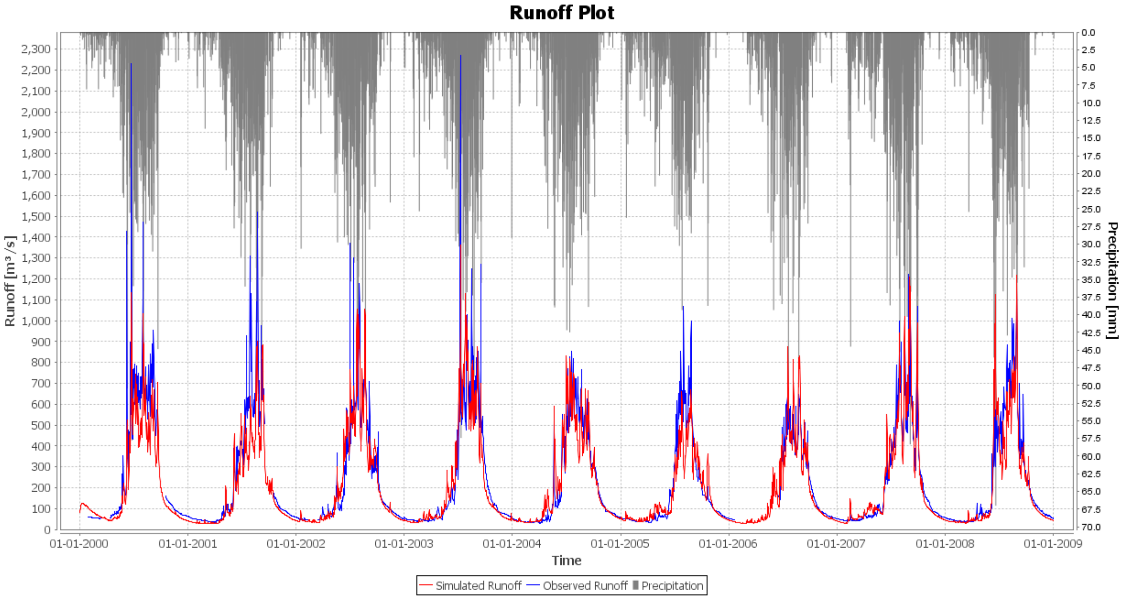
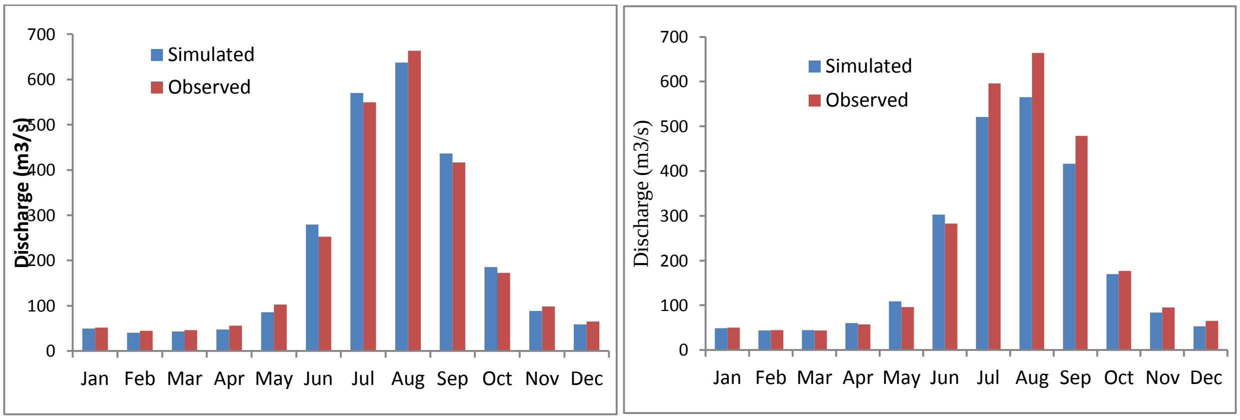


Figure 5.8 Observed and simulated discharge during the validation period (2000-2008) in the Marshyangdi river basin

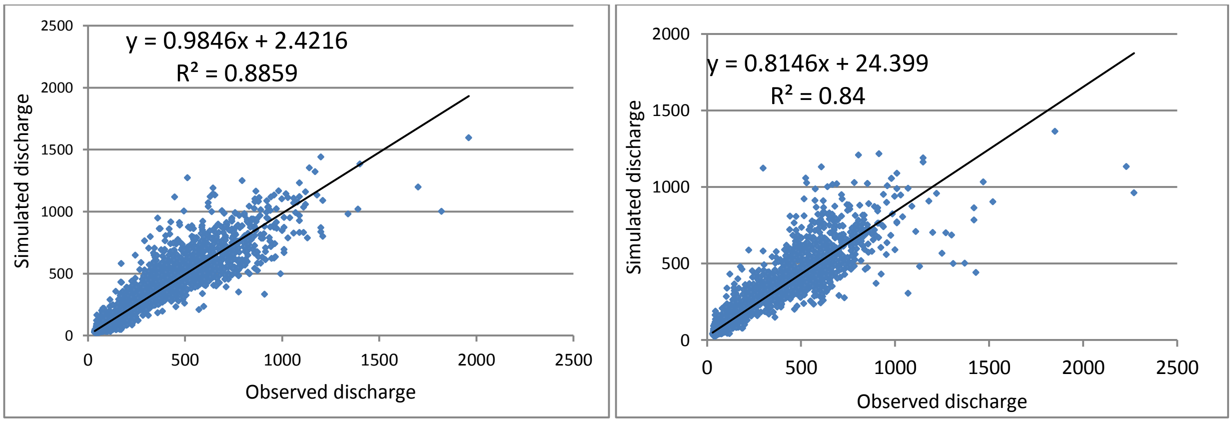
During the validation period (Figure 5.8), the low flows are simulated well during most of the year. The high flow (flood) period are under estimated. The rising and the recession limbs are reasonably well.

The comparison of monthly simulated and observed runoff shown in Figure 5.9 indicates a reasonably good fit throughout the year for calibration (1987-1999) and validation (2000-2008). The simulation of the low-flow period is quite good and high-flow months are slightly over-and under-estimated. Figure 5.9(a) and (b) shows monthly simulated and observed runoff for calibration and validation period respectively. In general, the agreement looks good except for some more extreme outliers during high-flow period towards the observed runoff side. In the calibration period, the low flows are slightly under estimated whereas the peak flows are over estimated. Flows in rainy seasons are over estimated except for the month August (Figure 5.9(a)). The validation predicted better result in pre-monsoon season (March- May). The high flow shows underestimated during the validation period. The flows during post monsoon (October-November) season also shows under predicted.



(a) Observed and simulated monthly discharge during calibration period (1987-1999)

(b) Observed and Simulated monthly discharge during validation period (2000-2008)



(c) Scatter plot between observed and simulated discharge during calibration period (1987-1999)

(d) Scatter plot between observed and simulated discharge during validation period (2000-2008)

Figure 5.9Comparison of observed and simulated results

Figure 5 (c) and (d) shows the scatter plots of observed and simulated daily discharge for calibration and validation period. All average the comparison appears good results. The coefficient of determination (r^2) gives better result for both calibration (0.88) and validation period (0.84) in scatter plots between simulated and observed discharge.

The efficiency results for the calibration and validation periods are shown in Table 5.3. From the table, it can be seen that, the Nash-Sutcliffe efficiency (e2) value for the calibration period was obtained as 0.87 and 0.83 for validation period which shows very good performance rating for calibration and validation period. High values of the standard Nash- Sutcliffe efficiency (e2) confirm a good agreement for the medium and high flows. The logarithmic Nash-Sutcliffe efficiency (loge2) shows very satisfactory result. High values of the logarithmic Nash-Sutcliffe efficiency (loge2) reflect the good agreement of the low flow periods. Here the loge2 value found 0.90 and 0.91 for calibration and validation period respectively. The PBIAS (percentage bias) shows good performance for calibration and validation period. Table 5.3 shows that the PBIAS for calibration was -0.37 whereas for validation its value was -7.97. Which shows that the simulated discharged values for the calibration period is reasonably well whereas during validation period it was under estimated. The coefficient of determination r^2 (Rsq) shows very good results for both calibration and validation period.

Table 5.3 Efficiency results during calibration and validation periods

Efficiency	Calibration(1987-1999)	Validation (2000-2008)
Nash- Sutcliffe (e2)	0.87	0.83
logarithmic Nash-Sutcliffe (Log e2)	0.90	0.91
Coefficient of determination (Rsq)	0.88	0.84
Percentage bias (PBIAS)	-0.37	-7.97

From the results, the model performance at the gauging station both in calibration and validation is acceptable. Therefore the model can be successfully applied for hydrological simulation in Marshyangdi river basin.

5.5 Sensitivity Analysis

A sensitivity analysis is a repeat of the primary analysis, substituting alternative decisions or ranges of values for decisions that were arbitrary or unclear. The sensitivity analysis is conducted as the optimization process of the J2000 model. It helps to analysis the behavior of model parameter towards the output of the model. It helps to find out which parameter is more sensitive to model outputs and should take as during a calibration process.

In this study, for the sensitivity analysis 16 out of 36 parameters were selected. The selection of the parameter is on the basis of trial and error calibration process. Parameters for sensitivity analysis are shown in Table 5.2 with incline bold letter. A Monte Carlo analysis was applied for 1600 simulations. A random sampling used which choose the actual value and range of the parameter, shown in the same Table 5.2. Further the OPTAS was used to analyze the sensitivity of the model parameter, which was a part of JAMS framework. The Figure 5.10 and Figure5.11 shows the sensitivity of parameter with e2- Nash-Sutcliffe efficiency and sensitivity of parameter with coefficient of determination r^2 respectively.

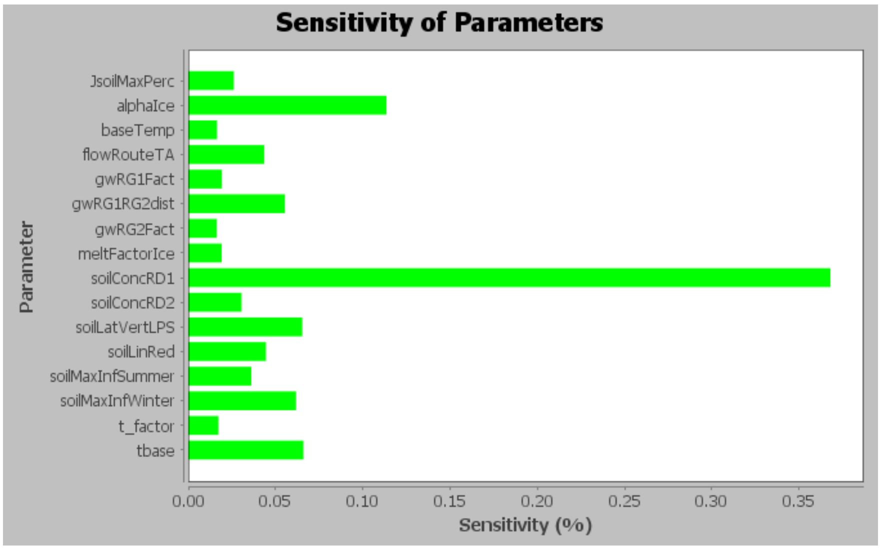


Figure 5.10 Sensitivity of the selected calibrated parameters with the Nash Sutcliffe efficiency

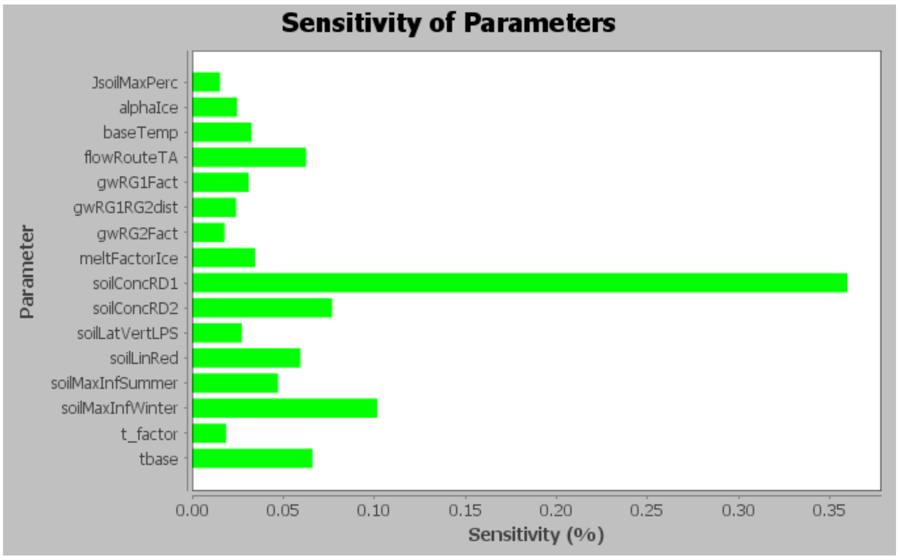


Figure 5. 11 Sensitivity of the selected calibrated parameters coefficient of determination r^2

The green stake shows the sensitivity of all 16 parameters. For example, parameter ConcRD1 is responsible for 35% of variation in the model results. The stake with higher length shows the highly sensitive parameter. Figure 5.10 and Figure 5.11 shows that the parameter soilConcRD1 is the most sensitive parameter on the basis of efficiency criteria and for coefficient of determination respectively, this parameter explained about 35% of the variation in model results. Secondly alphaIce is more sensitive on the basis of efficiency and soilMaxInfWinter is sensitive for coefficient of determination. soilLatVerLPS, tbase are moderately sensitive on the basis of efficiency and other parameters are less sensitive. SoilConcRD2 and tbase are moderately sensitive on the basis of coefficient of determination and other is less sensitive. The sensitivity of all 16 parameter also describe in annex. The sensitivity of the parameters is also described in Table 5.4 below with respect to high, moderate and low.

Table 5.4 Sensitivity of the parameters

Parameter	Nash Sutcliffe efficiency e2	Co-efficient of determination r2
baseTemp	Low	Low
t_factor	Low	Low
meltFactorIce	Low	Low
alphaIce	High	Low
tbase	Moderate	Moderate
soilLinRed	Low	Moderate
soilMaxInfSummer	Low	Low
soilMaxInfWinter	Moderate	Moderate
soilLatVertLPS	Moderate	Low
soilMaxPerc	Low	Low
soilConcRD1	High	High
soilConcRD2	Low	Moderate
gwRG1RG2dist	Moderate	Low
gwRG1Fact	Low	Low
gwRG2Fact	Low	Low
flowRouteTA	Low	Moderate

Low = < 5%, Moderate = 5% - 10%, High = <10%

The sensitivity analysis for low and high sensitive parameter was also shown in Figure 5.12 and Figure 5.13. The red line indicates the cumulative distribution function of the best group of parameter set and the blue line indicate worst group of parameter sets. Figure 5.13 shows a larger difference between the parameters set which shows that higher sensitivity of the parameter to the model performance whereas in the Figure 5.12 the differences between the parameters sets are very low which indicates the low sensitive toward the model performance.

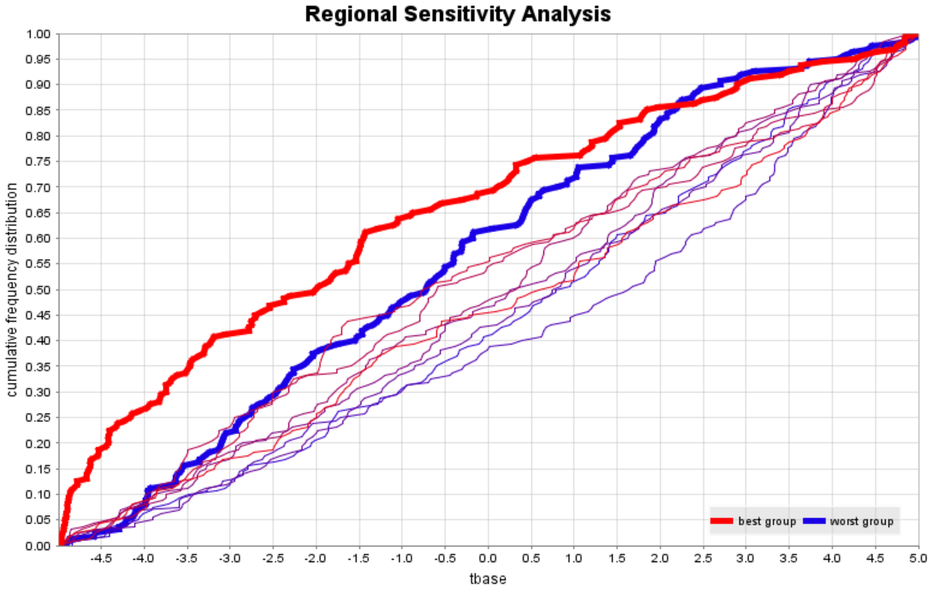


Figure 5.12 The RSA of the tbase parameter with Nash-Sutcliffe efficiency

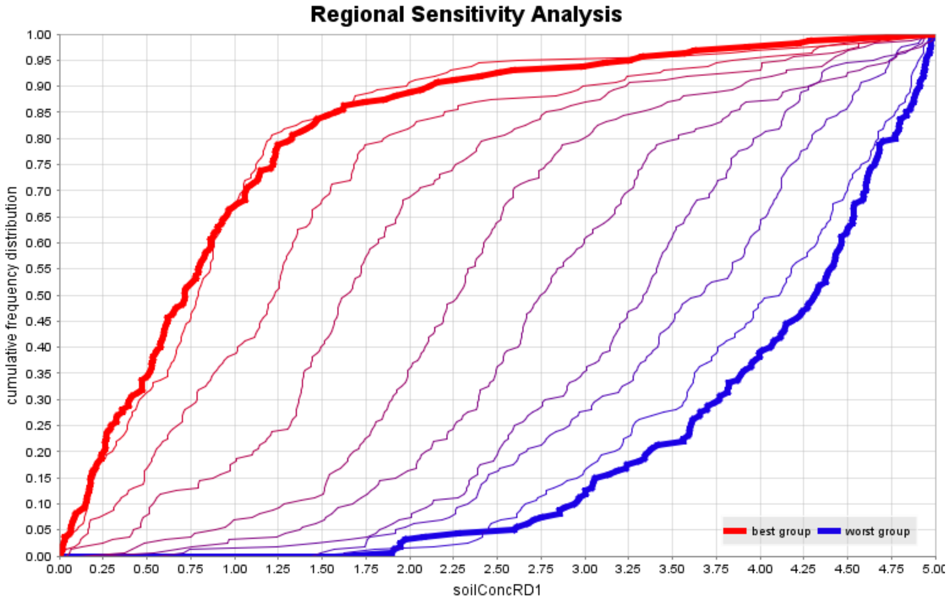


Figure 5.13 The RSA of the soilConcRD1 parameter with Nash-Sutcliffe efficiency

5.6 Snow and glacier melt contribution to the river discharge

The glacier module of the J2000 hydrological model provides insight into the snow and glacier melt processes from the glacier area. The glacier runoff consistent of three runoff components from the glacier area: snowmelt from glacier area, glacier ice runoff and rain runoff (if there is rain on top of snow). Figure 5.14 shows the monthly contribution of snow and glacier melt runoff to the stream flow. The total contribution of the snow and glacier melt runoff to the stream flow is about 20%. Out of this amount, glacier melt contribute about 13% including 9% of ice melt. The contribution of the snow melt (other than glacier area) to the stream flow is about 7 %. The snow and glacier melt contribution during the monsoon season (June-September) is about 19% of the stream flow of monsoon period. As we know the snow and glacier are very sensitive toward temperature, with increasing temperature during the pre monsoon season the contribution of the snow and glacier melt is also high. The contribution of the snow and glacier melt during pre-monsoon (March – May) is about 41% of the stream flow of pre-monsoon period. The contribution of melt water during this period is because of the increase temperature. The contribution of the melt runoff during post monsoon (Oct – Nov) and winter seasons (Dec- Feb) are about 16% and 11% respectively. During the winter and post monsoon season there is snow fall in high Himalayas which accumulates the snow is higher than the ablation which results the low contribution of snow and glacier melt.

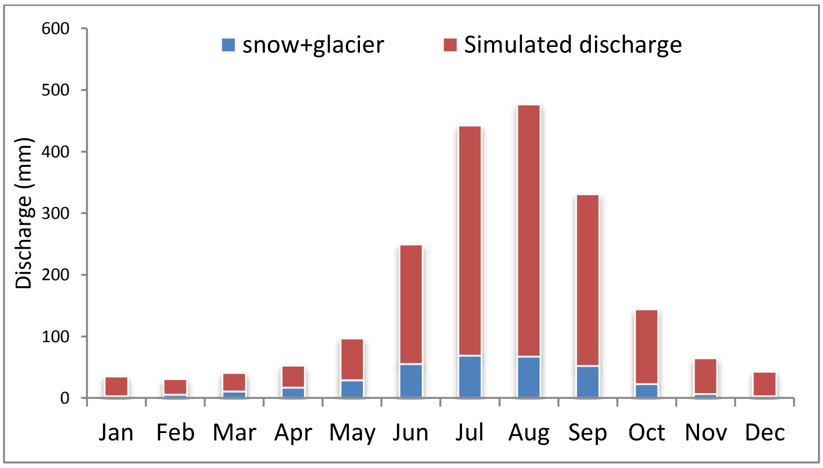


Figure 5.14 Monthly contributions of snow and glacier melt in Marshyangdi river basin from 1987-2008.

5.7 Contribution of various runoff components to river discharge

The J2000 hydrological model gives the result for the contribution of the various runoff components generated from the different sources to the stream flow. Figure5.15 shows the monthly contribution of various runoff components to the stream flow from 1987-2008. From the Figure 5.15, the RD1 gives the overland flow which contributes about 52% to the total runoff. The high contribution of the surface runoff is highly affected by the topography of the study area. The steep topography, Rocky Mountains and bare land surface provides the favorable conditions for the overland flow (RD1). Due to the high intensity rainfall during monsoon period results fully saturated soil moisture condition which is favorable for the overland flow. The glacier area only gives the overland flow RD1 because there is no infiltration occurs to the soil. The interflows RD2 and RG1 contribution to the total runoff is about 13% and 9% respectively. The unsaturated soil zone when becomes saturated after the rainfall events and the outflow comes from the LPS was known as slow direct runoff (RD2). The base flow contributes about 26% of the total runoff. The volume of base flow is highest in summer, during the snowmelt season. The high contribution of base flow may have resulted from the geological structure of the study area and it could also due to the high contribution of precipitation to the ground water. The base flow (RG2) contributes flows during the dry seasons. The result shows that the overland flow is the most dominating runoff component.

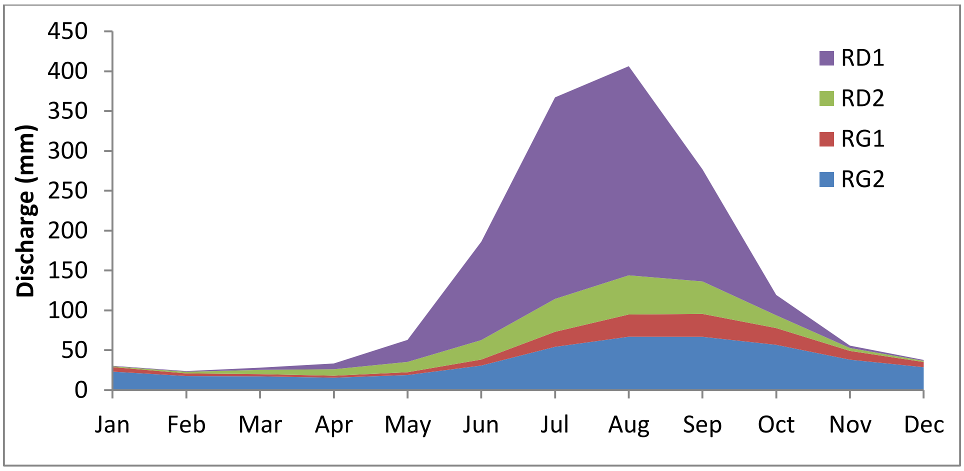


Figure 5.15 Monthly contributions of various runoff components to the Marshyangdi river basin from 1987-2008.

5.8 Potential and Actual Evapotranspiration

Evaporation is the process of transformation of the liquid water from land and water surfaces to the atmosphere. The water loss to the atmosphere by plants is known as Evapotranspiration which is one of the major components of the water balance. Potential Evapotranspiration (PotET) is measure of the ability of the atmosphere to remove water from the surface through the process of evaporation and transpiration by assuming no control on the water supply. And the actual evapotranspiration (Act ET) is the quantity of water actually removed from the surface by the process of evaporation and transpiration. The J2000 model calculates the potential evapotranspiration by Penman-Monteith equation. The equation is affected by principal parameters such as radiation, air temperature, humidity and wind speed. The Figure 5.16 shows the relation between monthly potential and actual evapotranspiration in the study area from 1987-2008.

The analysis shows that the potential evapotranspiration is higher than the actual evapotranspiration in whole year. The actual evapotranspiration is calculated depending upon the water availability in different storage components. The difference between the Pot ET and ActET in middle of the monsoon season is lower than the pre-monsoon season. This is due to the soil moisture characteristic. During the monsoon season there is enough soil moisture whereas the pre-monsoon season has lowest soil moisture. Act ET will increase with increased soil moisture. The highest ActETand PotET recorded during the pre-monsoon season because of higher temperature, more solar radiation and higher wind speed than other months and water availability in soil moisture storage. Yearly about 28 percent of the input precipitation was lost by actual evapotranspiration. As we know evpotranspiration is highly affected by soil infiltration. Low soil infiltration decreases the evapotranspiration.

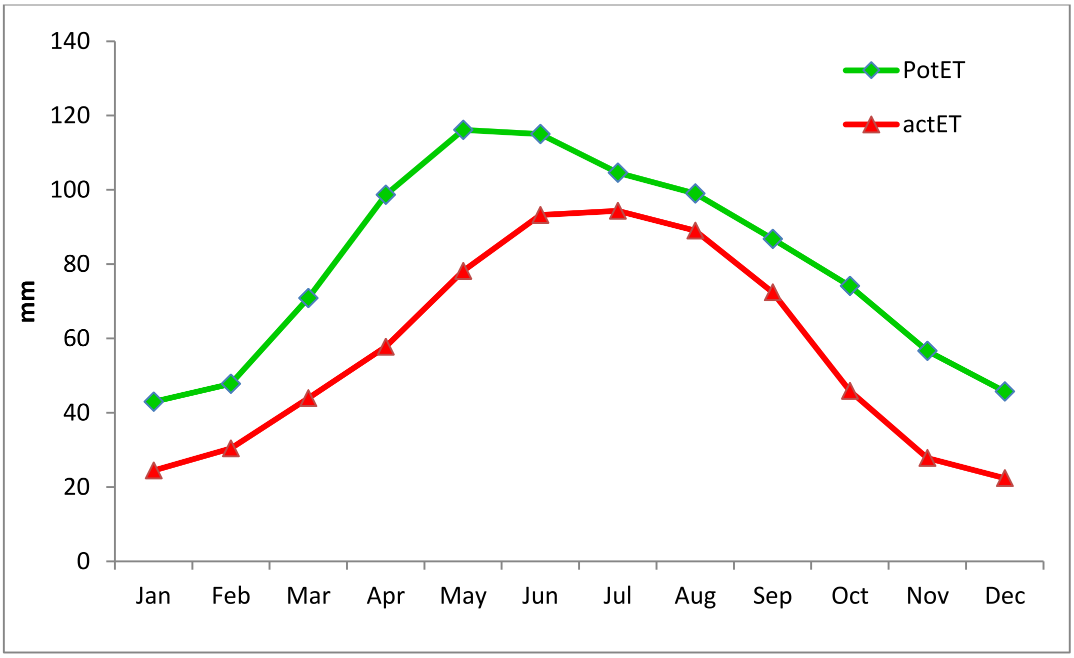


Figure 5.16 Monthly contribution of the Potential and Actual Evapotranspiration of the Marshyangdi river basin from 1987-2008

5.9 Water balance

The analysis of water balance indicates that the average input into the system from precipitation and ice runoff are 2,312 mm and 148 mm per year respectively between 1987 to 2008. Sixty six percent of the input is used to generate stream flow and 28 percent is estimated to be lost from actual evapotranspiration (Act ET). About 6 percent of the input of the system is stored in the basin. The storage of the basin is in the form of snow in high altitude. And the other forms of storages are soil, groundwater and interception storage. The Table 5.5 shows the yearly water balance of the Marshyangdi river basin from 1987-2008. The base flow contributes about 27 percent of the total stream flow.

Table 5.5 Water balance of the Marshyangdi river basin (1987-2008)

year	Input (mm)	Output (mm)	Act ET (mm)	Storage (mm)
1987	2515	1874	594	49
1988	2502	1659	679	164
1989	2537	1724	651	163
1990	2506	1681	706	119
1991	2340	1548	640	153
1992	1886	1206	603	78
1993	2289	1510	674	105
1994	2313	1536	690	87
1995	2750	1775	733	242
1996	2719	1854	713	153
1997	2491	1458	645	387
1998	2434	1932	596	-94
1999	2763	1888	660	214
2000	2365	1537	716	112
2001	2223	1403	695	124
2002	2502	1707	631	164
2003	2685	1783	683	219
2004	2582	1707	690	185
2005	2192	1278	727	186
2006	2195	1349	755	91
2007	2769	1761	737	270
2008	2565	1644	739	183
Average	2460	1628(66%)	680(28%)	153(6%)

5.10 Climate Projection data

Climate data for future is important for the study of impact of climate change. For this purpose, the projected data set of climate change from the IPCC approved GCMs data. This study used the RCM data downscaled from WRF (weather research and forecasting model) for RCPs scenarios which was approved by IPCC fifth Assessments Report. RCPs are the future climate data considering green house gas concentration. RCPs data are the scenarios data based on pathways of radiative forcing. Radiative forcing is a measure of the influence of a factor has in altering the balance of incoming and outgoing energy in the earth atmosphere system and is an index of the importance of the factor as a potential climate change mechanism. The radiative forcing is expressed in watts per square meter (W/m2). The study used the RCPs data to study the climate change impact on Marshyangdi river basin from 2020 to 2050.

In this study the temperature and precipitation data (2020-2050) from WRF (weather research and forecasting model) for scenarios RCP 4.5 and RCP8.5 are used to analyzed the impact of climate change on water balance components and snow and glacier contribution to the stream flow. The 12km x12km resolution data for RCP are downscaled from the WRF (weather and research forecasting model) was further corrected it bias with observed data of the study area. With compare to the basin data, the precipitation was increased by 2.5% for RCP 4.5 scenarios and by 0.1% for RCP 8.5 scenarios. In RCP 4.5 scenario, the Maximum temperature increased by 0.1^{0}C/year and minimum temperature increased by 0.35^{0}C/year inside the study basin and in RCP 8.5 scenario, the maximum temperature increased by 0.065 ^{0}C/year and minimum temperature increases by 0.4 ^{0}C/year Which indicates that the temperature of the study basin was increasing. The increase of temperature is higher in high altitude than lower altitude stations.

5.11 Impact on Rainfall and snowfall

Figure 5.17 shows the monthly rainfall and snowfall in different scenarios. Due to the change in climate scenarios the rainfall and snowfall contribution was different than the baseline contribution. With increase temperature gives the increase in rainfall contribution. By the analysis, it was found that the annual rainfall of the study basin will increases 4.5% in RCP4.5 scenario and 3.1% in RCP 8.5 scenario. The analysis indicates that the snowfall will be decrease in both scenarios. This may be due to shifting of snowfall to rainfall with increase temperature. The annual snowfall will decrease by 11.4% and 7.8% in RCP4.5 and RCP8.5 Scenarios respectively. The decrease snowfall will result for the shifting of snowline toward high elevation.

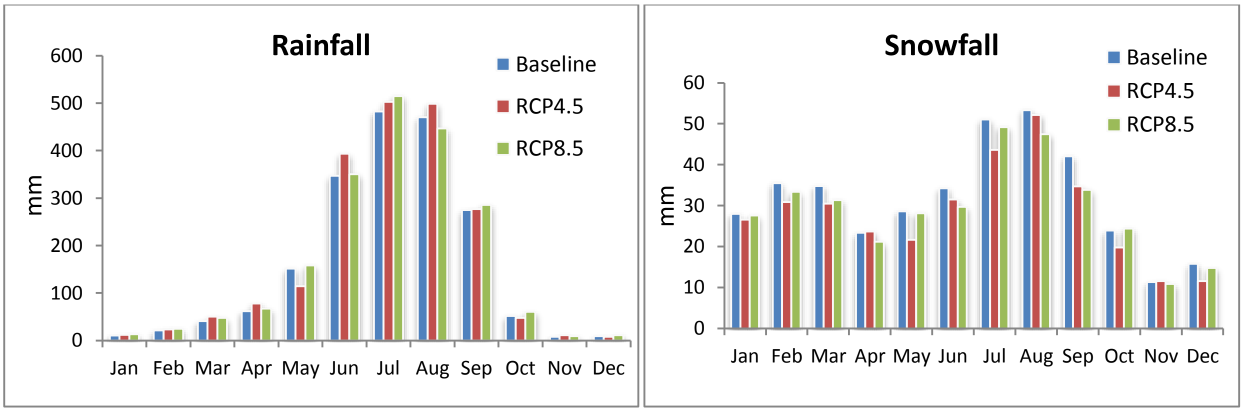


Figure 5.17 Monthly contribution of Rainfall and Snow fall in different scenarios.

5.12 Impact on River Discharge

The Figure 5.18 shows the comparison of the simulated discharge of the Marshyangdi river basin in different scenarios data. The result shows that the simulated discharge of the study basin will be increased in the both scenarios. As describe above, the increase percentage of rain precipitation in RCP 4.5 scenario is higher than in RCP8.5 scenario, which increases the discharge in RCP4.5 scenario than in RCP8.5 Scenario. As the rain precipitation increases than snow precipitation, contributes the high overland flow which helps to increase the high stream flow. The annual simulated discharge of the model used by RCP4.5 will increase by 14% whereas in RCP8.5 it will be increase by 13% than baseline simulated discharge.

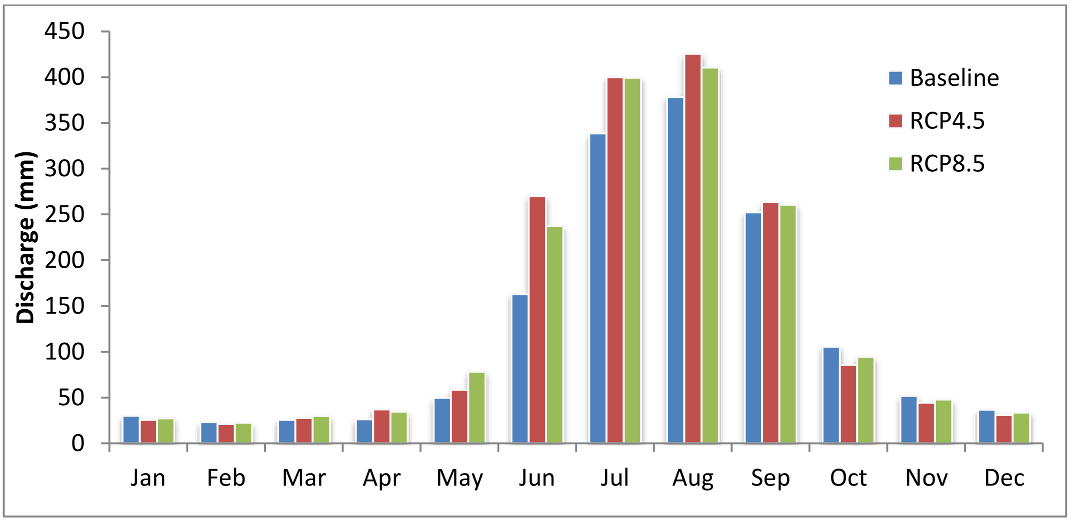


Figure 5.18 Monthly discharge of Marshyangdi river basin by using the baseline (1987-2008), RCP 4.5 (2020-2050) and RCP 8.5 (2020-2050)

5.13 Impact on snow melt contribution to river runoff

Figure 5.19 shows monthly contribution of snow and glacier melt in different scenarios. The analysis of the projected scenarios indicates that the snowmelt will be increase by 29% and 38% in RCP4.5 Scenario and RCP8.5 scenario respectively. In Figure 5.19, the snow melt started melting from early pre-monsoon in both future scenarios. During the monsoon season the snowmelt volume will be increase by 36% and 40% in RCP4.5 and RCP8.5 scenarios respectively. This may be due to the melting of snow associated with high temperature during this season in future scenarios. And this may be the result of increase rain form precipitation than snow precipitation. The snow melt contribution in RCP 4.5 scenario will be slightly less than the RCP 8.5. It is because; the snow precipitation in RCP 4.5 will be less than the RCP 8.5 scenario.

The ice melt from glacier is not included in the snowmelt contribution (Figure 5.19) because the feedback effect of glacier i.e. a change in spatial distribution of glacier area due to climate change or change in temperature is not included in the J2000 model. Higher temperature change increases the ice melt contribution.

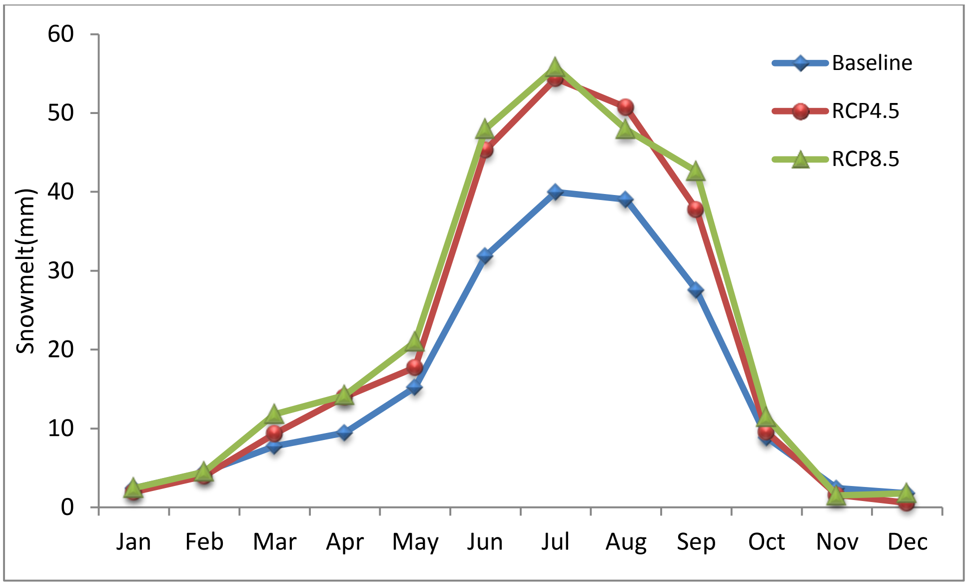


Figure 5.19 Monthly contributions of the snow melt runoff in different climatic scenarios.

5.14 Impact on various runoff components

The analysis of projected data shows that the surface runoff or overland flow (RD1) contribution to the stream flow will increase in both future scenarios (Figure 5.20). The overland flow will increase by 30% and 23% in RCP4.5 and RCP 8.5 scenarios respectively. The increase snow melt contribution results the high contribution of overland flow. The inter flows RD2 and RG1 will be decrease in both scenarios which directly impacts on the evapotranspiration. Dry soil contributes low evapotranspiration. The interflows RD2 and RG1 will decrease 8% and 30% in both RCP4.5 and RCP8.5 respectively. The base flow RG2 for both scenarios also will decrease however, more decreased in RCP 4.5 scenario. The base flow will decrease 24% and 21% in RCP4.5 and RCP 8.5 respectively. The increased overland flow may increase the flood events during the monsoon season.

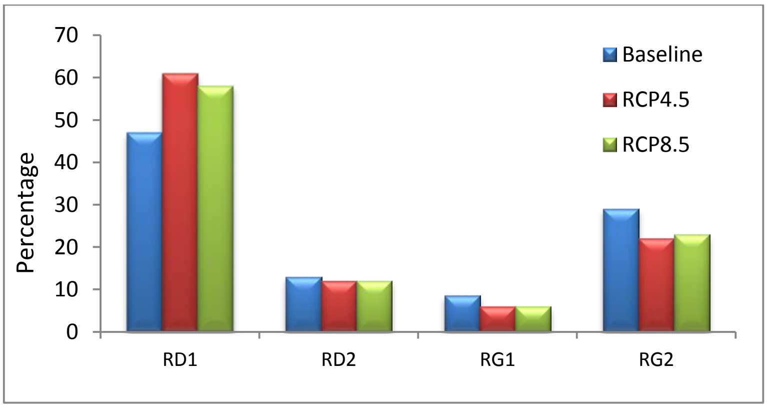
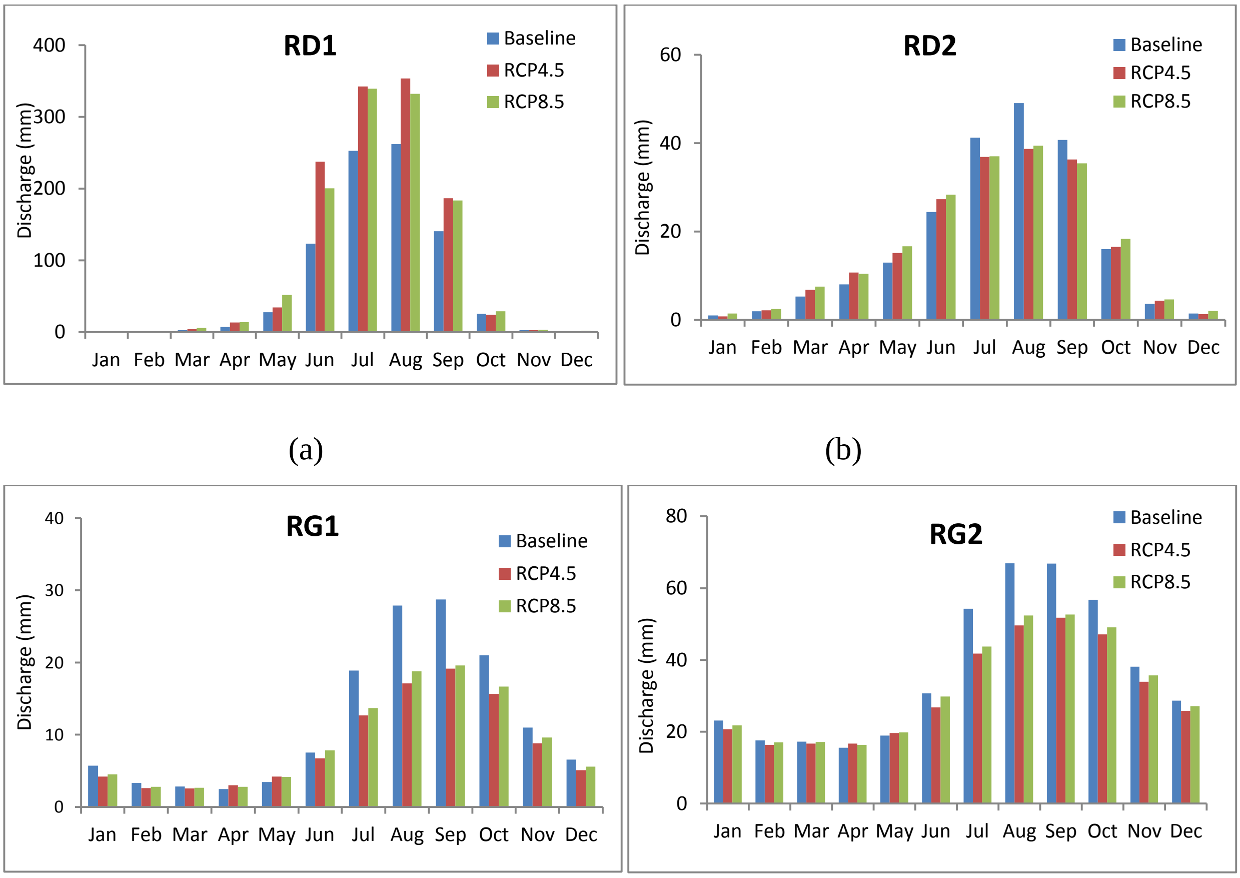


Figure 5.20 Annual distributions of various runoff components in different scenarios.

Figure 5.21 shows the monthly contribution of various runoff components in different scenarios. During the monsoon season (June-September), the overland flow RD1 (Figure (a)) contribute the high volume than baseline period whereas the interflows RD2, RG1 and the base flow RG2 (Figure (b), (c) and (d)) decreased than the baseline which may result the increase flood events. The increased overland flow is due to increase precipitation in the form of rain.



(a) (b)

(c) (d)

Figure 5.21 Change in monthly contribution of various runoff components in different climatic scenarios

The decrease slow direct runoff RD2 and fast base flow RG1 changes the water availability of soil moisture. It reduces the soil moisture of the unsaturated soil zone.

5.15 Impacts on Evapotranspiration

Normally the increased temperature increased the evapotranspiration but the analysis of future scenarios in this study basin indicates the potential and actual evapotranspiration will be decrease. The actual evapotranspiration will decrease by 21% and 19% in RCP4.5 and RCP 8.5 respectively. Figure 5.22 shows the monthly contribution of actual evapotranspiration in different scenarios.. The decrease interflows reduce the water availability on different storage components.

And the actual evapotranspiration is depends on the water availability of storage components. So less storage provides less evapotranspiration. The decrease actual evapotranspiration was highly depends on the reduce water availability at the unsaturated zones in future scenarios.

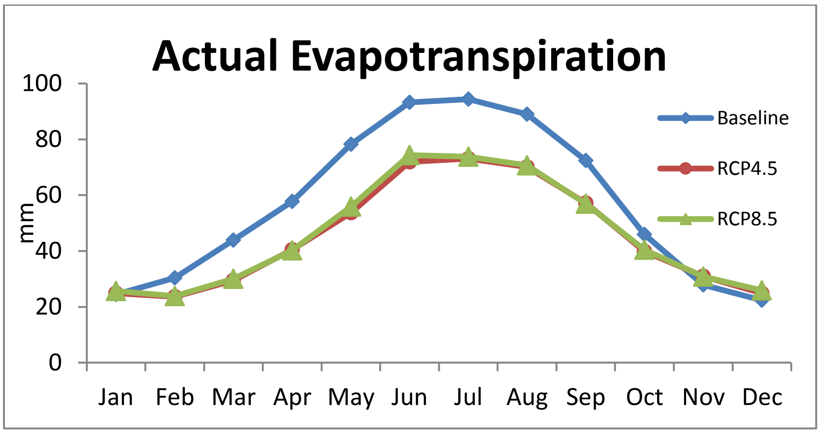


Figure 5.22 Monthly actual evapotranspiration in different climatic scenarios

CHAPTERVI: CONCLUSION AND RECOMMENDATION

6.1 Conclusion

The study was carried out in the snow fed perennial river in central Nepal i.e. Marshyangdi river basin. The study used only one hydrological gauging station at Bimalnagar station which is the outlet of the study basin. The study used the six precipitation and three temperature stations. The study used the J2000 distributed hydrological model to estimate the contribution of the snow and glacier melt in the Marshyangdi river basin. For the future climate impact study, the study used the RCP 4.5 and RCP8.5 scenarios which were introduced by IPCC fifth assessment report.

On the basis of this study, the following conclusion could be drawn.

1) The increasing trend of maximum and minimum temperature inside the basin shows the basin is warming in future.
2) The Mann Kendall and Sen’s slope estimator shows the decreasing trend of precipitation at northern part of the basin and increasing trend of precipitation at southern part of the basin.
3) Only one station shows the statistically significant decreasing trend of precipitation with value -6.2mm/year.
4) The J2000 model was able to represent the hydrograph well for different parts runoff components with Nash Sutcliffe coefficient value 0.87 and 0.83 for calibration and validation respectively
5) The increased rain form precipitation in future scenarios increases the river discharge.
6) The snow melt contribution to the stream flow was recorded as 20% of the total stream flow which will increase by 29% in RCP4.5 and 38% in RCP8.5 climatic scenarios, which conclude that the snowline will be shifted toward high altitude in RCP8.5 Scenario. The high contribution of snowmelt to the stream flow increases the river discharge in future scenarios.
7) The J2000 model able to distinguish various runoff components such as overland flow interflows and base flow. The overland flow RD1 contributes 52% of the total runoff which will increases by 30% in RCP4.5 and 23% in RCP8.5 scenarios data. The increase overland flow may cause the high flood during the monsoon season.
8) The base flow contributes 26% of the total runoff which will be decrease 24% in RCP4.5 and 21% in RCP8.5 scenarios. This shows the stream flow at driest season will reduce.

9) The decrease interflows RD2 and RG1 reduce the water availability on soil moisture for future. Climate change dominates the base flows.
10) There is about 28% of the total precipitation is lost by the actual evaporation only. The actual evapotranspiration will be decrease in both scenarios. There will be 21% and 19% decrease of actual evaporatranspiration in RCP4.5 and RCP8.5 Scenarios.

6.2 Recommendation

This study analyzed the impact of climate change on snow and glacier melt contribution, various runoff components to the stream flow. On the basis of the study the following recommendation are made to improve the efficiency of the model.

1) The model can be improved by applying more observed data in high altitude areas. Further, more refined future data helps to understand the future hydrology in a better way.
2) Similar study can be applied for different scenarios to compare the impact of climate change such as land use change.
3) The problem of missing data and poor quality data should be controlled and upgraded for determining the actual trend.
4) The J2000 model has static glacier layer which does not change in future due to higher temperature. Therefore, the future hydrology was analyzed without glacier ice melt. In future, the dynamic process of glacier area in J2000 can help to understand future hydrology better.

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Annex

Table A1: Details of hydrological and meteorological station used in the study basin

Station No.	PPT	Temp	Discharge	RH	SSH	WS	Lat	Long	Elevation
802	√	√		√			28°17'	84°22'	823
804					√	√	28°20'	83°97'	827
807	√						28°08'	84°21'	855
808	√						27°93'	84°41'	965
809		√		√			28°00'	84°37'	1097
816	√	√		√			28°33'	84°14'	2680
820	√						28°40'	84°01'	3420
823	√						28°12'	84°37'	1120
439.7			√				27°57'	84°25'	354

PPT: Precipitation, Temp: Temperature, RH: Relative Humidity, SSH: Sunshine hour, WS: Wind speed, Lat: Latitude, Long: Longitude

Table A2: Annual maximum and minimum temperature within study area in °C (1979-2012)

year	Khudibazar		Gorkha		Chame	
	Tmax	Tmin	Tmax	Tmin	Tmax	Tmin
1979	26.26	14.92	25.36	16.87	16.25	4.83
1980	26.11	14.43	25.10	16.39	14.98	6.22
1981	25.67	13.73	24.55	15.98	15.44	5.41
1982	25.64	13.13	24.47	15.68	15.60	6.02
1983	25.53	12.73	24.48	15.72	15.71	4.30
1984	26.05	13.52	25.19	16.18	16.00	5.61
1985	25.97	10.70	25.38	16.18	16.33	4.73
1986	26.08	11.69	25.22	15.22	16.36	4.73
1987	26.25	15.46	26.49	15.35	16.89	5.01
1988	26.63	16.18	26.38	16.07	16.81	5.33
1989	26.28	15.56	25.71	15.94	16.26	5.36
1990	26.98	15.21	25.59	15.93	16.37	5.33
1991	27.13	15.68	25.89	15.82	15.95	5.12
1992	27.05	15.41	27.23	15.96	15.86	4.96
1993	27.53	15.53	26.46	15.87	16.75	5.47
1994	28.36	15.08	26.33	15.39	16.91	5.47
1995	28.21	15.14	26.07	16.56	15.95	5.24
1996	28.08	15.03	27.09	16.98	16.14	5.11
1997	26.75	14.13	26.62	16.55	15.56	4.71
1998	27.18	15.52	25.01	15.04	17.21	5.68
1999	27.42	15.92	26.26	15.93	16.60	6.54
2000	27.05	15.41	25.95	15.75	14.94	4.58
2001	27.38	15.92	25.85	15.93	17.35	5.16

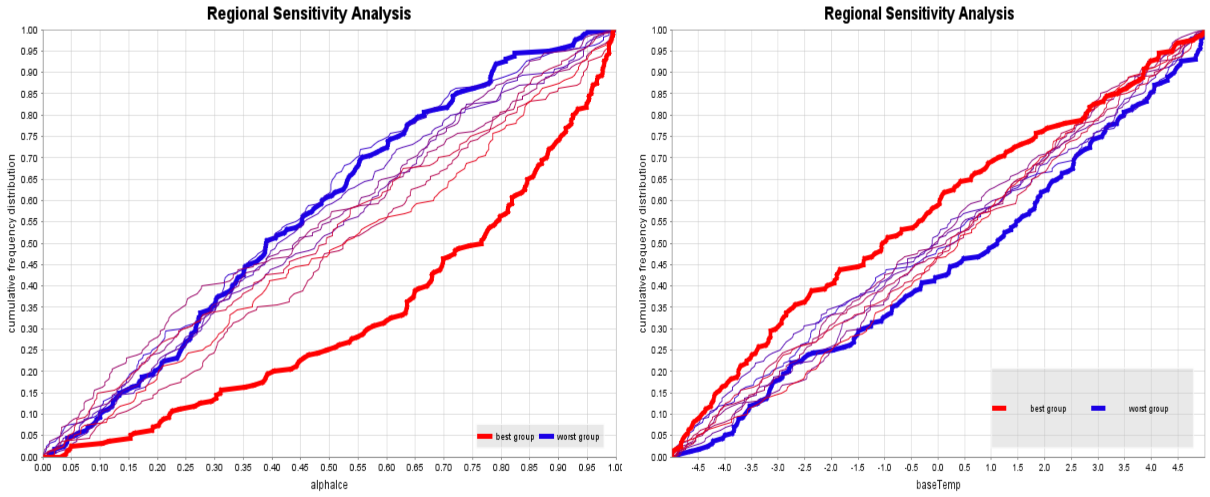
2002	27.35	16.02	26.72	15.72	17.44	5.34
2003	26.84	15.10	27.04	16.27	17.34	4.92
2004	26.41	15.49	26.91	11.09	19.03	3.93
2005	26.82	14.01	27.55	16.32	18.44	3.22
2006	27.67	16.14	28.12	17.33	19.28	3.84
2007	26.91	15.87	27.08	16.96	19.11	3.44
2008	27.64	14.31	27.72	16.66	18.56	2.73
2009	27.70	15.90	27.02	16.83	18.39	2.71
2010	28.66	16.37	28.60	16.46	17.37	2.61
2011	27.24	15.45	28.18	16.30	18.02	3.52
2012	27.79	14.44	28.25	16.23	18.50	3.06

TableA3: Annual precipitation within the basin mm/year

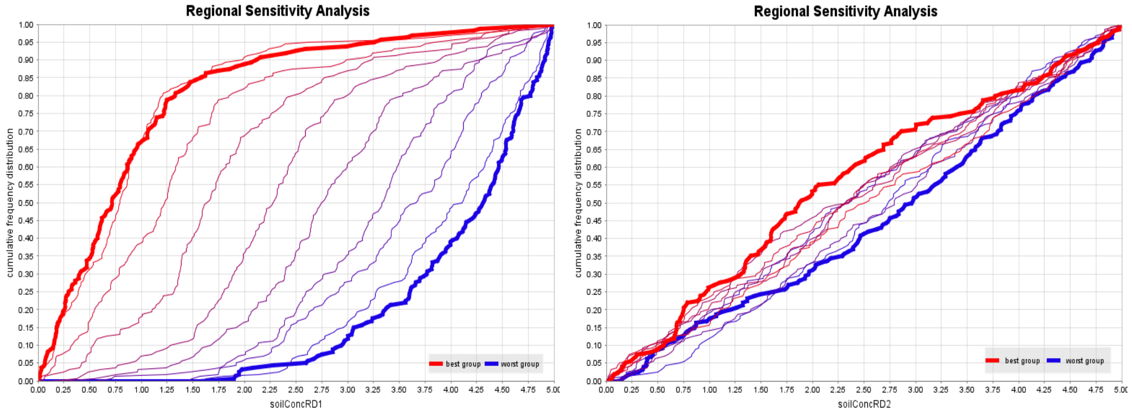
year	Khudibazar	Kunchha	Bandipur	Chame	ManangBhot	Gharedhunga
1979	3344	3096	3002	970	340	3078
1980	3060	2303	2279	1462	491	2848
1981	2247	2612	1668	997	530	2582
1982	2932	2332	2015	940	517	2973
1983	3175	2428	1312	1014	487	2850
1984	3736	2362	980	771	383	3016
1985	4131	2203	1392	1429	626	2889
1986	3594	2490	1399	859	581	3183
1987	3520	3007	1890	747	519	3192
1988	3524	2721	1416	814	459	3445
1989	3347	2467	1932	1252	518	2921
1990	3481	2868	524	956	312	3206
1991	3258	2030	1517	1004	361	2971
1992	2668	1754	2264	796	244	2346
1993	3261	2404	1772	798	334	3083
1994	3195	2345	1502	749	520	2898
1995	3487	3040	1884	1321	473	3430
1996	4437	2427	1741	1165	329	3356
1997	3400	1714	816	1221	790	2551
1998	3550	3198	1619	734	434	3299
1999	3436	2989	2701	753	1149	3653
2000	3545	3120	1941	595	316	3283
2001	3140	2825	2021	530	371	3308
2002	3304	3662	2148	910	379	3196
2003	3849	2620	578	960	521	3694
2004	4142	3235	490	975	325	2756
2005	2839	2093	597	1174	401	2680
2006	2853	2380	649	947	275	2938
2007	3373	2517	672	1683	447	3102

2008	3691	2430	522	1017	394	3574
2009	2642	1972	612	482	209	2337
2010	3281	3490	819	1235	331	3039
2011	3339	2551	699	871	235	2799
2012	3099	2443	910	814	245	2959

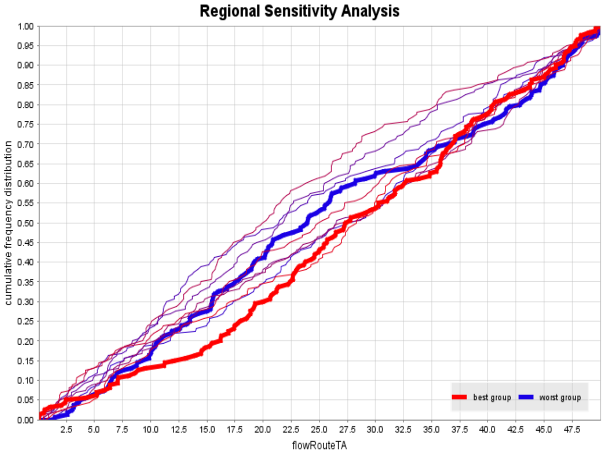
Figure A1: Sensitivity of parameters with Nash Sutcliffe efficiency (e2)



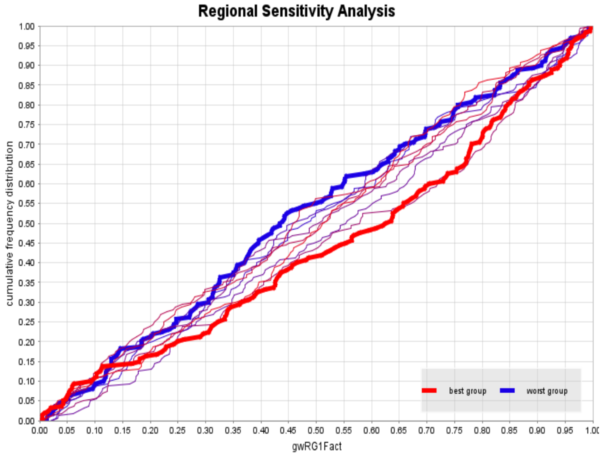
(a) Alphaice (b) basetemp



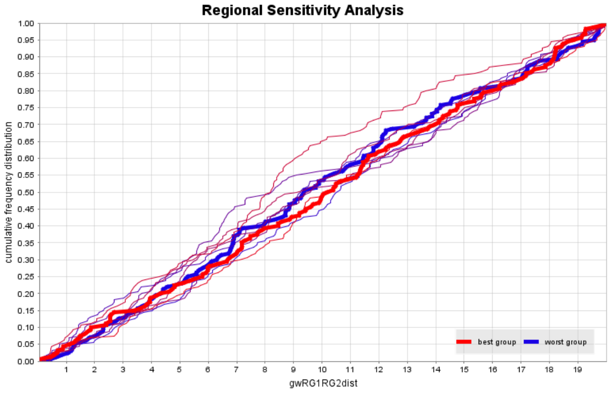
(c) soilconcRD1 (d) soilCocRD2



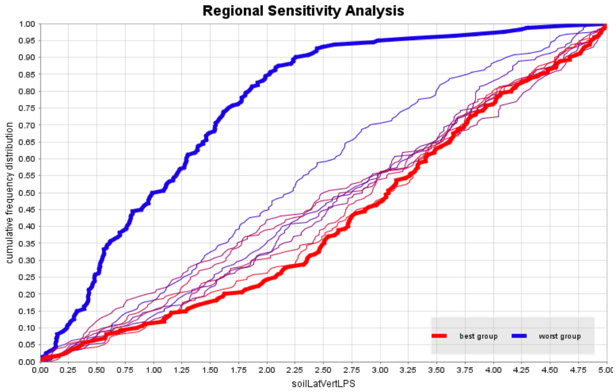
(e) flowRouteTA



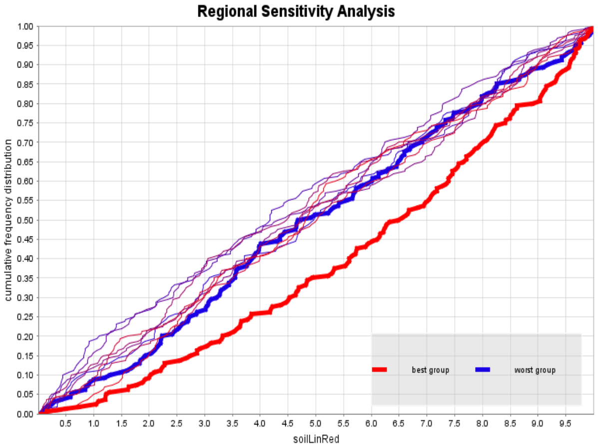
(f) gwRG1fact



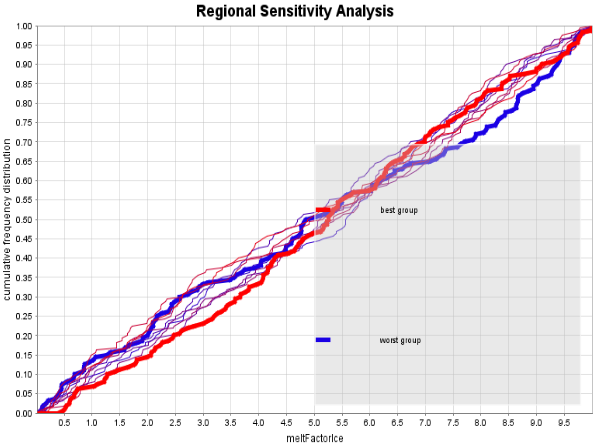
(g)gwRG1RG2fact



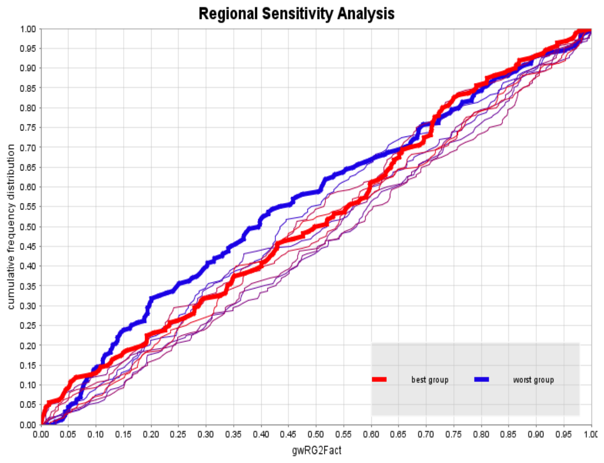
(h) soilLatvertLPS



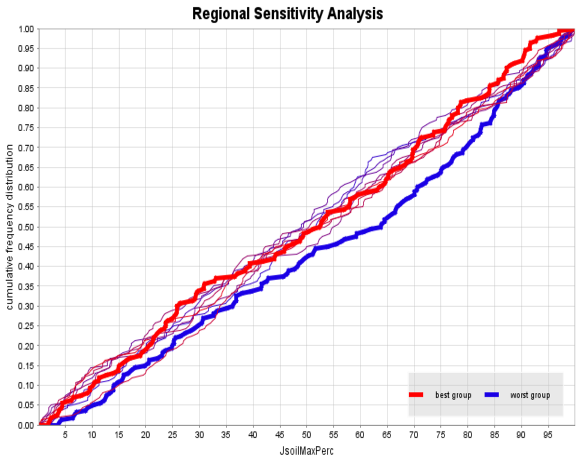
(i) SoilLinRed



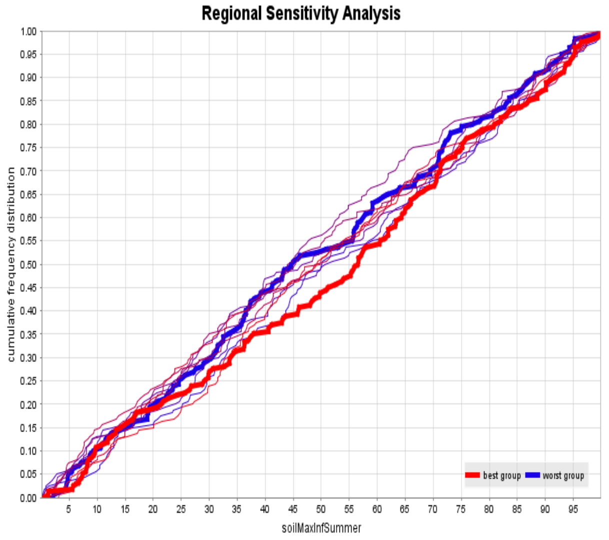
(j) meltfactorICe



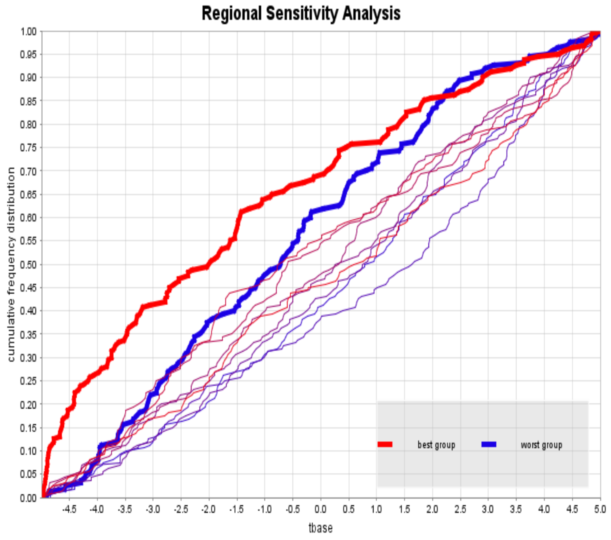
(k) gwRG2fact



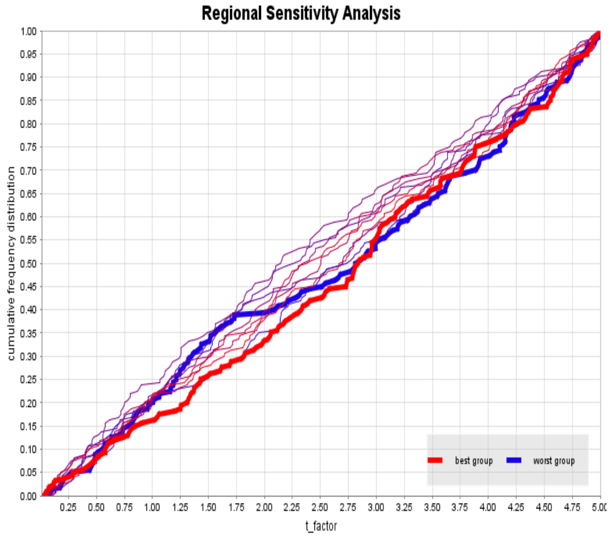
(l) soilMaxPerc



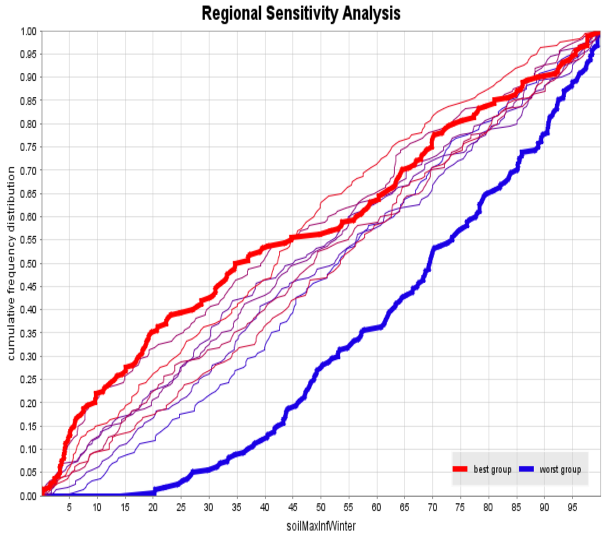
(m) soilMaxInfsummer



(n) tbase

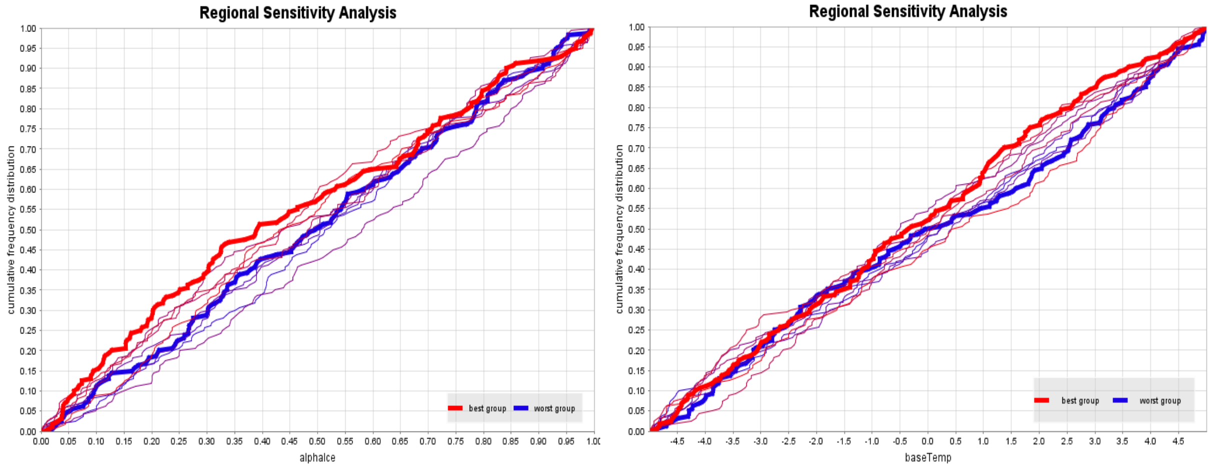


(o) t_factor



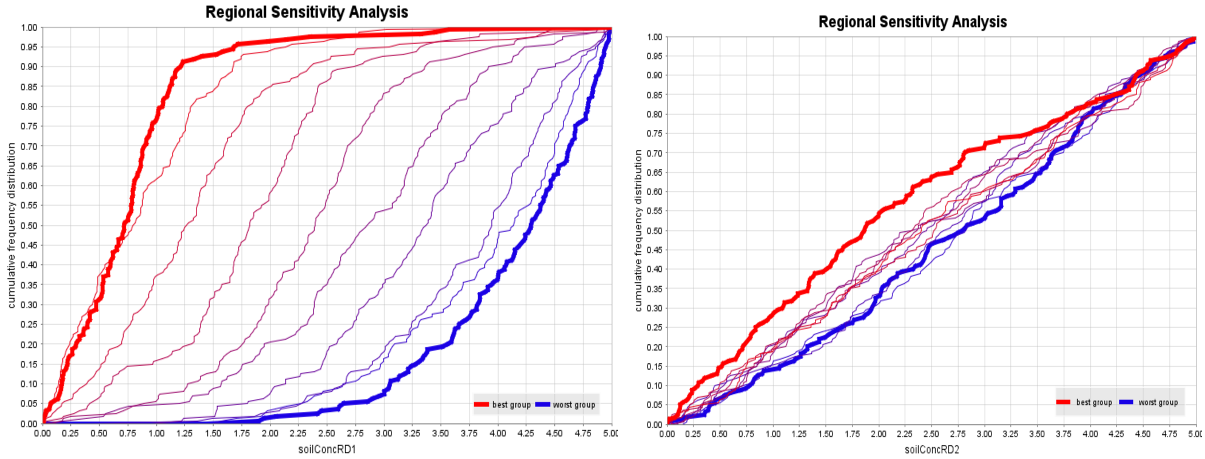
(p) soilMaxInfWinter

Figure A2: Sensitivity of parameters with coefficient of determination (r2)



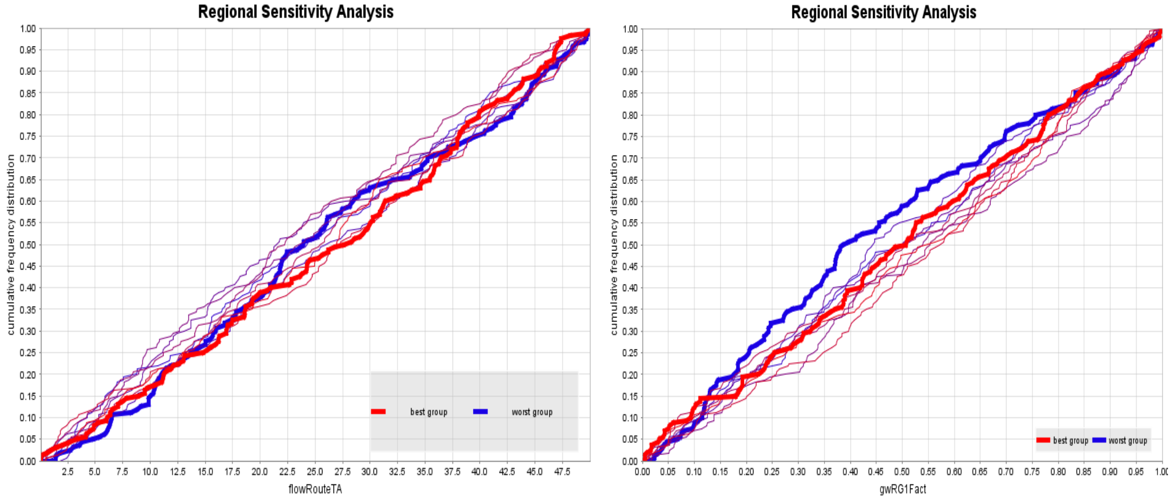
(a) Alphaice

(b) basetemp



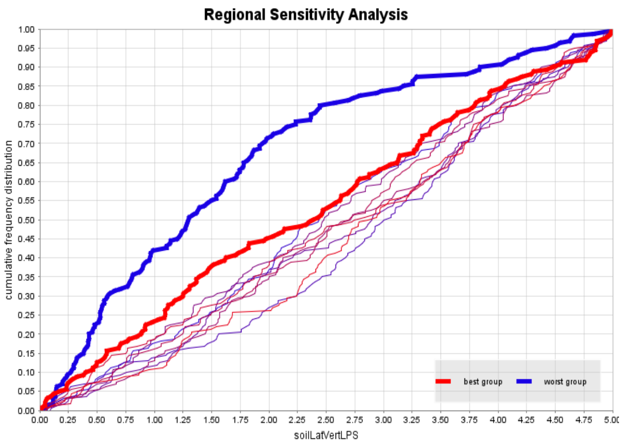
(c) soilconcRD1

(d) soilCocRD2

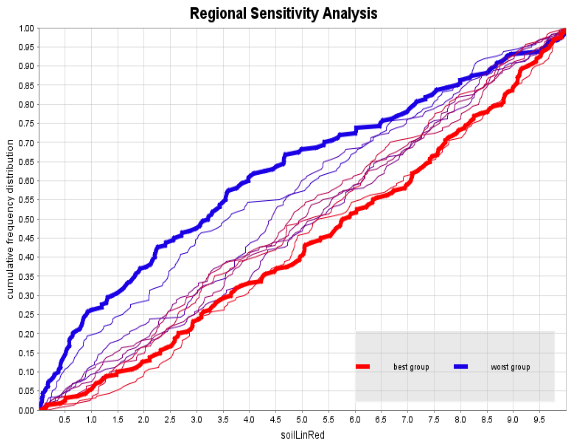


(e) flowRouteTA

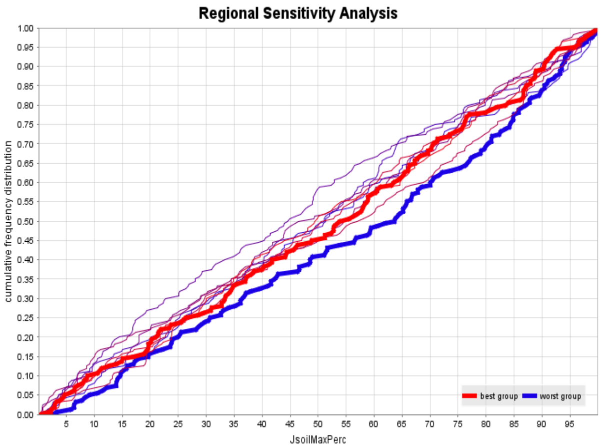
(f) gwRG1fact



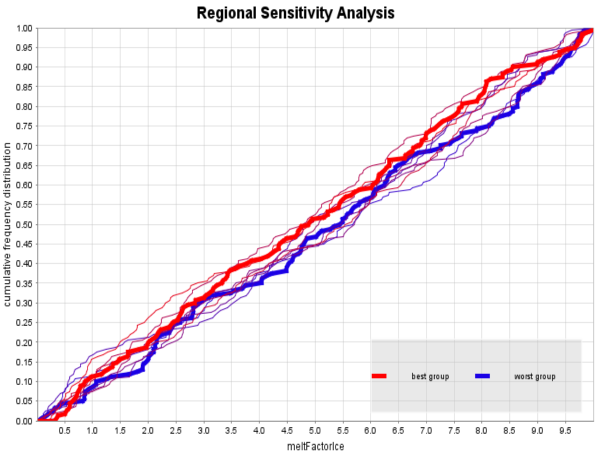
(g) soilLatvertLPS



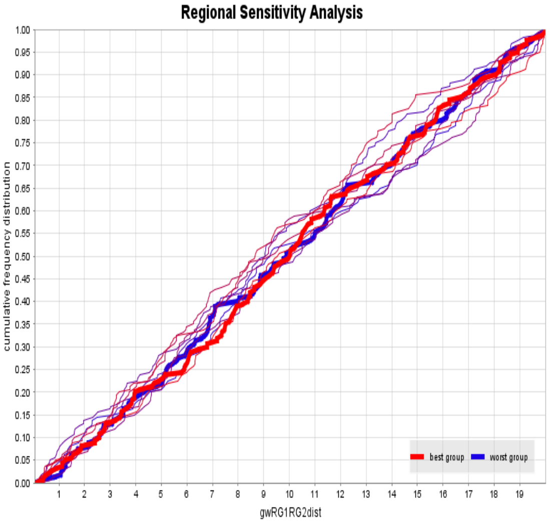
(h) SoilLinRed



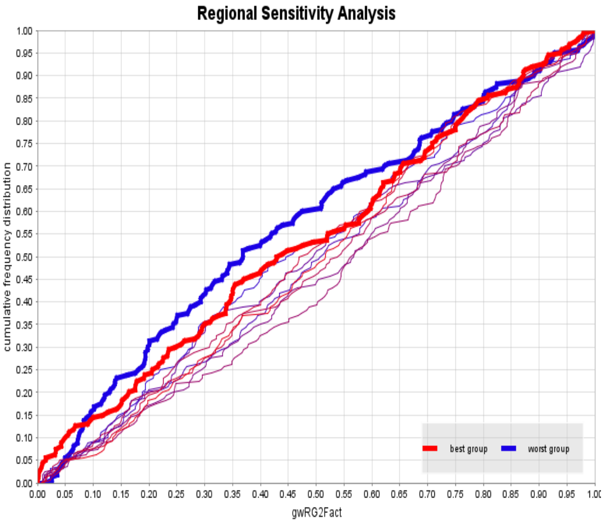
(l) soilMaxPerc



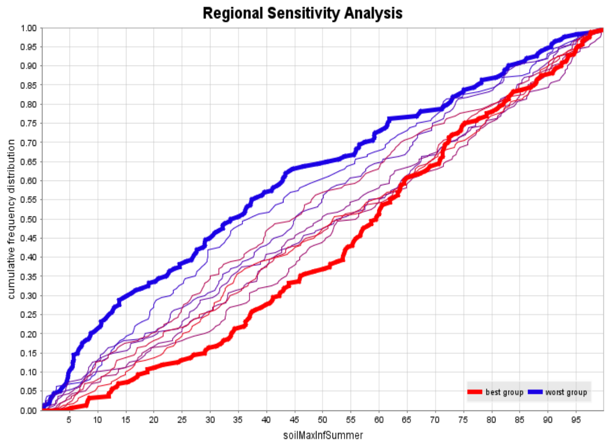
(j) meltfactorICe



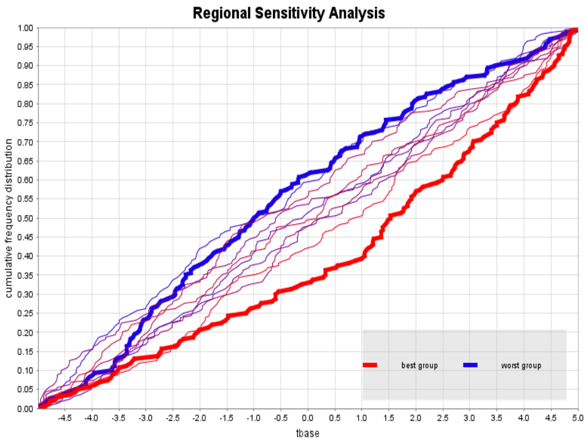
(k) gwRG1RG2fact



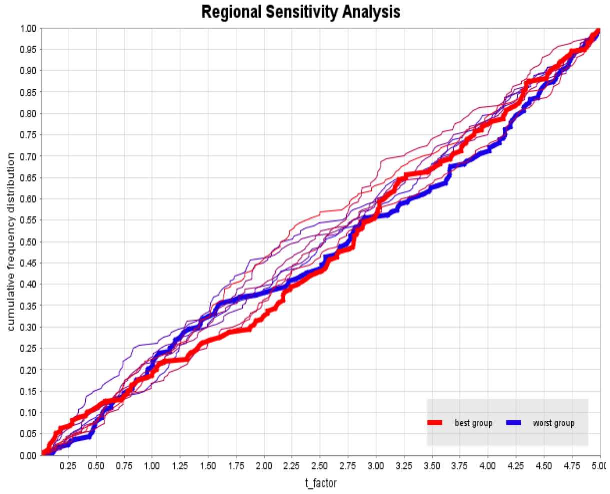
(l) gwRG2fact



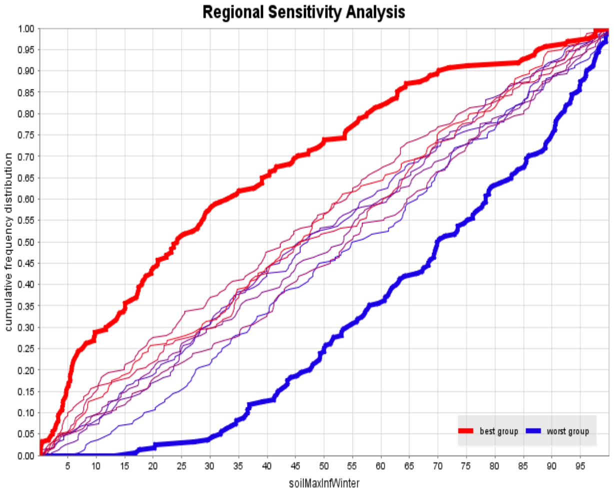
(m) soilMaxInfsummer



(n) tbase



(o) t_factor



(p) soilMaxInfWinter