CHAPTER 1
INTRODUCTION

1.1 Background

Climate change is imminent threat posed to natural and human system in this planet and atmosphere, as no single country and individual is likely to remain impervious to this global problem. Changing climate and a warming world are the key issues today and the world community faces many risks from climate change. It is now believed that the large flash floods, frequent flooding, prolonged drought, increase in vector borne diseases and rapid glacier melt are some important results of climate change. The effects of climate change are seen in different ways. Global warming since the end of the Little Ice Age has been observed all around the northern hemisphere. The global average surface temperature has increased by 0.6ºC ± 0.2ºC since the late 19th century and it is projected to rise by 1.4–5.8ºC by 2100 (IPCC, 2001). The updated 100 year's trend (1906–2005) of 0.76ºC is higher than the 100-year warming trend (1901–2000) of 0.6ºC at the time of the TAR- Third Assessment Report due to additional warmth years (IPCC, 2007). The year 2010 was likely to be the world's warmest year on record, the British Met Office has predicted. According to the Met Office, man-made climate change will be a factor and natural weather patterns was contributed less to 2010's temperature than they did in 1998, the current warmest year in the 160-year record (Times of India, 2010) .The World Meteorological Organization (WMO) concluded that the year 2010 was 0. 53ºC warmer than the average for the period 1961–1990, a period commonly used as a baseline. Regions of the world experiencing particularly warm conditions during 2010 included Africa, southern and western Asia, and the northern extremities of North America, including Greenland (BBC News, 2011). The global mean surface temperature has increased by 0.6ºC during the 20th century (IPCC, 2001a). Many studies confirmed that temperature increased in 20th century has been greater than in any centuries before. According to D. Douglos (1995), the magnitude of warming was rapid in the 19th century than in the 17th and 18th centuries in Nepal. In recent time, many studies have confirmed that there is a large variability in climate. Deviations in the variability of the climate apparently have significant impacts on the food production and livestock, water scarcity, flood disaster risk etc., particularly in the developing regions.

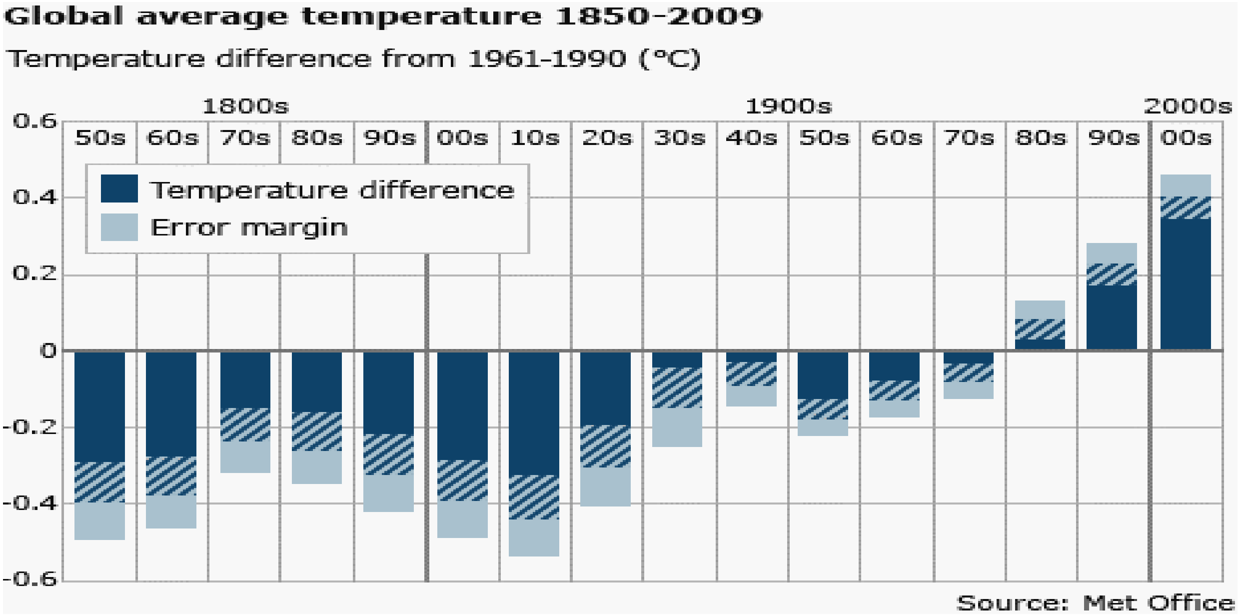


Figure1.1: Global average temperature, BBC 2010

The third assessment report for Intergovernmental Panel for Climate Change (IPCC, 2001b) indicates that warming in Asian region is projected to be 3ºC by 2050s. Also, the annual warming at Himalayan region of Nepal between 1994 and 1997 was found to be 0.06ºC (Shrestha et al., 1999). These changes could have large effects on Himalayan glaciers by shrinkage of glaciated areas. There will be substantial increase in the aerial extent of Glacier Lake which may cause catastrophic Glacier Lake Outburst Floods (GLOF).

Climate change is principally due to increase in temperature caused mainly by the combustion of fossil fuels to yield energy. Studies show that developing countries are more vulnerable to climate change and are expected to suffer more from the adverse climatic impacts than the developed countries (IPCC, 2001a). South Asian countries are especially vulnerable to its effects due to their poor resilience of most sectors in Asia (IPCC, 2001). The long term variations in annual and seasonal surface temperature over South Asia depicted warming trends (Panta et al., 1990). The Himalayan region including the Tibetan Plateau has shown consistent trends in overall warming during the past 100 years (Schild, 2007) and with this rising temperatures, areas covered by permafrost are decreasing in much of the region (Fukui et al., 2007) and Himalayan glaciers are retreating faster than the world average (Fujita et al., 1998; Bajaracharya et al., 2007). In Himalayas 67% percent of glaciers are retreating at a starling rate caused by climate change and the retreating rate of Himalayan glaciers are faster than the world average retreat rate and are thinning by 0.3-1 m/year (Schild, 2007). Potential changes in Hindu Kush Himalaya (HKH) resulting from global warming are reported in a regional meeting in 1990 (Tropping, Quershi and Sherer, 1990; Price and Haslett, 1995).

The global atmospheric concentration of carbon dioxide (CO_2) has increased dramatically over the last century and, at the present rate of increase, will double by the end of the century. Global circulation models (GCMs) have been used to study the effects of the increasing concentration of carbon dioxide and the other greenhouse gases on the Earth's climate are transient models and simulate the Earth's atmospheric circulation; they predict the changes in temperature, in the amount and distribution of precipitation and other climatic variables on the assumption of a rate of increase in CO_2 concentration of 1% per annum from 1990 to 2100. Such a change in climate will have important implications on the hydrological balance and water resources.

1.2 Climate change in Nepal Himalayas

Nepal's diverse topography, fragile ecosystems and extreme poverty make it very vulnerable to the negative impacts of climate change. It is one of the 100 countries most affected by climate change, yet it has one of the lowest emissions in the world — just 0.025% of total global greenhouse gas emissions. Nepal is one of the poorest countries in the world, with around 31% of its population of 28 million living below the poverty line. Most of Nepal's poor living in rural areas relies on rain-fed subsistence agriculture. They are vulnerable to extreme weather events; and often have poor access to information and lack resources to help them cope with and recover from weather-related disasters (OXFAM, 2009).

Nepal has already been suffering from climate change-led impacts. From the available studies, it has been found that temperatures in Nepal are increasing at a rather high rate (National Communication Report of Nepal, 2004). The minimum temperatures are increasing more rapidly than the maximum temperatures (Cook et al., 2003; Rupa Kumar et al., 2006). With warmer winters, particularly at higher altitudes, there will be less precipitation as snow fall which will further accelerate glacial retreat due to less or no snowfall. In the future, an annual average temperature rise of 2 ºC to 4ºC has been projected in Nepal when CO is doubled using Climate Change Circulation Model (CCCM) and regional climate models (MOPE and UNEP, 2004). Available data shows that the temperature of Nepal is increasing consistently after the mid-1970s with an annual average 0.06 ºC in between 1977 and 1994 (Shrestha et al., 1999) which is higher than other countries, and the warming is found to be more pronounced in the high altitude regions of Nepal such as the Middle Mountain and the

High Himalaya (WWF Nepal, 2006). This finding is reinforced by observations on the other side of the Himalayas on the Tibetan Plateau (Liu et al., 2000). Increase in temperature of Nepal with annual average of 0.06ºC in between 1977–1994 (Shrestha et al., 1999) causing rainfall to increase by 13 mm per year, while the number of rainy days is decreasing by 0.8 days per year suggesting rainfall occurs in burst.

In a humid climate like that of Nepal, there will be changes in the spatial and temporal distribution of temperature and precipitation due to climate change, which in turn will increase both the intensity and frequency of extreme events like droughts and floods (Mahtab, 1992). Increases in temperature result in a reduced growing season and a decline in productivity, particularly in South Asia (Pauchuri, 1992). A warming climate would increase water demand on the one hand and would decrease river flows on the other. Reduced river flows will affect the hydropower generation, inland water transport and aquatic ecosystems. Similarly, reduced water availability may create conflicts between users within and among nations.

1.3 Impact of climate change on runoff generation

Runoff generation is a complex multi-factor process. It consists of a large number of interconnected partial processes localized within the boundaries of a river basin. Therefore, by the process of runoff information, one should understand not only a direct appearance of water able to flow down in future, but the whole complex of a definite group of partial processes which together form the land part of the hydrological cycle in nature. Global warming, due to the build-up of greenhouse gases, is likely to have a significant effect on the hydrologic cycle (IPCC, 2001). Growing evidence indicates that the low-latitude mountainous cryosphere is undergoing change due to recent warming (IPCC, 2007). Geographic areas where the water cycle is dominated by snowmelt hydrology are expected to be more susceptible to climate change as it affects the seasonality of runoff (Adam et al., 2011).

Increasing numbers of scientific communities observing the global climate show a collective picture of a changing climate and a warming world. The hydrologic system, which consists of the circulation of water from oceans to air and back to the oceans, is an integral part of the global climate system, therefore, any changes in the climate system cause not only changes in the hydrologic system but also further modification of the climate itself due to these new changes in the hydrologic system. The hydrological cycle will be intensified, with more evaporation and more precipitation, but the extra precipitation will be unequally distributed around the globe. Response of runoff to climate change is closely related to the change in precipitation. Changes in precipitation are always amplified in changes of runoff, especially in drier regions. Runoff is more sensitive to change in precipitation than to change in temperature.

Recently a great deal of concerns has been expressed regarding the potential impacts of climate change. International bodies such as IPCC or local bodies like the University of Washington Climate Impacts Group (CIG) have attempted to assess the impacts of climate change at various levels. Temperature changes can have a profound effect on the amount, type and timing of precipitation (Mote and Salathe, 2010). Annual average precipitation volumes can increase or decrease, the ratio of rainfall to snowfall can increase, and the seasonality of precipitation can shift toward wetter winters and dryer summers (Mote and Salathe, 2010). Hydrology in particular is affected by a changing climate, as the primary driver of the hydrologic cycle is precipitation (Mote and Salathe, 2010). As there is uncertainty in the eventual effects of climate change on precipitation (Mote and Salathe, 2010).

Human disturbances in river basins, such as land use change, have long compromised the assumption of stationary within probability density functions governing uncertainties. Currently, substantial anthropogenic change of Earth's atmosphere, and therefore climate, is altering many hydrologic parameters, including the mean and extremes of precipitation, Glaciers are very sensitive to climate changes; therefore, they can be considered as good indicators of past climate changes (Nesje and Dahl, 2000). Widespread retreat of the world's glaciers was observed during the 20th century. The snow covered area of the world has decreased by 10% since the 1960s (IPCC, 2001a). The global mean sea level has increased at a rate of 1 to 2 mm/year during the 20th century due to thermal expansion of sea water and the melting of glaciers and ice sheets. Nepal is rich in water resources. There are more than 6000 rivers flowing from the Himalayan mountains to the hills and plains. Most of these rivers are glacier-fed and provide sustained flows during dry seasons to fulfill the water requirements of hydropower plants, irrigation canals and water supply schemes downstream. The hydrology of these rivers is largely dependent on the climatic conditions of the region, which in turn is a part of global climate.

The major rivers of Nepal are fed by melt-water from over three thousand glaciers scattered throughout the Nepal Himalayas. These rivers feed irrigation systems, agro-processing mills and hydroelectric plants and supply drinking water for villages for thousands of kilometers downstream (Agrawala et al., 2003). Climate change will contribute to increased variability of river runoff due to changes in timing and intensity of precipitation as well as melting of glaciers. Runoff will initially increase as glaciers melt, then decrease later as deglaciation progresses. Accelerated melting of glaciers during the last half century has caused creation of many new glacier lakes and expansion of existing ones (Mool et al., 2001). There have been more than 13 reported cases of glacier lake outburst flood events in the Nepal Himalayas since 1964 causing substantial damage to people's lives, livestock, land, environment and infrastructure (Rana et al., 2000). Accelerated retreat of glaciers with increased intensity of monsoon precipitation observed during recent years has most probably contributed to increased frequency of such floods (Agrawala et al., 2003). Catchment runoff is the best measured water balance component. However, runoff generation is yet not fully understood. There is still scientific discussion on the role of overland, subsurface and groundwater flows in runoff generation and its mechanisms.

There are several indications that changes in land cover have influenced the hydrological regime of various river basins. In addition, the effects of climate change on the hydrological cycle and on the runoff behavior of river catchments have been discussed extensively in recent years. However, it is at present rather uncertain how much and at which spatial scale these environmental changes are likely to affect the generation of storm runoff, and consequently the flood discharges of rivers. Nepal is well known for its pronounced geographic verticality due to large differences in the minimum and maximum altitudes. The snowy mountains are situated in the high altitude area in the north. Climate change-induced floods generated in these mountainous areas have significant negative effects on the society and economy of the mountains as well as the plains far downstream.

Therefore, it is very important to quantify such impacts of climate change on runoff generation in order to identify the adaptation options and thereby minimize the potential damage magnitude of climate change on a local and regional scale.

1.4 About the model and basin

Monthly Thornthwaite water balance model has been used to find the runoff generation of Langtang basin. The area of study is 361 km^2. This model is modified in 2010. The full description of the model is describe in subchapter 5.3, 5.4 and 5.5. The GSM data were available from the NCEP reanalysis product. We have use the SDSM to find the missing data and done the calibration and validation. The full description of SDSM is described in subchapter 5.6. We have used A1B data to analysis the projection of runoff generation.

CHAPTER 2

Objectives and limitations

2.1 Objectives of the Study

The main objectives of the study are:

1) To understand the impact of climate change on runoff generation.

2) To estimate snow melt runoff by using the Thornthwaite model from observed precipitation, temperature and GCMs data.

3) To analysed the observed and simulated result to understand impact of climate change.

2.2 Limitations

Following factors were considered as hindrance in acquiring accurate estimation from the study and these facts should be taken into account while making generalization of these findings.

1) Unavailability of sufficient data.

2) Temperature and precipitation are considered as climatic parameters responsible for climate change impacts.

2.3 Scope of the study

1) The information of snow accumulation and ablation.
2) The runoff information which will help for planning of irrigation, drinking water managements and hydropower.

CHAPTER 3

Literature Review

3.1 Climate change and Runoff generation; Global studies

Global warming has resulted in significant variability of global climate especially with regard to variation in temperature and precipitation. Surface temperature of the earth is rising globally, which is the major indicator of global climate change. The global climate change has already greatly affected the world in many folds. As a result, it is expected that river flow regimes will be accordingly varied (Nam et al., 2011). Climate change and anthropogenic activities have dramatically altered the spatial and temporal distribution of regional stream discharge and water resources, which poses a serious threat to wetland ecosystems and sustainable agriculture. On the other hand the Himalayas and glaciers are huge storage and very important source of fresh water, they are one of the most sensitive indicators of climate change as they grow and shrink in quick response to changing air temperature (Shilpakar et al., 2008). The effects of climate change on the hydrological cycle and on the runoff behavior of river catchments have been discussed extensively in recent years. However, it is at present rather uncertain, how much and at which spatial scale these environmental changes are likely to affect the generation of storm runoff and consequently the flood discharges of rivers runoff is the portion of precipitation or snow and glacial melt that flows across the landscape until it, ultimately, oceans. Surface runoff generation depends on rainfall or snowmelt characteristics (amount, duration, intensity, and time distribution) and landscape characteristics (vegetation, land use, topography, soil texture and structure, and antecedent soil moisture conditions). Surface runoff can be generated either by rainfall or by the melting of snow, or glaciers. Snow melt reaches streams, rivers, and snow and glacier melt occur only in areas cold enough for these to form permanently. Typically snowmelt will peak in the spring and glacier melt in the summer, leading to pronounced flow maxima in rivers affected by them. The determining factor of the rate of melting of snow or glaciers is both air temperature and the duration of sunlight. In high mountain regions, streams frequently rise on sunny days and fall on cloudy ones for this reason. Here are some studies regarding climate change and global perspective of climate change in runoff behavior of global as well as domestic catchments.

Absar, (2010) based on the literature review of articles and empirical studies published in international journals and other supplementary sources such as personal communications with local and international glaciologists and hydrologists working in HKH region, reveals that the

HKH region is under the influence of more than one weather influences. Owing to that and other geographic, topographic and hydrological reasons, most of the glaciers located in the higher elevations of the Karakoram mountain range are observed to be expanding, getting thicker and surging, which is a very interesting phenomenon. Other studies and observations in the western Himalayan region do show consistencies with the popular belief that glaciers are melting and forming large lakes close to their termini. Given that the science is there in its infancy and that the topography of the HKH region is highly heterogeneous with multiple factors controlling the receding and surging of glaciers, it is premature and challenging to come up with any generalized conclusions about what the glaciers will look like in the year 2030.

Adam et al., (2011) studied the long-term goal in conjunction with other projects is to identify the hydrological impacts of projected climate change for Region X and to use this information to evaluate existing Region X infrastructure and practices and to make recommendations for the design of new infrastructure to sustainably handle storm water. The objective of this specific application is to compare the hydrological conditions for historical climate to those of a future climate over the Palouse River basin as information necessary to design sustainable transportation infrastructure. The central hypothesis is that a 2- year storm for the future climate will produce a larger amount of highway runoff than the 2-year storm for the historical climate. The objective will be achieved through the offline coupling of a hydrology model with global climate models (GCMs). Climate change scenarios will be obtained from multiple GCMs and multiple emissions scenarios to produce a range of uncertainty in future simulated runoff. The expected outcome from this project is the development of a method (that can be applied elsewhere) to generate the hydrology data needed to design sustainable infrastructure.

Beyene et al., (2003) studied potential impacts of climate change on the hydrology and water resources of the Nile River basin are assessed using a macro scale hydrology model driven by 21st century simulations of temperature and precipitation downscaled from runs of 11 General Circulation Models (GCMs) and two global emissions scenarios (A2 and B1) archived for the 2007 IPCC report. The results show that, averaged across the multi model ensembles, the entire Nile basin will experience increases in precipitation early in the century (period I, 2010–2039), followed by decreases later in the century (periods II, 2040-2069 and III, 2070–2099) with the exception of the eastern-most Ethiopian highlands which is expected to experience increases in summer precipitation by 2080–2100. These changes in precipitation and temperature resulted in stream flows at High Aswan Dam (HAD) that are 111 (114), 92 (93), and 84 (87) percent of historical simulated stream flow (1950–1999) for periods I to III, respectively, for the global A2 (B1) emissions scenario. Implications of climate change on the water resources of the Nile River basin were analyzed by quantifying the annual hydropower production and irrigation water releases at High Aswan Dam, which generally would follow changes in stream flow, increasing early in the century to 112 (118) percent, but then decreasing to 92 (97) and 87 (91) percent in Periods I and III.

Bohrn, (2010) analyzed runoff generation of the Churchill River, has a total length in excess of 1600 kilometers and the land which drains into it covers parts of northern Manitoba, Saskatchewan, and Alberta. The Canadian Climate Change Modeling Agency has developed a Global Climate Model which postulates several future climate scenarios. Using the WATFLOOD hydrological model coupled with these scenarios, it is possible to estimate future runoff possibilities. The results of this study show that there is a general decreasing trend for flows generated in the Churchill River basin. This decrease is most dramatic in the 2020s timeframe and became less so as time progressed to year 2100. Equally significant was the seasonal shift which was displayed in the results. Projected future spring melts happen earlier in the year while summer flows were decreased significantly. This decrease in flow is likely to cause a decrease in the hydroelectric generation on the Nelson and Burntwood Rivers. Additionally, after modifying the evaporation subroutine of the model, calibration was determined to have a significant effect on the climate change model results.

Bronstert et al., (1999) addresses the different possible effects of climatic change on the areal storm runoff generation and on flood generation and also discusses some shortcomings of flood models in representing land cover and presents results of a pilot study in a small catchment in the Harz mountains in northern Germany, integrating possible changes in climatic conditions, land cover and vegetation water use. There are several indications that changes in land cover have influenced the hydrological regime of some river basins. In addition, the effects of climate change on the average hydrological cycle and on the runoff behavior of river catchments have been discussed in several reports. However, it is at present rather uncertain in which way, to what degree and at what spatial scale these/such environmental changes are likely to affect the generation of storm runoff and subsequently the extreme discharges of rivers. However, these interactions and the subsequent changes in storm runoff production have not been approached so far.

Dong et al., (2012) analyzed 55-yr (1956–2010) rainfall and runoff patterns in the Nanjing River Basin (NRB) to quantitatively evaluate the impact of human activities on regional hydrology. The long-term hydrologic series were divided into two periods: period I (1956–1974), during which minimum land use change occurred, and period II (1975–2010), during which land use change intensified. Kendall's rank correlation test, non-parametric Pettit test and precipitation-runoff Double Cumulative Curve (DCC) methods were utilized to identify the trends and thresholds of the annual runoff in the upstream, midstream, and downstream basin areas. Their results showed that the runoff in the NRB has continuously declined in the past 55 yr, and that the effects of climate change and human activities on the runoff reduction varied in the upstream, midstream and downstream area over different time scales. For the entire study period, climate change has been the dominant factor, accounting for 69.6–80.3% of the reduction in the total basin runoff. However, the impact of human activities has been increasing from 19.7% during the 1950s–1970s to 30.4% in the present time. Spatially, the runoff reduction became higher from the upstream to the downstream areas, revealing an increasing threat of water availability to the large wetland ecosystem in the lower river basin.

Guo et al., (1997) studied a procedure for the uncertainty analysis of climate change impact assessment is proposed and analyzed by application to two river basins in China. A monthly water balance model was chosen to simulate soil moisture and runoff. Monte Carlo simulation was used to generate different parameter sets, and probability density functions of runoff series were estimated by a nonparametric method. The results of the case study indicate that runoff is more sensitive to variation in precipitation than to increase in temperature; the smaller the runoff coefficient, the larger the uncertainty. At 5% significance level and the most likely climatic scenario (temperature increase of 1°C and rainfall increase by 10%), the future peak flood discharge at Huayuan and Nantang basins in the south of China may increase by 47.41% and 38.16% respectively, which may seriously affect flood protection works and water resources systems.

LIU et al., (2011) investigated the Impacts of land use and climate change on runoff by studying the runoff in the Yarlung Zangbo River basin, China. Trends in precipitation, mean air temperature, and runoff were analyzed by non-parametric Mann-Kendall tests. Land-use and climate changes showed several characteristics, Human activity caused great impact, especially within densely populated regions and cities. Annual mean air temperature, precipitation and runoff showed increasing trends between 1974 and 2000. The impacts of land use and climate change on runoff had different effects depending on region and season. In the season of freezing, climate change clearly affected runoff within regions that experienced precipitation. Altered evapotranspiration accounted for about 80% of runoff changes, whereas land-use changes appear to have had greatest impact on runoff changes within regions that have inconsistent relationships between runoff and climate change.

Nam et al., (2011) presents a preliminary projection of medium-term and long-term runoff variation caused by climate change at a Thu Bon River basin in Central Vietnam. Results show that by the middle and the end of this century annual rainfall will increase slightly; together with a rising temperature, potential evapotranspiration is also projected to increase as well. The total annual runoff, as a result, is found to be not distinctly varied relative to the baseline period 1981–2000; however, the runoff will decrease in the dry season and increase in the rainy season. The results also indicate the delay tendency of the high river flow period, shifting from Sep–Dec at present to Oct–Jan in the future. The present study demonstrates potential impacts of climate change on stream flow regimes in attempts to propose appropriate adaptation measures and responses at the river basin scales.

Palmer, (2011) addresses the potential future impacts of climate change on the Tualatin River Basin and the region's ability to meet current and future water demands. By considering the fact that there is a growing preponderance of evidence that the earth's climate is changing, the precise nature and magnitude of change that will occur in the future in relatively small river basins is not easily estimated. To address this issue, he presents the results of a series of loosely-integrated models that track the impacts of climate change on precipitation and temperature, stream flow, and water management.

Richer, (2009) examines sources of variability of Cache la Poudre River Northern Colorado in snowmelt runoff as a means of identifying methods that could help improve stream flow prediction for the basin. Naturalized flow records were developed by accounting for all diversions from the river, inputs of foreign water via trans-basin diversions, and reservoir operations. Using this Supervisory Control acquisition (SCA) data, the Snow Melt Runoff Model (SRM) was then configured to simulate snowmelt runoff hydrographs for the basin using both optimized Results show that flow modification delayed hydrograph timing and reduced water yields for all years included in the study period. The naturalized hydrograph displayed a wide range of relationships to SCA depletion patterns in the basin. Snow cover depletion in middle elevations, however, had a much stronger relationship to discharge, with steady snow cover depletion occurring in these areas during hydrograph rise. This suggests that the SRM could be used to generate seasonal stream flow forecasts given appropriate selection of parameter values and input variables.

Stanev, (2007) the paper presents an attempt for assessment of the Climate Change impact on the Mesta River runoff using Hydrologiska Byrans Vattenbalansavdelning (HBV) mathematical model. The HBV model has a simple vegetation parameterization including interception, temperature and evapotranspiration calculations, lake evaporation, lake routing, glacier mass balance simulation, special functions for climate change simulations etc. The main input variables used in this report are the average monthly temperature, monthly totals of the precipitation, the potential evapotranspiration and the monthly discharges. The River Mesta flows from North to South up to the Aegean Sea. Two different Climate Change scenarios are used (HadCM2 and ECHM4). The calculations are for years 2025, 2050 and 2100 using 30 years base period (1961–1990). The obtained results are promising and they show the potential possibility for the HBV model use.

Wagesho et al., (2012) investigate the potential impact of climate change on runoff generation at two agricultural watersheds. Climate change and key future signals of its variability are assessed using General Circulation Models (GCMs). As precipitation variables are composed of biases, both linear and power transformation bias correction methods are applied to obtain bias corrected daily precipitation. The statistical downscaling model, followed by bias correction, effectively reproduced the current weather variables. It is noted that increased extreme daily precipitation and temperature events prevail for future scenarios. Dry-spell length increases during the driest months and remains stable during wet seasons. There is no defined future precipitation change pattern. The simulated runoff varies from -4% to 18 % at Hare watershed and is within the range of −4 % and 14 % at Bilate watershed. Simulated average annual runoff shows slight variation between GCMs at both watersheds.

Zhang et al., (2007) conducted the study to evaluate the potential effects of climate change on mean annual runoff in the Yellow River basin under different climate change scenarios projected by the Hadley Centre's third-generation general Circulation Model (HadCM3) using an evaporation ratio function of the aridity index. The results showed that annual runoff was more sensitive to change in precipitation than to change in evaporation. Simulations using HadCM3 scenarios A2 and B2 indicated that the changes in annual runoff compared to 30-year average runoff for each region, which varied from region to region, ranged from

−34.1% to 49.6%. In general, the potential changes in annual runoff were greater in the middle and down reaches of the Yellow River basin. The expected increases in runoff require that more attention will be given to soil and water conservation practices such as vegetation and check-dam construction.

3.2 Studies from Nepal Himalayas

Bhattarai, (2011) carried out the study to investigate the contribution of snow melt in stream flow of snow fed stream to understand the impact of climate change on water resources. This study implemented the simple Temperature Index method i.e. Positive Degree Day approach to estimate the snowmelt from the catchment. The result showed that the Positive Degree Day or Temperature Index method integrated with Snowmelt Runoff Model (SRM) can be well applied in rugged and remote Himalayan catchment like Langtang Khola basin with limited data. The study demonstrates that the impact of climate change (i.e. temperature) to stream flow is significant. Due to the snow melt contribution, stream flow increases approximately at rate of 2 % in winter, 5 % in summer and 4 % in annual flow under the projected temperature rise of 1°C.

Braun et.al., (1998) describes a procedure to bridge data gaps in daily values of precipitation and air temperature from high mountain stations in Nepal based on continuous measurement records of the meteorological service network with stations located mainly in lowland areas. In a second step, a conceptual precipitation-runoff model is calibrated and verified in three Himalayan head watersheds. Discharge is calculated using a daily time step over a total of seven hydrological years. This approach enables the assessment of the temporal and spatial distribution of runoff from high mountain areas such as the Nepalese Himalaya, and forms a valuable basis for water resources planning and management, i.e. hydropower generation.

Chaulagain, (2006) analyze the long-term hydrological, meteorological and glaciological data from the Nepal Himalayas has revealed that the climate in the Nepal Himalayas is changing faster than the global average. Moreover, the changes in the high-altitudes have been found more pronounced than in the low-altitudes.

Lamadrid et al., (2010) provides a sound basis of HKH region for a feasibility study. Consequently, overall, a large scale study is feasible in terms of institutional, technical and scientific capacity. However, a climate change impact assessment study of this magnitude will be dependent on external support and cooperation, and local capacity building should be a cornerstone of any effort undertaken. Efforts to date have been piecemeal, performed by a variety of local, and more often foreign, agencies and institutions. A coordinated, local effort utilizing but not dominated by foreign expertise, aimed at developing both modeling capacity and the data to support model development and application, is needed to further this work in the HKH region. As part of this effort, close, on-going communications with projects currently underway should be prioritized to leverage existing modeling, data, expertise, and learning.

MoEnv, (2012) Global warming is often accompanied by changes in the hydrological cycle e.g. changes in rain and snowfall patterns, snow and glacier melt, atmospheric water vapor and evaporation, and changes in soil moisture and runoff. These changes have significant impact on water in glaciers, rivers, wetlands and underground aquifers and affect agriculture, energy, human health, water-related disasters and water supply. Drought has caused drying of springs, groundwater depletion, reduction in river water discharge, and wetland degradation. The "too little water" situation has particularly affected women and children who have to travel long distances to fetch water. They also face diseases caused by poor sanitation resulting from water scarcity. Rapid glacier melting in the Himalayan region has resulted Glacier Lake Outburst Floods (GLOFs) that have caused catastrophic floods downstream. Heavy precipitation in the form of extreme events have resulted in devastating floods and triggered landslides that have caused lost of lives and destroyed infrastructures downstream. The extreme climate events that result in "too much water" degrade drinking water sources. Similarly, prolonged droughts may cause reduction of discharge, which in turn, again makes water unfit for drinking and is therefore a major risk to human health.

Panday, (2007) in this study he utilizes a snowmelt runoff model in the Tamor River Basin in the eastern Nepalese Himalaya which is driven by remotely sensed snow cover from Moderate Resolution Imaging Spectroradiometer (MODIS). The Snowmelt Runoff Model (SRM) is calibrated using daily stream flow from 2002 to 2005 and the stream flow can be predicted with a high degree of accuracy. Three climate change scenarios were used to drive the model in order to understand the impact of changing conditions. A scenario of a 4°C temperature increase and 20% precipitation increase results in a significantly increased runoff volume by ~23%, with stream flow exceeding present conditions in all months.

Sherchand et al., (2005) analyzed the climatic data of 1980–1999 from the six stations viz: Okhaldhunga, Chlalsa, Bhojpur, Pakhrebas, Tarahara and Kankai representing Terai, Hill and Mountain environment. Analyzing data shows the annual maximum temperature showed increasing trend but the minimum temperature showed mixed response. The precipitation showed more decreasing trend over years except at Okhaldhunga.

Shilpakar et al., (2008) aims to assess impact of the climate change on snowmelt runoff in Tamakoshi basin. It is located at above than 1960 m altitude and more than 60% area lies above 4000 m. For simplicity, the Positive Degree Day (PDD) (temperature index) is used for snow and glacier melt estimation. Geographical Information System (GIS) is used for automatic delineation of watersheds from Digital Elevation Model (DEM) and ERDAS Imagine software is used to delineate the snow and glacier covered area of rugged and inaccessible terrain from processing of satellite images. Runoff pattern is analyzed using conceptual precipitation and snowmelt runoff modeling (SRM) tools in different climatic conditions (i.e. temperature). The results highlight considerable contribution of snowmelt and glaciers to runoff, and significant impact of climate change on snowmelt runoff.

Shrestha, (2009) attempts to find the impacts of climate change on water resources and food production over Langtang valley and identify the adaptation practices, strategies to reduce vulnerability due to climate and environmental changes. The investigation includes the analysis of temperature and precipitation data to identify the climate change trend and pattern during the period 1987 to 2007. The analysis of total precipitation and number of rainy days also shows the increasing trend. Similarly, the analysis on number of extreme precipitation events (>20 mm/day) and heavy events (10–20 mm/day) are found higher in the latest decade (1997–2007) as compared to the previous decade (1987–1996). Total glacier cover varies from 45% to 35% for the years 1988 to 2000 with highest glacier cover in 1988 and lowest cover in 2000.

Thayyen et al., (2009) analyzed the factors influencing the river flow variations in a "Himalayan catchment" in the Garhwali Himalaya, covering an area of 77.8 km^2. Study shows that the inter-annual runoff variations in a "Himalayan glacier catchment" are directly linked with the precipitation rather than mass balance changes of the glacier. Study suggest that warming induced initial increase of glacier degraded runoff and subsequent decline is a glaciers mass balance response and cannot be translated as river flow response in a "Himalayan catchment" as suggested by the IPCC, 2007.

Chapter 4

STUDY AREA

4.1 General Description of the Study Area

Langtang Khola (River) basin is situated approximately 60 km north of Kathmandu valley adjoining to the border of China, and is one of the tributaries of Trisuli River which join the Narayani River System. The total basin area of Langtang Khola is 361.0 km^2. The catchment lies between the altitudes of 3800 m above sea level (ASL) to 7234 m ASL (Konz M, 2003). The average altitude is 5169 m ASL with mean slope of 26.7° which reflects the high potential relief energy of the catchment. Glacier covers an area of 166 km^2 of the catchment, of which 32 km^2 is covered by debris, and most of the glacier tongue goes below 5200 m.

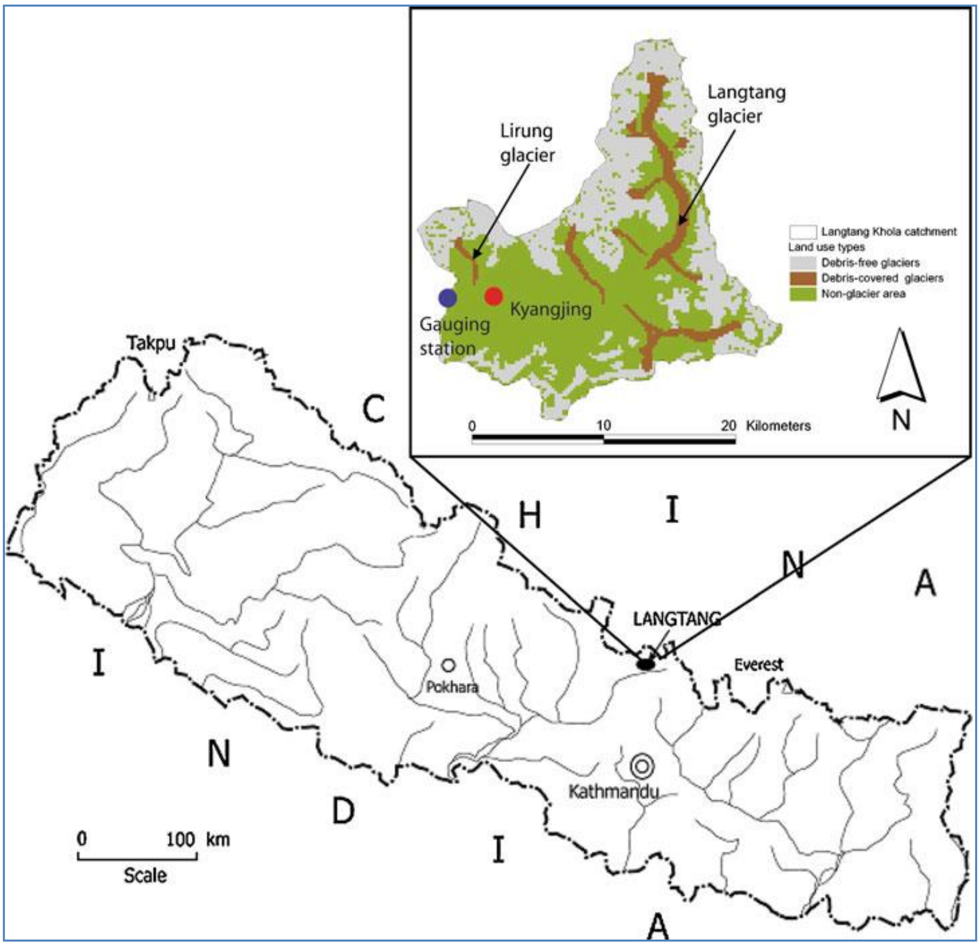


Fig 4.1 Location of study area, Map Source: Walter W.Immerzeel et al. (2011)

Geo-morphologically the main valley is U shaped in nature dissected by the Langtang Khola. Land cover in this catchment can be classified in to four categories i.e. bare land, clean glacier, debris covered glacier and bare rocks (Fig 4-1). Clean and debris cover glacier covers almost 50% area, where as the bare land including some patches of vegetation covers 42%. Only 8% of catchment is covered by rock.

4.2 Topography

The topographic features of the upper Langtang valley are very rugged and steep with its terrain cut by valleys, deep river gorges and glaciers. The general topographic feature is depicted in Figure 4-1. Some of the world's highest peaks such as Langtang Lirung (7248 m ASL), Langtang II (Ghenge Liru) (6581m ASL) and Yala Peak (5500 m ASL) exist in this region.

4.3 Climate

The seasonal climate is dominated by southern monsoon, which occurs between June and September. The incidence and type of precipitation is mainly related to aspect, altitude and the presence of rain shadow effect. In summer, snow accumulates only above 5,500 m. In autumn, it accumulates down to 4,000 m and during the winter precipitation is generally in the form of snow and it starts accumulating from 3000 m. In general, north and west facing slopes tend to be more protected allowing snow to accumulate.

Temperatures vary widely with aspect, altitude and cloud cover. The coldest months are December to February and the maximum temperature reaches between May and July. Humidity and cloud cover increases with the onset of the monsoon.

According to the Rasuwa and Nuwakot Integrated Development Project, the average annual temperature of this National Park is 22.5 ºC in maximum but in Langtang cluster maximum annual temperature may not exceed 10 ºC (ICIMOD, 2000). Climate of Langtang is strongly influenced by maritime air masses. This area receives most of its rain during summer season (May to October). Snow fall mostly occurs between November to March.

4.4 Soil

Mature soil occurs in the lower forested regions which mainly consist of fertile loam. In the upper Langtang Valley, the most textural component is sandy-loam with a large proportion of rocks.

CHAPTER 5

Methodology

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

5.1 Data Collection

The observed hydrological and meteorological data from Langtang Kyaging station were collected from department of hydrology and meteorology (DHM), for the projection of temperature and precipitation in study area predictors variables (CGCM3 and NCEP data) were downloaded from http://www.cics.uvic.ca/scenarios/index.cgi?Scenarios, http://loki.qc.ec.gc.ca/DAI/p redictors-e.html. These data are downscale by statistical downscale model (SDSM 4.2) with the basis of observed precipitation and temperature data (Predictand) for the A1B scenario. The detail downscale process by SDSM clearly describe in chapter 5.6. The monthly flow generation methodology by Thornthwaite model was presented in chapter 5.3.

5.2 Research design

This research was conducted to study the impact of climate change on stream runoff within Langtang basin. The data is collected and analyzed to get the results. The flow chart of the research design diagrammatically presented as bellow:

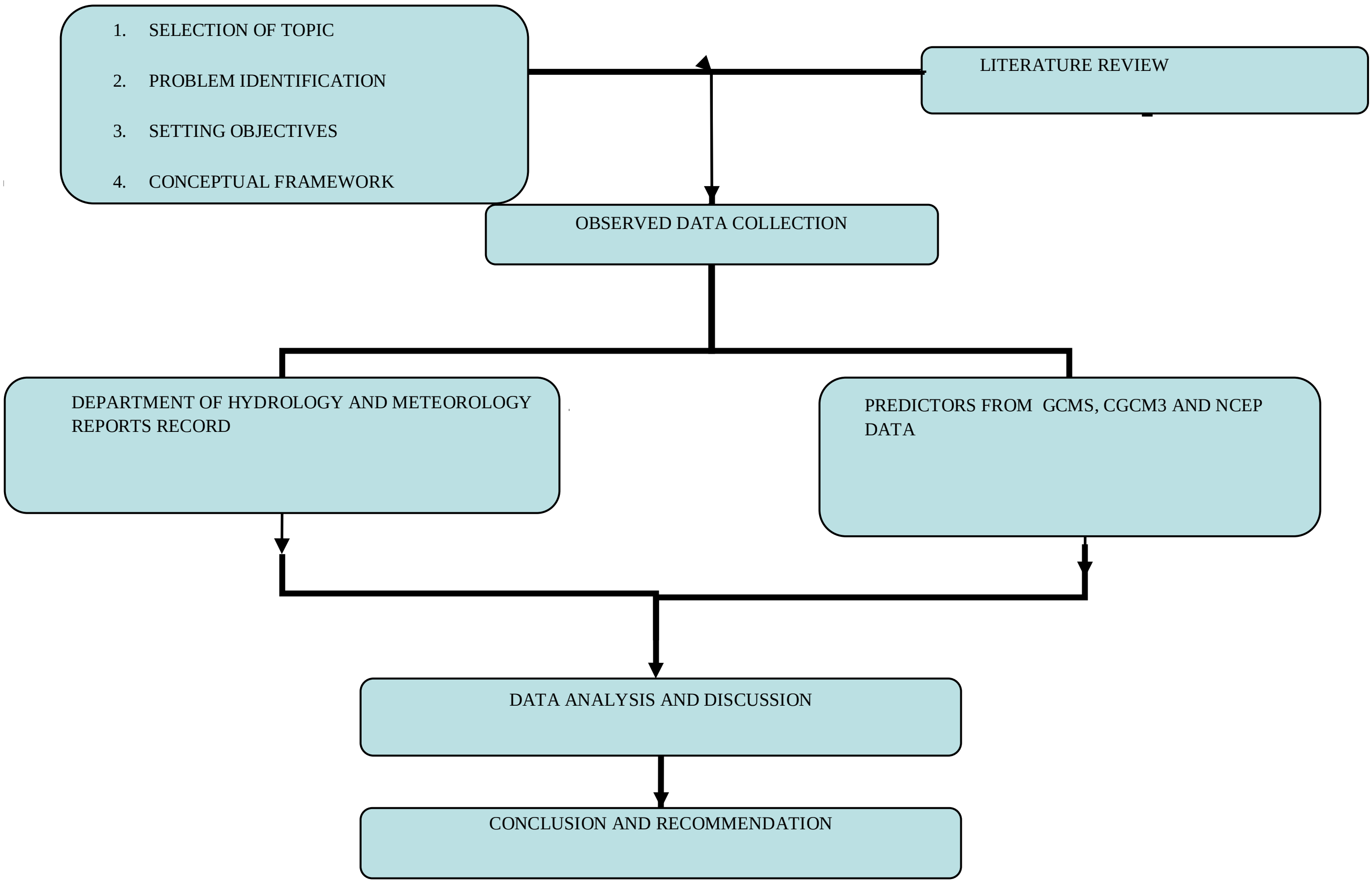


Figure5.1 Schematic sketch of research design

5.3 Background of the model

Monthly water-balance models have been used as a means to examine the various components of the hydrologic cycle (for example, precipitation, evapotranspiration, and run-off). Such models have been used to estimate the global water balance (Mather, 1969; Legates and Mather, 1992; Legates and McCabe, 2005); to develop climate classifications (Thornthwaite, 1948); to estimate soil-moisture storage (Alley, 1984; Mintz and Serafini, 1992), runoff (Alley, 1984, 1985; Yates, 1996; Wolock and McCabe, 1999), and irrigation demand (McCabe and Wolock, 1992); and to evaluate the hydrologic effects of climate change (McCabe and Ayers, 1989; Yates, 1996; Strzepek and Yates, 1997; Wolock and McCabe, 1999).

The water-balance model analyses the allocation of water among various components of the hydrologic system using a monthly accounting procedure based on the Markstrom methodology originally presented by Thornthwaite (Thornthwaite, 1948; Mather, 1978, 1979; McCabe and Wolock, 1999; Wolock and McCabe, 1999). Inputs to the model are mean monthly temperature (*T*, in degrees Celsius), monthly total precipitation (*P*, in millimeters), and the latitude (in decimal degrees) of the location of interest. The latitude of the location is used for the computation of day length, which is needed for the computation of potential evapotranspiration (*PET*). The model is referred to as the Thornthwaite model.

5.4 Method of Analysis

The first computation of the water-balance model is the estimation of the amount of monthly precipitation (*P*) that is rain (*Prain*) or snow (*Psnow*), in millimeters. When mean monthly temperature (*T*) is below a specified threshold (*Tsnow*), all precipitation is considered to be snow. If temperature is greater than an additional threshold (*Train*), then all precipitation is considered to be rain. Within the range defined by *Tsnow* and *Train*, the amount of precipitation that is snow decreases linearly from 100 percent to 0 percent of total precipitation. This relation is expressed as:

$$Psnow = P \times \left[\frac{Train - T}{Train - Tsnow}\right] \ldots\ldots\ldots\ldots \quad (1)$$

Prain then is computed as:

$$Prain = P - Psnow \ldots\ldots\ldots \quad (2)$$

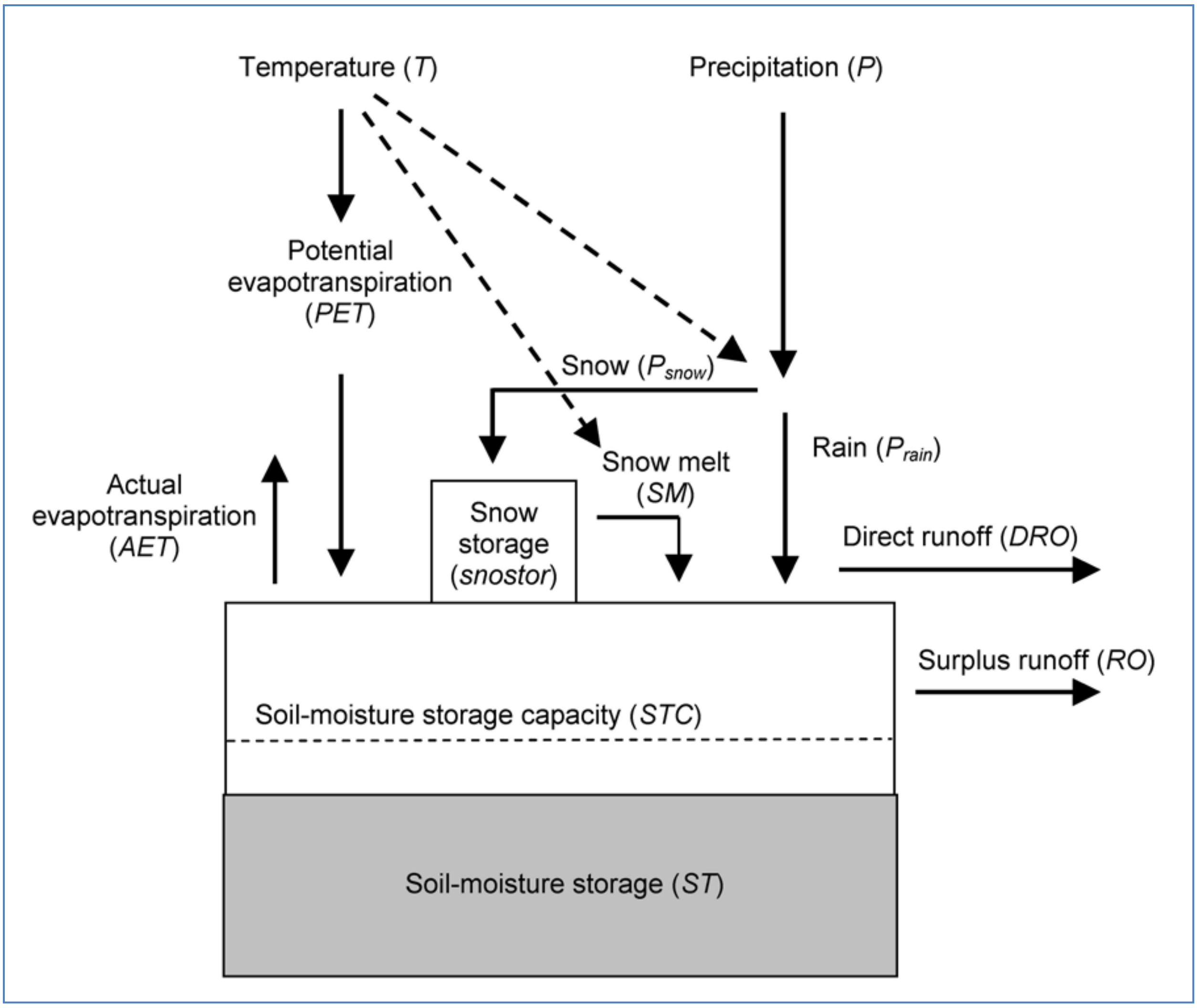


Figure 5.2 Diagram of the water-balance model.

Direct runoff (*DRO*) is runoff, in millimeters, from impervious surfaces or runoff resulting from infiltration-excess overflow.

The fraction (*drofrac*) of *Prain* that becomes *DRO* is specified; based on previous water-balance analyses, 5 percent is a typical value to use (Wolock and McCabe, 1999). The expression for *DRO* is:

$$DRO = Prain \times drofrac \ldots\ldots\ (3)$$

Direct runoff (*DRO*) is subtracted from *Prain* to compute the amount of remaining precipitation (*Premain*): *Premain* = Prain – *DRO* ……… (4)

Actual evapotranspiration (*AET*) is derived from potential evapotranspiration (*PET*), *Ptotal*, soil-moisture storage (*ST*), and soil-moisture storage withdrawal (*STW*). Monthly *PET* is estimated from mean monthly temperature (*T*) and is defined as the water loss from a large, homogeneous, vegetation-covered area that never lacks water (Thornthwaite, 1948; Mather, 1978). Thus, *PET* represents the climatic demand for water relative to the available energy. In this water balance, *PET* is calculated by using the Hamon equation (Hamon, 1961): and soil-moisture storage withdrawal (*STW*). Monthly *PET* is estimated from mean monthly temperature (*T*) and is defined as the water loss from a large, homogeneous, vegetation-covered area that never lacks water (Thornthwaite, 1948; Mather, 1978). Thus, *PET* represents the climatic demand for water relative to the available energy. In this water balance, *PET* is calculated by using the Hamon equation (Hamon, 1961).

$$PETHamon = 13.97 \times d \times D2 \times Wt \ldots\ldots (5)$$

Where *PETHamon* is *PET* in millimeters per month, *d* is the number of days in a month, *D* is the mean monthly hours of daylight in units of 12 hrs, and *Wt* is a saturated water vapor density term, in grams per cubic meter, calculated by: *STW*

$$Wt = 4.95 \times e0.062 \times T100 \ldots\ldots (6)$$

Where *T* is the mean monthly temperature in degrees Celsius (Hamon, 1961).

When *Ptotal* for a month is less then *PET*, then *AET* is equal to *Ptotal* plus the amount of soil moisture that can be withdrawn from storage in the soil. Soil-moisture storage withdrawal linearly decreases with decreasing *ST* such that as the soil becomes drier, water becomes more difficult to remove from the soil and less is available for *AET*. *STW* is computed as follows;

$$STW = STi\text{-}1 - abs\,(Ptotal - PET) \times STi\text{-}1STC\,(e0.062 \times T100) \ldots\ldots (7)$$

Where *STi*-1 is the soil-moisture storage for the previous month and *STC* is the soil moisture storage capacity. An *STC* of 150 mm works for most locations (McCabe and Wolock, 1999; Wolock and McCabe, 1999).

If the sum of *Ptotal* and *STW* is less than *PET*, then a water deficit is calculated as *PET–AET*. If *Ptotal* exceeds *PET*, then *AET* is equal to *PET* and the water in excess of *PET* replenishes *ST*. When *ST* is greater than *STC*, the excess water becomes surplus (*S*) and is eventually available for runoff.

Runoff (*RO*) is generated from the surplus, *S*, at a specified rate (*rfactor*). An *rfactor* value of 0.5 is commonly used (Wolock and McCabe, 1999). The *r factor* parameter determines the fraction of surplus that becomes runoff in a month. The remaining surplus is carried over to the following month to compute total *S* for that month. Direct runoff (*DRO*), in millimeters, is added directly to the runoff generated from surplus (*RO*) to compute total monthly runoff (*ROtotal*), in millimeters

$STW = ST_{i-1} - abs(P_{total} - PET) \times \frac{ST_{i-1}}{STC}$

$Wt = 4.95 \times e^{0.062 \times T}/100$

$PET_{Hamon} = 13.97 \times d \times D^2 \times Wt$

5.5 Running the Water-Balance Program

The window for the Thornthwaite monthly water-balance program will behave like any other window on the desktop. Resize, iconify, or close it like any other application by dragging the borders and clicking on the window controllers in the upper corners of the frame. Figure 5-2 is a screen image of the program's graphical user interface.

The water-balance model has seven input parameters (runoff factor, direct runoff factor, soil-moisture storage capacity, and latitude of location, rain temperature threshold, snow temperature threshold, and maximum snow-melt rate of the snow storage) that are modified through the graphical user interface (fig. 5-3). The range and default values for these parameters are set by the model. These values are changed by clicking on the corresponding slider bar and dragging the value. The system will not allow invalid values to be entered.

The model requires a simple input data file. To select the input file, click on the button corresponding to the file ("Input file") and a file browser will appear. The input file must be a file on the user's local file system that contains monthly water-balance input data. A sample data file (input.file) is provided with the model and is located in the USGS Thornthwaite installation folder. The data file must be organized into four columns with one or more space characters between the columns. The first column is the year, the second is the numeric month of the year, the third is mean monthly temperature in degrees Celsius, and the last is monthly total precipitation in millimeters.

When the model runs, tabular output is written to a popup window. The columns of the output are date, *PET*, *P*, *P–PET*, soil-moisture storage, *AET*, *PET–AET* (also known as moisture deficit), snow storage, surplus, and *RO total*. The contents of this window can be saved to a file

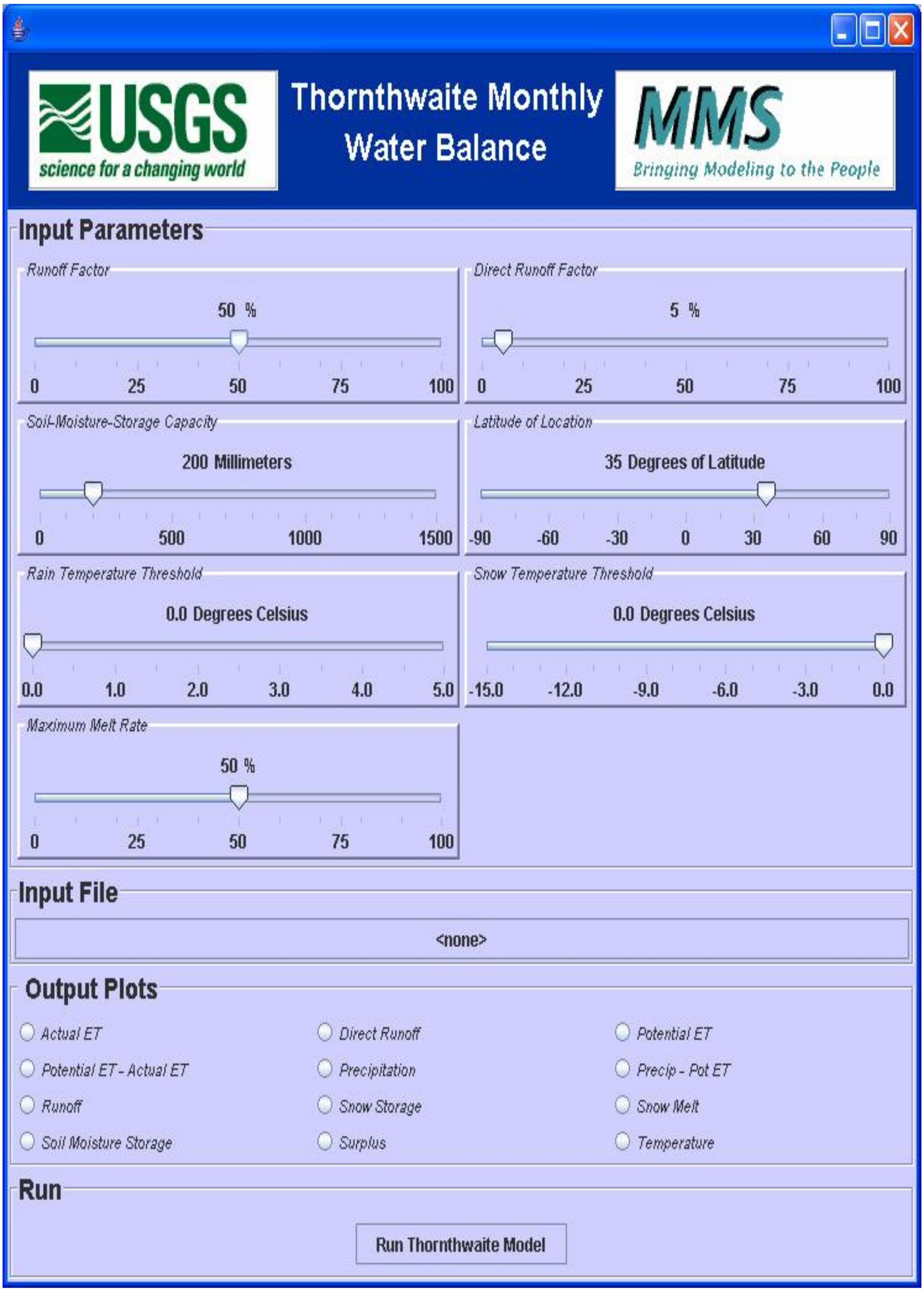


Figure 5.3 Thornthwaite monthly water balance model

by clicking on the Save button at the bottom of the window and specifying the name (and directory) of an output file in the file browser.

At the bottom of the main program window (fig. 5-3), the user can select the specific variables to be plotted by clicking on the corresponding circle. After the model runs, a window will open with the plotted time series. The model can be run any number of times, each time selecting a different set of variables to plot.

5.6 SDSM

General Circulation Models (GCMs) indicate that rising concentrations of greenhouse gases will have significant implications for climate at global and regional scales. Unfortunately, GCMs are restricted in their usefulness for local impact studies by their coarse spatial resolution (typically of the order 50,000 km^2) and inability to resolve important sub–grid scale features such as clouds and topography. As a consequence, two sets of techniques have emerged as a means of deriving local–scale surface weather from regional–scale atmospheric predictor variables (Figure 5-4). Firstly, statistical downscaling is analogous to the “model output statistics” (MOS) and “perfect prog” approaches used for short–range numerical weather prediction. Secondly, Regional Climate Models (RCMs) simulate sub–GCM grid scale climate features dynamically using time–varying atmospheric conditions supplied by a GCM bounding a specified domain. Both approaches will continue to play a significant role in the assessment of potential climate change impacts arising from future increases in greenhouse–gas concentrations.

In this study Statistical Downscaling Model (SDSM) version 4.2 was used for filling up the missing data for temperature and precipitation. Statistical downscaling has several practical advantages over dynamical downscaling approaches. In situations where low–cost, rapid assessments of localized climate change impacts are required, statistical downscaling (currently) represents the more promising option. Statistical downscaling methodology is, that enables the construction of climate change scenarios for individual sites at *daily* time–scales, using grid resolution GCM output. The software is named SDSM (Statistical DownScaling Model) and is coded in Visual Basic 6.0. (Wilby and Dawson, 2007).

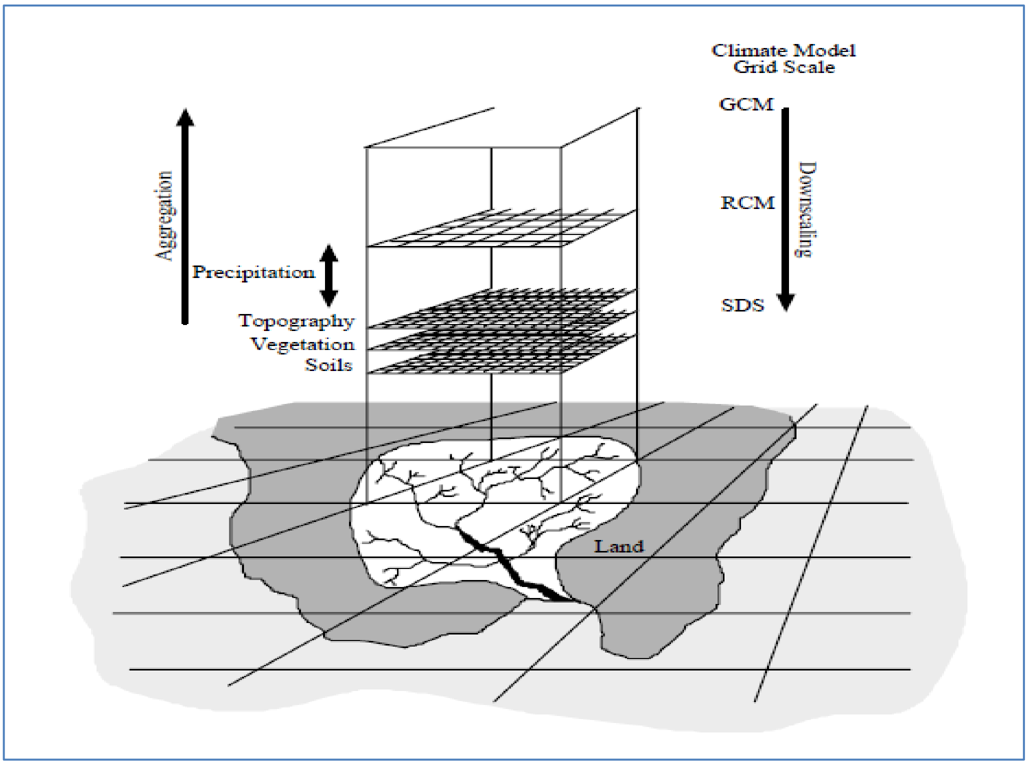


Figure 5.4 Schematic illustrating the general approach to downscaling.

The GCM data were available from the NCEP reanalysis product. The NCEP reanalysis products (Kalnay et al., 1996; Kistler et al., 2001) have been interpolated onto the CGCM3 grid (Gaussian), and made available for the calibration procedure of statistical downscaling models (SDSM, ASD), over the current climate period (1961 to 2001). The NCEP reanalysis use a T62 (~ 209 km) global spectral model to consistently collect observational data from a wide variety of observed sources. All the data included are of quality 'A' or 'B', which means that they are influenced directly (to some extent) by observational data. Details of the reanalysis project and this categorization scheme can be found in Kalnay et al. (1996). All NCEP data has been averaged on a daily basis from 6 hourly data, before being linearly interpolated to match the CGCM3 data. Where variables are derived, they are computed on the native 2.5° lat. × 2.5° lon. regular grid, and then interpolated. Surface reanalysis variables are originally available on a regular Gaussian grid (Kalnay et al., 1996). Therefore, surface variables (i.e. temperature) are instead interpolated from a native regular Gaussian grid to the CGCM3 regular Gaussian grid. The list of predictors has been chosen according to the data availability and to correspond to the same physical variables issued from the CGCM3 predictors.

CHAPTER 6

Data analysis

6.1 Analysis of data

The collected data i.e. temperature, rainfall and discharge from DHM of Langtang region is analyzed by using Thornthwaite monthly water balance model. The trend of runoff is specially focused and runoff is compared with temperature and rainfall. The trend of different condition is shown in figure below. The calibration and validation of NCEP runoff (data) is compared with observed runoff. The projected trend of A1B runoff scenario is also analyzed.

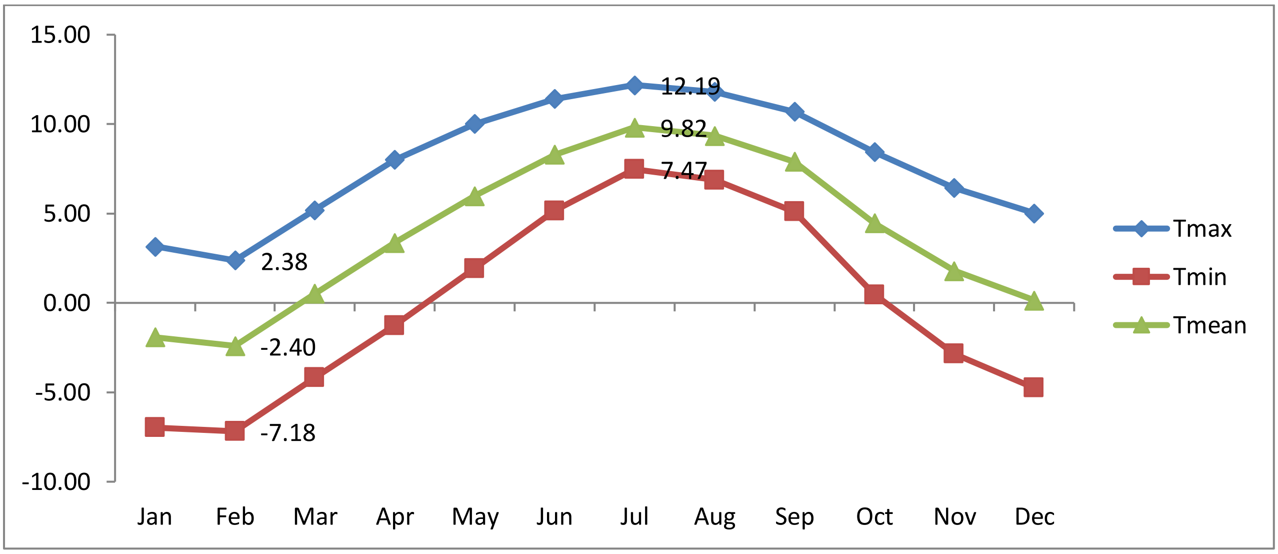
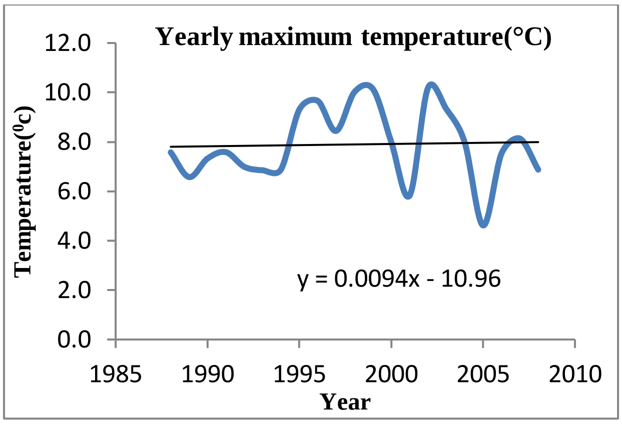


Figure 6.1 Langtant Kyanjing monthly average temperatures (1988 to 2008)



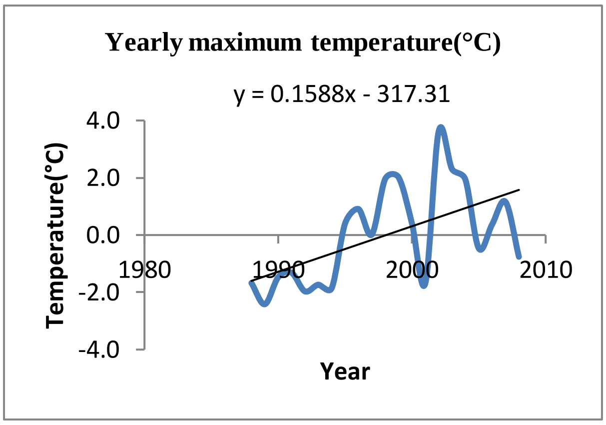


Figure 6.2 Yearly temperature trends from T-max   Figure6.3 Yearly temperature trend from T-min

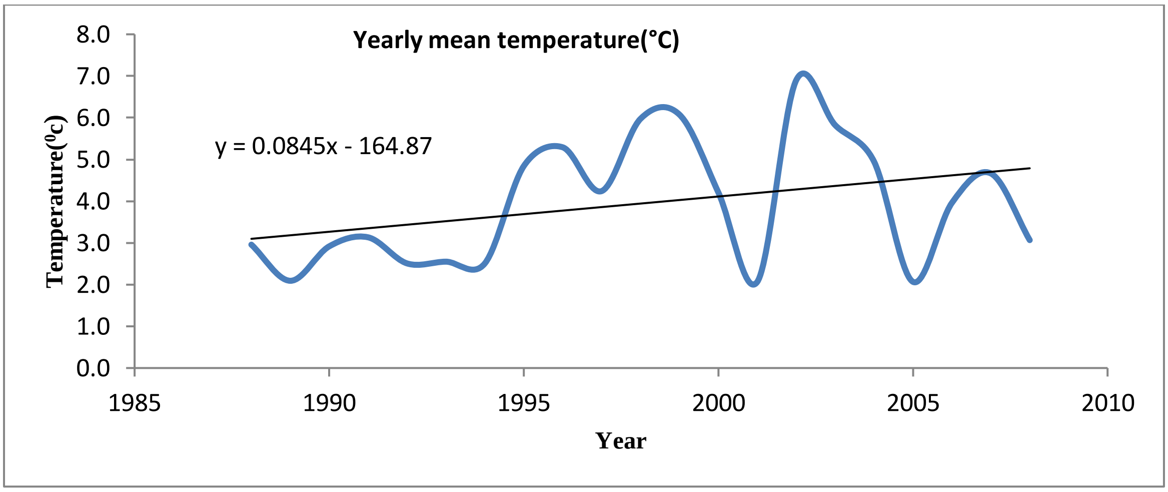


Figure 6.4 Yearly temperature trends from T-mean

In the Langtang basin the maximum average monthly temperature in 1988 to 2008 is in July in all three temperature series i.e. T-max, T-mean and T-min are 12.19 °C, 9.82 °C and 7.47 °C, respectively. The minimum average monthly temperature in 1988 to 2008 is in February in all three temperature ranges i.e. T-max, T-mean and T-min are 2.38°C, -2.4°C and -7.18°C (Figure 6.1). This shows February is the coldest month and July is the hottest month in this area.

While analyzing the average annual temperature from 1988 to 2008, the trend is increasing in all three temperature ranges. In T-max condition the increasing trend is 0.009 °C. The maximum temperature is 10.2 °C in 2002 where as the minimum is 4.6 °C in 2005 (Figure 6.2). In T-mean condition the increasing trend is 0.0845 °C. The maximum temperature is 6.9 °C in 2002 where as the minimum is 2.1 °C in 1989, 2001 and 2005 (Figure 6.4). In T-min condition the increasing trend is 0.158 °C. The maximum temperature is 3.6 °C in 2002 where as the minimum is -2.4°C in 1989 (Figure 6.3).

6.2 Monthly and Annual rainfall graph

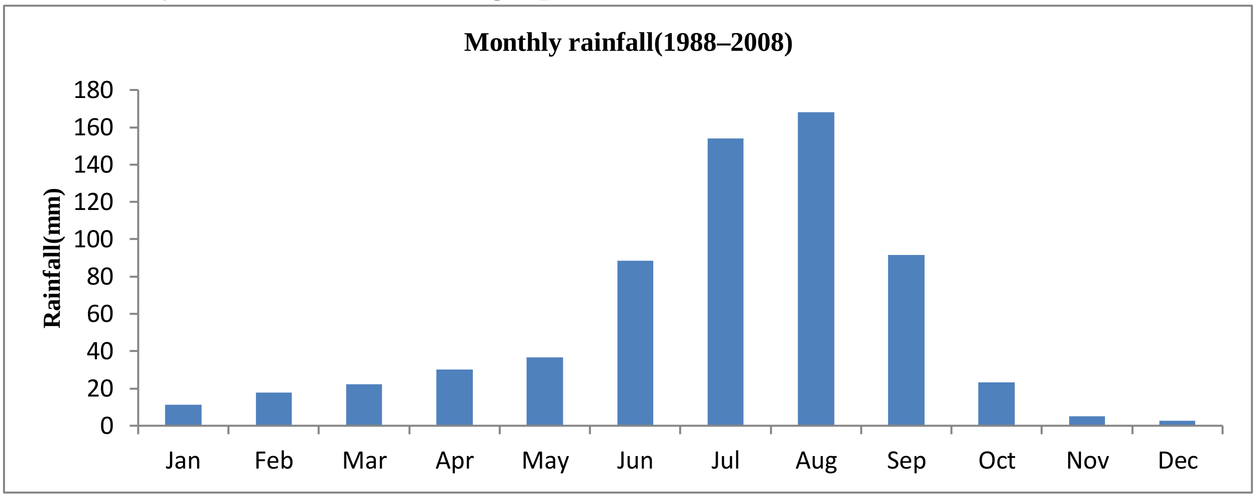


Figure 6.5 Average monthly rainfalls

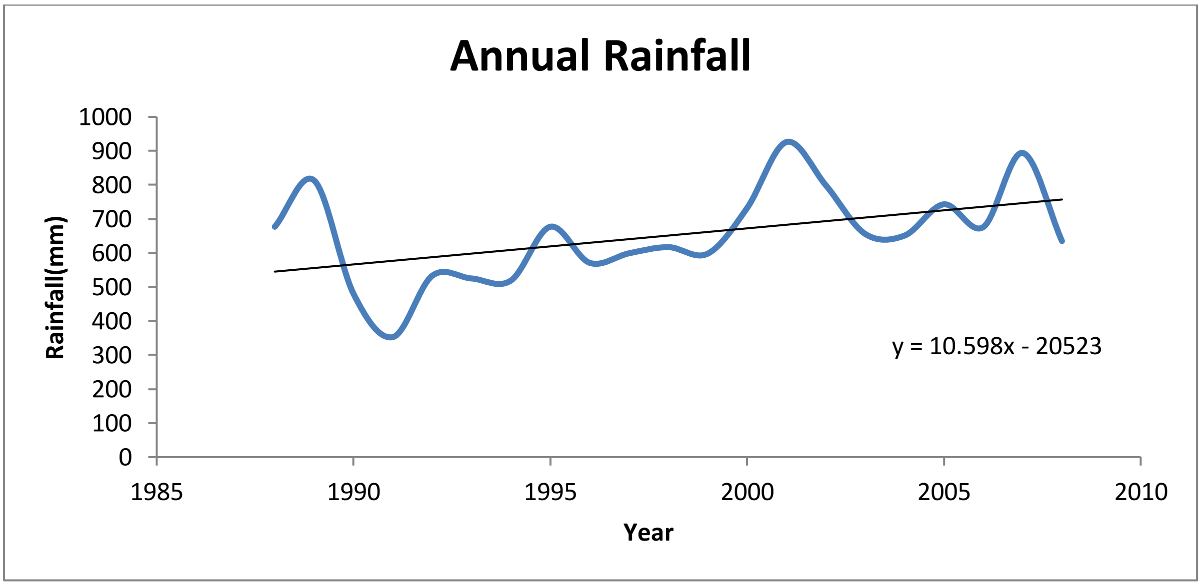


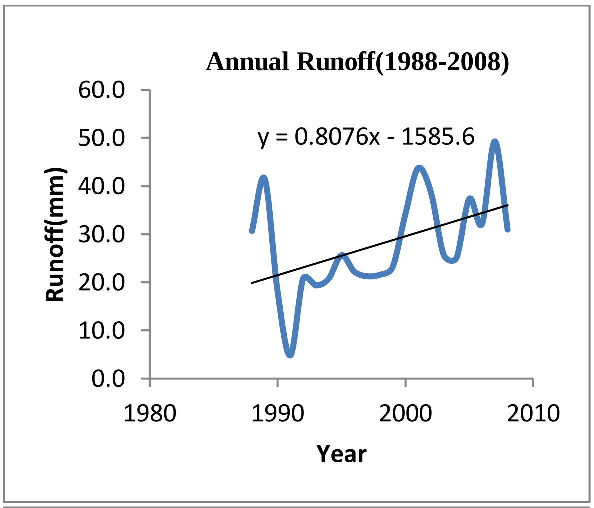
Fig 6.6 Annual rainfall of study area

The maximum monthly average rainfall is 168.10 mm in august whereas the minimum is in December i.e. 2.67 mm (Figure 6.5).

The increasing trend of annual rainfall is 10.59 mm. The maximum rainfall is observed 926mm on 2002 whereas the minimum was 352.7 mm in the year 1990 (Figure 6.6).

6.3 Annual runoff since 1988 to 2008

The annual runoff of Langtang basin using Thornthwaite water balance model shows the following results.



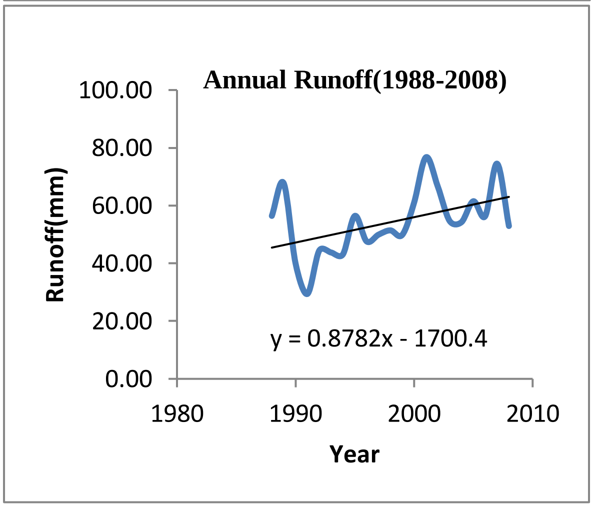


Figure 6.7 Annual runoff from T-mean

Figure 6.8 Annual runoff from T-max

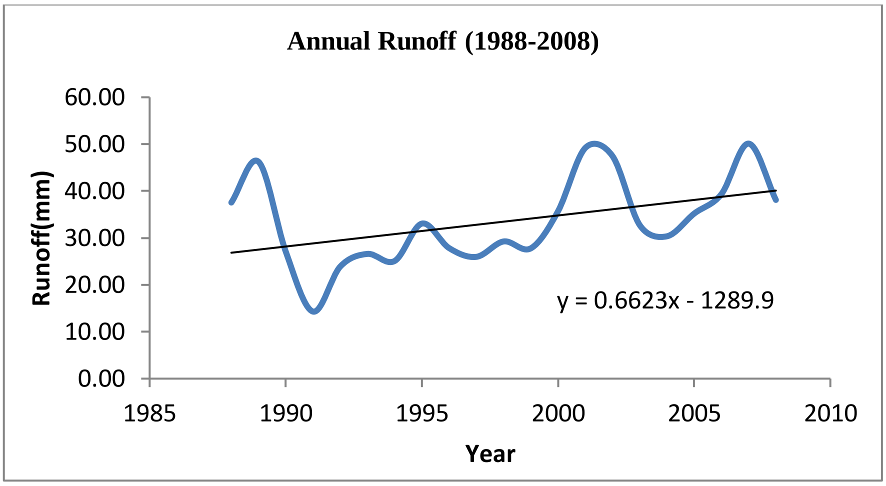


Figure 6.9 Annual runoff from T-min

The annual runoff from 1988 to 2008 of all three temperature series are seen in increasing trend. In T-mean condition the increasing trend is 0.8 mm and the minimum runoff is 4.8 mm in 1991 where as the maximum is 49.3 in 2007 (Figure 6.7). In t-max condition the increasing trend is 0.87 mm and the minimum runoff is 29.3 mm in 1991 where as the maximum is 76.7 mm in 2001(Figure 6.8). In T-min condition the increasing trend is 0.66 mm and the minimum runoff is 14.3 mm in 1991 where as the maximum is 50.1 mm in 2007 (Figure 6.9). In all temperature series minimum runoff is in same year 1991 and maximum runoff is slightly high in 2001 in T-max whereas in T-mean and T-min same in 2007.

6.4 Calibration and validation

The tables and figure of the calibration and validation runoff compared with observed and NCEP are shown in below:

Table6.1 Calibration of runoff

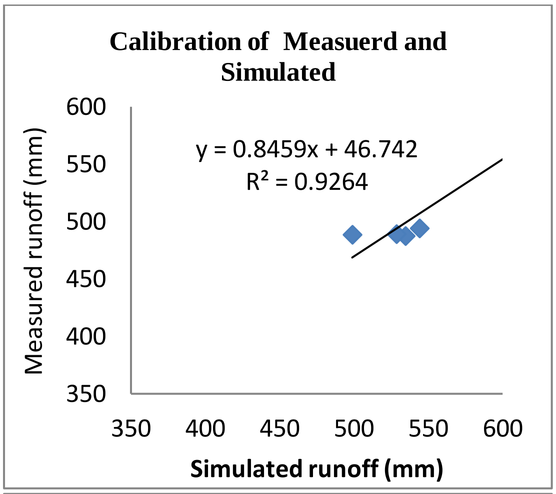
Year	Discharge (m3/s)	Measured Runoff (mm)	climate balance runoff (mm)	Total Runoff (Glacier +Snow) (mm)	Runoff Generated (mm)	% of diff
1993	6.12	535	23.59	511	487	9
1994	5.71	499	19.52	479	488	2
1995	6.05	529	22.37	506	489	7
1996	6.23	544	25.03	519	494	9
1997	7.14	624	20.94	603	582	7
1998	7.12	622	23.77	598	574	8

* Area of watershed 361 km^2

Table 6.2 Validation of runoff

Year	Discharge (m3/s)	Measured Runoff (mm)	climate balance runoff (mm)	Total Runoff (Glacier +Snow) (mm)	Runoff Generated (mm)	% of diff
1999	7.37	644	27.09	617	590	8
2000	4.95	432	27.42	405	378	13
2001	4.98	435	22.24	413	391	10
2002	5.56	486	21.20	465	443	9
2003	6.18	540	22.87	517	494	8

* Area of watershed 361 km^2



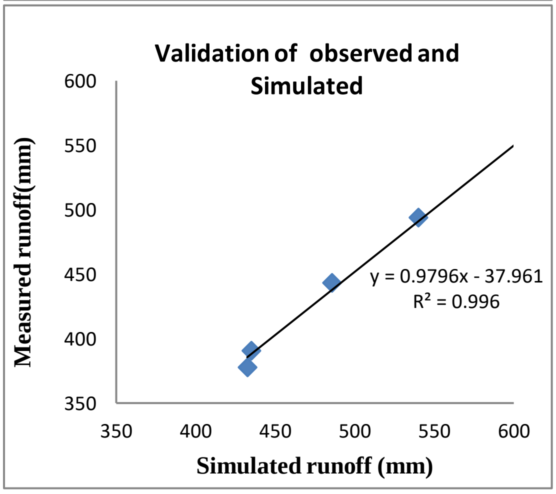


Figure 6.10 Calibration of runoff (1993-1998)

Figure 6.11 Validation of runoff (1999-2003)

The comparison of measured runoff and simulated runoff is shown in table 6.1 and 6.2. The coefficient of determination between measured and simulated runoff of calibration is 0.9264 (Figure 6.10) and the validation is 0.996 (Figure 6.11).

6.5 Comparison of runoff with temperature

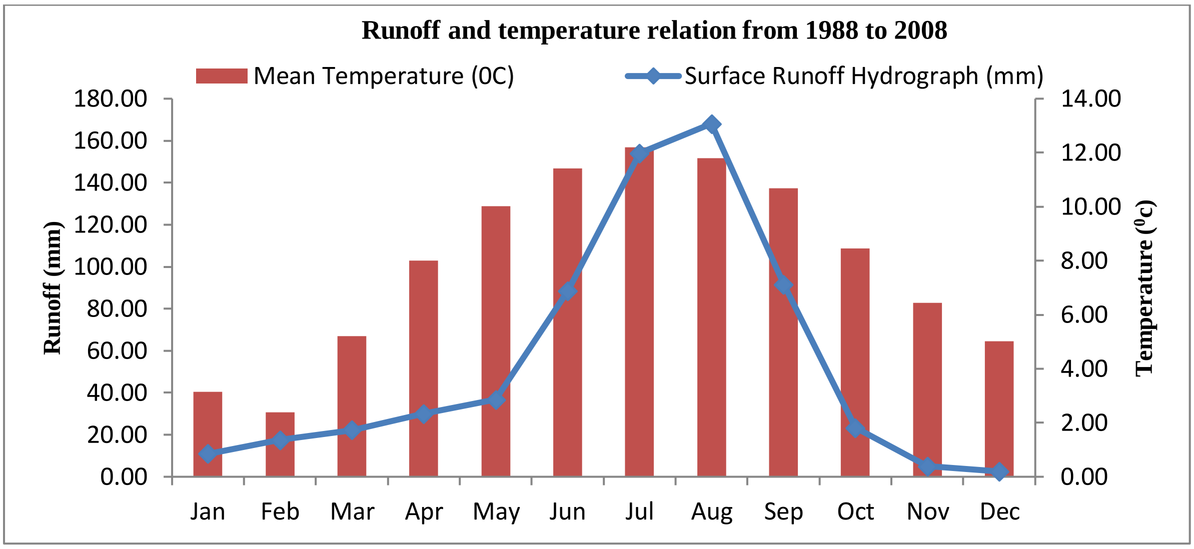


Figure 6.12 Runoff and temperature relation from **T-max**.

The relation between surface runoff and mean temperature by using T- max is shown in Figure 6.12. The maximum surface runoff in August is 168.1 mm whereas the minimum is observed in December i.e. 2.52 mm. The maximum temperature in July is 12.19°C whereas the minimum is in February i.e. 2.38°C.

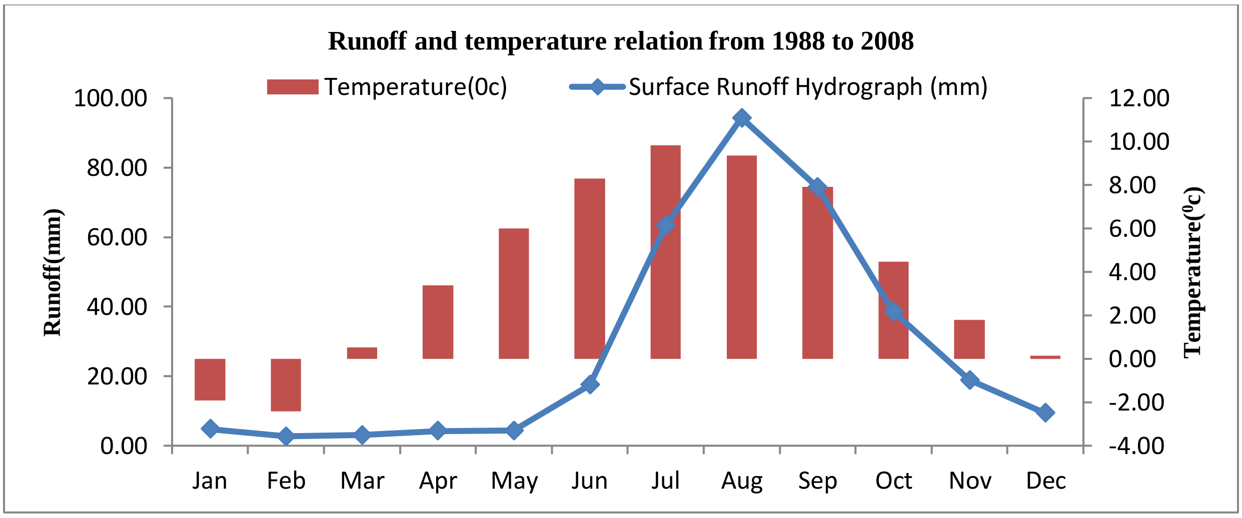


Figure 6.13 Runoff and temperature relation from **T-mean.**

The relation between surface runoff and mean temperature by using T- mean is shown in Figure 6.13. The maximum surface runoff in August is 94.32 mm whereas the minimum is in February i.e. 2.70 mm. The maximum temperature in July is 9.82°C whereas the minimum is in February i.e. -2.40°C.

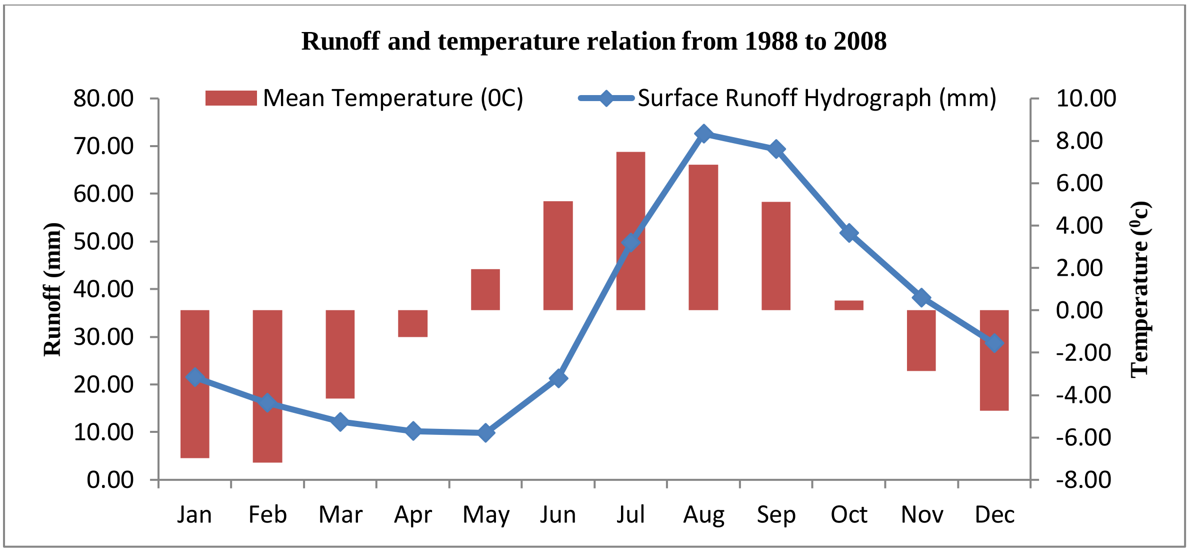


Figure 6.14 Runoff and temperature relation from **T-min.**

The relation between surface runoff and mean temperature by using T- min is shown in figure 6.14.The maximum surface runoff in August is 72.58 mm where as the minimum is in May i.e. 9.84 mm. The maximum temperature in July is 7.47°C whereas the minimum is in February i.e. -7.18°C.

From the figure of all three temperature series it is analyzed that the decrease in temperature and runoff has proportional relationship and vice versa.

6.6 Monthly Average Comparison of runoff with rainfall

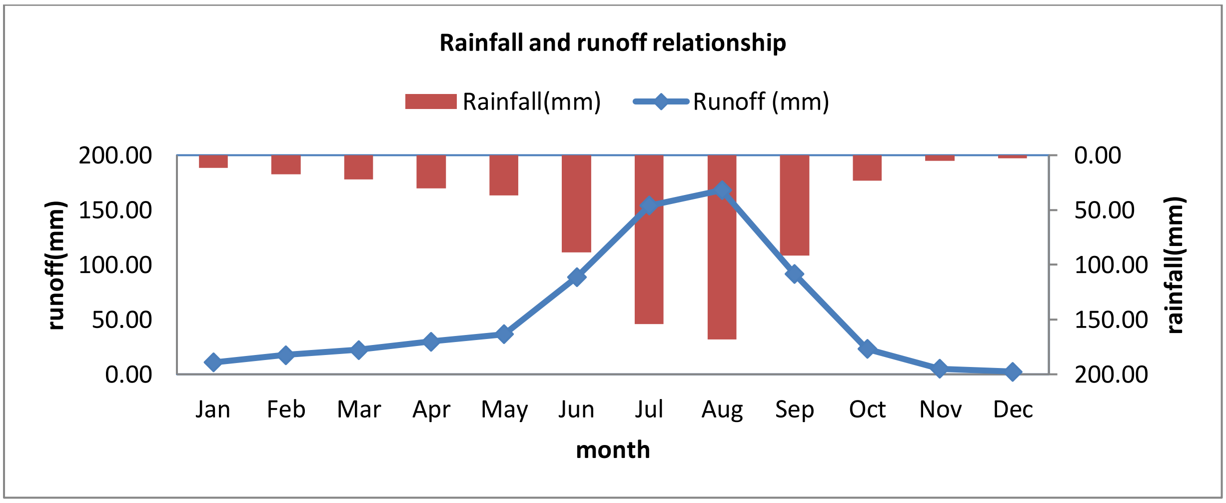


Figure 6.15 Runoff and rainfall relationship from **T- max**

The relation between surface runoff and rainfall by using T- max is shown in Figure 6.15. The maximum rainfall in August is 168.10 mm where as the minimum is on December i.e.

2.76 mm. Maximum runoff also in August is 168.10 mm and minimum is also in December i.e. 2.52 mm.

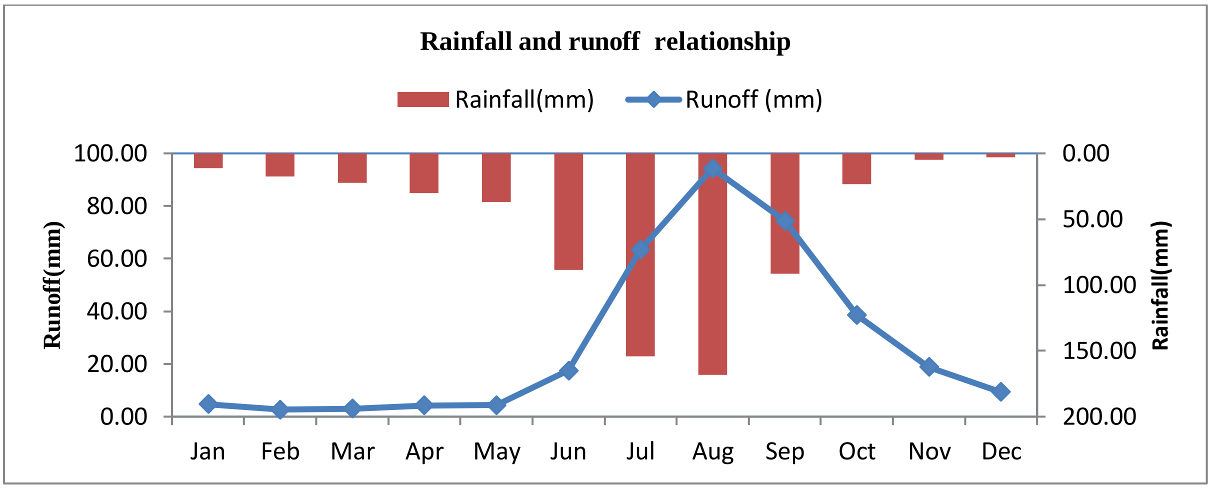


Figure 6.16 Runoff and rainfall relationship from **T- mean**

The relation between surface runoff and rainfall by using T- mean is shown in figure 6.16. The maximum rainfall in August is 168.10 mm where as the minimum is in December 2.76 mm. Maximum runoff also in August is 94.382 mm and minimum is also in February 2.7 mm.

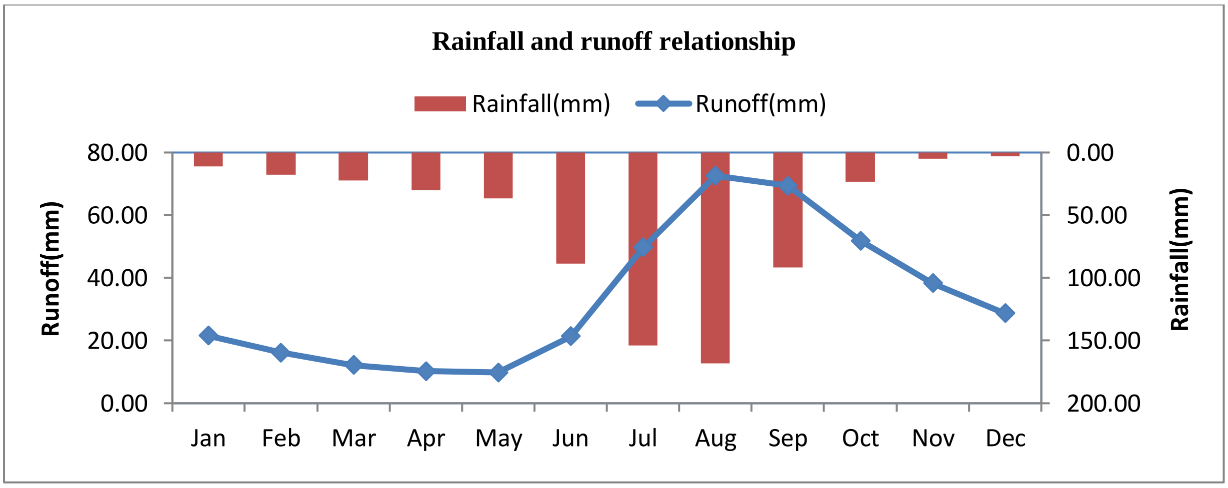
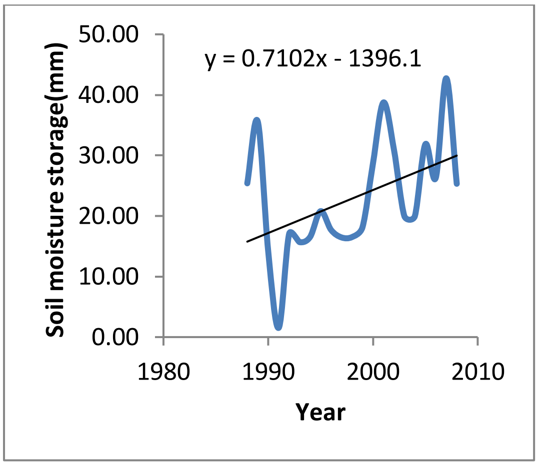


Figure 6.17 Runoff and rainfall relationship from **T- min**

The relation between surface runoff and rainfall by using T- min is shown in figure 6.17. The maximum rainfall in August is 168.10 mm where as the minimum was on December 2.76 mm. Maximum runoff also in August is 72.58 mm and minimum is in May i.e. 9.84 mm.

From the figure of all three temperature series it is analyzed that the increase in rainfall and runoff has proportional relationship and vice versa.

6.7 Soil moisture storage from 1988 to 2008



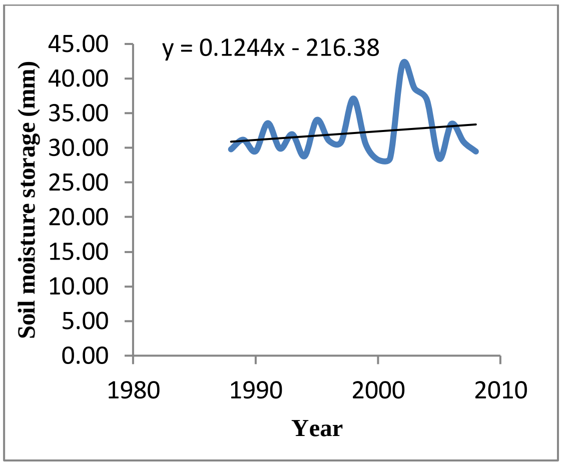


Figure6.18Annual soil Moisture storage (**T-mean)**

Figure 6.19Annual soil Moisture storage (**T-min**)

Annual Soil moisture storage is analyzed from all three temperature series, in T-mean and T-min condition the trend of soil moisture storage is in increasing whereas in T-max is zero.In T-mean condition the increasing trend is 0.71 mm. The maximum soil moisture storage is 42.74 mm in 2007 and minimum is in 1991 i.e. 1.53 mm (Figure 6.18). And in T-min condition the increasing trend is 0.12 mm. The maximum soil moisture storage is 42.04 mm in 2002 whereas the minimum is 28.29 mm in 2000 (Figure 6.19).

6.8 Water Deficit and Water Surplus

Table 6.3 Analysis of WD and WS

Year	Yearly WS (mm)	Yearly WD (mm)
1993	63	361
1994	54	358
1995	45	354
1996	75	577
1997	19	504
1998	128	381
1999	174	442
2000	269	402
2001	250	498
2002	289	315
2003	145	284
2004	126	263
Average	136	359

The WS and WD from 1993 to 2004 is analyzed that the maximum water surplus is 289 mm in 2002 whereas the minimum surplus is 19 mm in 1997 and the maximum water deficit is 577 mm in1996 whereas minimum is 263 in 2004. The average water surplus with in 12 years is 136 mm and the deficit is 359 mm (Table 6.3).

6.9 Monthly relation between runoff, rainfall and temperature

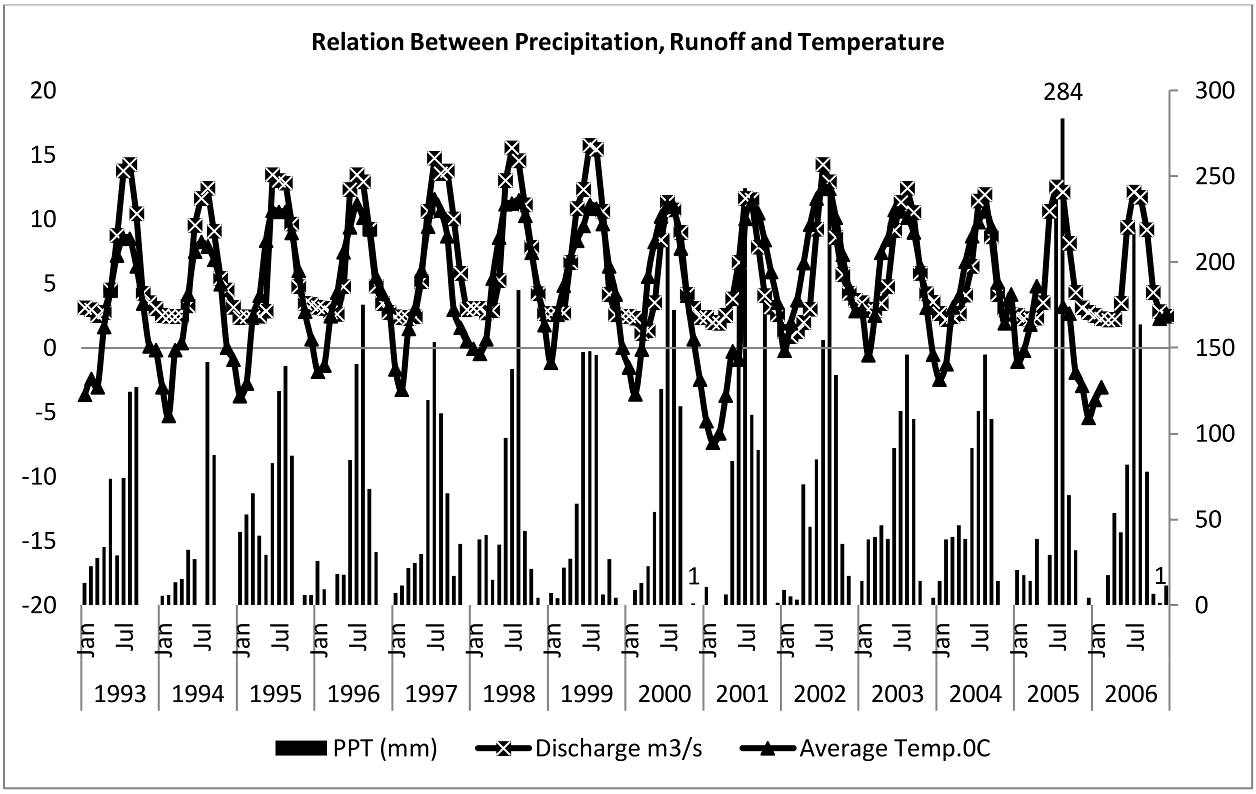


Figure 6.20 Relations between precipitation, runoff and temperature

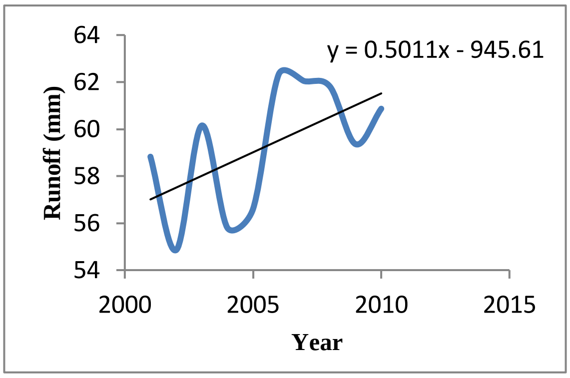
The relation between precipitation, runoff and temperature from 1993 to 2006 is shown in Figure 6.20. The maximum discharge is 15.7m^3/s in July 1999 where as the minimum is in December 2002 i.e. 0.82 m^3/s. The maximum temperature is 12.5°C in July 2002 where as the minimum is -7.4°C in February 2001. And maximum precipitation is 284 mm in July 2005 whereas the minimum was mostly in December i.e. 0 mm.

Furthermore, it can be said from the analysis: when there is maximum temperature the corresponding precipitation is also maximum for each year which has direct impact on discharge which is also maximum and vice versa. The precipitation, runoff and temperature are generally maximum in July and August and minimum in December and January.

6.10 Projected runoff from A1B scenario (2001–2060)

Projected runoff of A1B was analyzed from the year 2001 to 2060. The two different scenarios are observed: one using ten years gap other as a whole. The graphical representations of both are as follows.

6.10.1 Analysis of A1B projected runoff from T-Max



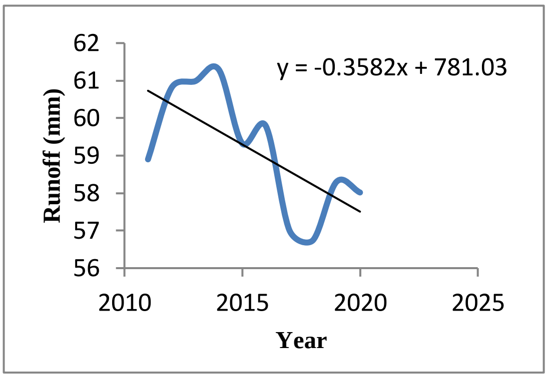
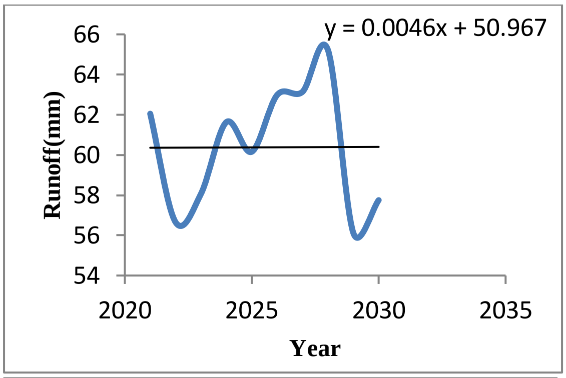


Figure 6.21 Runoff analysis from 2001 to 2010

Figure 6.22 Runoff analysis from 2011 to 2020



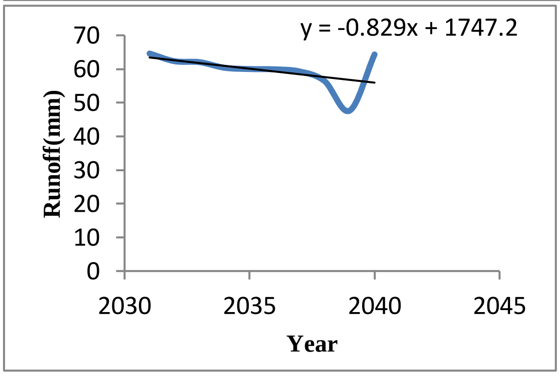
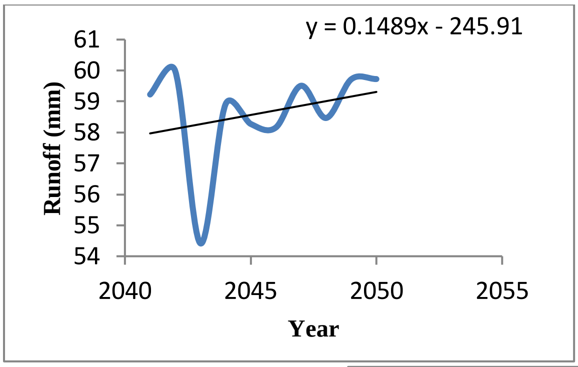


Figure 6.23 Runoff analysis from 2021 to 2030

Figure 6.24 Runoff analysis from 2031 to 2040



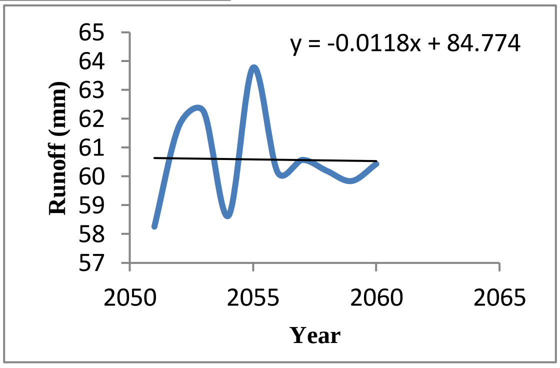


Figure 6.25 Runoff analysis from 2041 to 2050 Figure 6.26 Runoff analysis from 2051 to 2060

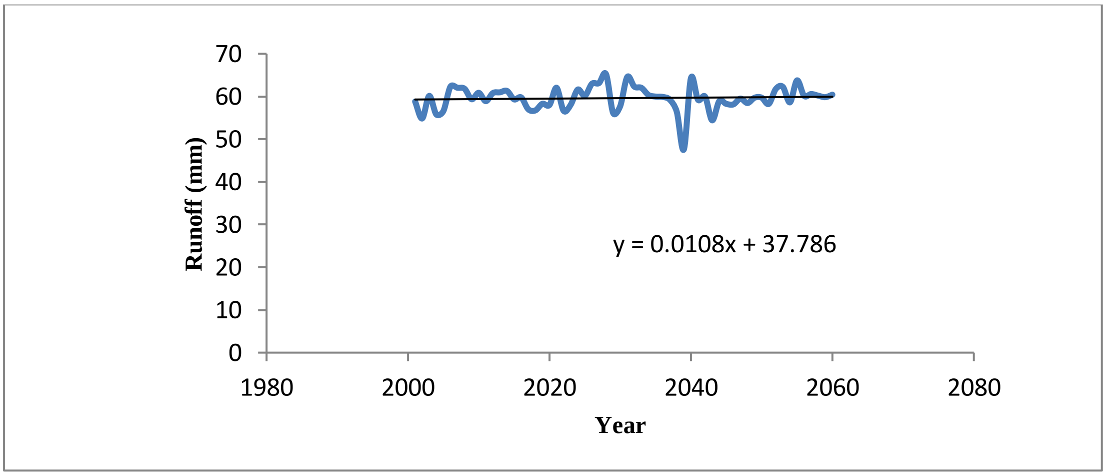


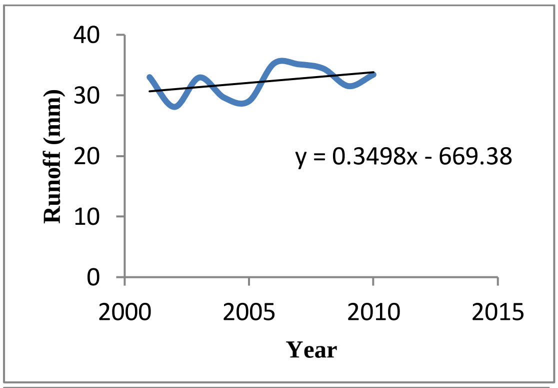
Figure 6.27 Runoff analyses from 2001 to 2060

The analyses of all projected runoff from T-max of A1B within different ten years period are as follows: on the decade 2001 to 2010, the increasing trend of runoff is 0.5 mm and the minimum runoff is 54.85 mm in 2002 and the maximum runoff is 62.32 mm in 2006 (Figure 6.21). But on the decade 2011 to 2020, the decreasing trend of runoff is 0.35 mm where the minimum is 56.74 mm in 2018 and the maximum runoff is 61.30 mm in 2014 (Figure 6.22). Similarly in the decade 2021 to 2030, the trend of runoff is increasing by 0.004 mm and the minimum runoff is 56.12 mm in 2029 whereas the maximum runoff is in 2028 i.e. 65.22 mm

(Figure 6.23). But in the decade 2031 to 2040, the decreasing trend of runoff is 0.82 mm and the minimum runoff is 47.6 mm in 2039 where as the maximum runoff is in 2031 i.e. 64.58 mm (Figure 6.24). Similarly in the decade 2041 to 2050, the increasing trend of runoff is 0.14 mm and the minimum runoff is 54.41 mm in 2043 whereas the maximum runoff is in 2042 i.e. 59.98mm (Figure 6.25). But in the last decade 2051 to 2060, the decreasing trend of runoff is 0.01 mm and the minimum runoff is 58.25 mm in 2051 whereas the maximum is in 2055 i.e. 63.77 mm (Figure 6.26).

Moreover in the whole year 2001 to 2060 the projected runoff is increasing trend by 0.01 mm and the minimum runoff is 47.6 mm in 2039 whereas the maximum runoff is in the year 2028 i.e. 65.22mm (Figure 6.27).

6.10.2 Analysis of A1B projected runoff T-Mean



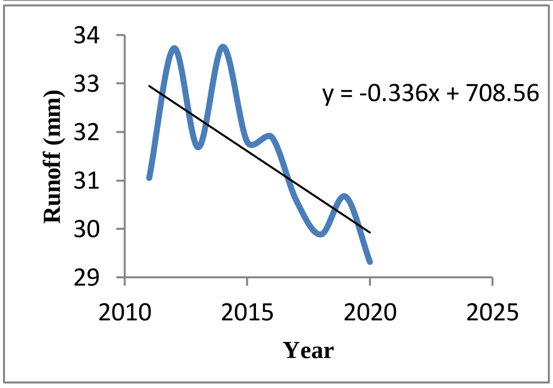
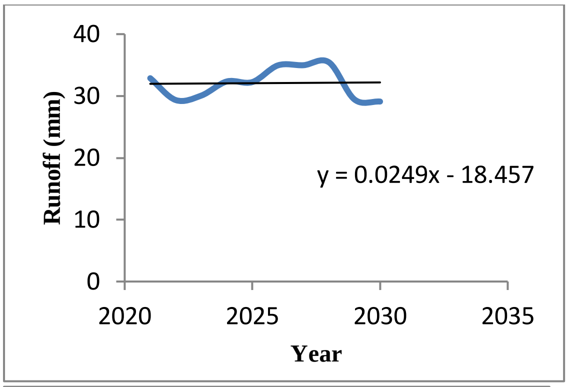


Figure 6.28 Runoff analysis from 2001 to 2010

Figure 6.29 Runoff analysis from 2011 to 2020



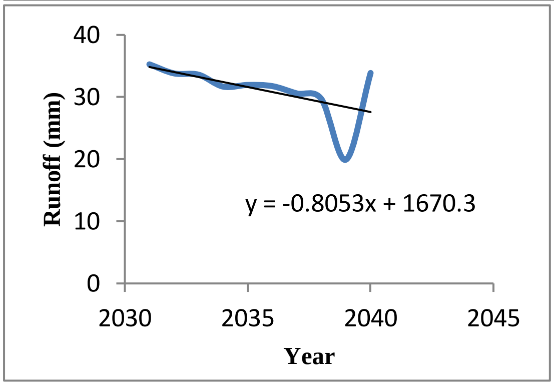


Figure 6.30 Runoff analysis from 2021 to 2030

Figure 6.31 Runoff analysis from 2031 to 2040

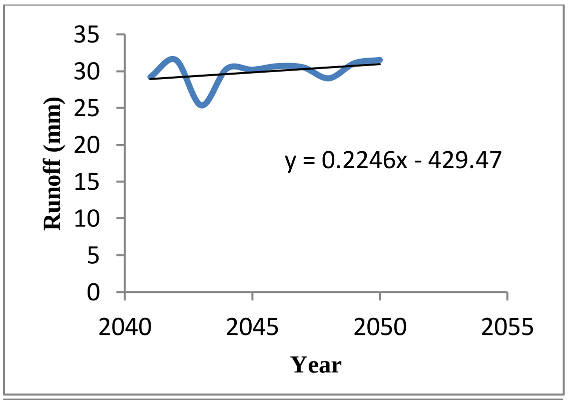


Figure 6.32 Runoff analysis from 2041 to 2050

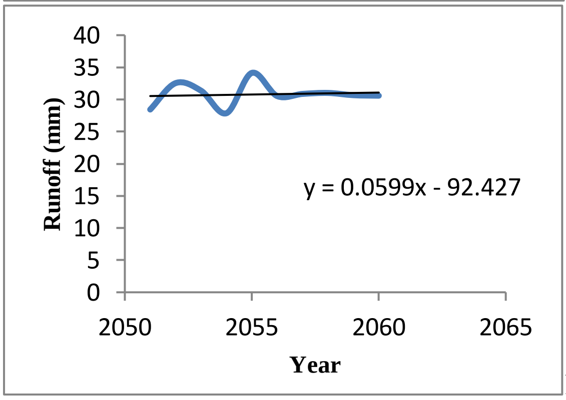


Figure 6.33 Runoff analysis from 2051 to 2060

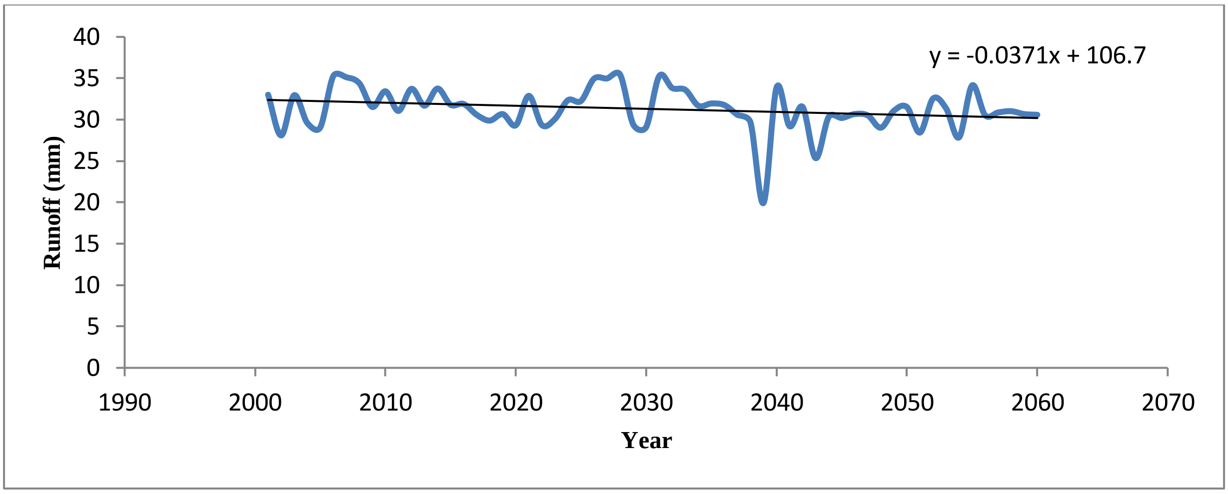
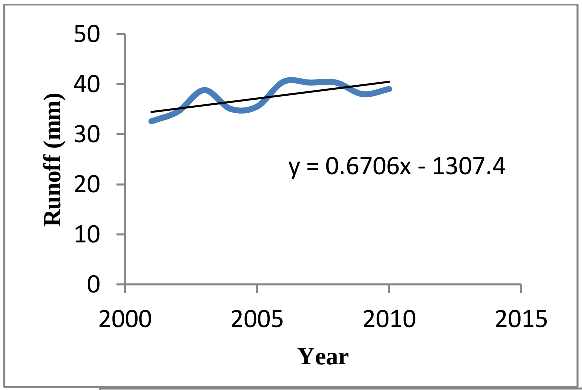


Figure 6.34 Runoff analyses from 2001 to 2060

The analyses of all projected runoff from T-mean of A1B within different ten years period are as follows: on the decade 2001 to 2010, the increasing trend of runoff is 0.34 mm and the minimum runoff is 28.09 mm in 2002 and the maximum runoff is 35.25mm in 2006 (Figure 6.28). But on the decade 2011 to 2020, the decreasing trend of runoff is 0.33 mm where the minimum is 29.31 mm in 2020 and the maximum runoff is 33.75 mm in 2014 (Figure 6.29). Similarly in the decade 2021 to 2030, the trend of runoff is increasing by 0.02 mm and the minimum runoff is 29.10 mm in 2030 whereas the maximum runoff is in 2028 i.e. 35.44mm (Figure 6.30). But in the decade 2031 to 2040, the decreasing trend of runoff is 0.8 mm and the minimum runoff is 19.93 mm in 2039 where as the maximum runoff is in 2031 i.e. 35.26 mm (Figure 6.31). Similarly in the decade 2041 to 2050, the increasing trend of runoff is 0.22 mm and the minimum runoff is 25.34 mm in 2043 whereas the maximum runoff is in 2042 i.e. 31.53 mm (Figure 6.32). Similarly in the last decade 2051 to 2060, the increasing trend of runoff is 0.05mm and the minimum runoff is 27.85 mm in 2054 whereas the maximum is in 2055 i.e. 34.13 mm (Figure 6.33).

Moreover, in the whole year 2001 to 2060 the projected runoff is increasing trend by 0.03 mm and the minimum runoff is 19.93 mm in 2039 whereas the maximum runoff is in the year 2028 i.e. 35.44mm (Figure 6.34).

6.10.3 Analysis of A1B projected runoff T-Min



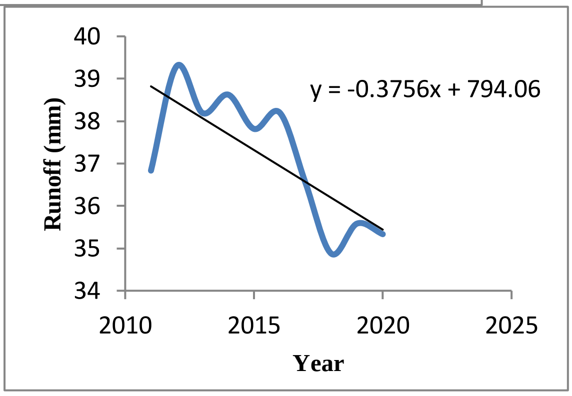
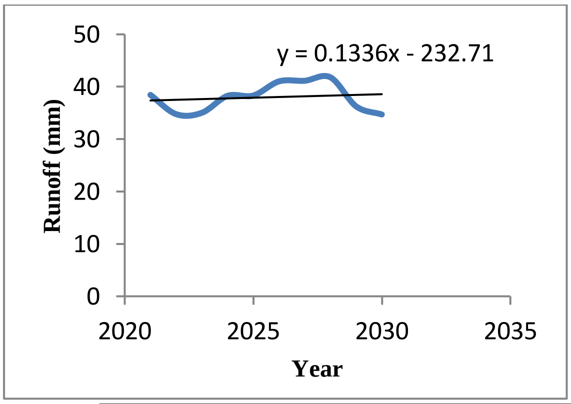


Figure 6.35 Runoff analysis from 2001 to 2010

Figure 6.36 Runoff analysis from 2011 to 2020



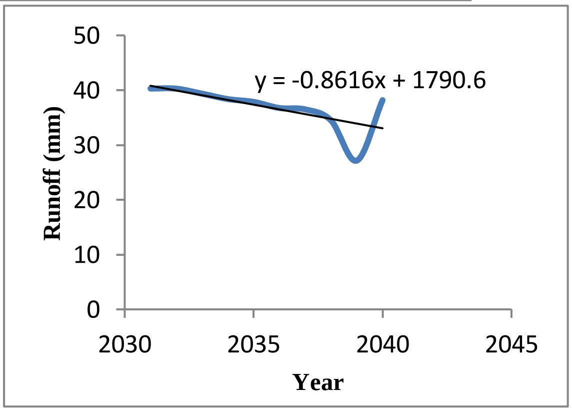
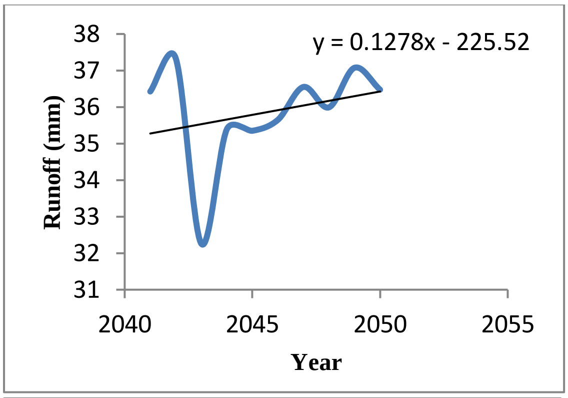


Figure 6.37 Runoff analysis from 2021 to 2030

Figure 6.38 Runoff analysis from 2031 to 2040



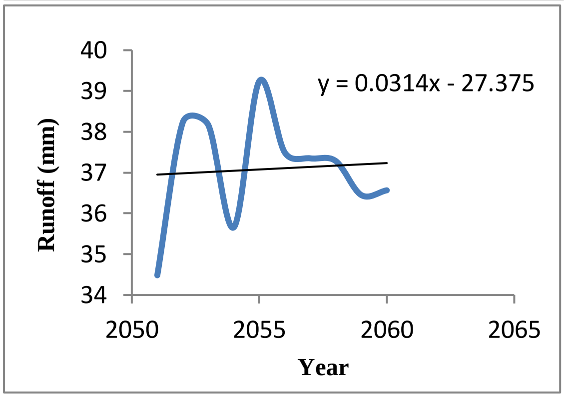


Figure 6.39 Runoff analysis from 2041 to 2050 Figure 6.40 Runoff analysis from 2051 to 2060

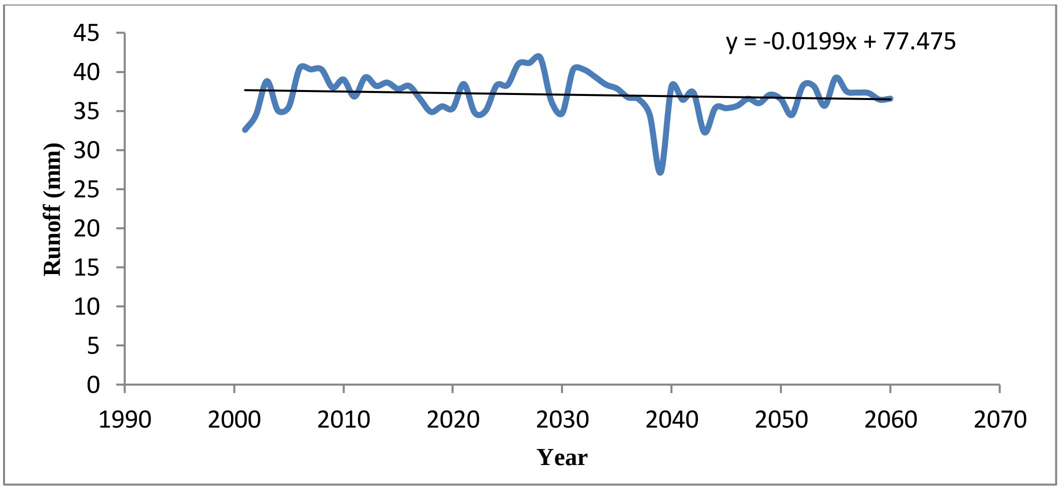


Fig 6.41 Runoff analysis from 2001 to 2060

Similarly, the analysis f all projected runoff from T-min of A1B within different ten years period are as follows: on the decade 2001 to 2010, the increasing trend of runoff is 0.67 mm and the minimum runoff is 32.57 mm in 2001 and the maximum runoff is 40.48 mm in 2006 (Figure 6.35). But on the decade 2011 to 2020, the decreasing trend of runoff is 0.37 mm where the minimum is 34.8 mm in 2018 and the maximum runoff is 39.3 mm in 2012 (Figure 6.36). Similarly in the decade 2021 to 2030, the trend of runoff is increasing by 0.13mm and the minimum runoff is 34.7 mm in 2030 whereas the maximum runoff is in 2028 i.e. 41.8 mm (Figure 6.37). But in the decade 2031 to 2040, the decreasing trend of runoff is 0.86 mm and the minimum runoff is 27.13 mm in 2039 where as the maximum runoff is in 2031 i.e. 40.29 mm (Figure 6.38). But in the decade 2041 to 2050, the increasing trend of runoff is 0.12 mm and the minimum runoff is 32.25 mm in 2043 whereas the maximum runoff is in 2042 i.e. 37.33 mm (Figure 6.39). Similarly in the last decade 2051 to 2060, the increasing trend of runoff is 0.03 mm and the minimum runoff is 34.48 mm in 2051 whereas the maximum is in 2055 i.e. 39.24 mm (Figure 6.40).

Moreover in the whole year 2001 to 2060 the projected runoff is slightly decreasing trend by 0.01 mm and the minimum runoff is 27.13 mm in 2039 whereas the maximum runoff is in the year 2028 i.e. 41.80 mm (Figure 6.41).

The projected runoff of Langtang basin according to A1B in all three temperature series shows the maximum and minimum runoff in same year i.e. 2028 and 2039.

CHAPTER 7

Discussion

The outputs of the analysis on temperature trend revealed a faster warming trend in Langtang area (i.e. 0.084 ºC/year) where as the global mean surface temperature has increased by 0.6°C during the 20th century (IPCC, 2001a) and it is projected to rise by 1.4-5.8°C by 2100 (IPCC 2001). The annual warming at Himalayan region of Nepal between 1994 and 1997 was found to be 0.06°C (Shrestha et al., 1999) and temperature rise in Langtang is almost same as in the higher ranges as reported by Shrestha (2001). So, from this we can say that temperature is rising significantly. We found the clear trend of increasing in precipitation with annual increase of 10.59 mm. Shrestha et al. (2000) found that there was no long term trend in all Nepal annual precipitation series for 1948–1994. These findings suggest a clear change in precipitation pattern. Snow cover is changes with season (Silpakar et al., 2008). The results showed a seasonal variation in snow cover with two peaks snow cover season. The reason of this seasonal variation of snow is explained by temporal variation in local temperature and precipitation. In winter time, it is colder than in summer. The precipitation is mainly in the form of snow for this catchment. But during annual dry autumn time in October to December, the precipitation is low, so snow cover decreases a little. After this dry period, the snow cover would increase again.The annual runoff of all three temperature ranges are in increasing pattern and the mean annual runoff is increased by 0.8 mm between the years 1988 to 2008. In the year 1993 to1998 the calibration with NCEP is done and the coefficient of determination (R^2) is found 0.926. The relation between runoff and mean temperature shows the increment of runoff flow while the temperature was high and less flow occur when temperature was low. From 1988 to 2008 the average maximum temperatures was on July i.e. 9.82°C whereas the maximum runoff was on August i.e.94.32 mm. The maximum rainfall also occurred on same month August i.e. 3530 mm. The minimum temperature was on February i.e. -2.40°C where as the minimum runoff was also on February i.e. 2.70mm and the minimum rainfall occurred on December i.e. 58 mm.

The mean annual soil moisture storage is also in increasing pattern by 0.71 mm between the year 1988 to 2008 this shows the result the rainfall is shifted.

The A1B scenario showed the projected runoff. We have done the analysis by breaking the 10 years scenario to know the runoff trend of short period also. The trend is in increasing from 2001 to 2010 in all temperature ranges i.e. T-max, T-mean and T-min. The result shows the same pattern with our result. From the 2011 to 2020 the pattern is in decreasing trend whereas there was increasing trend in 2021 to 2030. The trend will be increasing from 2031 to 2040 whereas the increasing from 2041 to 2050. The trend of T-max is decreasing from 2051 to 2060 where as the increasing trend will be found from T-mean and T-min.

The mean A1B scenario shows slightly decreasing trend from 2001 to 2060 where as the maximum and minimum shows the increasing trend.

CHAPTER 8

Conclusion and recommendation

8.1 Conclusion

This research was carried in the remote and rugged Himalayan region i.e. Langtang Basin. There is only one hydrological gauging station at the outlet of the catchment i.e. Kyangjing, operated by the DHM from where the temperature and precipitation data were extrapolated. This study employed the monthly Thornhtwaite water balance model to estimate the runoff from the catchment. The same monthly Thornhtwaite water balance model was run in climate change simulation mode for assessment of the Impact of Climate change and runoff generation.

1) The average maximum rainfall 926 mm occurred in August and minimum is 3 mm in December between the years 1988 to 2008 of Langtang region.

2) The maximum temperature was 12.5°C and minimum was -7.4°C between the years 1988 to 2008.

3) The increasing trend of temperature shows the result of global warming.

4) The pattern of annual runoff generated is in increasing trend.

5) The coefficient of determination of calibration and validation are 0.926 and 0.996.

6) The increase or decrease in temperature and runoff has proportional relationship.

7) The increase or decrease in rainfall and runoff has proportional relationship.

8) The increasing pattern of soil moisture storage shows the result the rainfall is shifted.

9) The projected scenario of runoff from A1B shows increasing trend in T-max and decreasing trend in T-mean and T-min from 2001 to 2060.

8.2 Recommendation

This study analyzes the impact of climate change on runoff generation using simple and readily available data. So using similar simulation, effective water resource management, plans and strategy can be developed. Moreover, it can be used for sustainable development and management of any basin. For more accurate and effectiveness of such study following recommendation is made:

1) The validation and calibration of glacier contribution and snow contribution may give better result.

2) Different models can be used to compare the results such that it will be known which one give the best result.

3) The runoff scenario with in the years 2011 to 2020 can be further study which may help to find the perfect trend of Langtang region.

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Appendix

Table A1- Average Monthly Temperature, Runoff and Rainfall

Month	S. Runoff(mm)	S. Runoff(mm)	S. Runoff(mm)	Mean Temp (^{0}C)	Mean Temp (^{0}C)	Mean Temp (^{0}C)	Average
	from T-max	from T-mean	from T-min	from T-max	from T-mean	from T-min	Rainfall(mm)
Jan	11.02	4.78	21.51	3.15	-1.92	-6.98	11.29
Feb	17.55	2.70	16.12	2.38	-2.40	-7.18	17.62
Mar	22.29	3.03	12.20	5.20	0.51	-4.18	22.29
Apr	29.99	4.23	10.24	8.00	3.37	-1.26	29.99
May	36.76	4.32	9.84	10.02	5.99	1.94	36.76
Jun	88.52	17.45	21.32	11.41	8.30	5.16	88.52
Jul	154.00	63.41	49.72	12.19	9.82	7.47	145.00
Aug	168.10	94.32	72.58	11.80	9.36	6.89	168.10
Sep	91.52	74.35	69.39	10.69	7.91	5.10	91.52
Oct	23.24	38.56	51.84	8.45	4.46	0.47	23.24
Nov	5.05	18.83	38.26	6.43	1.79	-2.85	5.05
Dec	2.52	9.34	28.67	5.01	0.14	-4.74	2.76

Table A2 - Used parameters to run the model by heat and trial method

Parameters	T-max	T-mean	T-min
Runoff factor	100%	50%	25%
Direct Runoff	100%	10%	5%
Soil Moisture Capacity	50mm	50mm	50mm
Latitude	28^{0}c	28^{0}c	28^{0}c
Rain Temperature Threshold	0.1^{0}c	2^{0}c	2^{0}c
Snow Temperature Threshold	-0.3^{0}c	-3^{0}c	-3^{0}c
Maximum Melt Rate	100%	8%	35%

Table A_3 -Original data from model (T-max)

Year	Month	PET	P	P-PET	Soil Moisture Storage (mm)	AET (mm)	Surplus(mm)	Runoff Total (mm)
1988	Jan	22.4	11	-22.4	0	0	0	11
1988	Feb	22.2	14	-22.2	0	0	0	14
1988	Mar	29.5	56	-29.5	0	0	0	56
1988	Apr	37.7	16	-37.7	0	0	0	16
1988	May	47	11	-47	0	0	0	11
1988	Jun	50.6	123	-50.6	0	0	0	123
1988	Jul	54.7	176	-54.7	0	0	0	176
1988	Aug	48	188	-48	0	0	0	188
1988	Sep	39.9	64	-39.9	0	0	0	64
1988	Oct	30	0	-30	0	0	0	0
1988	Nov	21.3	5	-21.3	0	0	0	5
1988	Dec	20.8	13	-20.8	0	0	0	13
1989	Jan	20	14	-20	0	0	0	14
1989	Feb	18.2	15	-18.2	0	0	0	15
1989	Mar	27.2	15	-27.2	0	0	0	15
1989	Apr	35.2	43	-35.2	0	0	0	43
1989	May	47.2	39	-47.2	0	0	0	39
1989	Jun	50.3	128	-50.3	0	0	0	128
1989	Jul	52.7	145	-52.7	0	0	0	145
1989	Aug	48.3	251	-48.3	0	0	0	251
1989	Sep	38.4	132	-38.4	0	0	0	132
1989	Oct	29.3	23	-29.3	0	0	0	23
1989	Nov	20.1	5	-20.1	0	0	0	5
1989	Dec	18.1	3	-18.1	0	0	0	3
1990	Jan	23.7	1	-23.7	0	0	0	1
1990	Feb	16.8	29	-16.8	0	0	0	29
1990	Mar	23.3	19	-23.3	0	0	0	19
1990	Apr	33.7	11	-33.7	0	0	0	11
1990	May	44.7	21	-44.7	0	0	0	21
1990	Jun	55.9	55	-55.9	0	0	0	55
1990	Jul	55.3	4	-55.3	0	0	0	4
1990	Aug	49.5	176	-49.5	0	0	0	176
1990	Sep	41.1	133	-41.1	0	0	0	133
1990	Oct	30.8	23	-30.8	0	0	0	23
1990	Nov	26.5	5	-26.5	0	0	0	5
1990	Dec	21.2	3	-21.2	0	0	0	3
1991	Jan	18.6	11	-18.6	0	0	0	11
1991	Feb	20.4	18	-20.4	0	0	0	18
1991	Mar	29.7	22	-29.7	0	0	0	22

1991	Apr	36.5	13.7	-36.5	0	0	0	13.7
1991	May	51.2	49	-51.2	0	0	0	49
1991	Jun	51.6	52	-51.6	0	0	0	52
1991	Jul	58.2	31	-58.2	0	0	0	31
1991	Aug	51	89	-51	0	0	0	89
1991	Sep	40.6	36	-40.6	0	0	0	36
1991	Oct	32.2	23	-32.2	0	0	0	23
1991	Nov	23	5	-23	0	0	0	5
1991	Dec	19.1	3	-19.1	0	0	0	3
1992	Jan	20.4	17	-20.4	0	0	0	17
1992	Feb	17.7	14	-17.7	0	0	0	14
1992	Mar	30.6	21	-30.6	0	0	0	21
1992	Apr	38.6	17	-38.6	0	0	0	17
1992	May	43.3	45	-43.3	0	0	0	45
1992	Jun	53.6	31	-53.6	0	0	0	31
1992	Jul	53.3	118	-53.3	0	0	0	118
1992	Aug	49.8	222	-49.8	0	0	0	222
1992	Sep	39.9	38	-39.9	0	0	0	38
1992	Oct	29.3	2	-29.3	0	0	0	2
1992	Nov	20.8	5	-20.8	0	0	0	5
1992	Dec	18.6	3	-18.6	0	0	0	3
1993	Jan	17.9	13	-17.9	0	0	0	13
1993	Feb	20	23	-20	0	0	0	23
1993	Mar	23.9	27	-23.9	0	0	0	27
1993	Apr	34.7	34	-34.7	0	0	0	34
1993	May	46.4	74	-46.4	0	0	0	74
1993	Jun	51.9	29	-51.9	0	0	0	29
1993	Jul	56.7	74	-56.7	0	0	0	74
1993	Aug	50.1	124	-50.1	0	0	0	124
1993	Sep	36.6	127	-36.6	0	0	0	127
1993	Oct	30.6	0	-30.6	0	0	0	0
1993	Nov	22.5	0	-22.5	0	0	0	0
1993	Dec	20.8	0	-20.8	0	0	0	0
1994	Jan	19.3	6	-19.3	0	0	0	6
1994	Feb	16.4	6	-14.9	0	1.5	0	4.5
1994	Mar	28.4	13	-28.4	0	0	0	13
1994	Apr	31.7	15	-31.7	0	0	0	15
1994	May	45.2	33	-45.2	0	0	0	33
1994	Jun	53.9	27	-53.9	0	0	0	27
1994	Jul	54.7	158	-54.7	0	0	0	158
1994	Aug	47.1	142	-47.1	0	0	0	142
1994	Sep	39.4	88	-39.4	0	0	0	88
1994	Oct	34.6	23	-34.6	0	0	0	23
1994	Nov	21.6	5	-21.6	0	0	0	5
1994	Dec	20.8	3	-20.8	0	0	0	3

1995	Jan	18.7	43	-18.7	0	0	0	43
1995	Feb	19	53	-19	0	0	0	53
1995	Mar	34.2	65	-34.2	0	0	0	65
1995	Apr	43.2	41	-43.2	0	0	0	41
1995	May	58.7	29	-58.7	0	0	0	29
1995	Jun	62.5	83	-62.5	0	0	0	83
1995	Jul	62.3	125	-62.3	0	0	0	125
1995	Aug	56.7	139	-56.7	0	0	0	139
1995	Sep	44	87	-44	0	0	0	87
1995	Oct	36.2	0	-36.2	0	0	0	0
1995	Nov	26.3	6	-26.3	0	0	0	6
1995	Dec	23.2	6	-23.2	0	0	0	6
1996	Jan	20.4	26	-20.4	0	0	0	26
1996	Feb	20.9	9	-20.9	0	0	0	9
1996	Mar	32.8	0	-32.8	0	0	0	0
1996	Apr	40.6	18	-40.6	0	0	0	18
1996	May	55.9	18	-55.9	0	0	0	18
1996	Jun	59.9	85	-59.9	0	0	0	85
1996	Jul	64.6	141	-64.6	0	0	0	141
1996	Aug	55.7	175	-55.7	0	0	0	175
1996	Sep	46.3	68	-46.3	0	0	0	68
1996	Oct	34.6	31	-34.6	0	0	0	31
1996	Nov	29.2	0	-29.2	0	0	0	0
1996	Dec	27	0	-27	0	0	0	0
1997	Jan	20.4	7	-20.4	0	0	0	7
1997	Feb	18.1	11	-18.1	0	0	0	11
1997	Mar	29.7	22	-29.7	0	0	0	22
1997	Apr	36.1	25	-36.1	0	0	0	25
1997	May	49	30	-49	0	0	0	30
1997	Jun	60.2	120	-60.2	0	0	0	120
1997	Jul	65	154	-65	0	0	0	154
1997	Aug	57.1	112	-57.1	0	0	0	112
1997	Sep	44.3	65	-44.3	0	0	0	65
1997	Oct	30.6	17	-30.6	0	0	0	17
1997	Nov	24.7	36	-24.7	0	0	0	36
1997	Dec	24	0	-24	0	0	0	0
1998	Jan	23.5	0	-23.5	0	0	0	0
1998	Feb	22.2	38	-22.2	0	0	0	38
1998	Mar	28.4	41	-28.4	0	0	0	41
1998	Apr	43.7	15	-43.7	0	0	0	15
1998	May	59.8	36	-59.8	0	0	0	36
1998	Jun	68.2	98	-68.2	0	0	0	98
1998	Jul	63.4	137	-63.4	0	0	0	137
1998	Aug	57.8	184	-57.8	0	0	0	184
1998	Sep	46.3	43	-46.3	0	0	0	43

1998	Oct	38.7	21	-38.7	0	0	0	21
1998	Nov	28.3	4	-28.3	0	0	0	4
1998	Dec	22.8	0	-22.8	0	0	0	0
1999	Jan	20.4	7	-20.4	0	0	0	7
1999	Feb	26	4	-26	0	0	0	4
1999	Mar	38	22	-38	0	0	0	22
1999	Apr	49.5	27	-49.5	0	0	0	27
1999	May	56.9	59	-56.9	0	0	0	59
1999	Jun	60.2	148	-60.2	0	0	0	148
1999	Jul	62.3	148	-62.3	0	0	0	148
1999	Aug	56.7	146	-56.7	0	0	0	146
1999	Sep	45.4	6	-45.4	0	0	0	6
1999	Oct	36.4	27	-36.4	0	0	0	27
1999	Nov	29	4	-29	0	0	0	4
1999	Dec	21.3	0	-21.3	0	0	0	0
2000	Jan	19.2	0	-19.2	0	0	0	0
2000	Feb	17	9	-17	0	0	0	9
2000	Mar	26.7	13	-26.7	0	0	0	13
2000	Apr	44	23	-44	0	0	0	23
2000	May	53.8	55	-53.8	0	0	0	55
2000	Jun	60.6	126	-60.6	0	0	0	126
2000	Jul	63.8	217	-63.8	0	0	0	217
2000	Aug	58.5	172	-58.5	0	0	0	172
2000	Sep	41.1	116	-41.1	0	0	0	116
2000	Oct	31.6	0	-31.6	0	0	0	0
2000	Nov	22.5	1	-22.5	0	0	0	1
2000	Dec	18.4	0	-18.4	0	0	0	0
2001	Jan	16.1	11	-10.6	0	5.5	0	5.5
2001	Feb	13.3	0	-13.3	0	0	0	0
2001	Mar	18.2	0	-18.2	0	0	0	0
2001	Apr	24.2	6	-24.2	0	0	0	6
2001	May	32.2	84	-32.2	0	0	0	84
2001	Jun	30.8	200	-30.8	0	0	0	200
2001	Jul	59.6	243	-59.6	0	0	0	243
2001	Aug	58.1	111	-58.1	0	0	0	111
2001	Sep	47.7	90	-47.7	0	0	0	90
2001	Oct	40.2	180	-40.2	0	0	0	180
2001	Nov	30.7	0	-30.7	0	0	0	0
2001	Dec	26	1	-26	0	0	0	1
2002	Jan	21.3	9	-21.3	0	0	0	9
2002	Feb	25.3	5	-25.3	0	0	0	5
2002	Mar	34.4	3	-34.4	0	0	0	3
2002	Apr	45.6	70	-45.6	0	0	0	70
2002	May	59.1	46	-59.1	0	0	0	46
2002	Jun	64.1	85	-64.1	0	0	0	85

2002	Jul	64.6	155	-64.6	0	0	0	155
2002	Aug	61.1	239	-61.1	0	0	0	239
2002	Sep	44	134	-44	0	0	0	134
2002	Oct	34.9	36	-34.9	0	0	0	36
2002	Nov	27.6	17	-27.6	0	0	0	17
2002	Dec	23.7	0	-23.7	0	0	0	0
2003	Jan	25.7	14	-25.7	0	0	0	14
2003	Feb	20.1	38	-20.1	0	0	0	38
2003	Mar	30.6	40	-30.6	0	0	0	40
2003	Apr	48.3	46	-48.3	0	0	0	46
2003	May	58	39	-58	0	0	0	39
2003	Jun	64.9	92	-64.9	0	0	0	92
2003	Jul	60	113	-60	0	0	0	113
2003	Aug	55	146	-55	0	0	0	146
2003	Sep	41.1	109	-41.1	0	0	0	109
2003	Oct	34	14	-34	0	0	0	14
2003	Nov	25.3	0	-25.3	0	0	0	0
2003	Dec	20	5	-20	0	0	0	5
2004	Jan	18.1	14	-18.1	0	0	0	14
2004	Feb	20	38	-20	0	0	0	38
2004	Mar	33.4	40	-33.4	0	0	0	40
2004	Apr	37	46	-37	0	0	0	46
2004	May	50.6	39	-50.6	0	0	0	39
2004	Jun	54.2	92	-54.2	0	0	0	92
2004	Jul	56	113	-56	0	0	0	113
2004	Aug	57.1	146	-57.1	0	0	0	146
2004	Sep	44	109	-44	0	0	0	109
2004	Oct	29.7	14	-29.7	0	0	0	14
2004	Nov	20.4	0	-20.4	0	0	0	0
2004	Dec	23.5	0	-23.5	0	0	0	0
2005	Jan	16.4	20	-16.4	0	0	0	20
2005	Feb	18.7	17	-18.7	0	0	0	17
2005	Mar	26.9	14	-26.9	0	0	0	14
2005	Apr	35.4	39	-35.4	0	0	0	39
2005	May	49.7	0	-49.7	0	0	0	0
2005	Jun	55.2	30	-55.2	0	0	0	30
2005	Jul	58.9	238	-58.9	0	0	0	238
2005	Aug	33.7	284	-33.7	0	0	0	284
2005	Sep	28.7	64	-28.7	0	0	0	64
2005	Oct	19.7	32	-19.7	0	0	0	32
2005	Nov	16.6	0	-16.6	0	0	0	0
2005	Dec	13.6	5	-13.6	0	0	0	0
2006	Jan	15.4	0	-15.4	0	0	0	0
2006	Feb	16.3	0	-11.3	0	5	0	0
2006	Mar	28.8	17	-28.8	0	0	0	17

2006	Apr	38.1	54	-38.1	0	0	0	54
2006	May	49.7	43	-49.7	0	0	0	43
2006	Jun	55.2	82	-55.2	0	0	0	82
2006	Jul	58.9	219	-58.9	0	0	0	219
2006	Aug	52.3	164	-52.3	0	0	0	164
2006	Sep	41.1	78	-41.1	0	0	0	78
2006	Oct	32.2	7	-32.2	0	0	0	7
2006	Nov	23.8	1	-23.8	0	0	0	1
2006	Dec	24	11	-24	0	0	0	11
2007	Jan	22.5	0	-22.5	0	0	0	0
2007	Feb	18.5	29	-18.5	0	0	0	29
2007	Mar	29.9	8	-29.9	0	0	0	8
2007	Apr	42.6	33	-42.6	0	0	0	33
2007	May	52.2	0	-52.2	0	0	0	0
2007	Jun	58.4	69	-58.4	0	0	0	69
2007	Jul	54.7	375	-54.7	0	0	0	375
2007	Aug	49.2	164	-49.2	0	0	0	164
2007	Sep	39.4	198	-39.4	0	0	0	198
2007	Oct	32.6	9	-32.6	0	0	0	9
2007	Nov	22.1	7	-22.1	0	0	0	7
2007	Dec	22.5	2	-22.5	0	0	0	2
2008	Jan	17.1	13	-17.1	0	0	0	13
2008	Feb	16.6	0	-16.6	0	0	0	0
2008	Mar	26.7	10	-26.7	0	0	0	10
2008	Apr	34.3	37	-34.3	0	0	0	37
2008	May	43.6	22	-43.6	0	0	0	22
2008	Jun	51	104	-51	0	0	0	104
2008	Jul	51.7	150	-51.7	0	0	0	150
2008	Aug	47.4	156	-47.4	0	0	0	156
2008	Sep	38.4	137	-38.4	0	0	0	137
2008	Oct	31.2	6	-31.2	0	0	0	6
2008	Nov	27.5	0	-27.5	0	0	0	0
2008	Dec	23.2	0	-23.2	0	0	0	0

Table A_4 -Original data from model (T-mean)

Year	Month	PET	P	P-PET	Soil Moisture Storage (mm)	AET (mm)	Surplus(mm)	Runoff Total (mm)
1988	Jan	15.2	11	-10.7	11.7	7.7	0	4.8
1988	Feb	15.5	14	-9.4	9.5	8.3	0	2.8
1988	Mar	20.1	56	6.2	15.6	20.1	0	3.8
1988	Apr	27.3	16	-8.8	12.9	21.2	0	2.1
1988	May	36.2	11	-22.5	7.1	19.5	0	1.4
1988	Jun	41	123	73.2	50	41	30.2	27.6
1988	Jul	46.2	176	115.4	50	46.2	115.4	82.9
1988	Aug	41.1	188	131.1	50	41.1	131.1	117
1988	Sep	32.3	64	28	50	32.3	28	69.5
1988	Oct	22	0	-19.5	30.5	22	0	31.5
1988	Nov	15.2	5	-12.3	23	10.4	0	16
1988	Dec	14.9	13	-8.4	19.1	10.3	0	8.5
1989	Jan	13.6	14	-13.2	14.1	5.4	0	4
1989	Feb	13	15	-13	10.4	3.6	0	2
1989	Mar	19.7	15	-11.6	8	10.6	0	1.6
1989	Apr	25.2	43	13.4	21.4	25.2	0	4.2
1989	May	36.6	39	4.2	25.7	36.6	0	4.1
1989	Jun	41.3	128	79.2	50	41.3	54.9	40.4
1989	Jul	46.8	145	88.6	50	46.8	88.6	72.6
1989	Aug	40.1	251	190.3	50	40.1	190.3	149.3
1989	Sep	31.7	132	91.2	50	31.7	91.2	120.9
1989	Oct	21.2	23	2.4	50	21.2	2.4	57.2
1989	Nov	14.6	5	-12.3	37.7	14.6	0	27.7
1989	Dec	12.7	3	-12.7	28.1	9.6	0	13.8
1990	Jan	16.4	1	-13.3	20.7	10.6	0	6.9
1990	Feb	12.4	29	-12.4	15.5	5.1	0	3.4
1990	Mar	16.7	19	-16.7	10.4	5.2	0	1.7
1990	Apr	24.4	11	-10.9	8.1	15.8	0	1.7
1990	May	34.4	21	-8.1	6.8	27.6	0	2.5
1990	Jun	45	55	11.3	18.1	45	0	5.7
1990	Jul	47.4	4	-37.5	4.5	23.4	0	0.5
1990	Aug	42.1	176	122	50	42.1	76.6	55.9
1990	Sep	33.5	133	91.5	50	33.5	91.5	78.2
1990	Oct	23.4	23	2.1	50	23.4	2.1	35.8
1990	Nov	18.8	5	-9.8	40.2	18.8	0	17.3
1990	Dec	15.1	3	-11.7	30.8	12.8	0	8.5
1991	Jan	12.9	11	-12.9	22.8	7.9	0	4.2
1991	Feb	14.7	18	-9.3	18.6	9.6	0	2.5
1991	Mar	21.8	22	-2.4	17.7	20.3	0	2.7

1991	Apr	26.4	13.7	-8.1	14.8	21.2	0	1.9
1991	May	37.8	49	11.9	26.7	37.8	0	5.2
1991	Jun	43.6	52	8.3	34.9	43.6	0	5.3
1991	Jul	49.2	31	-16.6	23.3	44.2	0	3.2
1991	Aug	43.4	89	41	50	43.4	14.3	16.1
1991	Sep	32.9	36	3.5	50	32.9	3.5	8.9
1991	Oct	23.9	23	0.5	50	23.9	0.5	5.2
1991	Nov	16.2	5	-11.2	38.8	16.2	0	1.8
1991	Dec	13.7	3	-12.6	29	10.9	0	0.8
1992	Jan	14.3	17	-10.4	23	10	0	0.7
1992	Feb	12.3	14	-12.3	17.3	5.6	0	0.2
1992	Mar	22.3	21	-1.9	16.7	21	0	1.8
1992	Apr	28.1	17	-7.3	14.2	23.3	0	1.7
1992	May	32.8	45	12.8	27.1	32.8	0	4.5
1992	Jun	42.3	31	-9.7	21.8	37.8	0	3.1
1992	Jul	45.1	118	65.4	50	45.1	37.2	30.4
1992	Aug	41.9	222	161.9	50	41.9	161.9	112.5
1992	Sep	32.1	38	5.7	50	32.1	5.7	51.8
1992	Oct	22.4	2	-17.3	32.7	22.4	0	24.2
1992	Nov	15.2	5	-12	24.9	11.1	0	12.2
1992	Dec	13.3	3	-12.8	18.5	6.9	0	6
1993	Jan	12.9	13	-12.9	13.7	4.8	0	3
1993	Feb	14.1	23	-10.9	10.7	6.2	0	1.8
1993	Mar	17.2	27	-17.2	7	3.7	0	0.8
1993	Apr	25.6	34	10.2	17.3	25.6	0	3.5
1993	May	35.1	74	39.3	50	35.1	6.6	10.9
1993	Jun	42.3	29	-9.1	40.9	42.3	0	4.6
1993	Jul	46.5	74	26.7	50	46.5	17.6	17.1
1993	Aug	42.4	124	75.3	50	42.4	75.3	54.9
1993	Sep	31.3	127	88.6	50	31.3	88.6	78.2
1993	Oct	23.6	0	-18.5	31.5	23.6	0	32.8
1993	Nov	16.2	0	-13.3	23.1	11.3	0	16.4
1993	Dec	15.4	0	-12.9	17.2	8.5	0	8.2
1994	Jan	13.4	6	-13.4	12.6	4.6	0	4.1
1994	Feb	11.8	6	-11.8	9.6	3	0	2
1994	Mar	20.6	13	-10.8	7.5	11.8	0	1.8
1994	Apr	23.7	15	-10.9	5.9	14.4	0	1.5
1994	May	34.4	33	0.8	6.7	34.4	0	3.6
1994	Jun	43.4	27	-14	4.8	31.3	0	2.8
1994	Jul	45.7	158	101.2	50	45.7	56	43.9
1994	Aug	40.6	142	91.5	50	40.6	91.5	74
1994	Sep	32.3	88	50.9	50	32.3	50.9	64.1
1994	Oct	25.7	23	-1.4	48.6	25.7	0	30
1994	Nov	16.1	5	-11.3	37.6	15.8	0	14.1
1994	Dec	14.8	3	-12.2	28.5	11.8	0	7

1995	Jan	12.8	43	-12.8	21.2	7.3	0	3.5
1995	Feb	13.8	53	-11.5	16.3	7.2	0	1.9
1995	Mar	24.2	65	45.2	50	24.2	11.5	13.1
1995	Apr	29.7	41	17.1	50	29.7	17.1	16
1995	May	44.7	29	-9.4	40.6	44.7	0	8.8
1995	Jun	52.9	83	30.3	50	52.9	20.9	21.7
1995	Jul	52.7	125	67.6	50	52.7	67.6	53
1995	Aug	48	139	84.3	50	48	84.3	76.3
1995	Sep	36.8	87	48.1	50	36.8	48.1	63.9
1995	Oct	27.5	0	-21.5	28.5	27.5	0	27.6
1995	Nov	19.2	6	-8.2	23.8	15.6	0	14.4
1995	Dec	16.2	6	-8.6	19.8	11.7	0	7.3
1996	Jan	14.4	26	-7.8	16.7	9.7	0	4
1996	Feb	15	9	-10.2	13.3	8.2	0	2
1996	Mar	24.2	0	-17.4	8.6	11.4	0	0.9
1996	Apr	30.3	18	-7.9	7.3	23.8	0	2.2
1996	May	42.3	18	-20.3	4.3	24.9	0	2
1996	Jun	48.8	85	33	37.3	48.8	0	8.6
1996	Jul	54.7	141	77.1	50	54.7	64.4	46.3
1996	Aug	46.8	175	115.2	50	46.8	115.2	91.2
1996	Sep	37.5	68	27.8	50	37.5	27.8	57.6
1996	Oct	26.7	31	5	50	26.7	5	31
1996	Nov	20.9	0	-17.4	32.6	20.9	0	13.9
1996	Dec	19.1	0	-15.9	22.2	13.5	0	7
1997	Jan	14.6	7	-12.1	16.9	7.9	0	3.7
1997	Feb	13.4	11	-13.4	12.3	4.5	0	1.7
1997	Mar	22.9	22	-1.1	12.1	22	0	2.9
1997	Apr	28.1	25	-1.6	11.7	26.9	0	2.9
1997	May	38.7	30	-8	9.8	32.6	0	3.2
1997	Jun	48.8	120	62.6	50	48.8	22.4	23.3
1997	Jul	56	154	85.7	50	56	85.7	63.9
1997	Aug	48.3	112	55.4	50	48.3	55.4	63.2
1997	Sep	36.3	65	24.8	50	36.3	24.8	44.9
1997	Oct	22.9	17	-5.1	44.9	22.9	0	20.9
1997	Nov	17.8	36	14.3	50	17.8	9.2	17.5
1997	Dec	16.1	0	-14.5	35.5	16.1	0	7.1
1998	Jan	16.1	0	-14.9	24.9	11.8	0	3.5
1998	Feb	15.9	38	3	27.9	15.9	0	3.7
1998	Mar	21.6	41	8.1	36	21.6	0	3.8
1998	Apr	32.4	15	-14.8	25.3	28.3	0	1.9
1998	May	45.2	36	-9.1	20.7	40.8	0	3.8
1998	Jun	54.6	98	37.1	50	54.6	7.9	13.8
1998	Jul	55	137	71.5	50	55	71.5	51.5
1998	Aug	51	184	117.5	50	51	117.5	96
1998	Sep	40.1	43	1.3	50	40.1	1.3	43.8

1998	Oct	29.8	21	-8.5	41.5	29.8	0	21.8
1998	Nov	21.4	4	-15.5	28.6	18.8	0	10.3
1998	Dec	17.4	0	-15.4	19.8	10.8	0	4.9
1999	Jan	15.1	7	-12	15.1	7.8	0	2.7
1999	Feb	19.3	4	-13.4	11	9.9	0	1.6
1999	Mar	28.1	22	-6.2	9.7	23.2	0	2.8
1999	Apr	35.8	27	-9.6	7.8	28.1	0	3
1999	May	44.7	59	10.2	18	44.7	0	6.1
1999	Jun	49.1	148	85.7	50	49.1	53.7	41.7
1999	Jul	54.7	148	80	50	54.7	80	68.3
1999	Aug	48.9	146	83.9	50	48.9	83.9	83.3
1999	Sep	38.4	6	-31.8	18.2	38.4	0	34.9
1999	Oct	28.1	27	-2.6	17.3	26.4	0	19.9
1999	Nov	20.8	4	-16.1	11.7	10.2	0	9
1999	Dec	15.6	0	-15	8.2	4.1	0	4.3
2000	Jan	14.7	0	-14.4	5.8	2.6	0	2.1
2000	Feb	13.1	9	-13.1	4.3	1.5	0	1.1
2000	Mar	20.7	13	-12.7	3.2	9.1	0	1.3
2000	Apr	32.6	23	-10	2.6	23.3	0	2.6
2000	May	44.4	55	6.9	9.5	44.4	0	5.6
2000	Jun	51.3	126	63.8	50	51.3	23.3	24.3
2000	Jul	54.3	217	142.5	50	54.3	142.5	98.8
2000	Aug	49.5	172	106.7	50	49.5	106.7	109.1
2000	Sep	34.2	116	71.5	50	34.2	71.5	93.3
2000	Oct	24.3	0	-23.1	26.9	24.3	0	40.9
2000	Nov	16.8	1	-15.3	18.6	9.7	0	20.5
2000	Dec	13.4	0	-13.3	13.7	5.1	0	10.2
2001	Jan	11.4	11	-11.4	10.6	3.1	0	5.1
2001	Feb	10.4	0	-10.4	8.4	2.2	0	2.6
2001	Mar	13.8	0	-13.8	6.1	2.3	0	1.3
2001	Apr	18.5	6	-18.5	3.8	2.2	0	0.6
2001	May	26.2	84	17.6	21.4	26.2	0	4.9
2001	Jun	25.8	200	55.9	50	25.8	27.3	22.2
2001	Jul	51.1	243	181.7	50	51.1	181.7	122.1
2001	Aug	50.4	111	62.4	50	50.4	62.4	91.2
2001	Sep	40.4	90	52.5	50	40.4	52.5	75.3
2001	Oct	32	180	141	50	32	141	121.6
2001	Nov	23.2	0	-13.2	36.8	23.2	0	51.8
2001	Dec	19.4	1	-9.3	30	17	0	26
2002	Jan	16	9	-6.5	26.1	13.4	0	13.5
2002	Feb	18.5	5	-5.8	23.1	15.7	0	7
2002	Mar	26.2	3	-15.7	15.8	17.7	0	3.5
2002	Apr	35	70	35.2	50	35	1	9.1
2002	May	48.1	46	-0.1	49.9	48.1	0	5.7
2002	Jun	55.9	85	26.6	50	55.9	26.5	22.3

2002	Jul	59.6	155	85.5	50	59.6	85.5	65.1
2002	Aug	54	239	166.3	50	54	166.3	131.8
2002	Sep	39.6	134	85.7	50	39.6	85.7	110.2
2002	Oct	29.7	36	7.1	50	29.7	7.1	55.5
2002	Nov	21.4	17	-2.1	47.9	21.4	0	27.7
2002	Dec	18.7	0	-15	33.5	18.1	0	13
2003	Jan	19.4	14	-3.4	31.2	18.3	0	7.9
2003	Feb	15.8	38	2.9	34	15.8	0	5.1
2003	Mar	24.3	40	16.2	50	24.3	0.2	5.7
2003	Apr	36.7	46	8.8	50	36.7	8.8	9.9
2003	May	45	39	-6	44	45	0	6.5
2003	Jun	52.9	92	33.4	50	52.9	27.4	24.2
2003	Jul	53	113	51.9	50	53	51.9	44.8
2003	Aug	46.8	146	87.6	50	46.8	87.6	75.1
2003	Sep	37	109	63.8	50	37	63.8	73.1
2003	Oct	28.1	14	-12.9	37.1	28.1	0	32.5
2003	Nov	19.5	0	-17.2	24.3	15.1	0	15.5
2003	Dec	15.2	5	-11.7	18.6	9.1	0	8
2004	Jan	13.9	14	-12.3	14	6.2	0	4
2004	Feb	15.1	38	-1.7	13.5	13.9	0	3.2
2004	Mar	25.2	40	15.8	29.4	25.2	0	5
2004	Apr	29.7	46	16.3	45.7	29.7	0	5.1
2004	May	40.5	39	-1.1	44.7	40.4	0	4.1
2004	Jun	46.7	92	40	50	46.7	34.8	26.7
2004	Jul	50.1	113	55.2	50	50.1	55.2	47.7
2004	Aug	48.3	146	86.5	50	48.3	86.5	76
2004	Sep	37.9	109	63.2	50	37.9	63.2	73.2
2004	Oct	25.9	14	-10.4	39.6	25.9	0	32.6
2004	Nov	18.1	0	-15.6	27.2	14.9	0	15.6
2004	Dec	20.2	0	-17.8	17.6	12.1	0	7.8
2005	Jan	15.1	20	-7.1	15.1	10.5	0	4.7
2005	Feb	16.2	17	-5.6	13.4	12.3	0	2.9
2005	Mar	23.3	14	-7.8	11.3	17.6	0	2.3
2005	Apr	31.3	39	7.1	18.5	31.3	0	4.4
2005	May	38.7	0	-35.7	5.3	16.2	0	0.2
2005	Jun	45.6	30	-15.8	3.6	31.5	0	3.1
2005	Jul	50.7	238	166	50	50.7	119.6	83.7
2005	Aug	30.5	284	227.5	50	30.5	227.5	172.1
2005	Sep	24.9	64	34.9	50	24.9	34.9	95.7
2005	Oct	16.8	32	-10.2	39.8	16.8	0	45.3
2005	Nov	13.4	0	-13.4	29.1	10.7	0	22.3
2005	Dec	11.1	5	-11.1	22.7	6.5	0	11.2
2006	Jan	12.6	0	-12.6	17	5.7	0	5.6
2006	Feb	13.5	0	-13.5	12.4	4.6	0	2.8
2006	Mar	21.5	17	-7.4	10.5	15.9	0	2.6

2006	Apr	28.7	54	24.5	35	28.7	0	6.1
2006	May	38.7	43	4.1	39.1	38.7	0	4.6
2006	Jun	45.6	82	32.1	50	45.6	21.2	19
2006	Jul	50.7	219	149.9	50	50.7	149.9	102.2
2006	Aug	44.8	164	106	50	44.8	106	109.6
2006	Sep	34.6	78	38.6	50	34.6	38.6	73.7
2006	Oct	25.1	7	-16	34	25.1	0	33.6
2006	Nov	18.5	1	-15	23.7	13.6	0	16.6
2006	Dec	18.4	11	-6.1	20.8	15.1	0	9.3
2007	Jan	16.7	0	-15.2	14.5	7.8	0	4.1
2007	Feb	14.1	29	-10.5	11.4	6.7	0	2.4
2007	Mar	22.7	8	-12.8	8.5	12.9	0	1.7
2007	Apr	32	33	1.5	10	32	0	3.8
2007	May	41.2	0	-37.7	2.4	11	0	0.3
2007	Jun	47.9	69	17.4	19.9	47.9	0	7
2007	Jul	49.2	375	291.3	50	49.2	261.1	168.1
2007	Aug	44.3	164	106.1	50	44.3	106.1	134.8
2007	Sep	35	198	145.7	50	35	145.7	151.8
2007	Oct	26.9	9	-16.5	33.5	26.9	0	66.9
2007	Nov	17.9	7	-10	26.9	14.6	0	33.7
2007	Dec	16.8	2	-13.6	19.5	10.5	0	16.7
2008	Jan	12.9	13	-12.9	14.5	5	0	8.3
2008	Feb	12	0	-12	11	3.5	0	4.1
2008	Mar	20.2	10	-14	7.9	9.3	0	2.6
2008	Apr	26.1	37	9.7	17.6	26.1	0	4.7
2008	May	34.7	22	-11.9	13.4	27	0	2.7
2008	Jun	42.8	104	53.5	50	42.8	17	19.1
2008	Jul	45.1	150	92.4	50	45.1	92.4	65.6
2008	Aug	41.9	156	100.9	50	41.9	100.9	91.3
2008	Sep	31.9	137	93.5	50	31.9	93.5	98.3
2008	Oct	24.5	6	-17.1	32.9	24.5	0	42.9
2008	Nov	20.5	0	-18.7	20.6	14.1	0	21.2
2008	Dec	17.4	0	-15.8	14.1	8.1	0	10.6

Table A_5 -Original data from model (T-min)

Year	Month	PET	P	P-PET	Soil Moisture Storage (mm)	AET (mm)	Surplus(mm)	Runoff Total (mm)
1988	Jan	10.3	11	-10.3	22	5.7	0	23
1988	Feb	10.9	14	-10.9	17.2	4.8	0	17.2
1988	Mar	13.8	56	-13.8	12.5	4.7	0	12.9
1988	Apr	19.9	16	-14.7	8.8	8.9	0	9.8

1988	May	27.7	11	6.2	15	27.7	0	7.7
1988	Jun	33	123	111.3	50	33	76.3	30.7
1988	Jul	39.1	176	145.9	50	39.1	145.9	63.7
1988	Aug	35	188	155.2	50	35	155.2	89.4
1988	Sep	26	64	42.3	50	26	42.3	73.8
1988	Oct	16.2	0	-15.8	34.2	16.2	0	52.9
1988	Nov	11	5	-11	26.7	7.5	0	39.7
1988	Dec	10.6	13	-10.6	21.1	5.7	0	29.8
1989	Jan	9.2	14	-9.2	17.2	3.9	0	22.3
1989	Feb	9.2	15	-9.2	14	3.1	0	16.7
1989	Mar	14.2	15	-14.2	10.1	4	0	12.6
1989	Apr	18	43	-18	6.4	3.6	0	9.4
1989	May	28.2	39	35.4	41.8	28.2	0	8.6
1989	Jun	33.8	128	120.1	50	33.8	111.9	39.7
1989	Jul	41.9	145	116.9	50	41.9	116.9	61.4
1989	Aug	33.1	251	219	50	33.1	219	108
1989	Sep	26.2	132	108.1	50	26.2	108.1	105.2
1989	Oct	15.3	23	-15.3	34.7	15.3	0	73.9
1989	Nov	10.6	5	-10.6	27.4	7.3	0	55.5
1989	Dec	8.9	3	-8.9	22.5	4.9	0	41.6
1990	Jan	11.5	1	-11.5	17.3	5.2	0	31.2
1990	Feb	9.2	29	-9.2	14.2	3.2	0	23.4
1990	Mar	11.9	19	-11.9	10.8	3.4	0	17.5
1990	Apr	17.7	11	-17.7	7	3.8	0	13.2
1990	May	26.7	21	9.6	16.6	26.7	0	10.5
1990	Jun	36.5	55	47.8	50	36.5	14.4	13.8
1990	Jul	40.6	4	-16	34	40.6	0	8.5
1990	Aug	35.8	176	144.9	50	35.8	128.9	47.2
1990	Sep	27.5	133	107.7	50	27.5	107.7	62.4
1990	Oct	17.8	23	-4.9	45.1	17.8	0	42.3
1990	Nov	13.3	5	-13.3	33.1	12	0	31.3
1990	Dec	10.7	3	-10.7	26	7.1	0	23.5
1991	Jan	8.9	11	-8.9	21.4	4.7	0	17.6
1991	Feb	10.6	18	-10.6	16.9	4.5	0	13.2
1991	Mar	16.1	22	-16.1	11.4	5.4	0	9.9
1991	Apr	19.3	13.7	-19.3	7	4.4	0	7.4
1991	May	27.7	49	34.1	41.1	27.7	0	7.3
1991	Jun	36.9	52	41.9	50	36.9	33	15
1991	Jul	41.6	31	7	50	41.6	7	12.6
1991	Aug	36.7	89	60.2	50	36.7	60.2	27.8
1991	Sep	26.7	36	15.6	50	26.7	15.6	23.2
1991	Oct	17.6	23	-6	44	17.6	0	16.5
1991	Nov	11.5	5	-11.5	33.8	10.1	0	12.1
1991	Dec	9.9	3	-9.9	27.2	6.7	0	9
1992	Jan	10.1	17	-10.1	21.7	5.5	0	6.8

1992	Feb	8.5	14	-8.5	18	3.7	0	5.1
1992	Mar	16.3	21	-16.3	12.1	5.8	0	3.8
1992	Apr	20.6	17	-9.4	9.8	13.5	0	3
1992	May	24.6	45	4.3	14.2	24.6	0	2.9
1992	Jun	33.4	31	33.4	47.6	33.4	0	3.2
1992	Jul	38.2	118	98.3	50	38.2	95.8	31.1
1992	Aug	35.2	222	191.5	50	35.2	191.5	77.9
1992	Sep	25.7	38	20.7	50	25.7	20.7	57.1
1992	Oct	17.3	2	-14.6	35.4	17.3	0	41.5
1992	Nov	11.1	5	-11.1	27.6	7.9	0	31.1
1992	Dec	9.6	3	-9.6	22.3	5.3	0	23.3
1993	Jan	9.3	13	-9.3	18.1	4.2	0	17.5
1993	Feb	10	23	-10	14.5	3.6	0	13.1
1993	Mar	12.4	27	-12.4	10.9	3.6	0	9.8
1993	Apr	18.9	34	-18.9	6.8	4.1	0	7.4
1993	May	26.7	74	47.6	50	26.7	4.4	8.8
1993	Jun	34.7	29	35.1	50	34.7	35.1	15.2
1993	Jul	38.4	74	59.4	50	38.4	59.4	28.9
1993	Aug	35.6	124	100	50	35.6	100	50.1
1993	Sep	26.8	127	105.4	50	26.8	105.4	65.6
1993	Oct	18.2	0	-14.7	35.3	18.2	0	44.5
1993	Nov	11.7	0	-11.7	27.1	8.2	0	33.3
1993	Dec	11.4	0	-11.4	20.9	6.2	0	25
1994	Jan	9.3	6	-9.3	17	3.9	0	18.8
1994	Feb	8.5	6	-8.5	14.1	2.9	0	14.1
1994	Mar	14.9	13	-14.9	9.9	4.2	0	10.5
1994	Apr	17.8	15	-17.8	6.4	3.5	0	7.9
1994	May	26.2	33	4.6	10.9	26.2	0	6.8
1994	Jun	34.9	27	11.5	22.5	34.9	0	5.8
1994	Jul	38.2	158	125.5	50	38.2	97.9	35.7
1994	Aug	35	142	108.7	50	35	108.7	55.1
1994	Sep	26.7	88	62.7	50	26.7	62.7	56.1
1994	Oct	19.1	23	-1.4	48.6	19.1	0	39.5
1994	Nov	12	5	-12	36.9	11.7	0	29.1
1994	Dec	10.4	3	-10.4	29.2	7.7	0	21.8
1995	Jan	8.8	43	-8.8	24.1	5.2	0	16.4
1995	Feb	10	53	-10	19.2	4.8	0	12.3
1995	Mar	17.2	65	-17.2	12.6	6.6	0	9.2
1995	Apr	20.6	41	4.6	17.2	20.6	0	7.4
1995	May	34.2	29	63.1	50	34.2	30.3	14.2
1995	Jun	44.5	83	79.8	50	44.5	79.8	33.7
1995	Jul	44.8	125	103.4	50	44.8	103.4	54.2
1995	Aug	40.8	139	110.4	50	40.8	110.4	70.5
1995	Sep	30.5	87	64.6	50	30.5	64.6	68.2
1995	Oct	21	0	-13.5	36.5	21	0	47.9

1995	Nov	13.9	6	-12.3	27.5	10.6	0	35.9
1995	Dec	11.3	6	-11.3	21.3	6.2	0	26.9
1996	Jan	10.2	26	-10.2	16.9	4.3	0	20.2
1996	Feb	10.8	9	-10.8	13.3	3.7	0	15.1
1996	Mar	18	0	-15.4	9.2	6.6	0	11.4
1996	Apr	22.6	18	-1.5	8.9	21.4	0	9
1996	May	32	18	4.4	13.3	32	0	7.3
1996	Jun	39.5	85	53.7	50	39.5	17	13.3
1996	Jul	46.5	141	95.5	50	46.5	95.5	37.7
1996	Aug	39.3	175	132.2	50	39.3	132.2	64.8
1996	Sep	30.2	68	44.2	50	30.2	44.2	56.5
1996	Oct	20.6	31	9.1	50	20.6	9.1	43.4
1996	Nov	14.9	0	-14.9	35.1	14.9	0	31.6
1996	Dec	13.4	0	-13.4	25.7	9.4	0	23.7
1997	Jan	10.4	7	-10.4	20.4	5.4	0	17.8
1997	Feb	9.9	11	-9.9	16.3	4	0	13.3
1997	Mar	17.5	22	-16.1	11	6.6	0	10
1997	Apr	21.8	25	-4.8	10	18.1	0	8
1997	May	30.6	30	14	24	30.6	0	7.1
1997	Jun	39.5	120	85	50	39.5	59	25
1997	Jul	48.3	154	104.8	50	48.3	104.8	48.1
1997	Aug	41.1	112	69.7	50	41.1	69.7	53.4
1997	Sep	29.6	65	40.4	50	29.6	40.4	49.2
1997	Oct	17	17	-12	38	17	0	34.6
1997	Nov	12.7	36	-12.7	28.3	9.7	0	25.8
1997	Dec	10.8	0	-10.8	22.2	6.1	0	19.4
1998	Jan	11	0	-11	17.3	4.9	0	14.5
1998	Feb	11.4	38	-11.4	13.3	3.9	0	10.9
1998	Mar	16.6	41	-16.6	8.9	4.4	0	8.2
1998	Apr	24.1	15	19.2	28.1	24.1	0	6.7
1998	May	34.4	36	34.1	50	34.4	12.2	9.4
1998	Jun	43.4	98	72	50	43.4	72	28.6
1998	Jul	47.7	137	97	50	47.7	97	48.9
1998	Aug	44.8	184	139.4	50	44.8	139.4	75.6
1998	Sep	34.8	43	12.2	50	34.8	12.2	55
1998	Oct	23.1	21	0.8	50	23.1	0.8	40.9
1998	Nov	16.3	4	-5.1	44.9	16.3	0	30
1998	Dec	13.3	0	-13.3	33	12	0	22.4
1999	Jan	11.1	7	-11.1	25.7	7.3	0	16.8
1999	Feb	14.2	4	-13.2	18.9	7.8	0	12.6
1999	Mar	20.8	22	-4.4	17.2	18.1	0	10.1
1999	Apr	26	27	4	21.2	26	0	8.4
1999	May	35.3	59	24.4	45.7	35.3	0	8.3
1999	Jun	39.8	148	107.7	50	39.8	103.4	37.2
1999	Jul	47.7	148	92.9	50	47.7	92.9	53

1999	Aug	42.1	146	96.6	50	42.1	96.6	65.6
1999	Sep	32.5	6	-26.8	23.2	32.5	0	44.1
1999	Oct	21.6	27	4	27.2	21.6	0	34.2
1999	Nov	15	4	-11	21.2	9.9	0	24.7
1999	Dec	11.5	0	-11.5	16.3	4.9	0	18.5
2000	Jan	11.3	0	-11.3	12.6	3.7	0	13.8
2000	Feb	10.1	9	-10.1	10.1	2.5	0	10.4
2000	Mar	16	13	-16	6.9	3.2	0	7.8
2000	Apr	24.2	23	-0.8	6.8	23.5	0	6.7
2000	May	36.6	55	22.9	29.6	36.6	0	7.1
2000	Jun	43.4	126	81	50	43.4	60.7	24.8
2000	Jul	46.5	217	168.4	50	46.5	168.4	66.8
2000	Aug	41.6	172	121.8	50	41.6	121.8	81
2000	Sep	28.4	116	81.8	50	28.4	81.8	80.6
2000	Oct	18.7	0	-18.7	31.3	18.7	0	56.1
2000	Nov	12.6	1	-12.6	23.4	7.9	0	42.1
2000	Dec	9.8	0	-9.8	18.8	4.6	0	31.5
2001	Jan	8	11	-8	15.8	3	0	23.7
2001	Feb	8.1	0	-8.1	13.2	2.6	0	17.7
2001	Mar	10.4	0	-10.4	10.5	2.8	0	13.3
2001	Apr	14	6	-14	7.5	2.9	0	10
2001	May	21.5	84	-21.5	4.3	3.2	0	7.5
2001	Jun	21.4	200	-21.4	2.5	1.8	0	5.6
2001	Jul	43.7	243	292.8	50	43.7	245.3	77.7
2001	Aug	43.7	111	130.4	50	43.7	130.4	87.3
2001	Sep	34.4	90	95.8	50	34.4	95.8	89.8
2001	Oct	25.2	180	174.8	50	25.2	174.8	116.6
2001	Nov	17.6	0	-1	49	17.6	0	80.7
2001	Dec	14.5	1	-9.4	39.8	14.3	0	60.6
2002	Jan	12	9	-12	30.3	9.5	0	45.4
2002	Feb	13.5	5	-13.5	22.1	8.2	0	34.1
2002	Mar	19.9	3	-10.8	17.3	13.9	0	25.6
2002	Apr	26.6	70	54.2	50	26.6	21.5	28
2002	May	39.5	46	13.5	50	39.5	13.5	24.1
2002	Jun	48.8	85	38	50	48.8	38	30.1
2002	Jul	54.7	155	96.5	50	54.7	96.5	51.3
2002	Aug	47.7	239	186.7	50	47.7	186.7	91.3
2002	Sep	35.7	134	91.6	50	35.7	91.6	89.1
2002	Oct	25.4	36	8.8	50	25.4	8.8	65.8
2002	Nov	16.7	17	-0.3	49.7	16.7	0	48.6
2002	Dec	14.7	0	-14.7	35.1	14.6	0	36
2003	Jan	14.7	14	-10	28.1	11.7	0	27.2
2003	Feb	12.4	38	-12.4	21.1	7	0	20.2
2003	Mar	19.2	40	2.4	23.5	19.2	0	15.9
2003	Apr	27.8	46	38.6	50	27.8	12.1	16.7

2003	May	35.1	39	16.7	50	35.1	16.7	16.9
2003	Jun	43.1	92	53.9	50	43.1	53.9	29.3
2003	Jul	46.8	113	66.8	50	46.8	66.8	40.9
2003	Aug	39.8	146	102.9	50	39.8	102.9	59.4
2003	Sep	33.1	109	78	50	33.1	78	64
2003	Oct	23.1	14	-9.8	40.2	23.1	0	44.6
2003	Nov	15.1	0	-15.1	28.1	12.1	0	33
2003	Dec	11.4	5	-11.4	21.7	6.4	0	24.7
2004	Jan	10.7	14	-10.7	17	4.6	0	18.5
2004	Feb	11.5	38	-11.5	13.1	3.9	0	13.9
2004	Mar	19.1	40	2.5	15.6	19.1	0	11.1
2004	Apr	24.1	46	29.5	45.1	24.1	0	9.5
2004	May	32.2	39	27.8	50	32.2	22.9	13.5
2004	Jun	40	92	62.3	50	40	62.3	28.9
2004	Jul	45.1	113	71.9	50	45.1	71.9	41.8
2004	Aug	40.8	146	104.2	50	40.8	104.2	60.5
2004	Sep	32.5	109	75.1	50	32.5	75.1	64.1
2004	Oct	22.7	14	-1.8	48.2	22.7	0	44.7
2004	Nov	16.1	0	-16.1	32.7	15.5	0	33
2004	Dec	17.3	0	-17.3	21.4	11.3	0	24.8
2005	Jan	14.1	20	-10.6	16.9	8	0	18.7
2005	Feb	14.1	17	-11.3	13	6.5	0	14
2005	Mar	20.2	14	-7	11.2	15	0	10.8
2005	Apr	27.6	39	20.3	31.5	27.6	0	9.8
2005	May	30	0	-23.1	16.9	21.5	0	5.9
2005	Jun	37.6	30	-4.5	15.4	34.6	0	5.9
2005	Jul	43.7	238	191	50	43.7	156.4	54.3
2005	Aug	27.5	284	224.3	50	27.5	224.3	100.7
2005	Sep	21.7	64	29.1	50	21.7	29.1	75.4
2005	Oct	14.4	32	-14.4	35.6	14.4	0	54.9
2005	Nov	10.8	0	-10.8	28	7.7	0	41.2
2005	Dec	9.2	5	-9.2	22.8	5.1	0	30.9
2006	Jan	10.3	0	-10.3	18.2	4.7	0	23.2
2006	Feb	11.3	0	-11.3	14	4.1	0	17.4
2006	Mar	16.1	17	-16.1	9.5	4.5	0	13
2006	Apr	21.4	54	10.3	19.8	21.4	0	10.7
2006	May	30	43	46.6	50	30	16.4	13.5
2006	Jun	37.6	82	64.8	50	37.6	64.8	28.9
2006	Jul	43.7	219	180.3	50	43.7	180.3	74.6
2006	Aug	38.4	164	127.8	50	38.4	127.8	87.9
2006	Sep	28.9	78	51.9	50	28.9	51.9	76.6
2006	Oct	19.6	7	-11.3	38.7	19.6	0	54.8
2006	Nov	14.3	1	-13.2	28.4	11.3	0	40.9
2006	Dec	14.1	11	-9.6	23	9.9	0	30.8
2007	Jan	12.3	0	-12.3	17.3	5.7	0	23

2007	Feb	10.8	29	-10.8	13.6	3.7	0	17.3
2007	Mar	17.2	8	-17.2	8.9	4.7	0	12.9
2007	Apr	24.2	33	15.2	24.1	24.2	0	10.9
2007	May	32.4	0	-16.1	16.4	24.1	0	7.3
2007	Jun	39.3	69	36.9	50	39.3	3.3	9.7
2007	Jul	44	375	319.1	50	44	319.1	103.2
2007	Aug	39.6	164	120.7	50	39.6	120.7	101.7
2007	Sep	30.9	198	165.5	50	30.9	165.5	121.4
2007	Oct	22.3	9	-13.8	36.2	22.3	0	84.1
2007	Nov	14.4	7	-7.5	30.8	12.4	0	62.8
2007	Dec	12.6	2	-12.6	23.1	7.8	0	47.1
2008	Jan	9.7	13	-9.7	18.6	4.5	0	35.3
2008	Feb	8.7	0	-8.7	15.3	3.2	0	26.5
2008	Mar	15.3	10	-15.3	10.7	4.7	0	19.8
2008	Apr	19.9	37	-14.3	7.6	8.6	0	15.1
2008	May	27.4	22	1.9	9.5	27.4	0	11.9
2008	Jun	36	104	79.7	50	36	39.2	23.4
2008	Jul	39.4	150	114.1	50	39.4	114.1	49.7
2008	Aug	37	156	118.4	50	37	118.4	69
2008	Sep	26.5	137	108.3	50	26.5	108.3	79.8
2008	Oct	19.1	6	-13.2	36.8	19.1	0	54.9
2008	Nov	15.4	0	-6.9	31.7	13.6	0	41.1
2008	Dec	12.9	0	-12.9	23.5	8.2	0	30.8