Impacts of Climate Change on Water Resources of Nepal

The Physical and Socioeconomic Dimensions

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Acronyms and Abbreviations

AD	of the Christian era (from the Latin *anno domini*)
AET	actual evapotranspiration
BP	before present
CBS	Central Bureau of Statistics, Nepal
CO_2	carbon dioxide
DHMN	Department of Hydrology and Meteorology, Nepal
DIO	Department of Irrigation, Nepal
e.g.	for example (from the Latin *exempli gratia*)
ELA	equilibrium line altitude
et al.	and others (from the Latin *et alii*)
etc.	and so forth (from the Latin *et cetera*)
FAO	Food and Agriculture Organization
GCM	general circulation model
GDP	gross domestic product
GLOF	Glacier Lake Outburst Flood
GW	gigawatt
i.e.	that is (from the Latin *id est*)
ibid	in the same book as previously mentioned (from the Latin *ibidem*)
ICIMOD	International Centre for Integrated Mountain Development
IIASA	International Institute for Applied Systems Analysis
IPCC	Intergovernmental Panel on Climate Change
ISRSC	Informal Sector Research and Study Center
km	kilometre
km^2	square kilometre
km^3	cubic kilometre
kPa	kilo Pascal
kPa $^{o}C^{-1}$	kilo Pascal per degree centigrade
lpcd	litre per capita per day
LRMP	land resources mapping project
m	metre
m w.e.	metre of water equivalent
m^2	square metre

m^2/yr	square metre per year
m^3	cubic metre
masl	metre above sea level
MJ	mega joule
mld	million litres per day
mm	millimetre
mm day^{-1}	millimetre per day
MOF	Ministry of Finance
MOPE	Ministry of Population and Environment
ms^{-1}	metre per second
MW	megawatt
NDIN	National Development Institute Nepal
NEA	Nepal Electricity Authority
ºC	degree centigrade
P	precipitation
PET	potential evapotranspiration
s	second
T	temperature
UK	United Kingdom
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
US	United States
WECS	Water and Energy Commission Secretariat
WGMS	world glacier monitoring services
WMO	World Meteorological Organization
yr	year

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Abstract

The analysis of 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. For example, annual temperatures at the Rampur station at an altitude of 286 m were increasing at a rate of 0.04°C yr^{-1} while those at Kathmandu (1136 m), Daman (2314 m) and Langtang (3920 m) were increasing by 0.05, 0.07 and 0.27 ºC yr^{-1} respectively. Though no definite trends could be found in the annual precipitation records, clear decreasing trends could be seen in the annual number of rainy days during the study period of 1971-2000.

The physical and socio-economic impacts of climate change with reference to water resources were also assessed. Sensitivity analyses of river runoff, total water availability, glacier extent and evapotranspiration to a temperature rise were also carried out. The analysis has revealed that the glaciers in the Nepal Himalayas are shrinking rapidly and that there will be no glaciers left by 2180, if the current glacier melting rate continues. Most of the small glaciers will disappear within 3-4 decades. There will be only 11% of the present glacier-ice reserve in the Nepal Himalayas left by 2100, even if the present temperatures do not rise. Previous research and present findings have shown a clear warming trend in the Nepal Himalayas, which will cause an accelerated glacier melt. The accelerated glacier melt will increase the water availability at the beginning but ultimately will reduce it after the glaciers disappear. For example, at a warming rate of 0.06°C yr^{-1}, Nepal's total water availability may increase up to 178.4 km^3yr^{-1} in 2030 from the present 176.1 km^3yr^{-1} and then will drop down to 128.4 km^3yr^{-1} in 2100. Warming would increase the water requirement on the one hand and decrease the water supply on the other. This will widen the gap between water supply and demand. Changing climate may further exacerbate the water stress, which is already evident in Nepal due to the monsoon-dominated climate. Almost every year in Nepal, there is a usual problem floods and landslides during the rainy seasons because of too much water, whereas there is a common problem of droughts during the dry seasons because of too little water. Climate change would further increase this seasonal imbalance of water in Nepal.

Similarly, there will be substantial socioeconomic implications of reduced water availability. The hydropower potential and agricultural production of Nepal would be seriously affected. A reduction in agricultural production would have significant impact on the food security and

livelihoods of the subsistence farmers, who make up the majority of the Nepal's population. Nepal's current income and food distribution is very uneven. For example, the poorest 20% of the population of Nepal currently consume 6.2% of the total available food, while the richest 20% consume 53.3% of the total food. Currently, per capita daily calorie consumption of the poorest 20% of the population is less than 40% of the minimum calorie requirement for carrying out normal physical activities. Any further reduction in agricultural production may have substantial negative impacts on the food security for these poorest people.

Chapter I: Problem Statement and Objectives of the Study

1.1 Background of the Study and Problem Statement

Increasing numbers of scientific communities observing the global climate show a collective picture of a changing climate and a warming world. The global average surface temperature has increased by about 0.6ºC during the twentieth century (IPCC, 2001a, p 152). Many analyses show that the temperature increase in the twentieth century has been greater than in any other century during the past 1000 years (ibid). The 1990s was the warmest decade of the millennium and 1998 was the warmest year on record (IPCC, 2001a, p.173). Natural and human systems are expected to be exposed to direct effects of climatic variations such as changes in temperature and precipitation variability, as well as frequency and magnitude of extreme weather events. Similarly, there are indirect effects of climate change such as sea-level rise, soil moisture changes, changes in land and water conditions, changes in the frequency of fire and changes in the distribution of vector-borne diseases (ibid, p.245).

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 (Critchfield, 2002, p.249). 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. Glaciers are very sensitive to climate changes; therefore, they can be considered as good indicators of past climate changes (Nesje and Dahl, 2000, p.7). Widespread retreat of the world's glaciers was observed during the 20^{th} century. The snow covered area of the world has decreased by 10% since the 1960s (IPCC, 2001a, p.46). The global mean sea level has increased at a rate of 1 to 2 mm/year during the 20^{th} century due to thermal expansion of sea water and the melting of glaciers and ice sheets (ibid). For example, a local warming of 3ºC, if sustained for thousands of years, would lead to a virtually complete melting of the Greenland ice sheet with a resulting sea-level rise of about 7 m (IPCC, 2001a, p.84). Such a projected sea-level rise may threaten the existence of coastal zones and their ecosystems.

Decreasing snow cover and the melting of glaciers as a result of warming provide positive feedback to warming due to decreased surface albedo and increased absorption of solar energy (Meehl, 1994, p.1033). The estimated quantity of the earth's total water is about 1.4 x

10^9 km^3, but only about 2.5% is fresh water. About 97% of the world's water is contained in the oceans. It is salty and not suitable for direct consumption (Singh and Singh, 2001, p.5). Out of the available fresh water, about 77% ($30x10^6$ km^3) is frozen in the polar ice caps and in the glaciers of the world and the remainder is contained in the lakes, reservoirs, rivers, atmosphere and in the aquifers under the ground (ibid, p.9). Therefore, the melting of ice-sheets and glaciers due to warming is a threat to the limited freshwater reserves of the earth.

Climate change will result in more intense precipitation events causing increased flood, landslide, avalanche and mudslide damages that will cause increased risks to human lives and properties (IPCC, 2001a, p.226). Besides, intensified droughts are expected due to climate change that may result in decreased agricultural productivity (ibid). Likewise, warmer temperatures increase the water-holding capacity of the air and thus increase the potential evapotranspiration, reduce soil moisture and decrease ground water reserves (IPCC, 2001b, p.199), which ultimately affects the river flows and water availability.

The sensitivity of a hydrologic system to climate change is a function of several physical features and societal characteristics. Some of the physical features most sensitive to climate change are agriculture and livestock, regions with seasonal precipitation or snowmelt and topography and land-use patterns that promote soil erosion and flash floods (IPCC, 2001b, p.212). Similarly, the societal characteristics most susceptible to climate change are poverty and low income levels, lack of water control structures, lack of human capital skills for system planning and management, lack of empowered institutions, high population densities, increasing demand for water because of rapid population growth and lack of formal links among the various parties involved in water management (ibid, p.213).

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, p. 287). 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, p.37). Increases in temperature result in a reduced growing season and a decline in productivity, particularly in South Asia (Pachauri, 1992, p.82). 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 hydro power generation, inland water transport and aquatic ecosystem. Similarly, reduced water availability may create conflicts between water users within and among nations (ibid, p.85).

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 fulfil 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. 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., 2001a, p.121). 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, p.563). 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, p.28).

Nepal has about 83 GW of hydropower potential, but only about 1% of that has been developed so far (MOF, 2005, p.212). About 91% of the total electricity in Nepal comes from hydropower plants and only about 9% from thermal plants (NEA, 2003a, p.43; Agrawala et al., 2003, p.12). Therefore, hydropower is one of the most important tools for the present and future economic development of Nepal. 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 kilometres downstream (Agrawala et al., 2003, p.29). 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 (ibid).

The majority of Nepal's present population depends on agriculture for their subsistence but still about 63% of the agricultural lands are deprived of modern irrigation facilities (FAO, 2004a, p.1). All the crop water requirements of the non-irrigated lands are met solely by rainfall. The increased precipitation variability may create difficulties in cultivating these lands and could result in probable food scarcity for the population. Moreover, the agricultural land currently having irrigation facilities may not have sufficient water during dry seasons in the future due to climate change. That may result in water stress in the agricultural sector of Nepal. Currently, 93% of Nepal's labour force work in the agricultural sector (FAO, 2004a, p.1), which provides about 39% of the gross domestic product (MOF, 2005, p.1). However, agriculture is largely at subsistence level. In the rural hills and mountain areas of Nepal, where as much as 70% of the population is poor, local food production sometimes covers just three months of the annual households needs (FAO, 2004c, p.7). Changing climatic conditions causing soil moisture reduction, thermal and water stress, flood and drought etc are putting the whole agricultural sector at serious risk (AfDB et al., 2002, p.7). In some cases, due to rugged topography and lack of roads, people cannot access food even when they could afford to buy it (ibid). Currently, about 31% of Nepal's total population is below the poverty line and 95% of them live in rural areas (MOF, 2005, p.154). The poor people are more vulnerable to climatic extremes as well as gradual changes in climate than the rich because they have less protection, less reserves, fewer alternatives and a lower adaptive capacity and because they are more reliant on primary production (IPCC, 2001b, p.939; AfDB et al., 2003, p.9).

Climate change may alter rainfall and snowfall patterns. The incidence of extreme weather events such as droughts, storms, floods and avalanches is expected to increase. This can lead to loss of lives and severely reduce agricultural production (IPCC, 1998, p.397). Traditional wisdom and knowledge to cope with such natural hazards that once ensured food security may no longer prove effective (Jenny and Egal, 2002, p.12). Climate-induced natural hazards have very serious human implications because they affect the livelihood security of the majority of the population (Swaminathan, 2002, p.210). About 29% of the total annual deaths of people and 43% of the total loss of properties from all different disasters in Nepal are caused by water-induced disasters like floods, landslides and avalanches (Khanal, 2005, p.181).

Climate change increases the vulnerability of poor people, affects their health and livelihoods and undermines growth opportunities crucial for poverty reduction (AfDB et al., 2003, p.7). Extreme events due to man-made climate change would cause forced migration and human resettlement resulting in the damage of the social cohesion including the loss of human lives and physical properties. Due to limited knowledge of regional and local impacts of climate change, there are substantial uncertainties on quantifying the global impacts of climate change (IPCC, 1996a, p.218). Research efforts in these areas are "priorities for advancing understanding of potential consequences of climate change for human society and the natural world, as well as to support analyses of possible responses" (IPCC, 2001b, p.73).

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 of the plains far downstream. As in other heavily impacted developing countries, there have been very few scientific studies carried out in Nepal to determine the level of possible impacts of climate change on society and economy with reference to water resources. The IPCC has flagged this as a major area for necessary future research (IPCC, 2001b, p.73). It is crucial to understand the changing patterns of hydrological phenomena and their possible impacts on environmental, economic and social aspects. As hydropower could serve as a very important economic vehicle for Nepal's development, it is important to study the impacts of climate change on water resources of Nepal.

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

1.2 Objectives

The main objective of the study is to identify the impacts of climate change on the development paradigm of Nepal in relation to water resources. The vision behind this study is to contribute to the future development of Nepal regarding poverty alleviation, social equity, security and welfare. The specific objectives of the study are:

- To determine the change parameters of climate through the analysis of hydrological and meteorological information of Nepal
- To determine the physical impacts of climate change in relation to water resources through the analysis of water availability, water demand and the supply situation
- To analyze the socio-economic impacts of climate changes through the analysis of impacts on agriculture, food security, hydropower and irrigation sectors

- To analyse the impacts of climate change on the water-induced extreme events such as flooding, landslides, drought etc.

1.3 Organisation of the Report

Chapter I covers the introductory and background information including significance of the study and its objectives. Chapter II deals with the state-of-the-art review and explores the open questions regarding research topics. At the end of chapter II, a set of hypotheses is developed in order to test whether the formulated objectives have been achieved. Chapter III describes the research methodology in order to be able to answer the research questions and to test the hypotheses as well as the limitation of the study. Chapter IV explains the empirical findings on climate change, viz. temperature and precipitation changes. Chapter V deals with the empirical findings on physical impacts of climate change with reference to water resources e.g. sensitivity of river flows, glacier mass balance, total water availability, etc. Likewise, chapter VI covers empirical findings on the socio-economic impacts of climate change including hydropower potential, food security, poverty, extreme events etc. Finally, Chapter VII deals with conclusions and recommendations of the current research as well as propositions for future research.

Chapter II: State-of-the-Art Review and Development of Hypotheses

2.0 General

Weather and climate have a very important influence on life on the earth. They are part of the daily experience of human beings and are essential for food, health and well-being (IPCC, 2001c, p.87). Weather is the fluctuating state of the atmosphere, characterised by the temperature, precipitation, wind, solar radiation, clouds, air pressure and humidity (IPCC, 2001c, p.87; Oliver and Hidore, 2003, p.7). Climate is defined as average statistics of meteorological conditions (Graedel and Crutzen, 1993, p.5). It refers to the average weather in terms of the mean and its variability over a period of time ranging from months to thousands or millions of years. The classical period used as modern measures of climate is 30 years (IPCC, 2001c, p.788). Climate on the earth varies in space and time because of natural as well as anthropogenic forcing factors (IPCC, 2001c, p.89). Any change in the forcing factors and their interactions may result in climate variations leading to possible impacts on life on the earth (ibid). This chapter aims to briefly summarise the information on the state-of-the-art review on climate change and its impacts on the world and on Nepal. Based on the available information, the knowledge gaps in this field in case of Nepal Himalayas are pointed out. At the end of this chapter, some working hypotheses for the current study have also been developed.

2.1 Global Climate Change

The climate system consists of five major components: the atmosphere, the hydrosphere, the cryosphere, the land surface and the biosphere (IPCC, 2001c, p.88). The atmosphere is the most unstable and rapidly changing part of the system. Climate has changed considerably throughout the history of the earth due to change in its forcing components, whether natural or anthropogenic. But the rate of global climate change during the 20th century was greater than before (IPCC, 2001a, p.45). For example, average global temperature increased by approximately 0.6±0.2^{0}C during the 20th century, which was greater than in any other century in the last 1,000 years (IPCC, 2001a, p.45). The warming rate became even more pronounced during the second half of the last century, which was predominantly due to the increase in anthropogenic greenhouse gas concentrations in the atmosphere (IPCC, 2001a, p. 51; Graedel and Crutzen, 1993, p. 5)

2.1.1 Global Temperature Change

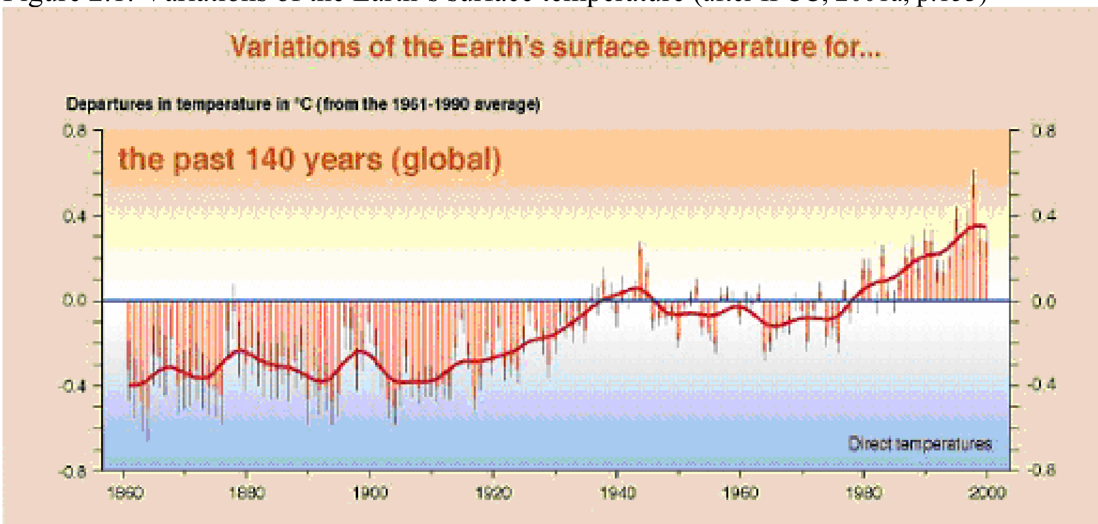
Measured temperature records of the earth have only been available since 1861 (IPCC, 2001c, p.113). The earth's temperature before the instrumental period has been reconstructed using different indirect tools and methods like tree rings, corals, ice sheets, ice cores, borehole measurements, glaciers, ancient sediments and sea level changes etc (IPCC, 2001c, p.130; Oliver and Hidore, 2003, p.261). The long term temperature record derived from paleoclimatic record shows clear evidence of fluctuations in temperature resulting in glaciation and deglaciation periods in the history of the earth since its formation some 4 billion years ago (WMO, 1991, p.72; Graedel and Crutzen,1993, p.209).

Reconstructed temperature records of the Earth during its entire history of development showed that there was a cooling trend up to 150,000 years before the present (yr BP) and a rapid warming trend thereafter till 120,000 yr BP (Graedel and Crutzen, 1993, p.209; Oliver and Hidore, 2003, p.267). Again, there was a cooling trend from 120,000 yr BP to 18,000 yr BP. The period from 18,000 to 5,500 yr BP corresponds to the deglaciation of the earth, i.e. a warming period (Oliver and Hidore, 2003, p. 275). The warming peaked about 5,500 yr BP when the mean atmospheric temperature of mid-latitudes of the northern hemisphere was about 2.5°C above that of the present (ibid, p.276). Then, there was a cooling trend up to some 2500 yr BP and again warming after that (WMO, 1991, p.73).

The warming trend continued up to about 1200 AD, when the average temperature was higher than today (Oliver and Hidore, 2003, p. 276). Then, there was a cooling trend up to about 1800 AD. During the time from 1450 AD to 1880 AD, which is also known as the Little Ice Age, glaciers enlarged to their maximum extent in the present era, "very cold winters led to the freezing of rivers and lakes that are seldom deeply frozen today, the ice was so thick that ice fairs were held on the frozen water" (ibid, p. 277).

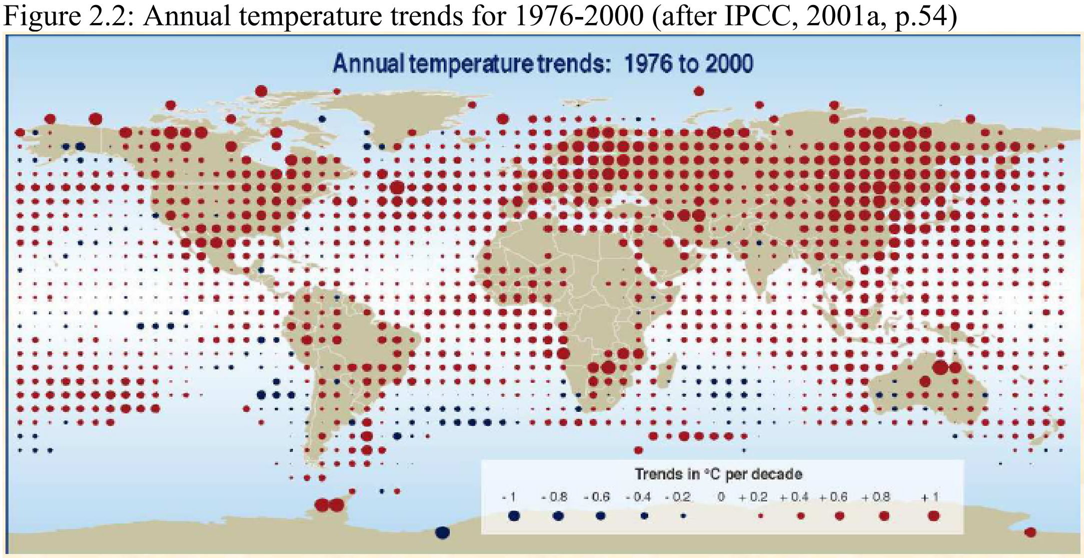
The observed temperature record from 1861 to 2000 shows that the earth's temperature is increasing (see Figure 2.1) and most of the warming occurred during the second half of the twentieth century (IPCC, 2001a, p.152). The equivalent linear rate of global temperature trend for the period of 1861 to 2000 was 0.044°C/decade, but that for the period of 1901 to 2000 was 0.058°C/decade (ibid, p.115). The warming rate over the period 1976-2000 was nearly twice that of the years 1910-1945.

Figure 2.1: Variations of the Earth's surface temperature (after IPCC, 2001a, p.153)



The 1990s was the warmest decade and 1998 was the warmest year in the instrumental record since 1861 (IPCC, 2001a, p.152). Available daily maximum and minimum temperature data indicate that the minimum temperature has increased at nearly twice the rate of maximum temperature since 1950s (IPCC, 2001c, p.106).

Figure 2.2: Annual temperature trends for 1976-2000 (after IPCC, 2001a, p.54)

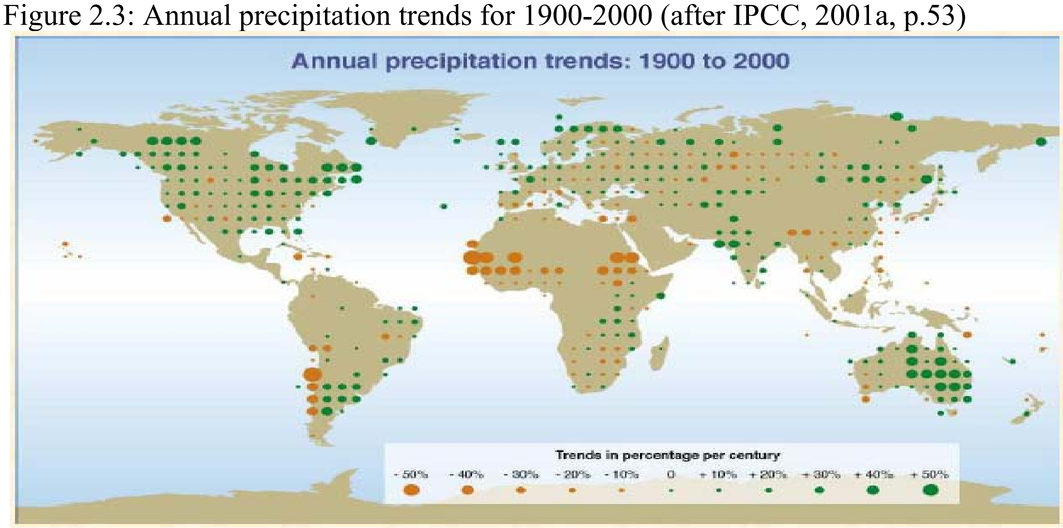


The rate of temperature change is not uniform around the globe (see figure 2.2). The magnitude of the change varies in space and time. For example, the northern hemisphere and especially mid- and high latitude land areas show faster warming trends than others (IPCC, 2001a, p.54). Likewise, maximum temperatures have increased over most of the areas of the earth with the exception of eastern Canada, southern USA, portions of eastern and southern Europe, southern China and parts of southern South America but the minimum temperatures have increased almost everywhere (IPCC, 2001c, p.108). In India, the diurnal temperature range has increased due to a decrease in minimum temperature (ibid).

2.1.2 Change in Precipitation and Atmospheric Moisture

Temperature change causes alteration in relative humidity, vapour pressure and evaporation from land and water bodies and this relation is largely nonlinear (FAO, 1998, p.40). Increasing temperatures generally result in an increase in the water holding capacity of the atmosphere that leads to change in precipitation pattern and increase in atmospheric moisture (IPCC, 2001b, p.198). Warmer temperatures could lead to more active hydrological cycle and changes in atmospheric circulation (IPCC, 2001c, p.142). Global land precipitation has increased by 2% since the beginning of the 20th century, but largely varied in space and time (ibid). Despite the irregularity in the trends of precipitation in the last century (see Figure 2.3), the annual average precipitation in mid- and high latitudes was increasing while that in tropics and sub-tropics was decreasing (IPCC, 2001c, p.143).

Figure 2.3: Annual precipitation trends for 1900-2000 (after IPCC, 2001a, p.53)



Annual average precipitation over the 20th century increased by between 7 to 12% for the zones 30ºN to 85ºN and by about 2% between 0ºS to 55ºS (ibid, p. 142). Similarly, there were significant decreases in rainy days throughout Southeast Asia and the South Pacific and there has been a pattern of continued aridity throughout North Africa since 1961 (ibid, p. 143).

2.2 Climate Change in the Himalayan Region and Nepal

2.2.1 Climate Change in the Himalayas

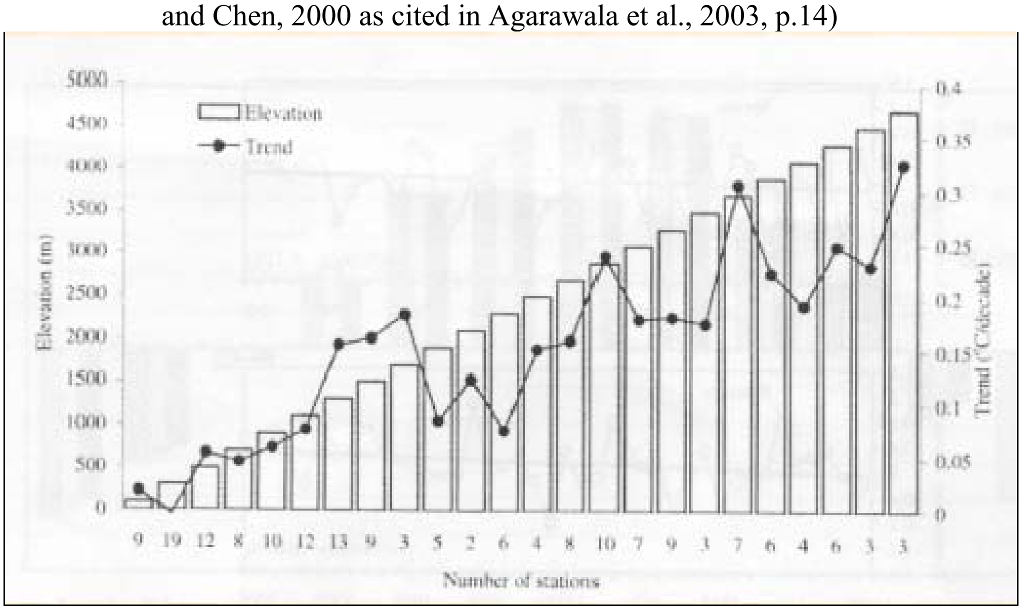
Basic patterns of the climate in the Himalayan region are governed by the summer and winter monsoon systems of Asia (Mani, 1981, p.4). The central and eastern Himalaya receives most precipitation during summer and the western Himalayan region receives most of its precipitation in winter. In the summer, the land mass of Asia gets much hotter than the sea areas to the east and south resulting in the formation of low- pressure area over land and high-pressure area over the north pacific and south Indian oceans. This pressure difference makes the moist air move from the oceanic areas towards the centre of Asia. The moist air moving towards the land areas releases part of its moisture under appropriate conditions as rain over the Indian subcontinent. This is known as summer monsoon rain. In the winter, the land area of Asia gets much colder than the adjoining seas and becomes the high-pressure area. Therefore, the air moves from land to sea in the winter (see Critchfield, 2002, p.169).

The Himalayan regions show a wide variety of climates. For every 1000 m of altitude, there is generally about a 6°C temperature drop (Mani, 1981, p.5). However, the temperature may vary from place to place. An east-facing slope has warm mornings and cool afternoons while a west-facing slope the opposite. The Himalaya itself acts as a climatic divide between the Indian subcontinent to the south and the central Asian highland to the north. A substantial part of the summer monsoon rain occurs largely because of the orographic influence of the Himalaya on the monsoon winds (ibid, p.8). The snow and ice over the Himalaya play an important role on the radiation balance of the region and on the strength of Indian monsoon (Meehl, 1994, p.1033; Khandekar, 1991, p.637).

It is very difficult to identify an accurate change in the Himalayan climate because of its large size, inaccessibility and unavailability of systematic climatological data (Chalise, 1994, p.383). The data on actual measurements of the changes in microclimate in most of the areas of the Himalaya remain empty and the limited climate observations are available only at the hill-stations in the foot-hills that have to be used to build up a broader picture of the climatology of the Himalaya (Mani, 1981, p.14)

Historic and pre-historic evidences show that mountain areas undergo major changes in glacio-hydrological and ecological conditions in response to changes in climate. Global models necessarily represent the orography of mountain areas in a highly simplified manner and the outputs give a generalized nature of the results (Barry, 1990, p. 161). The evidence for changes in the climate has been mainly studied in a regional context and from a hemispheric or global perspective. The vertical spatial dimension has been largely neglected (ibid, p.164). In order to assess the possible future climatic trends and their effects, it is important to know whether these changes will be felt equally in mountain areas, or whether they will be reduced or amplified compared with the adjoining lowlands. The temperatures on the Tibetan Plateau were increasing as well, but the higher elevations were warming faster than the lower ones (Agrawala et al., 2003, p.14). For example, the temperature trend was about 0.1ºC per decade at elevations lower than 1000 m, whereas it was more than 0.3ºC per decade at elevations higher than 4000 m (see Figure 2.4).

Figure 2.4: Temperature trend as a function of elevation on the Tibetan Plateau (after Liu and Chen, 2000 as cited in Agarawala et al., 2003, p.14)



Hingane et al. (1985, p. 521) analysed the mean annual temperature data for the period of 1901-1982 from 73 stations in India and discovered a warming trend of 0.4ºC per century. An analysis carried out by Kothyari and Singh (1996, p.365) showed that average annual rainfall as well as annual number of rainy days were decreasing while average annual temperature was increasing in India for the period 1901-1989. Another similar study carried out by Nakawo et al. (1994, p.11) at the other side of the Himalaya in China found that there was a decreasing trend of precipitation for the period of 1951-1980. Hakkarinen and Landsberg (1981, p.59) found no significant positive or negative trends in the observed East Asian monsoon rainfall for the period of 1878-1978. Similarly, Rupa Kumar et al. (2002, p.33) concluded that monsoon rainfall was trendless during the last four decades and was random in nature in all-India scale over a long period of time. There have been high spatial and temporal variations in rainfall intensities and amounts in the mountain ranges in the Himalayas during the last 130 years (Rupa Kumar et al., 2002, p.48). There has been an increase in extreme rainfall events over northwest India during summer monsoons of the recent decades (IPCC, 2001b, p.543).

2.2.2 Climate Change in Nepal

Nepal has a wide variation of climates from subtropical in the south, warm and cool in the hills to cold in the mountains within a horizontal distance of less than 200 km (UNEP, 2001, p. 21; Shankar and Shrestha, 1985, p.39; Chalise, 1994, p.383). Generally, there are four seasons in Nepal: summer monsoon (June-September), post-monsoon (October-November), winter (December-February) and pre-monsoon (March-May) (Yogacharya, 1998, p.184). The climate of Nepal is dominated by monsoon and about 80% of annual precipitation occurs during the summer monsoon (UNEP, 2001, p.21). The amount of precipitation varies considerably from place to place because of the non-uniform rugged terrain (Shankar and Shrestha, 1985, p.41). However, the amount of rainfall generally declines from east to west (UNEP, 2001, p.22).

The length of the regular and systematic observations of climatological and hydrological data in Nepal is only about 50 years (Mool et al., 2001, p.16). The longest systematic temperature and precipitation data have been available for Kathmandu since 1921 recorded by the then-Indian Embassy under British rule (Shrestha et al., 1999, p.2776). The existing climatological and hydrological stations are generally located at the lower elevations. The high mountain areas with very low population density and negligible economic activities are mostly left without any hydrological and meteorological stations. So, even the available climatic data are also very sparse, poorly representing the high mountain areas. The meteorological observations in high mountain areas were only initiated in 1987 after the establishment of the Snow and Glacier Hydrology Section in the Department of Hydrology and Meteorology of Nepal (Mool et al., 2001, p.16).

2.2.2.1 Change in Temperature

The oldest temperature records available so far for Kathmandu and its surroundings were documented by Hamilton during his stay in Nepal from April 1802 to March 1803, but this information does not provide the information on site and equipment of measurement (Chalise, 1994, p.390). There is no continuous temperature record at all for the subsequent years up to 1921. The studies on analyses of the temperature records of Kathmandu for the period of 1921-1994 showed a similar temperature trend as that of 24º-40ºN of the earth, i.e. a general warming trend till 1940s, a cooling trend during 1940s-1970s and a rapid warming after the mid 1970s (Shrestha, 2001, p.93; Shrestha et al., 1999, p. 2781). Sharma et al. (2000a, p.152) indicated that the increasing trend of average temperatures during that period was primarily due to the increasing trend of maximum temperatures and there was no increasing trend of minimum temperatures. The temperature trends for 1971-1994 as analysed by Shrestha et al. (1999, p.2781) widely varied among the geographical regions and the seasons in Nepal. Low-elevation areas in the south showed a slower warming rate than the high mountain areas in the north. Average annual temperatures in the Terai regions in the south increased by about 0.04ºC/yr, whereas those in the middle mountain areas in the north increased by about 0.08ºC/yr (ibid). Similarly, the pre-monsoon season (March-May) showed the lowest warming rate of 0.03ºC/yr, while the post-monsoon season (October-November) showed the highest one of 0.08ºC/yr (Shrestha, 2001, p.92).

2.2.2.2 Change in Precipitation

Shrestha et al. (2000, p.317) reported that there was no distinct long-term trend in the precipitation records in Nepal during 1948-1994, though there was significant variation on annual and decadal time scales. The same study revealed that there was a strong relationship between all-Nepal monsoon precipitation and the El-Nino- Southern Oscillation (ibid, p.325). However, Sharma et al. (2001a, p.157) found an increasing trend in observed precipitation data from Koshi Basin in eastern Nepal but the trend widely varied in seasons and in sites. The precipitation fluctuation in Nepal is not the same as the all-India precipitation trend; but it is well related with rainfall variations over northern India (Shrestha et al, 2000, p.324; Kripalani et al., 1996, p.689). Similarly, there was no significant trend in the observations of the rainfall in Monsoon Asia during the last century and the monsoon had a significant connection with the El-Nino- Southern Oscillation (Hakkarinenm et al., 1981, p.v). Another study based on the precipitation records from 80 stations for the period 1981-1998 across Nepal revealed that the hills and mountains in the north showed positive trends while the plains in the south were experiencing negative trends (MOPE, 2004, p.72).

2.3 Physical Impacts of Climate Change

2.3.1 Impacts on Water Resources and Hydrology- a Global Perspective

Water is fundamental to human life and many other social, economic and industrial activities. It is required for agriculture, industry, ecosystems, energy, transportation, recreation and waste disposal (Frederick and Gleick, 1999, p.1). Therefore, any changes in hydrological system and water resources could have a direct effect on the society, environment and economy. There are very complex relations between climate, hydrology and water resources. Climatic processes influence the hydrologic processes, vegetation, soils and water demands (Kaczmarek et al., 1996, p.5). Water resources are influenced by various social, technical, environmental and economic factors. Climate change is just one of many pressures that hydrological systems and water resources are facing (IPCC, 2001b, p.195).

Water on the earth exists in a space called hydrosphere at the crust of the earth, which extends about 15 km up into the atmosphere and about 1 km down into the lithosphere. The process of water circulation in the hydrosphere through different paths and states is called hydrological cycle (Chow et al., 1988, p.2). The hydrological process has no end or beginning and its processes occur continuously. Water evaporates from the land surface and water bodies into the atmosphere; is transported and lifted in the atmosphere until it condenses and precipitates back on the land or water bodies (Dixit, 2002, p.6). Precipitated water may be intercepted by vegetation, may flow through the surface or subsurface, may return to the atmosphere through evaporation and/or may flow to the sea. The cycle begins again and the water remains in continuous movement because of solar energy (Chow et al., 1988, p.2). Therefore, any changes in the climatic system or the energy balance in the atmosphere may alter the water balance of the hydrological cycle.

Precipitation is the main driver of variability in the water balance over space and time. Change in precipitation could have very important implications for hydrology and water resources (IPCC, 2001b, p.197). Floods and droughts primarily occur as a result of too much or too little of precipitation. Various empirical and model studies suggest that the trends in precipitation vary in space and time over the globe, with a general increase in mid- and high latitudes in the northern hemisphere and a general decrease in the tropics and subtropics in both hemispheres. Increasing temperatures mean decreasing proportions of precipitation as snowfall. Snow may cease to occur in areas where snowfall currently is marginal. This would have substantial implications for hydrological regimes (ibid).

Warmer temperature increases the water holding capacity of the atmosphere (Cline, 1992, p.21, IPCC, 2001b, p.198); which generally results in an increased potential evaporation, i.e. evaporative demands. However, the actual rate of evaporation is constrained by water availability. The amount of water stored in the soil influences directly the rate of actual evaporation, ground water recharge and generation of runoff (IPCC, 2001b, p.199). A reduction in soil moisture could lead to a reduction in the rate of actual evaporation from a catchment despite an increase in evaporative demands that creates moisture deficit in the soil as well as in the atmosphere (Cohen et al., 1996, p.42). The local effects of climate change on soil moisture will vary not only with the degree of climate change but also with soil characteristics. The lower the water holding capacity of the soil, the greater is the sensitivity to climate change (IPCC, 2001b, p.199).

Changes in precipitation and evaporation have a direct effect on the ground water recharge. More intense precipitation and longer drought periods, which are considered to be expected impacts of climate changes for most of the land areas of the world (IPCC, 2001a, p.246), could cause reduced ground water recharge. Ground water is the major source of water across much of the world. Less ground water recharge means reduction in water availability in these areas (IPCC, 2001b, p.199).

Changes in river flows from year to year have been found to be much more strongly related to precipitation changes than to temperature changes (IPCC, 2001b, p.200). The patterns of changes in river flow are broadly similar to the change in annual precipitation, i.e. increases in high latitudes and many equatorial regions, but decreases in mid-latitudes and some subtropical regions (ibid, p. 203). Generally, increase in evaporation means that some areas may experience reduction in runoff despite some increases in precipitation. The real impacts of climate changes vary with catchment characteristics. For example, the streams with smaller catchments are generally more sensitive to these changes (IPCC, 2001b, p.203). Under climate change, many river systems show changes in the timing and magnitude of seasonal peak and low flows. For example, peaks tend to occur earlier due to earlier snowmelt in cold climate zones (Cohen et al., 1996, p.30). Although there is widespread consensus that climate changes cause substantial impacts on hydrology and water resources, the magnitude and direction of these impacts vary in space and time (ibid, p.42).

Over 97% of the world's water is contained in the oceans. It is salty and not suitable for drinking (Singh and Singh, 2001, p.5). Out of the available fresh water on the earth, about 77% is stored as glaciers and ice caps (ibid, p.9), which are very sensitive to climate change. The warmer temperatures would cause widespread melting of glaciers and many small glaciers may disappear (IPCC, 2001b, p.193). Many rivers maintaining flows through the summer season are supported by glaciers. Snow and glaciers supply at least one-third of the water used for irrigation in the world (Singh and Singh, 2001, p.20). Higher temperatures will increase the ratio of rain to snow; accelerate the rate of snow- and glacier-melt; and shorten the overall snowfall season (Frederick and Gleick, 1999, p.9). Since the end of the Little Ice Age, the temperatures have been generally increasing (Oliver and Hidore, 2003, p. 277) and the majority of the world's glaciers are retreating (IPCC 2001b, p.208). Orlemans and Hoogendorn (1989, p.399) have reported that 1 K temperature change leads to a change of equilibrium-line altitude (i.e. the altitude where the accumulation of a glacier equals to its ablation) of 130 m in the Alps. Increasing temperature shifts the permanent snowline upward. This could cause a significant reduction of water storage in the mountains, which is likely to pose serious problems of water availability to many people living in the hills and downstream (Kulkarni et al., 2004, p.185).

2.3.2 Impacts of Climate Change on Water Resources – the Himalayan Perspective

2.3.2.1 Snow and Glacier

Changes in the snowfall pattern have been observed in the Himalayas in the past decades (IPCC, 2001b, p.553). Almost 67% of the glaciers in the Himalayas have retreated in the past decade (IPCC, 2001b, p.553). The Gangotri glacier in the western Himalayas has been retreating by about 30 m yr^{-1} (ibid, p.554). The Pindari glacier in Uttar Pradesh of India retreated by 2,840 m during 1845-1966 with an average retreat rate of 135.2 m yr^{-1} (Shrestha, 2005, p.77). Snow and glacier melt forms an important part of annual runoff of many Himalayan rivers. For example, the snow and glacier contribution into annual flows of major rivers in the eastern Himalayas is about 10% but more than 60% in the western Himalayas (IPCC, 2001b, p.565). Streamflow in most of the Himalayan Rivers is minimal in winter and early springs because flows decrease rapidly after the monsoon rains (Kattelmann, 1993, p.103). Dry season runoff of these rivers is largely comprised of snow and glacier melts, which is the main source of water for irrigation, hydroelectric power and drinking water supply for the population downstream (Singh and Singh, 2001, p.21). Increasing temperature would lead to reduction in snow and glacier volume and thereby reduction in water availability in the Himalayas. In addition, reduction in Himalayan snow cover would lead to heavier monsoon in the Indian sub-continent (Khandekar, 1991, p.644; Meehl, 1994, p.1047) that would increase the likelihood of floods.

Currently, about 10% of total precipitation in Nepal falls as snow (UNEP, 2001, p.129). About 23% of Nepal's total areas lie above the permanent snowline of 5000 m (MOPE, 2004, p.95). Presently, about 3.6% of Nepal's total areas are covered by glaciers (Mool et al.2001b, p.77). There are 2323 glacier lakes in the Nepal Himalayas, which have been developed at glacier termini during the process of glacier retreat (Mool et al., 2001a, p.188). One of the widely studied glacier AX010 in the eastern Nepal Himalayas retreated by 160 m in 1978-1999 and has shrunk by 26% in 21 years, from 0.57 km^2 in 1978 to 0.42 km^2 in 1999 (Fujuta et al., 2001a, p.52). Similarly, the Rikha Sambha glacier in the western Nepal Himalayas retreated by 300 m during 1974-1999 (Fujuta et al., 2001b, p. 32). Moreover, the rate of glacier retreat was found to be increasing in recent years. For example, the glacier AX010 retreated by 30 m yr^{-1} in 1978-1989, whereas it retreated by 51 m yr^{-1} in 1998-1999 (Fujuta et al., 2001a, p.52). All of the observed glaciers in the Himalayas have been retreating during recent decades (Ageta et al., 2001, p.45) at a higher rate than any other mountain glaciers in the world (Nakawo et al., 1997, p.54).

Increasing temperatures reduce the proportion of snow to rain that causes the reduction in the glacier accumulation and a decrease in the surface albedo, which result in an increased glacier ablation (Ageta et al., 2001, p.45). Therefore, reduced snowfall simultaneously decreases accumulation and increases ablation, which ultimately results in accelerated glacier retreat. Melting of snow and glacier amplifies the warming effect by providing additional feedback (Meehl, 1994, p.1034) that may result in a rapid retreat of glaciers, creation of many new glacier lakes and expansion of existing glacier lakes. Glacier lakes are developed in the space once occupied by their mother glaciers and are generally supported by loose moraine dams (Mool et al., 2001a, p.121). Many glacier lakes have been formed during the second half of the last century in the Himalayas (Yamada, 1998, p.1). The supporting moraine dam can collapse due to the increased hydrostatic pressure of greater water depths in the glacier lakes. This may cause an immediate release of a large volume of the lake water and a devastating flood known as glacier lake outburst flood (Yamada, 1998, p.1; IPCC, 1998, p.400).

2.3.2.2 River Discharge

The Himalayan rivers are expected to be very vulnerable to climate change because snow and glacier meltwater make a substantial contribution to their runoff (Singh, 1998, p.105). However, the degree of sensitivity may vary among the river systems. The magnitudes of snowmelt floods are determined by the volume of snow, the rate at which the snow melts and the amount of rain that falls during the melt period (IPCC, 1996b, p.337). Because the peak melting season in the Himalayas coincides with the summer monsoon season, any intensification of monsoon or accelerated melting would contribute to increased summer runoff that ultimately would result in increased flood disasters (IPCC, 2001b, p.565). The increase in temperature would shift the snowline upward, which reduces the capacity of natural reservoir. This situation would increase the risk of flood in the Himalayan region (ibid).

The annual runoff of the Alkananda River in the western Himalayas increased by 2.8% yr^{-1} for 1980-2000, whereas that of Kali Gandaki River in Nepal Himalayas increased by about 1% annually for 1964-2000 (Shrestha, 2005, p.75). A runoff sensitivity analysis by Mirza and Dixit (1997, p.78) showed that a 2ºC rise in temperature would cause a 4% decrease in runoff, while a 5ºC rise in temperature and 10% decrease in precipitation would cause a 41% decrease in the runoff of the Ganges River near New Delhi. Glacier retreat has immediate implications for downstream flows in the Himalayan Rivers. In rivers fed by glaciers, the runoff first increases as more water is released by melting due to warming. As the snow and glacier volume gets smaller and the volume of meltwater reduces, dry season flows will decline to well below present levels (Shrestha, 2005, p.77). About 70% of the dry season flow of the Ganges River is supplied by the catchments in the Nepal Himalayas (IPCC, 1998, p.395), which will be badly affected by the recession of glaciers.

River discharge is influenced by climate, land cover and human activities (Sharma et al., 2000a, p157), so it is difficult to disaggregate the climatic impact from non-climatic impacts on river discharge. However, river discharge analysis for 1947-1994 in the Koshi Basin in eastern Nepal showed a decreasing trend particularly during the low-flow season (ibid). Sensitivity analysis of river runoff in the same basin showed that the runoff increase was higher than the precipitation increase assuming temperature constant and an increase in temperature of 4°C assuming precipitation constant would cause a decrease in runoff by two to eight percent (Sharma et al., 2000b, p.139). Gurung (1997, p.37) has revealed that there will be decrease in runoff in dry seasons and increase in runoff in monsoon season under the doubled CO_2-scenario using the Canadian Climate Centre Model (CCCM) and Geophysical Fluid Dynamics Laboratory (GFDL) models. Such a change would mean more water scarcity in dry season and more floods during monsoon (ibid). MOPE (2004, p. 97) has indicated that river discharges in Nepal are more sensitive to precipitation change than to temperature change.

2.4 The Socioeconomic Impacts

The impacts of climate change on the earth system will not be always gradual and even, rather mostly nonlinear. Substantial lags, thresholds and interactions can be anticipated even if the human-caused forcing functions themselves vary gradually and continuously (Vitousek and Lubchenco, 1995, p.61). The impacts will be the highest for the least developed countries in the tropical and subtropical areas (AfDB et al., 2003, p.5; DFID, 2004, p.1). The countries with fewest resources are likely to bear the greatest burden of climate change in terms of loss of life and relative effect on the economy (AfDB et al., 2003, p.5). Many of the world's poor are living in geographically vulnerable places under vulnerable environmental, socioeconomic, institutional and political conditions. Climate change provides an additional threat placing additional strains on the livelihoods of the poor (ibid, p.11). Agriculture, which is the only available means of livelihood for many of these poor, is one of sectors most vulnerable to climate change. Increased water demand and decreased water availability as a result of climate change may adversely affect the society and economy. People in the remote regions of the Himalayas have for centuries managed to maintain a delicate balance with the fragile mountain environments. This balance is likely to be disrupted by climate change and it would take a long time for a new equilibrium to be established (IPCC, 1996b, p.204).

2.4.1 Effects on the Water Withdrawals

Climate fluctuations affect human behaviour, which in turn may alter the water supply-demand balance in different regions of the world (Kulshrestha, 1996, p.107). Warmer conditions would most likely increase water withdrawals (Frederick and Gleick, 1999, p.30). A rise in temperature of 1.1ºC by 2025 would lead to an increase in average per capita domestic water demand by 5% in the UK (IPCC, 2001b, p.211). In a warmer climate, dry season water use for crops may be higher because of higher evapotranspiration (Mirza and Dixit, 1997, p.86). Agricultural water demand is considerably more sensitive to climate change (IPCC, 2001b, p.211), which accounts for almost 70% of the total water withdrawal in the world (Kulshrestha, 1996, p.125). For example, a change in temperature by 1.5ºC in Czechoslovakia could increase its irrigation water requirements by 20% to 35% (ibid, p.132).

2.4.2 Agriculture and Food Security

Climate change will have a significant impact on agriculture in many parts of the world (IPCC, 1998, p.397). Particularly vulnerable are subsistence farmers in the tropics, who make up a large portion of the rural population and who are weakly coupled to markets (IPCC, 2001b, p.270). Agriculture in Tropical Asia is vulnerable to frequent floods, severe droughts, cyclones and storm surges that can damage life and property and severely reduce agricultural production and could threaten food security of many developing countries in Asia (IPCC, 1998, p.397; Pachauri, 1992, p.82; IPCC, 2001b, p.535). Reduced food production may have several adverse impacts for these people, such as loss of income to farmers, loss of nutritional base, increased suffering/illness due to hunger, loss of life due to starvation etc (Hohmeyer, 1997, p.76). Increased temperature could result in a reduced growing season for rice and decline of its productivity in South Asia (Pachauri, 1992, p.82). Mountain agriculture, practised close to the margins of viable production, could be highly sensitive to climate change (Carter and Pary, 1994, p.420). Risk levels of climate change often increase exponentially with altitude, therefore, small changes in the mean climate can induce large changes in agricultural risks in mountain areas (ibid, p.421).

The growing water scarcity due to climate change will pose a serious threat to food security, poverty reduction and protection of the environment (IIASA, 2002, p.9). Sensitivity of food production to climate change is greatest in developing countries due to less advanced technological buffering to droughts and floods (Parry et al., 1998, p.8.2). Domestic production losses in these countries resulting from climate change will further worsen the prevalence and depth of hunger, and this burden will fall disproportionately on the poorest of the poor (IIASA, 2002, p.12). Debt and poor level of infrastructure in these countries will make it difficult to distribute food in food-deficit areas that could create a threat to the lives of many poor people (Hohmeyer and Gärtner, 1992, p.32). A doubling of CO_2 could result in about 900 million deaths over a 20-year period in the world by 2030 (ibid). The developing countries, which account for more than four-fifths of the world's population, share relatively lower level of global CO_2 emission but will suffer most from the negative impact of the global CO_2 emission (see IIASA, 2002, p.12).

Kavi Kumar (2003, p.349) has shown that a 1ºC rise in mean temperature in India would have no significant effects on wheat yields, while a 2ºC increase would decrease wheat yields in most places in India. Similarly, every 1ºC rise in temperature would cause a decline in rice production in the southern Indian state of Kerala by about 6% (ibid). Bhatt and Sharma (2002, p.118) pointed out that each 0.5ºC increase in temperature would reduce wheat productivity in north-west India by about 10%. Likewise, with a temperature change of +2ºC and accompanying precipitation changes by +15%, the fall in farm-level total net-revenue in India would be nearly 25% (ibid, p.119). A 4ºC temperature rise might cause a wheat yield reduction in Nepal of as much as 60% of the potential yield (Pradhan, 1997, p.45). Yield losses for rice in India would vary between 15 to 42% for temperature increases of 2.5ºC to 4.9ºC (Parikh and Parikh, 2002, p.220).

Food security is "*a situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for active and healthy life*" (FAO, 2001, p.49). In other words, food security consists of availability of food, access to food and absorption of food (Swaminathan, 2002, p.198). Food-availability is a function of production; and food-access depends mainly on purchasing power (Ziervogel et al., 2006, p.4). Similarly, food-absorption depends upon access to safe drinking water and environmental hygiene (FAO, 2001, 32), which might be deteriorated by climate change.

Rice, maize and wheat are the major cereal crops of Nepal that constitute about 38%, 17% and 14% of the total calorie supply respectively (FAO, 2004a, p.2). The average optimum temperatures for rice, maize and wheat are 22-30ºC, 25ºC and 15-20ºC respectively (MOPE, 2004, p.76) and there might be a substantial reduction in production when the temperatures exceeds the ranges. Agricultural land occupies nearly 20% of the total area of Nepal (UNEP, 2001, p.12). Out of the total cultivated area of 29,680 km^2, only about 9200 km^2 of the land is currently irrigated (NDIN, 2002, p.7) and the rest of the area is dependent solely on rainfall for meeting crop water requirements. Agriculture plays a very important role in Nepal's economy because about 93% of Nepal's total labour force is currently involved in the agriculture sector (FAO, 2004a, p.1) and agriculture forms about 39% of Nepal's gross domestic product (MOF, 2004, p.1). The majority of the population suffer from extreme poverty. About 81% of the population currently have a daily income of less than US $ 2 (World Bank, 2005, p.65) and most of them are subsistence farmers. The impact of climate change on the livelihoods of the poorest of the poor in Nepal would be substantial (see IPCC, 2001b, p.270) because there is large income and consumption disparity in the country. For example, the poorest 20% of the population consume only 6.2% of the resources, whereas the richest 20% of the population consume about 53.3% of the resources (CBS, 2004b, 27).

2.4.3 Effects on the Hydropower Potential

Climate change can greatly alter the water resources in mountain environments with substantial snow and ice-cover areas (Garr and Fitzharris, 1994, p.380). Daily and seasonal fluctuations in temperature and precipitation have a significant impact on the seasonal distribution of snow storage and runoff for hydro electricity production (ibid). The hydropower potential is sensitive to the amount, timing and pattern of rainfall as well as temperature (IPCC, 2001b, p.399). Climate change will increase the variability of river runoff due to glacier retreat and changes in timing and intensity of precipitation. Runoff will initially increase as glaciers melt and then decrease later as deglaciation progresses (Agrawala et al, 2003, p.29). Decreased snow-to-rain ratio, wetter monsoon and drier low flow seasons, which are likely impacts of climate change on river runoff, will adversely affect the hydropower potential of these mountain rivers (ibid). Hydroelectric projects are generally designed for a specific river flow regime including a margin of safety and future climate would change the flow regime to levels outside these safety margins (IPCC, 2001b, p.399). Longer drought periods and less precipitation occurring as snowfall would cause less water availability in the dry periods leading to reduced hydropower generation (ibid).

Flow in most of the rivers of Nepal is at a minimum in the early spring. This period of minimum flow is problematic for run-of-river hydroelectric plants (Kattelmann, 1993, p.103). About 43% of Nepal's total area is located above 3000 m altitude (CBS, 2004a, p.15), above which a significant portion of precipitation falls as snow (Sharma, 1993, p.114). Though melt water contributes only about 10% to the annual runoff of Nepalese rivers (MOPE, 2004, p.95), it exceeds 30% of the average monthly discharges in May (Sharma, 1993, p.113). Almost all existing hydropower plants in Nepal are the run-of-river type, with no associated storage dams, which make them more vulnerable to streamflow variability (Agarawala et al., 2003, p.33). Because run-of-river type hydropower plants are generally designed based on the minimum river flow (Dixit, 2002, p.364), decreasing low flows, as a result of climate change, would subsequently reduce the hydropower potential of Nepal.

2.4.4 Effects on Extreme Events

2.4.4.1 Changes in Flood and Drought Frequency

Because global climate models are currently not able to accurately simulate high-intensity, localized heavy rainfall, a change in monthly rainfall may not represent a change in high-intensity rainfall (IPCC, 2001b, p.205). Generally, most floods are caused by a torrential downpour i.e. high intensity rainfall (ibid). Therefore, it is difficult to get a real picture of changes in flood frequency from the GCM studies without having a real picture of precipitation. However, long-term changes in the mean climate are generally accompanied by changes in the frequency of extremes (Carter and Parry, 1994, p.421). Frequencies and magnitudes of floods are likely to increase with an increase in precipitation and temperature in region where floods are generated from heavy summer rainfall (IPCC, 2001b, p.206; Frederick and Gleick, 1999, p.24). Changes in the magnitudes of snowmelt and rain-to-snow ratio will change the flood magnitudes (IPCC, 1996b, p.337).

Floods are the most frequently faced natural disasters in India (Mohapatra and Singh, 2003, p.131). Water-induced disasters like floods, landslides and avalanches cause nearly 29% of the annual deaths and 43% of the annual property losses from all disasters in Nepal (Khanal, 2005, p.181). Floods in Nepal result from heavy rainfall, snowmelt, glacier lake outburst, landslide dam outburst, or a combination of two or more of them (Dixit, 2003, p.161). Floods and landslides should be considered together when their impact in Nepal is analysed. Landslides, which are triggered by heavy rainfall, may destroy agricultural fields, displace households/villages, destroy infrastructures and disrupt the normal inter-village linkages mainly in the hills; whereas floods may cause heavy damage to life, property and the environment along riverbanks for several kilometres downstream and in the plains (Dixit, 2003, p.162). For example, the extreme precipitation event of 19-20 July 1993 in Kulekhani area of central Nepal, when recorded maximum daily precipitation was 540 mm, triggered devastating landslides and floods causing substantial damages to about 800 km^2 and affected around 69,000 families with substantial loss of properties and 975 human deaths (Khanal, 2005, p.184).

2.4.4.2 Glacier Lake Outburst Floods

Glacier lakes are a common feature at altitudes of 4,500 to 5,500 m in many river basins of the Nepal Himalayas. They have been formed during the process of glacier retreat (Kattelmenn, 2003, p.146). As the glacier retreats and the lake grows, increasing hydrostatic pressure of the rising lake-water level makes the supporting dam more vulnerable to collapse (Mool et al., 2001a, p.121). A flood created by the outburst of such glacier lakes with a sudden release of large amount of lake water and debris is called a glacier lake outburst flood (GLOF) (Shrestha, 2001, p.88). The large mass of water mixed with debris rushes along the stream channel downstream in the form of disastrous flood waves. The severity of GLOF depends on the amount water released, debris load and basin characteristics (ibid). Though a GLOF is not a completely new event, it became more frequent and one of the most devastating natural disasters in Nepal during the second half of the last century (UNEP, 2001, p. 35). There have been 13 reported cases of GLOFs in Nepal since 1964 with substantial losses of human lives, livestock, land and infrastructures (Rana et al., 2000, p. 563, Mool et al, 2001a, pp. 77-78). A recent study has revealed that there are 20 glacier lakes identified as potentially dangerous glacier lakes in Nepal with an imminent threat of GLOFs (Mool et al., 2001b, p.81). The increasing temperature and accelerated melting of glaciers would increase the risk of GLOFs from these lakes and would create many new dangerous glacier lakes in the mountain valleys.

Due to the rapid retreat of Himalayan glaciers, the number and volume of potentially dangerous glacier lakes is increasing (Agrawala et al, 2003, p.29). The past studies on GLOFs suggest that the frequency of GLOF events is increasing (ibid, p.31). At the extreme, a GLOF can release millions of cubic metres of lake water in a few hours and instantaneous discharge can be up to thousands of cubic metres per second (Kattelmann, 2003, p.147). The flood water is largely hyper-concentrated with a large amount of debris from the moraine and river bed and valley slopes (ibid) that may wash away the forest, farmland, settlements, infrastructures, livestock and people's lives along the river valley for more than 100 km downstream (Dixit, 2003, p.164; Agrawala et al., 2003, p.29). For example, the Dig Tsho GLOF on 4 August 1985 caused an immediate release of about 900,000 m^3 of debris and water with an estimated peak discharge of 1600 m^3/s that damaged cultivated land, houses, 14 bridges, the nearly-completed Namche hydropower plant (worth US $ 3 million), livestock, 4 people's lives and long stretches of the trail along the river of Bhote Koshi and upper Dudh Koshi over the distance of more than 42 km (Vuichard and Zimmermann, 1986, p.91; 1987, p.91; Ives, 1986, p.30).

In the developing countries, the 'normal' daily life of a large section of the people is not so different from the living conditions of those hit by disasters (Dixit, 2003, p.167). Even in normal times, people in these areas live in vulnerable conditions. The poorest of the poor are generally living in the most vulnerable flood plains not because of the ignorance or erroneous perception of flood risks, but because of the inability to own assets in safer areas. The poor individuals and families suffer most from flood disasters because they have no access to basic resources, such as land, food, shelter, health and education (ibid).

Drought is another hydrologic extreme, resulting from a significant water deficit (WMO, 1994, p.405). Droughts are more difficult to define in quantitative terms than floods (IPCC, 2001b, p.206). Increasing precipitation may not necessarily decrease the drought events, if there is a decreasing number of rainy day. The areas having relatively greater variations in annual rainfall are more vulnerable to droughts (Hudson, 1964, p.18-2). There will be a general drying of land areas where the increase in potential evaporation exceeds the increase in precipitation due to increased temperatures (IPCC, 2001c, p.527). On top of that, the decreasing number of rainy days may exacerbate the drought severity. However, the effects of climate change on the magnitude and frequency of droughts largely depend on the water storage capacity of the soil. The areas with smaller soil storage capacity will face greater impacts of climate change (ibid). Though a prolonged drought may affect virtually all sectors of the economy, agriculture is the most vulnerable to drought (Frederick and Gleick, 1999, p.25). Drought has very serious human implications as it affects agriculture, the livelihood security of a majority of the population in the developing world (Swaminathan, 2002, p.210).

2.5 Projected Future Climate

2.5.1 Future Global Climate

The future climate change largely depends on the existing and expected level of influencing factors of climate change, e.g. level of greenhouse gas emissions. Future greenhouse gas emissions are mainly determined by the economic and technological advancement, policy intervention, industrial development, type of energy sources etc. So, different scenarios have been developed to project the future climate change. The estimated range of temperature changes from 1990 to 2100 is +1.4 to +5.8°C according to scenarios developed by the IPCC (IPCC, 2001c, p.527). The major changes expected in the future are as followings (ibid, p. 528):

- Land areas warm faster than sea and mid- and high latitudes have a greater warming.
- Globally averaged mean water vapour, evaporation and precipitation will increase.
- There will be an increase in precipitation extremes.
- There will be general drying of mid-continental areas during summer due to increased temperature and potential evapotranspiration.
- There will be more frequent extreme high maximum temperatures and less frequent extreme low minimum temperatures.
- There will be enhanced interannual variability of northern summer monsoon precipitation.

2.5.2 Climate Change Scenarios for Nepal

Climate change scenarios are used to predict the future climate based on a certain change in forcing agents such as doubling of the CO_2 levels in the atmosphere. Different General Circulation Models (GCMs) have been applied for developing probable climate change. Not all of the developed GCMs give a realistic scenario for particular country. For example, Shrestha (1997, p. 22) has indicated that the Canadian Climate Centre Model (CCCM) and the Geophysical Fluid Dynamics Laboratory R-30 Model (GFD3) are more reliable for predicting Nepal's future climate. The outputs of the models using the temperature data from

22 stations for 1971-1990 indicated an area-average temperature change with the doubling of CO_2 lying between +1.42°C to +4.11°C. The temperature change in summer was found to be smaller than that in winter (ibid, p.23). Similarly, the models showed more temperature change in higher altitudes than that in lower altitudes (ibid) which was well supported later by Shrestha et al. (1999, p.2781).

Based on the combined results of the best seven MAGIC/SCENGEN models, Agrawala et al. (2003, p.12) reported that there would be a significant increase in temperatures as well as in annual precipitation in the future. The warming trend already observed in recent decades in Nepal would continue through the 21st century (ibid, p.13). According to the analysis, increase in temperatures would be more pronounced in winter months whereas increase in precipitation would be more significant during monsoon months (see Table 2.1).

Table 2.1: GCM estimates of temperature and precipitation changes for Nepal (after Agrawala et al., 2003, p.13)

Year	Temperature change, ºC mean (standard deviation)			Precipitation change (%) mean (standard deviation)		
	Annual	DJF*	JJA**	Annual	DJF*	JJA**
Average				1433 mm	73 mm	894 mm
2030	1.2(0.27)	1.3(0.40)	1.1(0.20)	5.0(3.85)	0.8(9.95)	9.1(7.11)
2050	1.7(0.39)	1.8(0.58)	1.6(0.29)	7.3(5.56)	1.2(14.37)	13.1(10.28)
2100	3.0(0.67)	3.2(1.00)	2.9(0.51)	12.6(9.67)	2.1(25.02)	22.9(17.89)

* - December, January, February; **- JJA – June, July, August

2.6 Open Questions

The following open questions were found after analysing the available information:

- How are the seasonal temperature and precipitation changes observed in the past climatic records?
- What are the expected physical impacts of climate change on water availability, river flows and glaciers mass balances in the Nepal Himalayas?
- What are the economic and social implications of these changes? How will the poorest of the poor be affected by such changes?

2.7 Development of Hypotheses

Based on the analysis of the aforementioned information, the following hypotheses were developed:

- The temperatures in Nepal are increasing and the rates of warming are higher in the higher elevations.
- The maximum temperatures in Nepal are increasing faster than the minimum temperatures.
- A rise in temperatures will cause an accelerated glacier retreat and a decreased snow-to-rain ratio in the Nepal Himalayas.
- There is a change in precipitation and the rates of change vary in seasons.
- The river runoff will be substantially affected by climate change.
- There will be reduced water availability and a decreased hydropower potential in Nepal as a result of warming.
- Climate change will cause significant impacts on agriculture, food security and poverty.
- The likelihoods of floods and droughts will increase due to climate change.

Chapter III: Research Methodology

3.1 Study Design and Context

The data for the study were collected during a field study from May to October 2003 in Nepal. Analyses of hydrological, meteorological, glaciological and socio-economic data were carried out in order to quantify the climate change and its physical and socioeconomic impacts with reference to the water resources in Nepal. The temperature and precipitation data were analysed in order to identify the change, while river flow, sunshine hours, wind speed and glaciological data were analysed to identify the physical impacts particularly on the water resources of Nepal. Population, agriculture production, income distribution and calorie supply data were analysed in order to identify the socio-economic impacts of climate change in Nepal.

The climatic data from 4 meteorological stations covering different physiographic regions in central Nepal collected by the Department of Hydrology and Meteorology, Nepal were taken in order to determine the climate change. Bagmati basin at Chovar and Langtang basin at Langtang (Kyangjing) were selected as sample basins for detecting the physical impacts of climate change. Total glaciers in the Nepal Himalayas were assessed using the results obtained in the Langtang basin in order to determine their sensitivities to warming. The selection of the sample area for the study was based on the data availability and the study requirements. The Bagmati River basin was chosen as the rainfed basin and the Langtang Khola basin as the snow-fed basin.

3.2 Source of Data

The hydrological and meteorological data were provided by the Department of Hydrology and Meteorology of Nepal. Similarly, the information on glaciers in the Nepal Himalayas was obtained from the publications of the International Centre for Integrated Mountain Development (ICIMOD), whereas the socio-economic data of Nepal were taken from the publications of the Central Bureau of Statistics of Nepal. Additionally, some primary data were also collected during the field visit to some of the flood/landslide affected areas and during face-to-face interviews with key people. Relevant study reports, publications and maps were also collected from various governmental and non-governmental organisations.

3.3 Detecting the Climate Change

In order to detect the climate change, precipitation and temperature data were analysed. Available monthly meteorological data were first grouped into seasonal and annual average data. Missing data were estimated by linear interpolation of the data of the same months of the adjacent years on either side of the missing value (WMO, 1983, p.5.31). The data were grouped into four seasons: winter (December-February), pre-monsoon (March-May), monsoon (June-September) and post-monsoon (October-November). Temperature data were averaged for each of the seasons of the corresponding months, while precipitation data were totalled. Similarly, annual average temperatures were obtained from the average of whole months of a particular year and annual precipitation data from the total of all months. The data were taken from the Department of Hydrology and Meteorology of Nepal collected at climatological stations from different physiographic regions of central Nepal as given in Table 3.1.

Table 3.1: Descriptions of reference meteorological stations

Station Name	DHMN Index No.	Altitude, masl	Physiographic Region	Data Period
Rampur	0902	256	Inner Terai	1971-2000
Daman	1030	2314	Mid-mountain	1973-2000
Kathmandu Airport	0905	1336	Mid-mountain	1971-2000
Langtang	Kyangjing	3920	Himalaya	1988-2000

Maximum, minimum and mean temperatures, precipitation and number of rainy days were analysed separately for each station. To start with, the data sets were tested for normality because parametric tests are valid only for normal distribution (WMO, 1966b, p.58; Kothari, 1990, p.237). The Kolmogorov-Smirnov (K-S) test was applied to test the normality of the distribution. If the data sets were found normally distributed, then parametric tests like t-test and χ^2-test (chi-square test) were conducted. Otherwise, non-parametric tests were applied (Kothari, 1990, p.237). A nonparametric test called run test was applied to test the homogeneity of the data of a particular station. Too many runs would be an indication of an oscillation, while too few runs would be an indication of a trend during the sample record (WMO, 1966a, p.5). Simple statistical parameters like mean, median, standard deviation, standard error etc were also identified from the particular time series. The trends were calculated by simple linear regression analysis using the following equation (Anderson et al., 1993, p. 509):

$$y_{est} = \beta_0 + \beta_1 x \qquad (3.1)$$

Where,

y_{est} = estimated value of the dependent variable like temperature or precipitation

β_0, β_1 = intercept and slope of the estimated regression line, which can be obtained from the sample data with the least squares criterion (Anderson et al., 1993, p.476):

$$\min \Sigma(y_i - y_{iest})^2 \qquad (3.2)$$

Where,

y_i = observed value of the dependent variable for the i^{th} year

y_{iest} = estimated value of the dependent variable for the i^{th} year

The least squares method is very general and may be applied to almost any type of function (WMO, 1966a, p.38). The values of the intercept (β_0) and slope (β_1) for the estimated regression equation can be determined by (Anderson et al., 1993, p.476):

$$\beta_1 = [\Sigma x_i y_i - (\Sigma x_i \Sigma y_i)/n] / [\Sigma x_i^2 - (\Sigma x_i)^2/n] \qquad (3.3)$$

$$\beta_0 = y_{av} - \beta_1 x_{av} \qquad (3.4)$$

Where,

x_i, y_i = values of the variables x and y for the i^{th} year

x_{av} = average value of the independent variable

y_{av} = average value of the dependent variable

The significance of the estimated trend is tested using the t-test with the null hypothesis (H_0) and alternative hypothesis (H_a) as followings:

H_0: $\beta_1 = 0$

H_a: $\beta_1 \neq 0$

H_0 is rejected, if t-calculated is less than $-t_{n,\alpha/2}$ or more than $t_{n,\alpha/2}$. Here, $t_{n,\alpha/2}$ is the tabulated value of t-statistics with n-degrees of freedom and α-level of significance of a two-tailed distribution. Alternatively, if the calculated t-statistics lies within the range of the tabulated value, then H_0 is accepted and no trend is considered.

3.3.1 Testing for Significance

After determining the trend, it is necessary to test the fitted regression for reality and for linearity. This is done by the analysis of variance with the determination of the squared correlation coefficient (r^2), which is the ratio of the sum of squares accounted for by regression (Q_R) to that accounted for by total (Q_T) as follow (WMO, 1966a, p.40):

$$r^2 = Q_R / Q_T$$

Where,

$$Q_R = [\Sigma y(x-x_{av})]^2 / \Sigma(x-x_{av})^2 \quad (3.5)$$

$$Q_T = \Sigma y^2 - (\Sigma y)^2/n \quad (3.6)$$

Here,

n= sample size; x_{av}= average x; y_{av}= average y

According to WMO (1966a, p.40), there are two kinds of significance, practical and statistical. If the regression is not practically significant, it is of little use to test its statistical significance. If, however, it is practically significant, then the test of the hypothesis must be made in order to test for statistical significance. Practical significance is measured by the squared correlation coefficient, r^2. A larger correlation coefficient indicates a better fit of the regression equation. If $r^2 < 0.25$, the regression is very doubtful for practical use and a further test for statistical significance is meaningless (ibid). But, if $r^2 > 0.25$, then the regression should be tested further for statistical significance. Statistical significance is tested by estimating the error in the regression equation (Anderson et al., 1993, p.491):

$$y = \beta_0 + \beta_1 x + \varepsilon \quad (3.7)$$

Where,

ε = error in estimating the regression equation, which may be calculated as the mean square error, S (Anderson et al., 1993, p.494)

$$S = \sqrt{[\Sigma(y_i - y_{iest})^2/(n-2)]} \quad (3.8)$$

Estimated standard deviation of β_1

$$S_{\beta 1} = S / \{\sqrt{[\Sigma x_i^2 - (\Sigma x_i)^2/n]}\} \quad (3.9)$$

The t-statistic is defined by

$$t = \beta_1 / S_{\beta 1} \quad (3.10)$$

This value is compared with the tabulated value of $t_{n,\alpha/2}$ with defined significance level (α) and degrees of freedom- n. H_o is rejected if $\beta_1/S_{\beta 1} < -t_{n,\alpha/2}$ or $\beta_1/S_{\beta 1} > t_{n,\alpha/2}$. Otherwise, H_o is accepted and no trend is considered. Annual and seasonal records of temperature and precipitation were analysed using MS Excel and SPSS 10.0 in order to calculate statistical parameters and test their significance.

3.4 Estimating the Physical Impacts of Climate Change

In order to identify the impacts of climate change on river runoff, two river basins were chosen, the Bagmati River basin and the Langtang Khola basin. The Bagmati River basin is located in central Nepal. It is one of the major rainfed basins in Nepal. The capital city of Kathmandu also lies in the basin. The Shivpuri peak to the north of Kathmandu Valley with an elevation of 2760 m is the highest point in the basin while the elevation of 75 m at the Nepal-India border is the lowest one (DHMN, 2001, p.10). Likewise, Langtang basin is located in the central Himalayan district of Rasuwa about 60 km north of Kathmandu. The total area within the study basin is 340 km^2 and the altitude varies from 3800 masl at the Langtang Khola (Kyangjing) hydrological station to 7232 masl at the peak of Langtang Himal.

After detecting the change in climate, the second step was to estimate the possible impact of such change. The entire natural and human systems are expected to be affected by climate change due to changes in the average, range and variability of temperature and precipitation, as well as the frequency and severity of weather events (IPCC, 2001b, p.28). In addition, systems would be affected indirectly by soil moisture changes, changes in the land and water conditions and changes in the distribution of infectious diseases etc (ibid). The current study is limited to the study of impacts related to water resources. Mainly the following two areas have been examined during this study:

- Impacts on river runoff
- Impacts on glacier extent

3.4.1 Impacts of Climate Change on River Runoff: the Water Balance Model - *WatBal*

Many models have been developed to investigate the impact of climate change on river runoff but many models use daily or hourly input data to calibrate and validate them. In countries like Nepal, daily or hourly hydrological and meteorological data are not easily available. *WatBal* is a lumped conceptual model that uses the continuous functions of relative water storage to represent inflows and outflows. In this model, mass balance is written as a differential equation and storage is lumped as a single conceptualized “bucket” (see Figure 3.1). Therefore, varying time steps can be used in this model depending on the data availability and basin characteristics (Yates, 1994, p.2). The model is simple to use and mean monthly data also can be used with no significant differences in output (Yates, 1996, pp.121; Yates and Strzepek, 1994a, p. 43). The system of *WatBal* model was designed as an MS Excel macro making use of the Visual Basic programming language.

This model was developed by Yates (1994, p.1) for climate impact assessment of river basin runoff. It was first used in Nepal within the US country study programme for the Koshi Basin (Gurung, 1997, p.33). Recently, MOPE (2004, p.98) used the same model for the Karnali, Narayani, Koshi and Bagmati Rivers in Nepal in order to assess the vulnerability of climate change to water resources. Potential evapotranspiration was calculated separately using the Penman-Monteith equation (Allen et al., 1998, p.65) and applied as input data in the model.

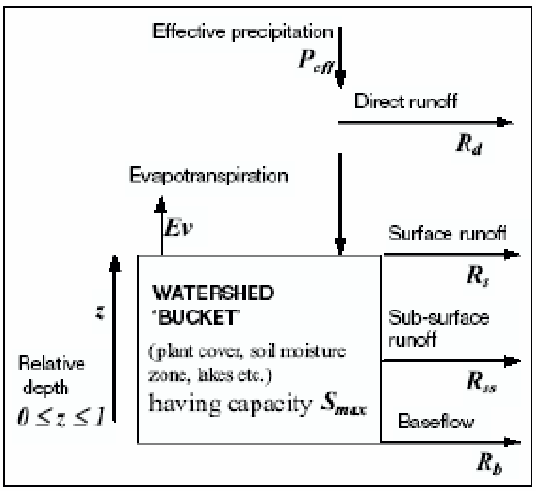


Figure 3.1: Conceptualization of water balance for the WatBal model (Yates, 1994, pp.3-6)

The soil moisture balance is written as (ibid, p. 3):

$$S_{max} \frac{dz}{dt} = [P_{eff}(t)*(1- \beta)] - R_s(z,t) - Rss\ (z,t) - E_v\ (PET, z, t) - R_b \qquad (3.10)$$

Where,

P_{eff}	=	Effective precipitation, (mm/month)
β	=	Direct runoff coefficient
R_s	=	Surface runoff (mm/month)
R_{ss}	=	Sub-surface runoff (mm/month)
E_v	=	Evapotranspiration (mm/ month)
PET	=	Potential evapotranspiration (mm/ month)
R_b	=	Base flow (mm/ month)
S_{max}	=	Maximum storage capacity (mm)
z	=	relative storage ($0 \leq z \leq 1$)

The functional components used in the equation are as follow (Yates, 1996, p.124-126):

Evapotranspiration- E_v: Potential evapotranspiration (PET) was calculated separately using the FAO Penman-Monteith method in this model.

Surface Runoff- R_s : Surface runoff was described in terms of the storage state, z, the effective precipitation, P_{eff} and the baseflow, R_b.

Effective Precipitation- P_{eff}: This was the amount of precipitation after adjustment for elevation affects, gauge error, seasonal interception etc.

Base flow- R_b: Base flow was taken as 0.95 percentile low flow.

Sub-surface Runoff- R_{ss} : Sub-surface runoff was a function of the relative storage times a coefficient, α.

In order to assess the climate change impacts on river runoff, the model was calibrated and validated for two hydrological stations in the current study: 1. Chovar in the Bagmati basin (rain-fed) and 2. Kyangjing in the Langtang basin (snow-fed). Calibration was done for each station with trial and error until the minimum average error was obtained. Then, the model parameters with the minimum average error were used with another set of time series data in order to validate the model. Correlation coefficients and the average error during calibration and validation were taken as controlling parameters for the model application.

After defining the model parameters through calibration and validation, the model was run with climate change scenarios i.e. changes in temperature, precipitation and potential evapotranspiration while keeping other parameters constant. This was done in order to estimate the sensitivity of river runoff to temperature and precipitation changes.

3.4.2 Impacts on Glacier Mass Balance in the Nepal Himalayas

Glaciers are very sensitive to climate change. The accumulation or ablation of glaciers is determined mostly by the climate parameters like temperature and precipitation. An empirical glacier mass balance model initially developed by Ageta and Kadota (1992, p.89) was used in order to detect the impact of climate change on glacier mass balance in the Nepal Himalayas. The model was applied in a small Himalayan catchment of Langtang in Central Nepal. For the sake of simplicity, only the temperature change scenario was applied during the sensitivity analysis. All 24 glaciers in the Langtang Valley upstream of the hydrological station of Langtang (Kyangjing) were analysed using the empirical model. The output parameters were then applied to the whole glacier system of the Nepal Himalayas and the long-term effects of the climate change on glacier extent were also analysed. Different scenarios were developed with different rates of temperature increase.

3.4.2.1 Empirical Glacier Mass Balance Model

The empirical model was originally developed by Y. Ageta in 1983 using the observational data in 1978 and 1979 to calculate the mass balance of Glacier AX010 in the Nepal Himalayas (Kadota and Ageta, 1992, p.2). The general assumptions for the model application are as follow (Ageta and Kadota, 1992, p.90):

1. A rise in temperature does not affect precipitation and other climatic factors.
2. The amount of precipitation on the glaciers is independent of altitude and uniform for the whole glacier area under study.
3. The temperature changes with an adiabatic lapse rate of -0.6°C per 100 m of altitude.

In reality, the first and the second assumptions are only partly correct. The third assumption is relatively accurate and tested largely for its validity. The Asian high-mountain regions are still lacking the quantitative information describing the relationship between temperature and other climatic parameters (Ageta and Kadota, 1992, p.90). Also, the distribution of precipitation in the mountains of the Himalayas is very complicated and defined largely by local micro-climatic features (Mani, 1981, p.14) due to changes in orientation, altitude, slopes and size of the mountains and valleys (Chalise, 1994, p.387). Moreover, the precipitation data can be found only for limited stations mainly in the valleys at lower levels (ibid, p.386).

The relationship between the temperature, precipitation and glacier mass balance is defined by the following equations (Ageta and Kadota, 1992, p.90; Kadota et al., 1997, p. 92; Naito et al., 2000, p.247; Naito et al., 2001, p. 316; and Kadota and Ageta, 1992, p. 2):

c	=	P	if $T < -0.6$	(3.11)
c	=	$P\,(0.85-0.24T)$	if $-0.6 \leq T \leq 3.5$	(3.12)
c	=	0	if $T > 3.5$	(3.13)
a	=	0	if $T < -3.0$	(3.14)
a	=	$-0.30(T+3.0)^{3.2}$	if $-3.0 \leq T \leq 2.0$	(3.15)
a	=	$-30 * 0.9T$	if $T > 2.0$	(3.16)
b	=	$c+a$		(3.17)

Where,

c	=	Accumulation, cm/month
a	=	Ablation, cm/month
b	=	Mass balance, cm/month
P	=	Average monthly precipitation, cm
T	=	Average monthly temperature, °C

This model received a wide acceptance to estimate the glacier mass balance in the Nepal Himalayas. Naito et al. (2000, p. 245) applied this model in the Eastern Himalayas for a numerical simulation of shrinkage of the Khumbu glacier and predicted the likelihood of formation and succeeding enlargement of a glacier lake in the lower ablation area of the glacier. Similarly, Naito et al.(2001, p. 315) used the same model for estimating sensitivities of some other glaciers in the Nepal Himalayas in relation to climate change. This analysis has revealed that the glaciers in the Nepal Himalayas, which are mostly summer-accumulation type, are more sensitive to temperature change than other glaciers in the world. Likewise, Kadota et al. (1997, p. 246) used this model to monitor and predict the shrinkage of a small glacier in the Nepal Himalayas and concluded that the shrinkage would accelerate in the years to come.

3.4.2.2 Application of the Empirical Glacier Mass Balance Model

In the present study, the model was applied in the Langtang basin in order to calculate the mass balance of the glaciers within the basin of the Langtang Khola upstream of the hydrological station of Langtang (Kyangjing). The average monthly hydrological and meteorological data were calculated from observed data for the period of 1988-2000 at Langtang (Kyangjing). The glaciers within the basin were identified with the help of topographic maps (HMGN, 1997) and glacier inventory of the Nepal Himalayas (Mool et al., 2001a, pp.224-225; ICIMOD/UNEP, 2002). The areas of identified glaciers were linearly interpolated between the highest and the lowest point of each glacier. The area of each glacier was calculated for each 100 m of altitude. The precipitation within the considered basin area is assumed to be uniform over the entire basin and be represented by the observed data at the meteorological station of Langtang (Kyangjing). Similarly, the temperature within the basin is assumed to be changing with altitude at an adiabatic lapse rate of -0.06°C per 100 m. By summing up the areas of all glaciers inside the study basin, the total glacier area in each 100 m was identified. On the other hand, the specific mass balance for each month and for each

100 m altitude-level was calculated using the empirical model. Total annual mass balance for each 100 m level was obtained by summing up all-monthly mass balances and multiplying it by the glacier areas in a particular level. Similarly, the total mass balance was obtained by summing up all-level mass balances. After that a sensitivity analysis of the glacier mass balance to a temperature rise was carried out with different temperature change scenarios (i.e. from +1ºC to +5ºC).

The calculated accumulation, ablation and mass balance values of the glaciers in Langtang valley were tested for their validity by calculating total water balance at the Kyangjing hydrological station. The observed average annual runoff (Q_o) at Kyangjing was compared with the calculated average annual runoff (Q_c). The following relation was used for calculating the average annual runoff:

$$Q_c = P + M_w - E \qquad (3.18)$$

Where,

Q_c = average calculated annual runoff, m^3

P = average annual precipitation, m^3

M_w = average annual melt water, m^3

E = average annual evapotranspiration, m^3

The infiltration into the ground was ignored for the annual water balance calculation. Average annual melt water was calculated as the net glacier mass balance within the study basin.

From the total glacier mass balance, the specific mass balance was obtained by:

$$b = B/A \qquad (3.19)$$

Where,

b = specific mass balance, metres of water equivalent (m w.e.)

B = total glacier mass balance, m^3

A = total glacier surface area, m^2

3.4.2.3 Sensitivity of the Glaciers in the Nepal Himalayas to Temperature Rise

In order to estimate the amount of glacier-melt water and its sensitivity to a temperature rise in the Nepal Himalayas, all glaciers in the Nepal Himalayas were analysed by assuming the same rate of glacier mass balance as in the Langtang Valley (Equation 3.19). Similarly, the remaining ice reserve for each glacier was calculated as:

$$IR_{n+1}=IR_n+b*A_n \qquad (3.20)$$

Where,

IR_{n+1} = ice reserve in the particular glacier in n+1th year, m^3

IR_n = ice reserve in the particular glacier in nth year, m^3

b = specific glacier mass balance, m.w.e/year

A_n = surface area of that particular glacier in nth year, m^2

The estimated life of any glacier was calculated by:

$$N= IR_0/(b* A_0) \qquad (3.21)$$

Where,

N = estimated life of ice reserve in the particular glaciers, years

IR_0 = ice reserve in the particular glacier in 2001, m^3

b = specific glacier mass balance, m.w.e/year

A_0 = surface area of that particular glacier in 2001, m^2

A projected time series of average annual ice reserve in any particular glacier was developed. The projected time series of glacier ice reserve for the whole of Nepal was created by summing up the ice reserve of all glaciers in the Nepal Himalayas for any particular year. Any glacier was considered as disappeared, when $IR_{n+1}< 0$, i.e. when there was no more ice-reserve left in the glacier. Similarly, sensitivity analyses of glacier ice reserve, glacier number and glacier areas in relation to a temperature rise were carried out for different rates of warming from 0.03ºC/yr to +0.15ºC/yr.

3.5 Estimating the Socioeconomic Impacts of Climate Change

The physical impacts of climate change on water resources might have serious socio-economic impacts. The socio-economic impacts of climate change with reference to water resources were determined by calculating the sensitivity of total water availability, hydropower potential, the water supply-demand situation, irrigation water requirement, agriculture production and weather-induced extreme events.

3.5.1 Impacts on the Total Water Availability in Nepal

In order to quantify the impacts on the total water availability of Nepal, the current status of the water balance in Nepal was taken from previous studies (UNEP, 2001, p.129; Yogacharya and Shrestha, 1998, p.205). The current amount of snow, rain and evaporation water was taken from these sources and the glacier-melt water was calculated in the physical impacts section of this study. As all these components of the water balance are sensitive to temperature rise, a sensitivity analysis was carried out for different temperature change scenarios. Total water availability for a particular year was calculated by summing up all rain-water and meltwater and subtracting evapotranspiration losses. Losses through infiltration were assumed to be unchanged in the analysis.

3.5.2 Impacts on the Hydropower Potential

Out of the total annual surface runoff of Nepal, about 76% is collected from the areas inside Nepal (UNEP, 2001, p.129). Nepal's current total hydropower potential is estimated at about 83 GW (Shrestha, 1985, p.33). The runoff component coming from outside Nepal could not be disaggregated into different components like snow, rain and meltwater due to lack of data. Therefore, the current study was limited to the analysis of the runoff data from inside Nepal. The hydropower potential of the runoff from inside Nepal was assumed to be 76% of the total potential (63 MW) assuming that hydropower potential would be directly proportional to available runoff.

An all-Nepal monthly hydrograph was developed based on the long-term average runoff data observed by the Department of Hydrology and Meteorology at 50 hydrological stations across Nepal (Yogacharya and Shrestha, 1998, pp. 214-217). From the total monthly hydrograph, separate hydrographs were prepared for rainwater and meltwater components based on the results of the analysis of Langtang Basin. Generally, the run-of-river hydropower plants, which dominate the existing hydropower plants in Nepal, are designed based on the minimum flows in the dry seasons, when the meltwater contribution is the highest. Therefore, hydropower potentials contributed by rainwater and meltwater were calculated as the proportion of rainwater and meltwater in the dry season. As both of the components are sensitive to temperature rise, a sensitivity analysis of the hydropower potential was carried out for different temperature change scenarios.

3.5.3 Impacts on the Water Balance Situation

In order to quantify the impacts of a temperature rise on the water balance situation, the data regarding the supply and use of water upstream from the Chovar of the Bagmati basin were analysed. Irrigation water demand was calculated according to the information from WECS (1997, table A6.1). Domestic and industrial water demand was calculated based on the secondary information on per capita demand (WECS, 1997 p.3-5; WECS, 2000c pp.20-24) and the population data (ISRSC, 2002, pp.228-256). The sensitivity analysis looking at the effects of warming on the water balance situation at the Chovar of Bagmati Basin was limited to the sensitivity analysis of irrigation water demand in relation to temperature rise. The change in industrial and domestic water demand due to warming was ignored for the present study due to greater uncertainties under climate change. In addition to evapotranspiration losses, irrigation water requirements depend on several other factors like type of crop, cropping pattern, type of soil, irrigation method, land slope, conveyance losses, etc (DIO, 1990, pp.34-41). However, only the evapotranspiration component was taken for sensitivity analysis and all other components of the irrigation water demand were kept unchanged for the sake of simplicity.

Evaporation is the process whereby liquid water is converted into water vapour and removed from the evaporating surface. The supply of energy to provide the latent heat of vaporization and the ability to transport the vapour away from the evaporating surface are the main factors influencing the evaporation (Chow et al., 1988, p. 80). Solar radiation is the main source of heat. Wind speed and the relative humidity determine the ability to transport vapour away from the evaporating surface. Transpiration is the vaporization of liquid water contained in plant tissues and removal of the vapour to the atmosphere. Plants predominantly lose their water through small openings on the leaves. Evaporation and transpiration occur simultaneously and there is no easy way of distinguishing between these two processes (Allen et al., 1998, p.3). The processes of evaporation from the land surface and transpiration from plants are collectively defined as evapotranspiration.

Evapotranspiration is one of the major contributors of the total irrigation water requirement. The amount of evapotranspiration is largely governed by weather parameters. Evapotranspiration might be potential or actual. Potential evapotranspiration assumes the continuous supply and no deficit of moisture in the air (WMO, 1994, p.507). The atmosphere becomes drier when there is a deficit of moisture as demanded by the energy supplied. In this case actual evapotranspiration will be less than the potential one. The current study is limited to the detection of the sensitivities of potential evapotranspiration. The Penman-Monteith equation is regarded as one of the most accurate equations to estimate evapotranspiration (Yates and Strzepek, 1994b, p. 7). So, the current study used the Penman-Monteith equation (Allen et al., 1998, p.23) for estimating potential evapotranspiration. The calculation estimated the sensitivities of the irrigation water requirement associated with the evapotranspiration through the use of hypothetical temperature change scenarios from the business as usual scenario (T_0) to temperature change scenarios (from T+1°C to T+5 °C).

3.5.3.1 The FAO Penman-Monteith Method

The FAO Penman-Monteith method was developed after the consultation of experts and researchers in May 1990 organized by the FAO (Allen et al., 1998, p.23). The meeting of experts developed the FAO Penman-Monteith Equation by combining the Penman-Monteith equation, aerodynamic resistance and surface resistance. Potential evapotranspiration is calculated as a reference crop evapotranspiration as following (Allen et al., 1998, p. 24):

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad (3.22)$$

Where,

ET_o	=	reference evapotranspiration [mm day^{-1}],
R_n	=	net radiation at the crop surface [MJ m^{-2} day^{-1}],
G	=	soil heat flux density [MJ m^{-2} day^{-1}],
T	=	mean daily air temperature at 2 m height [°C],
u_2	=	wind speed at 2 m height [m s^{-1}],
e_s	=	saturation vapour pressure [kPa],
e_a	=	actual vapour pressure [kPa],
$e_s - e_a$	=	saturation vapour pressure deficit [kPa],
Δ	=	slope vapour pressure curve [kPa °C^{-1}],
γ	=	psychrometric constant [kPa °C^{-1}].

The ET_0 is a potential evapotranspiration from a hypothetical crop with an assumed height of 0.12 m having a surface resistance of 70 s/m and an albedo of 0.23, closely resembling the evaporation of an extension surface of green grass of uniform height, actively growing and adequately watered (Allen et al., 1998, p. 24). This equation uses standard climatological records of temperature, humidity, sunshine hours and wind speed.

3.5.4 Climate Change Impacts on Agricultural Production, Poverty and Food Security

Actual specific irrigation water requirement was calculated based on water use inventory data (WECS, 1997, p.3-5; NDIN, 2002, pp.384-435). An increase in irrigation water requirement due to temperature rise was expressed in terms of decreased equivalent land area and subsequently decreased equivalent agricultural production. Direct decrease in agriculture production due to temperature increase was out of the scope of this study. The potential impact of possible decrease in rice production due to increase in irrigation demand was analysed in order to quantify likely effects on food security and poverty. As the majority of the population are subsistence farmers and live in poverty, the decreased agricultural production might disproportionately affect the food security for the poorest of the poor. In order to analyse this, the income distribution and calorie consumption information collected by CBS (2004b, pp.21-34) was used.

3.5.5 Impacts on Extreme Weather Events

Droughts, landslides and floods are the major weather-induced extreme events causing substantial socio-economic losses in Nepal. Long-term averages of instantaneous extreme minimum and maximum flow records across Nepal collected by the Department of Hydrology and Meteorology, Nepal (Yogacharya and Shrestha, 1998, pp. 214-217; WECS/DHMN, 1996, Annex A) were analysed to assess the impacts of decreased snow cover on extreme floods. Similarly, the number of rainy days, amount of precipitation and 24-hour precipitation records for some meteorological stations were also analysed in order to assess the impacts on droughts, landslides and floods. In addition, the impact of climate change on glacier lake outburst floods (GLOF) was also analysed based on the recent records of GLOF in the Nepal Himalayas.

3.6 Limitations of the Study

There were some limitations in the study as following:

- The meteorological data for the Himalayan station were available only for 13 years.
- The analysis was largely based on the secondary information available from the Department of Hydrology and Meteorology, Nepal (hydrological and meteorological data), the International Centre for Integrated Mountain Development, Kathmandu (information related to glaciers) and the Central Bureau of Statistics, Nepal (socio-economic information). This study could not verify the accuracy of these data by direct observations.
- The glacier sensitivity analysis was based on the data only from the Langtang station, though there are other five glaciological stations in Nepal. Further analysis is necessary using all the glaciological stations in order to get more accurate results.
- Precipitation data recorded at the Langtang station was taken as the representative for the whole Langtang Basin under study, though it may not be accurate enough due to mountainous topography.

Chapter IV: Empirical Findings on Climate Change in Nepal

4.0 General

Long-term temperature and precipitation records from different physiographic regions of central Nepal were analysed. Annual and seasonal maximum, minimum and mean temperatures from each of the meteorological stations were separately assessed in order to identify trends in the temperature records. Similarly, the amount of precipitation and number of rainy days were also analysed in order to detect the changes in precipitation amount and pattern during the study period.

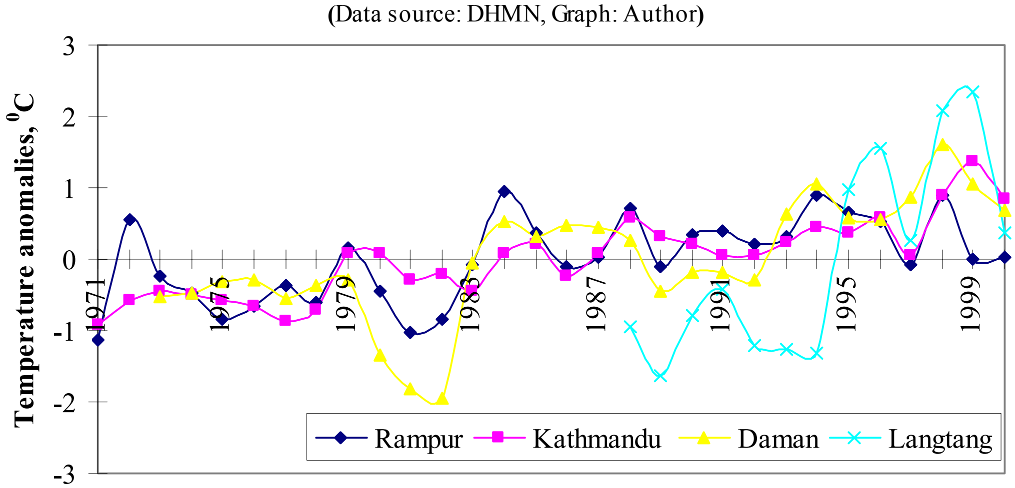
4.1 Temperature Change

4.1.1 Empirical Findings on Temperature Change

To begin with, the mean temperature data from all four reference stations were analysed. Annual and seasonal temperature trends were calculated separately for each station and for each season. Statistical tests of the temperature data showed the existence of the trends in the records. The results of the analysis of the mean temperature record clearly showed that all the stations had positive trends and the temperature trends were more pronounced in the higher altitudes (see Figure 4.1).

Figure 4.1: Mean temperature anomalies (1971-2000)

(Data source: DHMN, Graph: Author)



The trend values for the Langtang station located in the Himalayan region were relatively higher, but the errors in the calculated values were also higher for this station. The temperature data for the Langtang station were available for only 13 years (1988-2000), not long enough to come to a definite quantitative conclusion about the trend values. Therefore, the output values from the Langtang station should be used with greater caution. Nevertheless, the trends from the Langtang station qualitatively told us that the Himalayan areas were warming more rapidly than the lower altitude areas (see Table 4.1).

Table 4.1: Annual and seasonal mean temperature trends of reference stations

Station	Data period	Altitude, masl	Mean Temperature Trend, ºC/year				
			Annual	Pre-monsoon	Monsoon	Post-monsoon	Winter
			Jan-Dec	Mar-May	Jun-Sep	Oct-Nov	Dec-Feb
Rampur	1971-2000	286	0.04 [a] *(0.0014)*	0.01 [b] *(0.0024)*	0.06 [a] *(0.0015)*	0.06 [a] *(0.0030)*	0.02 [b] *(0.0025)*
Kathmandu Airport	1971-2000	1336	0.05 [a] *(0.0008)*	0.05 [a] *(0.0022)*	0.04 [a] *(0.0008)*	0.05 [a] *(0.0019)*	0.08 [a] *(0.0017)*
Daman	1973-2000	2314	0.07 [a] *(0.0021)*	0.08 [a] *(0.0039)*	0.06 [a] *(0.0024)*	0.08 [a] *(0.0031)*	0.06 [a] *(0.0030)*
Langtang	1988-2000	3920	0.27 [a] *(0.012)*	0.34 [a] *(0.016)*	0.27 [a] *(0.010)*	0.30 [b] *(0.018)*	0.15 [b] *(0.016)*

Note: Values in the parentheses indicate the error on estimation of trends,
[a] - Trends are significant at 0.05 levels,
[b] - Trends are significant at 0.1 levels.

As far as the seasonal trends are concerned, no definite conclusions in terms of stations or seasons could be drawn. For example, the monsoon season was warming faster than others at the Rampur station, whereas the winter season was warming faster than others at the Kathmandu station. There was one thing common to all seasons and all stations: all the stations had a warming trend in all seasons, though the magnitudes of the warming were different.

After analysing the mean temperatures, an attempt was made to find out the component of temperature values responsible for warming trends. The mean temperatures for all the reference stations were increasing. Was this because of an increase in maximum temperatures or an increase in minimum temperatures or both? In order to answer this, the maximum and minimum temperatures were also analysed (see Table 4.2; Annex 4.1).

Table 4.2: Minimum, maximum and mean annual temperature trends

Temperature data	Temperature Trends, ºC/year			
	Rampur	Kathmandu Airport	Daman	Langtang
Period	1971-2000	1971-2000	1973-2000	1988-2000
Maximum	0.05 * *(0.0016)*	0.09 * *(0.0011)*	0.10 * *(0.0022)*	0.32 * *(0.0129)*
Mean	0.04 * *(0.0014)*	0.05 * *(0.0080)*	0.07 * *(0.0021)*	0.27 * *(0.0123)*
Minimum	0.03 ** *(0.0018)*	0.01 ** *(0.0012)*	0.04 ** *(0.0040)*	0.26 * *(0.0123)*

Note: * - Significant at 0.05 level; ** - Significant at 0.1 level
Values in parentheses indicate the error on the estimation of trends

The analysis showed that the maximum temperature trends were higher than the minimum temperature trends for all stations. This showed that the temperature ranges (i.e. difference between maximum and minimum temperatures) were increasing in all stations for the study period. In order to avoid the error related to base year, the annual temperature trends for all the stations were again calculated for the period of 1988-2000 (see Table 4.3) and compared with the values presented in Table 4.1.

Table 4.3: Annual temperature trends of reference stations for 1988-2000

Station	Altitude, masl	Mean annual temperature, ºC	Trend, ºC/year	Error in trend, ºC/year	Significance level
Rampur	286	24.4	Trend is statistically not significant		
Kathmandu Airport	1336	18.8	0.06	0.0044	0.1
Daman	2314	13.7	0.12	0.0055	0.05
Langtang	3920	2.9	0.27	0.0122	0.05

A comparison of the findings from Table 4.1 and Table 4.3 reveals that the rate of warming is more pronounced in the higher altitudes and the rate of warming has increased in the recent decade. For example, the rates of warming at the Kathmandu Airport and the Daman stations for the period of 1988-2000 were 0.06 and 0.12 ºC/year whereas those at the same stations for the whole observation period were 0.05 and 0.07 ºC/year respectively .

4.1.2 Discussion of Empirical Findings on Temperature Change

The outputs of the analysis on temperature trend revealed a faster warming trend in Nepal than the global average. The lowest calculated value of mean temperature trend was found at the Rampur station of 0.04ºC yr^{-1}. Even this was higher than the annual average land-surface temperature trends for the globe (i.e. 0.011-0.022ºC yr^{-1}) and for the northern hemisphere (i.e.

0.018-0.031ºC yr^{-1}) for the period of 1976-2000 as reported by IPCC (2001c, p.108). Shrestha et al. (1999, p.2781) showed earlier that maximum temperatures for the period of 1971-94 in Nepal were increasing at a rate of 0.06ºC yr^{-1}. Likewise, the annual maximum temperatures in southern low-altitude regions of Nepal were increasing by 0.04ºC yr^{-1} while those in northern high-altitude regions were increasing by 0.06-0.12ºC yr^{-1} for the same period (ibid, p.2775; Shrestha, 2001, p.92). Shrestha (1997, p.26), while developing climate change scenarios with reference to Nepal, also reported that the stations at higher elevations showed more increase in temperature than at lower elevations in a scenario with doubling of CO_2. Similar trends were also found on the other side of the Himalayas on the Tibetan Plateau where the temperature trends were less than 0.005ºC yr^{-1}at elevations lower than 500 m whereas the trends were more than 0.03ºC yr^{-1}at elevations higher than 4000 m (Agrawala et al., 2003, p.14). Both of these findings on the southern and northern sides of the Himalayas have reinforced the finding of the present study that the temperatures in the higher altitudes are increasing faster than those in the lower altitudes.

The mean temperature trend at the Langtang station, located in the high Himalayan region, was almost 4-7 times higher than that in the low-altitude stations. A possible explanation for this may be a reduction of snow-covered areas in the Langtang regions due to warming. The reduction in snow-covered areas due to a temperature rise results in the reduction in albedo[1] in the areas. Albedo is highly variable for different surfaces. It may be as large as 0.95 for freshly fallen snow and as small as 0.05 for a wet bare soil (Allen et al., 1998, p.43). A reduction in surface albedo would result in more absorption of solar radiation, the major source of warming. Moreover, snow-melt moistens the soil surface and gives way to soil moisture feedback to the atmosphere, an additional source of natural greenhouse warming (Meehl, 1994, p.1034; Shrestha et al., 1999, p.2781; Fujita et al., 1997, p.587). Melting of snow, thus, provides a strong positive feedback to warming and amplifies the warming effect.

Maximum temperature trends were higher than minimum temperature trends for all the reference stations which confirmed the previous findings by Sharma et al. (2000a, p.153) for Kathmandu Valley for 1971-92. This indicated that the temperature ranges were widening during the study period, which contradicted the IPCC findings on global trends of maximum and minimum temperatures. The IPCC (2001c, p.108) reported that overall global maximum

[1] The fraction of the solar radiation reflected by the surface is known as albedo.

temperature was increasing by 0.01ºC yr^{-1}, whereas the minimum temperature was increasing by 0.02ºC yr^{-1} during 1950-1993 leading to narrowing temperature ranges.

The trend analysis further revealed that the difference between the trends in the maximum and minimum temperatures was the highest for the Kathmandu Airport station. A possible explanation for this may be the effect of rapidly increasing urbanization in the Kathmandu valley (Sharma et al., 2000a, p.153). Similar trends were found for the seven meteorological stations around the Kali Gandaki river in Nepal, where the maximum, mean and minimum temperatures were increasing by 0.26, 0.25 and 0.24ºC/decade respectively for the period of 1970-2000 (Shrestha, 2005, p. 73). The maximum and minimum temperatures for 1961-2000 from Siran watershed in the moist Himalayas of Pakistan were increasing by 0.2 and 0.1ºC/decade respectively (ibid).

Similarly, the mean temperature in the Alkananda valley in India was increasing by 1.5ºC/decade (Shrestha, 2005, p.73). Despite a rapid warming in the Nepal Himalayas, the all-India mean temperature was increasing only by 0.03ºC/decade for 1901-98 (Rupa Kumar et al., 2002, p.46), much slower than the global warming trend of 0.058ºC/decade for the period of 1901-2000 (IPCC, 2001a, p.115). These figures suggest that the temperature differences between low-altitude areas of Nepal/India and high-altitude Himalayan regions would be greater in the future due to an increasing warming. This situation will create a new temperature gradient that might affect atmospheric circulation, monsoon dynamics and extreme weather events. Land and sea have different cooling and heating properties- land mass will heat and cool faster than the sea. Increasing temperatures, therefore, will result in greater land-sea temperature contrast. Meehl (1994, p.1047) reported that a strong summer monsoon with heavy precipitation was associated with high temperatures over the southern Asian land area, low snow cover and low albedo. Because of being one of the most important actors of the hydrological cycle, temperature plays a great role in moisture circulation. Any changes in the temperature regime, therefore, will require new balance conditions in the hydrological cycle that will impact all the components of the cycle.

To conclude, the temperatures in Nepal are increasing at a faster rate than the global average. Furthermore, the high-altitude regions are warming faster than the low-altitude ones.

4.2 Precipitation Change

4.2.1 Empirical Findings on Change in Precipitation Amount

Precipitation records are more sensitive to exposure, aspect, surface roughness and surface heating (WMO, 1966b, p. 10) than temperature records. However, an attempt was made to identify whether there are some significant changes over time and space in the precipitation amount and patterns for the reference stations. The run test (i.e. the run above and below the mean), a procedure that examines consecutive occurrences of a variable, showed that the precipitation data from all four stations did not have any significant trends but they contained oscillations. Too many runs in the tests indicated the presence of oscillation (WMO, 1996a, p.5.31).

The trends, their confidence limits and the errors on estimation for all the reference stations were calculated by a simple linear regression analysis. Rampur and Kathmandu precipitation records clearly showed an oscillation because the numbers of runs were higher than 50% of the cases. Daman showed a weak trend as the number of runs was just below the 50% line of the cases (i.e. 46%). In contrast, the precipitation records from Langtang clearly showed a trend in the record with a significance level of 0.025 as the number of runs was only 23% of the cases. On the other hand, the trends contained a higher level of uncertainties due to the presence of relatively larger errors on estimation up to 40% of the calculated trend values (see Table 4.4).

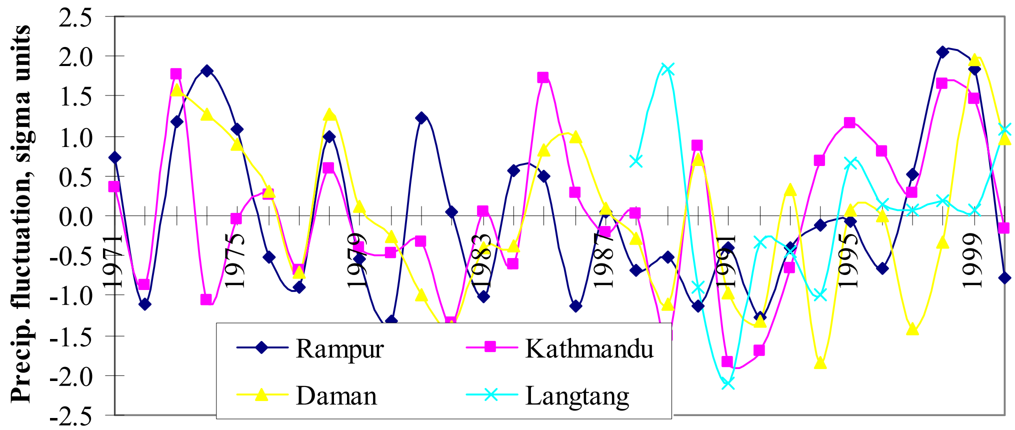
Table 4.4: Analysis of trends in annual precipitation records

Station	Av. precip., mm	Runs Test		Trend detection			Remarks
		Cases	Runs	Trends, mm/yr	Error, mm	Confidence %	
Rampur	1961	30	16	-0.31	0.91	<1	Clear oscillation
Kathmandu	1439	30	18	4.22	0.60	85	Weak oscillation
Daman	1807	28	13	-9.99	3.38	65	Weak trend
Langtang	587	13	3	4.75	1.86	60	Clear trend

In order to compare fluctuations in mean annual precipitation among different stations, all precipitation series were standardised by subtracting means and dividing by the standard deviations (Shrestha et al., 2000, p.319) and expressed in sigma units (see Figure 4.2).

Figure 4.2: Fluctuation of standardized precipitation (1971-2000)

(Data source: DHMN; Graph: Author)



4.2.2 Empirical Findings on Change in Number of Rainy Days

Though there were no definite trends in precipitation, the number of rainy days was analysed in order to find out whether there were any trends in the precipitation pattern (see Table 4.5; Annex 4.2). The analysis could detect decreasing trends in the number of rainy days at three out of four stations. The findings show that only Langtang (the Himalayan station) had a positive trend and other lower altitude stations had negative trends in the annual number of rainy days.

Table 4.5: Fluctuations of number of rainy days at reference stations

Stations	Annual number rainy days				Number of July-August rainy days			
	Av., day	Trend, day/yr	Trend, %/yr	Confid. limit, %	Av., day	Trend, day/yr	Trend, %/yr	Confid. limit, %
Rampur	106	-0.023	-0.02	<1	45	0.09	0.20	85
Kathmandu	111	-0.041	-0.04	40	46	0.16	0.35	90
Daman	119	-0.430	-0.36	90	50	0.02	0.04	40
Langtang	97	0.445	+0.45	60	44	1.18	2.68	90

On the other hand, the number of rainy days in July-August (the heart of the monsoon season) had positive trends for all stations. Moreover, the increasing trend in July-August rainy days at the Langtang station was almost 6 times higher than that in the annual number of rainy days. Though the annual trend was not uniform, it was very clear for all stations that rainy days were concentrating to the monsoon season resulting in a longer drought period.

In the next step, the study aims to find out whether there are any changes in the amount of daily precipitation. The analysis of trends in the number of rainy days ordered by the amount of precipitation in 24 hours from the reference stations revealed that the rainy days with a higher amount of daily precipitation were increasing, while those with a lower amount of daily precipitation were decreasing (see Table 4.6).

Table 4.6: Trends in number of rainy days as per daily precipitation

Station	Number of rainy days								
	With daily precipitation < 25mm			With daily precipitation 25-50 mm			With daily precipitation >50 mm		
	Av. No.	Trend, day/year	Trend, %/year	Av. No.	Trend, day/year	Trend, %/year	Av. No.	Trend, day/year	Trend, %/year
Rampur	80	-0.07 (0.60)	-0.09	16	0.08 (85%)	0.50	9	Not significant	-
Kathmandu Airport	94	-0.20 (85%)	-0.21	13	0.16 (95%)	1.23	4	0.011 (45%)	0.28
Daman	99	-0.34 (90%)	-0.34	14	-0.13 (90%)	-0.93	5	0.06 (80%)	1.20
Langtang	96	+0.34 (50%)	+0.35	1	0.08 (80%)	+8.00	NA	NA	NA

Note: Figures in parentheses indicate confidence limits of the trends

In the case of the Langtang station, all types of rainy days were increasing but the days with higher precipitation were increasing much faster than the days with lower precipitation. For example at the Langtang station, the number of days with daily precipitation of more than 25 mm was increasing more than 10 times faster than that with daily precipitation of less than 25 mm.

Similarly, decade-to-decade changes in the precipitation parameters were also evaluated because of the presence of interannual and decadal variability in the precipitation series in Nepal (Shrestha et al., 2000, p.321). Only three stations were taken for this purpose- Rampur (286 m), Kathmandu Airport (1336 ma) and Daman (2314 m) (see Table 4.7). The results from the Table 4.7 again supported the results of Table 4.6 by indicating a greater change in precipitation patterns at higher altitudes, a larger increase in more intense precipitation events and a decrease in the number of rainy days. However, this study could not find any uniform trends in precipitation amount at the studied stations.

Table 4.7: Analysis of precipitation at Rampur, Kathmandu and Daman (1971-2000)

Period	Number of rainy days with 24-hour rainfall					Total precipitation, mm	Total number of rainy days
	<100 mm	100-199 mm	200-299 mm	300-400 mm	> 400 mm		
Rampur							
1971-1980	1076	21	1	0	0	20270	1098
1981-1990	1029	15	2	0	0	19200	1046
1991-2000	1060	10	3	0	0	20359	1073
Kathmandu							
1971-1980	1357	3	0	0	0	14263	1360
1981-1990	1344	1	0	0	0	14217	1345
1991-2000	1331	0	0	0	9	15446	1340
Daman							
1981-1990	1230	5	0	0	0	17306	1235
1991-2000	1120	6	1	2	0	17063	1129

Source: Data from DHMN, analysed by author

As the results of Table 4.7 show, the Rampur station had less visible trend in total number of rainy days than other two higher altitude stations. The total number of rainy days and the number of rainy days with daily precipitation of less than 100 mm were decreasing while those with daily precipitation of more than 100 mm were increasing.

4.2.3 Discussion of Empirical Findings on Precipitation Change

The findings of this study could not find definite long-term trends for 3 out of 4 stations. The analysis of present research revealed a clear oscillation for Rampur (286 masl [2]), a weak oscillation for Kathmandu (1336 masl), a weak trend for Daman (2314 masl) and a clear trend for Langtang (3920 masl). This means that the precipitation record had clearer trend from lower to higher altitudes. Earlier, Kothyari and Singh (1996, p.357) found out that the precipitation in India was decreasing during 1901-89. The IPCC (2001b, p.543) reported that there was no distinct trend in long-term rainfall series in India. Kripalani et al. (1996, p.689) pointed out that rainfall variability in Nepal was well related with rainfall variations over northern and central India, but not with all-Indian rainfall variations. Shrestha et al. (2000, p. 317) earlier found out that there was no long-term trend in all-Nepal annual precipitation series for 1948-1994. Recently, Nayava (2004, p.32) pointed out that the number of rainy days was decreasing for the period 1971-2000 at 17 rain gauge stations across Nepal while the intensity of rainfall was increasing for the same period.

[2] masl – metres above sea level

The findings of the current research reinforced these earlier findings except for the Himalayan station of Langtang, which suggest that the precipitation trends and patterns in the high Himalayan regions might not be the same as in the lower altitude regions. Furthermore, this study has revealed that the number of days with lower precipitation is decreasing while that with higher precipitation is increasing. This tendency has clearly indicated a prolonging drought period and increasing likelihoods of landslides and floods.

Despite lack of clear trends in annual precipitation, the number of rainy days was decreasing in low altitude stations and increasing in the high altitude station of Langtang. In addition, the rainy days with lower rainfall (i.e. < 25 mm/day) were decreasing while those with heavier rainfall were increasing in the three lower altitude stations. In the case of Langtang, all types of rainy days were increasing; moreover, the rate of increase in rainy days with heavier precipitation was much higher than that with lighter precipitation. These findings suggest a clear change in precipitation pattern. Chaulagain (2003, p. 187) reported that annual rainy days at the Jiri station (2003 masl) in eastern Nepal was decreasing by 0.4% per year while the rainy days with daily precipitation of more than 50 mm were increasing by 2% per year. The IPCC (2001b, p.543) pointed out that there was some evidence of increases in the intensity and frequency of extreme weather events like intense rainfall, prolonged dry spells etc in Asia throughout the 20th century.

4.3 Conclusion

4.3.1 Summary of Findings

The aforementioned analysis and discussion on temperature and precipitation records at reference stations in the current study suggest that there are significant changes in temperature and precipitation pattern. The changes in high-altitude regions are more pronounced than those in low-altitudes. The temperatures in higher altitudes were increasing much faster than those in lower altitudes. The high-altitude precipitation was increasing, whereas there were no significant trends in precipitation in low-altitudes. The number of days with heavier precipitation was increasing despite the decreasing trend of the total annual number of rainy days indicating the increasing likelihoods of droughts, floods and landslides. It once again became clear that high-altitude Himalayan regions are very sensitive to climate change and low altitude research results often cannot simply be extrapolated to high altitude regions.

4.3.2 Open Questions

About 43% of Nepal's total areas lie above 3000 masl, but only about 6% of the meteorological stations are located above this elevation (CBS, 2004a, p.15; Grabs and Pokhrel, 1992, p. 4). Similarly, about 23% of the areas lie above 5000 masl but there is no existing meteorological station above this altitude in Nepal (ibid). Therefore, the high-altitude regions of the Nepal Himalayas are largely under-represented by the climatological network. How is the climate changing in the high mountains of the Nepal Himalayas? Furthermore, there are very limited sub-daily precipitation data, which are not properly analysed yet. How are the daily or hourly precipitation patterns changing with climate in Nepal? How does changing climate affect the intensity of precipitation in an hour or in shorter time period? More climatological data should be analysed covering wider spatial and temporal scale in order to answer these questions.

Chapter V: Empirical Findings on the Physical Impacts

5.0 General

Any changes in temperature and precipitation may affect the evapotranspitation, soil moisture, river flows and snow/glacier regime. This chapter aims to quantify the impacts of climate change on these parameters in the Nepal Himalayas analysing the hydrological, meteorological and glaciological information from the study basins and sample sites of the study.

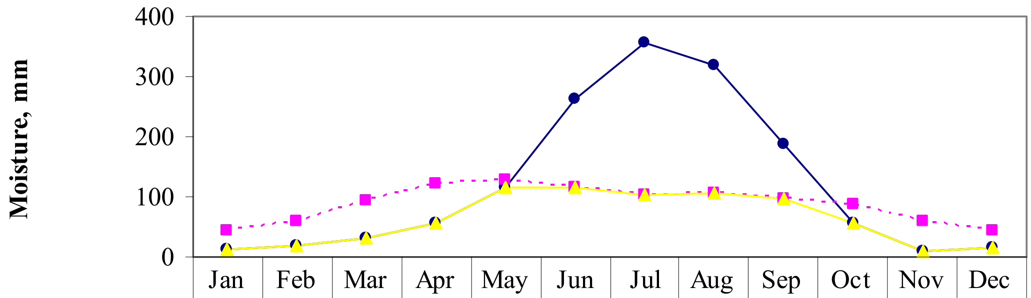
5.1 Impacts on Evapotranspiration and Moisture Balance

5.1.1 Empirical Evidence on Impacts on Evapotranspiration and Moisture Balance

Evapotranspiration is directly proportional to the vapour deficit (i.e. the difference between saturation vapour pressure and actual vapour pressure) in the atmosphere. With an increase in temperature, the saturation vapour pressure (i.e. the ability of the atmosphere to hold water) increases exponentially. Actual evapotranspiration may be equal to or less than the potential evapotranspiration depending on the supply of water to the atmosphere. In order to find out the potential and actual evapotranspiration, the average monthly weather parameters, such as precipitation, maximum and minimum temperatures, relative humidity, wind speed, sunshine hours and solar radiation data for the period of 1971-2000 from the Kathmandu Airport meteorological station were analysed. Potential evapotranspiration was calculated using the FAO Penman-Monteith equation.

The analysis of the average monthly precipitation, actual evapotranspiration and potential evapotranspiration at the Kathmandu Airport showed that potential evapotranspiration exceeded the actual evapotranspiration and the atmosphere remained largely under a moisture deficit for eight out of twelve months (i.e. from October to May). There was a moisture surplus only for the summer monsoon months from June to September (see Figure 5.1).

Figure 5.1: Mean monthly moisture balance at Kathmandu Airport



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
P	13.7	17.41	30.31	56.9	116.3	261.6	356.5	319.6	186.9	56.67	7.897	15.09
PET	45.24	59.38	94.14	120.4	127.5	116.4	102.8	106.5	95.48	86.21	60.11	43.87
AET	13.7	17.41	30.31	56.9	116.3	116.4	102.8	106.5	95.48	56.67	7.897	15.09

Note: P= precipitation, PET= potential evapotranspiration; AET = actual evapotranspiration

Increasing temperatures might further cause deterioration in the moisture balance conditions. A sensitivity analysis of the atmospheric moisture to temperature change (from +1ºC to +5ºC) has shown that moisture deficit increases faster than evapotranspiration. For example, a 5^0C rise in temperature could result in an increase in the actual evapotranspiration of only 6.6% despite an increase in the potential evapotranspiration (i.e. evaporative demand) of 13.1%. This is because actual evaporation is constrained by the availability of moisture in the surroundings despite an increased evaporative demand. Assuming no change in precipitation, the moisture deficit will increase by 28%, if there is a rise in temperature of 5^0C (see Table 5.1).

Table 5.1: Sensitivity analysis of atmospheric moisture to a temperature rise

Parameters	Temperature change scenarios					
	T_0	T_{+1}	T_{+2}	T_{+3}	T_{+4}	T_{+5}
PET, mm	1058	1085	1112	1140	1168	1197
Change, %	0	2.6	5.1	7.8	10.4	13.1
AET, mm	735	745	755	764	774	784
Change, %	0	1.3	2.6	3.9	5.2	6.6
Annual deficit, mm	-323	-340	-358	-376	-394	-413
Change, %	0	-5.4	-10.9	-16.5	-22.2	-28.0
Max. monthly deficit, mm	-64	-67	-69	-72	-75	-78
Month	March	April	April	April	April	April

Note: PET – Potential evapotranspiration, AET – Actual evapotranspiration

The alteration in the atmospheric moisture will have a direct impact on the soil moisture conditions. The soil moisture storage conditions for two separate crops, namely shallow-rooted (i.e. maximum storage of 100 mm) and deep rooted (maximum storage of 200 mm) were analysed with different temperature change scenarios (up to a 5ºC rise in mean temperatures). At present, there is a crop-growing season of 6 months (June-November) for shallow-rooted crops and 9 months (June-February) for deep-rooted crops with the existing soil moisture storage and without any application of artificial irrigation. The crop-root zone is fully saturated for only 4 months (June-September) in the case of shallow-rooted crops and for 3 months (July-September) in case of deep-rooted crops (see Table 5.2).

Table 5.2: Sensitivity of soil moisture storage with a temperature rise at Kathmandu Airport

Month	Soil moisture storage, mm											
	Shallow-rooted crops						Deep-rooted crops					
	T_0	T_{+1}	T_{+2}	T_{+3}	T_{+4}	T_{+5}	T_0	T_{+1}	T_{+2}	T_{+3}	T_{+4}	T_{+5}
Jan							58	51	44	36	29	21
Feb							16	7				
Mar												
Apr												
May												
June	100	100	100	100	100	100	145	142	140	137	134	132
July	100	100	100	100	100	100	200	200	200	200	200	200
Aug	100	100	100	100	100	100	200	200	200	200	200	200
Sept	100	100	100	100	100	100	200	200	200	200	200	200
Oct	70	68	66	63	61	58	170	168	166	163	161	158
Nov	18	14	10	6	1		118	114	110	106	101	96
Dec							89	84	78	72	66	60
Annual	489	482	476	469	462	458	1197	1166	1137	1115	1092	1068
Change, %		-1.3	-2.7	-4.1	-5.5	-6.2	0.0	-2.6	-5.0	-6.9	-8.8	-10.8

Note: The numbers in subscription with T indicate the rise in mean temperature in ºC

Without artificial irrigation facility, shallow-rooted crops are already facing water shortages during most of the dry seasons. A warming would further exacerbate the problem of water shortages for the crops. For example, a temperature increase of 5ºC would cause a reduction in the annual soil moisture storage of 6.2% and 10.8% for the shallow-rooted and the deep-rooted crops respectively. With a warming of 5ºC, the growing season for the deep-rooted crops and the shallow-rooted crops could decrease to 8 months and to 5 months respectively (see Table 5.2).

The seasonal impact of a temperature rise may be more significant and pronounced than the annual average effect. A substantial surplus of precipitation during the summer monsoon (June-September) could mask an increasing deficit during the dry seasons. A further warming could exacerbate the water stress especially during the dry seasons, which are already facing a moisture deficit.

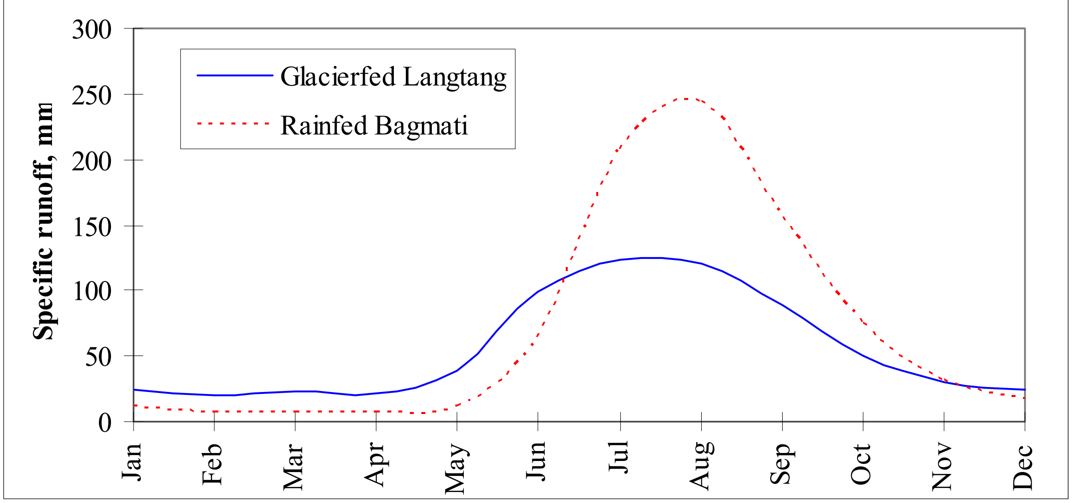
5.1.2 Discussion about the Impacts on Evapotranspiration and Moisture Balance

Rising temperatures increase evaporation from land surfaces and water bodies, which could increase atmospheric water content. Increasing water vapour in the atmosphere could enhance the greenhouse-gas effect and thereby could cause a further rise in the global temperature (Mirza and Dixit, 1997, p.75). Higher temperatures and reduced snow cover can cause reduced soil moisture (IPCC, 2001a, p.199). Increased evaporation could increase the moisture deficit and could reduce the ground water recharge that may adversely affect the river runoff. Additionally, increased evaporation and decreased soil moisture might result in an increased demand on water for irrigation. Without any modern irrigation facilities, a reduction in soil moisture storage can cause a shortening of the growing season for the agricultural land (Vinnikov, 1992, p.126). Increased temperatures may widen the gap between demand and supply of irrigation water, which could have a direct impact on the agricultural production and the farming activities.

5.2 Impacts on the River Flows

There are apparent differences in flow patterns between rain-fed and glacier-fed rivers. The climate of Nepal is dominated by the monsoon. The runoff of the rain-fed rivers is only due to precipitation, whereas that of the glacier-fed rivers consists of glacier-melt as well. Analysis of the long-term river runoff data from both the Langtang and Bagmati basins showed a visible difference in variations of monthly hydrographs between the glacier-fed Langtang Khola and the rain-fed Bagmati River (see Figure 5.2) despite the variations in monthly precipitation for both cases being almost the same (see Table 5.3). For example, the ratios of maximum to minimum monthly precipitation for the Langtang and for the Bagmati were 43 and 45 respectively, while the ratios of maximum to minimum monthly discharge for the same were 6 and 34.5 respectively. The snow and glacier melt component most probably has helped maintain a sustained flow in the glacier-fed river even during the non-rainy seasons.

Figure 5.2: Comparative mean monthly hydrographs



Data source: DHMN; Graph by author

The Figure 5.2 clearly illustrates that there is a greater variability of flows, i.e. higher likelihood of floods and droughts in the rain-fed Bagmati River than in the glacier-fed Langtang Khola. The hydrograph of the present glacier-fed rivers may take the shape of that of the rainfed rivers in the future after the glaciers disappear due to a temperature rise. Therefore, it is likely that disappearance of glaciers will enhance the variability of flows.

Table 5.3: Precipitation and river runoff of the Langtang Khola and the Bagmati River

	Basin	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
P, mm	A	17.2	17.2	23.0	23.1	33.2	74.2	112.0	163.4	82.2	15.2	7.8	3.8
	B	13.7	17.4	30.3	56.9	116.3	261.6	356.5	319.6	186.9	56.7	7.9	15.1
q, mm	A	23.8	20.5	23.5	22.2	39.2	99.2	123.3	120.8	89.0	50.2	30.6	23.8
	B	11.5	7.7	7.1	7.9	11.3	64.4	207.8	244.6	156.9	75.1	30.9	17.8

Note: P= Precipitation; q= Specific runoff; A= Glacier-fed Langtang; B= Rain-fed Bagmati

The rain-fed river has the highest flow in August whereas the glacier-fed river has the highest flow in July because there is a significant melt-water component in the glacier-fed river. Any changes in precipitation and temperature may have a direct impact on the runoff pattern and the water balance of the whole river system.

5.2.1 Runoff Modelling of the Bagmati River at Chovar

In order to detect the impacts of climate changes on river flows, the water balance model *WatBal* was applied at the Chovar hydrological station of the Bagmati River. The Bagmati River is one of the major rain-fed rivers of Nepal, which originates at Shivpuri in the north east corner of the Kathmandu Valley at about 2760 metres above sea level (masl). The river crosses the capital city of Kathmandu, currently experiencing the highest population pressure in Nepal. It passes through the middle mountains, mid-hills and low plain areas down to the Nepal-India border at about 73 masl. The hydrological station Chovar of the Bagmati River is located at an altitude of 1280 masl with a catchment area of 585 km^2. The average monthly hydrological and meteorological data, viz. river flow, temperature, precipitation, relative humidity, sun shine hours and wind speed were used as the input variables for calibration and validation of the model. The hydrologic data observed by the Chovar station (DHMN Index No 550) and meteorological data by the Kathmandu Airport station (DHMN Index No 1030) were included in the model calibration and validation. The model was calibrated with the observed data for 60 months (1971-1975). The model parameters identified during the calibration were validated with the data for another 60 months (1976-1980). The input data and identified model parameters are:

	Input data	Correlation coefficient	Error, mm
Calibration	1976-1980	0.93	916
Validation	1971-1975	0.91	2376

Subsurface runoff coefficient (SSRC), $\alpha = 136.5$

Surface runoff (SRC), $\varepsilon = 4$

Initial storage, $Z_i = 0.15$

Temperature changes: +1ºC to +5ºC

Base flow = 4.03 mm/month

Direct runoff coefficient = 0.005

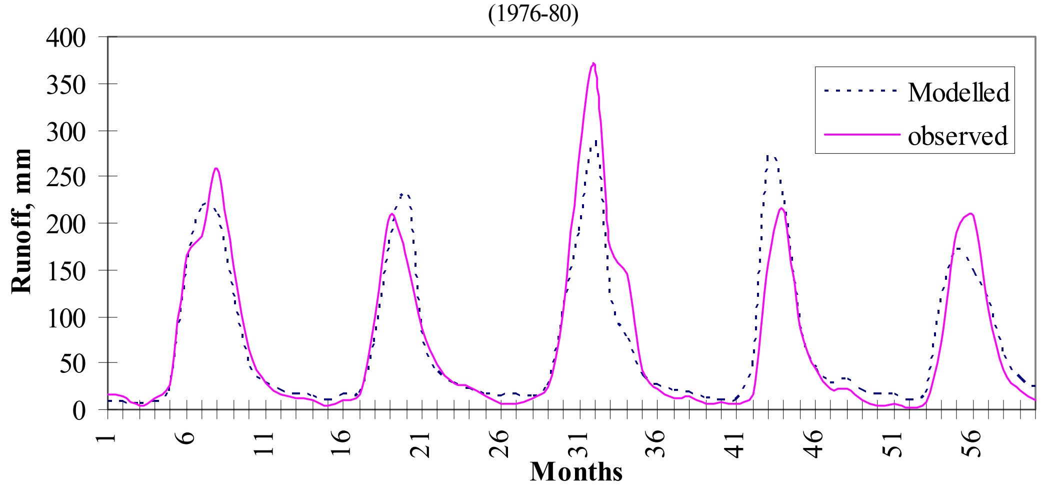
Maximum storage, S_{max}= 624 mm

Precipitation changes: -10% to +10%

The model outputs have revealed that the modelled and observed runoff values are quite comparable except for peak flood months (see Figure 5.3a, Annex 4.3).

Figure 5.3a: Modelling of the Bagmati River Runoff at Chovar

(1976-80)



After identifying the model parameters, a sensitivity analysis was carried out by changing the temperature and the precipitation in order to detect impacts of the temperature and precipitation changes on the river runoff. The temperatures were changed from T_{+1} (i.e. temperature rise of 1ºC) to T_{+5} (i.e. temperature rise of 5ºC) and precipitation from P_{-10} (i.e. precipitation decrease of 10%) to P_{+10} (i.e. precipitation increase of 10%) (see Table 5.4).

Table 5.4: Sensitivity of the river runoff to climate change at the Chovar station

	Change in Runoff, %					
	T_0	T_{+1}	T_{+2}	T_{+3}	T_{+4}	T_{+5}
P_{-10}	-11.6	-13.9	-14.7	-15.5	-17.0	-17.4
P_{-5}	-5.7	-8.0	-9.5	-11.0	-11.4	-14.0
P_0	0	-1.5	-2.8	-4.4	-5.8	-7.5
P_{+5}	6.6	5.1	3.5	2.1	0.1	-1.1
P_{+10}	13.6	12.0	10.4	8.8	7.2	3.6

Note: The subscriptions of T & P denote the changes in temperature (ºC) & precipitation (%)

The results in Table 5.4 show that the runoff has a negative correlation with temperature change but a positive correlation with precipitation change. There will be a 7.5% decrease in annual runoff with a 5ºC rise in the temperature assuming no change in precipitation. Similarly, a 10% decrease in the precipitation and a 5ºC rise in the temperature may result in a 17.4% decrease in the river runoff of the Bagmati River at Chovar.

5.2.2 Runoff Modelling of the Langtang Khola at Langtang

After modelling the runoff of the rain-fed Bagmati River, the runoff modelling was made with *WatBal* model for the glacier-fed Langtang Khola too. The Langtang Khola is one of the very few glacier-fed rivers with continuous hydrological data since 1988 in the Nepal Himalayas. The hydrological as well as meteorological data for modelling were obtained from the Snow and Glacier Hydrology Unit of the Department of Hydrology and Meteorology in Nepal, which were recorded at the Langtang (Kyangjing) station. The model was calibrated with the observed data for 72 months (1993-98) and validated with the data for another 60 months (1988-1992). The basin area upstream of the modelling site is 340 km^2, out of which 142 km^2 is currently covered by glaciers. About 61% of the total basin area is located above 5000 masl. The altitude of the Langtang hydrological station is 3800 masl. The highest point within the basin is at 7232 masl. The input data and identified model parameters are as following:

	Input data	Correlation coefficient	Error, mm
Calibration	1993-1998	0.84	508
Validation	1988-1992	0.74	968

Subsurface runoff coefficient, α = 19.04 | Base flow = 15.2 mm/month

Surface runoff (SRC), ε = 0.14 | Direct runoff coefficient (DRC) = 0.005

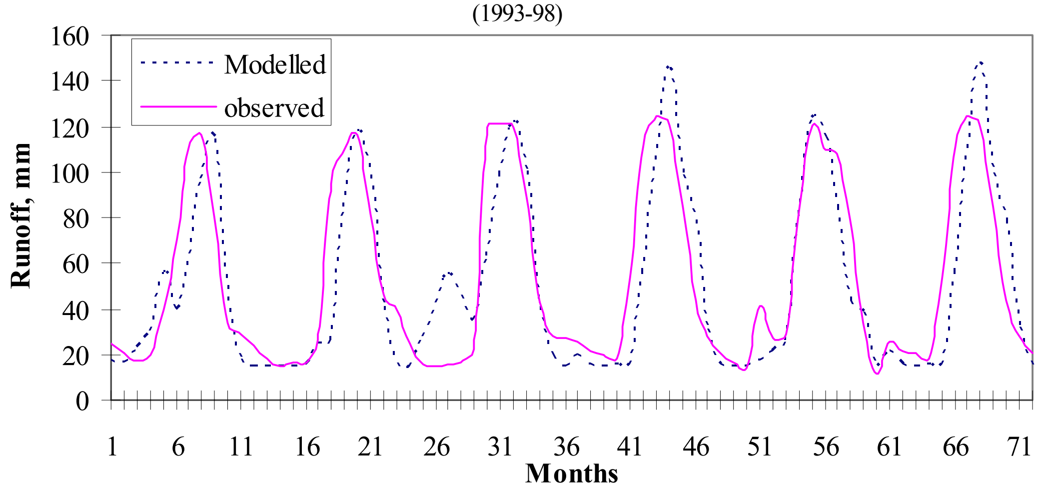
Initial storage, Z_i = 0.5 | Maximum storage, S_{max}= 81 mm

Temperature changes: +1ºC to +5ºC | Precipitation changes: -10% to +10%

The model output is given in Figure 5.3a (see also Annex 4.4).

Figure 5.3b: Runoff Modelling of the Langtang Khola at Langtang

(1993-98)



A sensitivity analysis for the Langtang Khola was carried out for the temperature changes from +1^{0}C to +5^{0}C and the precipitation changes from -10% to +10% (see Table 5.5).

Table 5.5: Sensitivity of the Langtang Khola runoff to climate change at Langtang

	Change in Runoff, %					
	T_0	T_{+1}	T_{+2}	T_{+3}	T_{+4}	T_{+5}
P_{-10}	-6.4	-6.8	-6.9	-7.0	-7.1	-7.4
P_{-5}	-1.9	-2.1	-2.3	-2.9	-3.5	-4.2
P_0	0	-0.2	-0.3	-0.4	-0.5	-0.6
P_{+5}	3.6	2.4	2.3	2.2	1.9	1.6
P_{+10}	6.2	5.2	4.0	3.2	2.2	1.9

Note: The subscriptions of T & P denote the changes in temperature (ºC) & precipitation (%)

5.2.3 Synthesis of the Runoff Modelling of the Bagmati River and the Langtang Khola

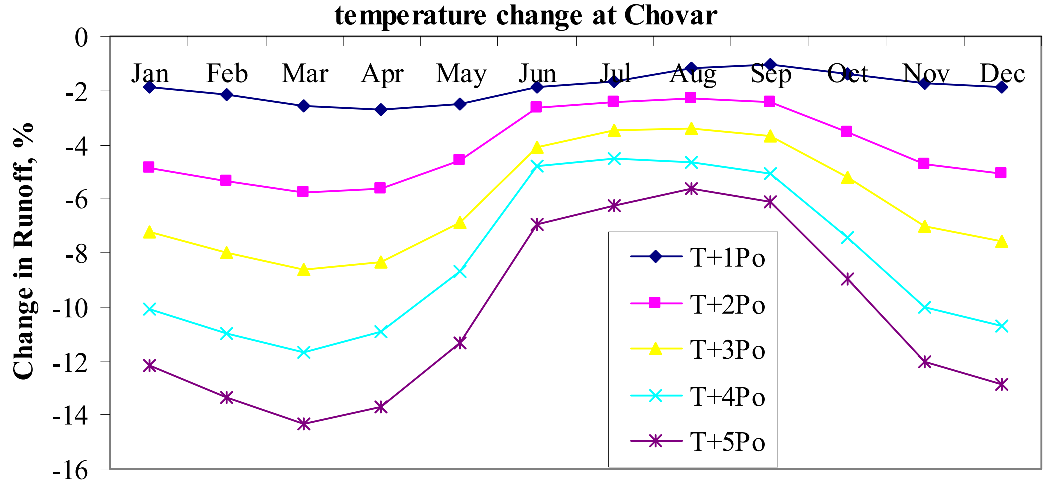
The data in Table 5.5 show that the runoff of the Langtang Khola is less sensitive to temperature rise than that of the Bagmati River (see Table 5.4). This is because of the existence of the melt-water component in the runoff of the Langtang Khola, which masks the effect of decreasing runoff due to warming by providing additional runoff from glacier-melt. Therefore, there will be only a 0.6% decrease in annual runoff with a 5ºC rise in the temperature assuming no change in the precipitation. Similarly, a 10% increase in the precipitation and a 5ºC rise in the temperature may result in only a 1.9% increase in the annual runoff of the Langtang Khola (see Table 5.5).

The climate of Nepal is highly dominated by the monsoon. The data presented in Table 5.3 shows that the monsoon season (i.e. June-September) contributes more than three quarters to the annual precipitation (e.g. about 76% in the Langtang and about 78% in the Bagmati). Because of this uneven distribution of precipitation and subsequently uneven distribution of the river runoff, Nepal is already facing water shortages during the non-monsoon seasons and flood problems during the monsoon season. The impacts of climate change will further exacerbate the problem of uneven distribution of the river runoff. For example, a temperature rise of 4ºC and a precipitation decrease of 10% will result in 17% and 7.1% decreases in annual runoff in the Bagmati River and the Langtang Khola respectively (see Table 5.4 and Table 5.5).

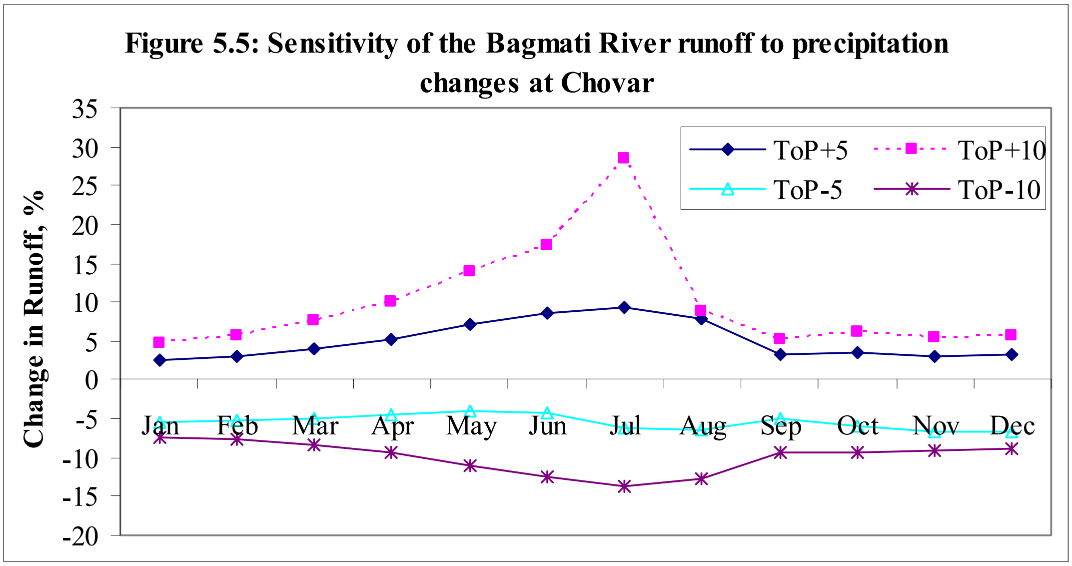
An analysis of the seasonal distribution of changes in river runoff due to climate change was carried out for the whole scenarios of temperature rises from 1ºC to 5ºC rise (i.e. T_{+1} to T_{+5})

and precipitation changes from 10% decrease to 10% increase (i.e. P_{-10} to P_{+10}) at Chovar of the Bagmati River. The findings of the sensitivity analysis of the river runoff to temperature change assuming no precipitation change at the Chovar reveal that sensitivity of the runoff to a temperature change will vary among the months, and the river runoff during the non-monsoon season (i.e. dry months) is more sensitive to warming (see Figure 5.4; Annex 5.4). For example, a temperature rise of 5ºC will cause a decrease in March-runoff of 14.3%, but it will cause a decrease in August-runoff only of 5.6%.

Figure 5.4: Sensitivity of monthly runoff of the Bagmati River to temperature change at Chovar



Similarly, a sensitivity analysis of the river runoff to the precipitation change assuming no temperature change was carried out. This analysis revealed that an increase in the precipitation would substantially affect the monsoon runoff. For example, a precipitation increase of 10% would cause an increase in July-runoff of 28.5% but only a 4.7% increase in January-runoff assuming no change in temperature (see Figure 5.5; Annex 5.5). This indicates that climate change would enhance the pronounced seasonality and the uneven distribution of the runoff in the Nepalese rivers. The low flows (i.e. dry-season runoff) are more sensitive to the temperature change whereas wet season flows (i.e. flood flows) are more sensitive to precipitation change (see Figures 5.4 and 5.5).



After detecting the seasonal disproportion of impacts on runoff of the Bagmati River, a comparative analysis of the impacts of climate change on the river runoffs of the rain-fed Bagmati River and the glacier-fed Langtang Khola was carried out (see Table 5.6).

Table 5.6: Sensitivity of monthly runoff with temperature and precipitation changes

Month	Change in runoff, %							
	T_{+2}, P_{+10}		T_{+2}, P_{-10}		T_{+4}, P_{+10}		T_{+4}, P_{-10}	
	Langtang	Bagmati	Langtang	Bagmati	Langtang	Bagmati	Langtang	Bagmati
Jan	4.1	0.2	-5.6	-20.0	1.2	13.9	-5.6	-30.5
Feb	2.5	0.6	-3.6	-19.9	1.8	10.9	-3.8	-29.9
Mar	2.7	1.6	-4.8	-19.3	2.0	6.8	-5.1	-27.8
Apr	2.0	4.0	-5.5	-17.3	1.6	1.6	-5.7	-23.2
May	3.8	8.4	-8.3	-14.2	2.4	-3.7	-8.4	-15.7
Jun	3.0	13.5	-4.3	-10.1	1.6	-6.6	-5.2	-6.4
Jul	3.9	25.3	-7.3	-12.2	1.5	-2.4	-7.6	-10.5
Aug	4.6	6.4	-7.3	-14.1	2.1	4.1	-7.6	-15.1
Sep	4.9	3.0	-7.6	-15.5	2.6	9.1	-7.8	-20.4
Oct	4.0	3.0	-9.9	-19.0	2.5	12.9	-9.4	-27.5
Nov	5.1	1.2	-9.3	-22.8	5.9	17.5	-8.7	-34.7
Dec	1.5	1.1	-0.5	-22.6	1.4	16.3	-0.4	-34.2
Annual	**3.9**	**10.8**	**-6.9**	**-15.4**	**2.2**	**3.8**	**-7.1**	**-16.9**

Note: The subscriptions of T & P denote the changes in temperature (ºC) & precipitation (%)

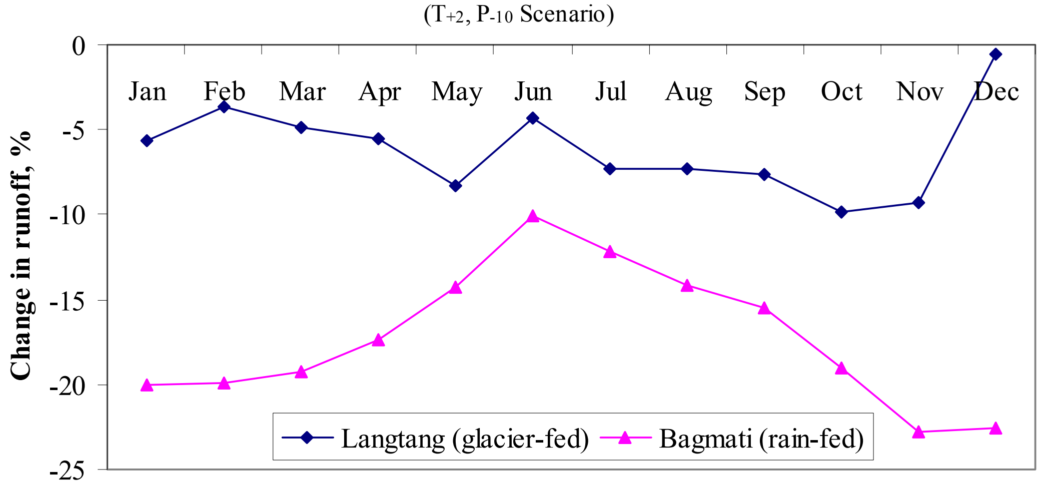
The results in Table 5.6 show an uneven distribution of the change in runoff among the months despite a uniform change in precipitation and temperature in a particular scenario. For example, a 2ºC rise in temperature and a 10% decrease in precipitation (T_{+2}, P_{-10}) will result in 6.9% and 15.4% decreases in the annual runoff of the Langtang Khola and the Bagmati

River respectively (see Table 5.6). For an annual-runoff decrease of 6.9% under T_{+2}, P_{-10} scenario, December-runoff will decrease by 0.5% whereas May-runoff will decrease by 8.3% for the Langtang Khola. Similarly, for an annual decrease of 15.4% for the Bagmati River, June-runoff will decrease by 10.1% whereas November-runoff will decrease by 22.8% for the same scenario. These results clearly indicate that the problem of seasonal imbalance of river-flows will be more exacerbated in the future with the temperature and precipitation change scenarios.

The seasonal effect will be more pronounced for rain-fed rivers than for glacier-fed ones. In case of the Bagmati River for the given scenario (T_{+2}, P_{-10}), the biggest changes will occur during non-monsoon seasons. In case of the Langtang, there will be minimum decrease of flows during dry seasons because there will still be the glacier-melt component masking the warming effect (see Figure 5.6; Annex 5.6). The model WatBal itself assumed the snow- and glacier area within the basin as constant and not variable at least for the present application, which may not be true for increasing temperatures. Therefore, further assessment is necessary to identify the possible impacts of temperature increase on the snow and glacier contribution to the river flows.

Figure 5.6: Sensitivity of River Runoff to Climate Change

(T_{+2}, P_{-10} Scenario)



5.2.4 Discussion of the Empirical Evidence on the Impacts on the River Flows

Mirza and Dixit (1997, p. 78) reported that for an increase in temperature by 2ºC and increase in precipitation by 10%, the runoff of the Ganges in Delhi might increase by 19%. By simulating an integrated water balance model *WatBal,* Yates (1994, p.13) found out that for an increase in temperature of 4ºC and an increase in precipitation of 10%, the runoff of the Mulberry River in Arkansas and the East River in Colorado in USA would increase by 11% and 4% respectively. Similarly, MOPE (2004, p.99) revealed using the *WatBal* model that for an increase in temperature of 4% and an increase in precipitation of 10%, the runoff in the Karnali, the Narayani, the Koshi and the Bagmati Rivers in Nepal would increase by 1%, 9%, 5% and 11% respectively. The simulation of the *WatBal* model in the current study revealed that for an increase of temperature of 4ºC and an increase in precipitation of 10%, the runoff in the Bagmati River at Chovar and the Langtang Khola at Langtang would increase by 3.8% and 2.2% respectively. The findings of the current study, thus, support the results of the previous studies.

Recently, Shrestha (2005, p.75) reported that the annual river runoff of the Kali Gandaki River at Kotagaun in western Nepal was increasing by approximately 1% per year. The snow area upstream of the station within the basin is about 19% (WECS/DHMN, 1996, Annex-2), which might have contributed a substantial percentage of melt-water to the annual runoff, which may be the possible explanation for an increasing annual runoff. The low flows in the rivers (during April-May) in the present study were found to be more sensitive to an increase in temperature and a decrease in precipitation. Likewise, the high flows (during July-August) were more sensitive to an increase in precipitation. Besides, the low flows in the rain-fed Bagmati River were more sensitive to warming than those in the snow-fed Langtang Khola due to the lack of the melt-water component in the rain-fed river during the dry period.

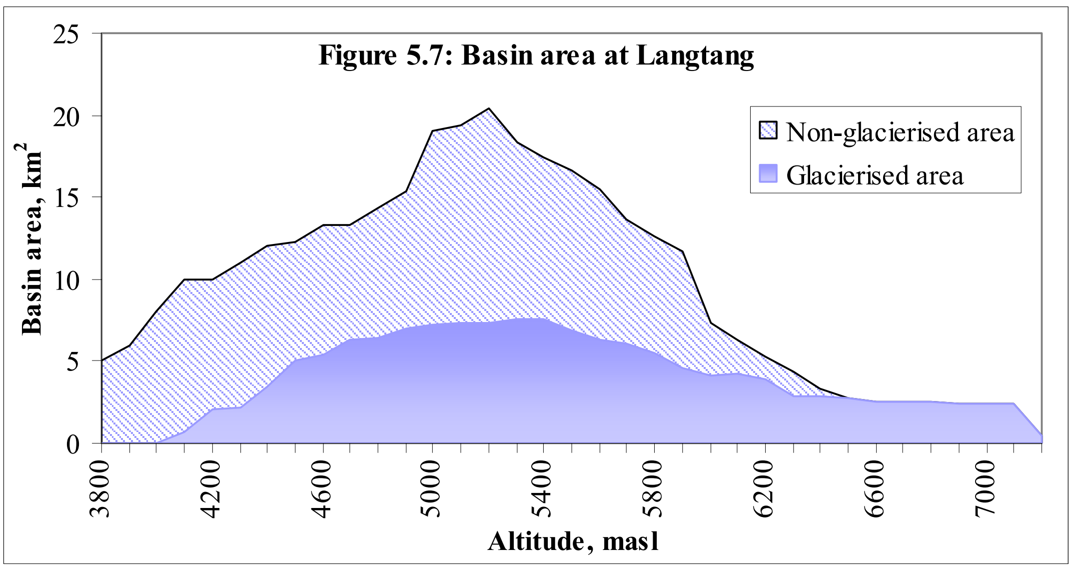
Climate change will significantly increase the intra-annual variability of stream flow (Agrawala et al., 2003, p.29). This statement reinforced the findings of the current study. For example, the range of flow (i.e. the difference between the highest and the lowest flows) of the Bagmati River would increase from the present 268 m^3/s (i.e. from 7.3 m^3/s to 275.3 m^3/s) to 371.6 m^3/s (i.e. from 6.9 m^3/s to 379.6 m^3/s) for a temperature rise of 4ºC and a precipitation increase of 10%.

5.3 Impacts of a Temperature Rise on Snow and Glacier Systems

5.3.1 General Findings

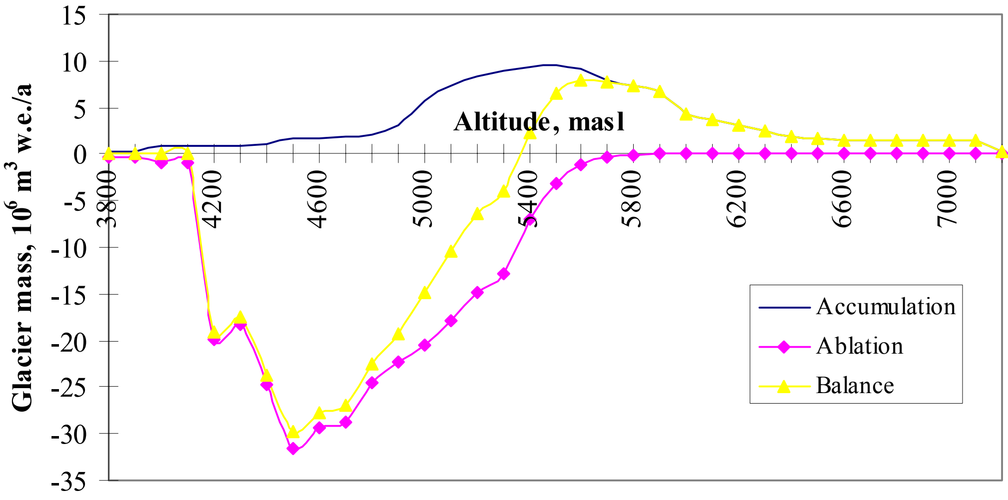
To begin with, the information on the glaciers located upstream of the Langtang hydrological station was collected from the topographical maps of Nepal (HMGN, 1997, Sheet Nos. 2885 10, 2885 11, 2885 14, 2885 15, Scale: 1:50 000) and the Inventory of Glaciers in the Nepal Himalayas (ICIMOD/UNEP, 2002; Mool et al., 2001a, pp.224-225). The total area of the study basin was 340 km^2. There were altogether 24 glaciers with a total surface area of 140.8 km^2 (about 41% of the total basin area) within the study basin (see Figure 5.7; Annex 5.8).

Figure 5.7: Basin area at Langtang



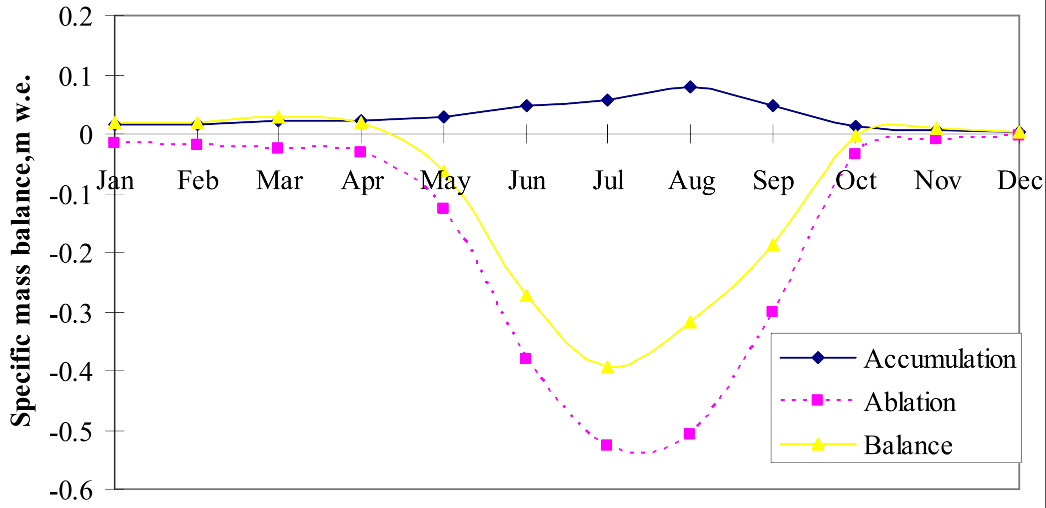
The highest and lowest altitudes within the basin were 7232 metres above sea level (masl) and 3800 masl respectively. The glaciers were distributed from the lowest point of 4130 masl to the highest point of 7218 masl. The smallest glacier was 0.01 km^2 whereas the largest one was 67.93 km^2. The thickness of the glaciers also varied from 2.1 m to 177.3 m. Out of the 24 glaciers, the largest one alone had an ice reserve of 12.04 km^3 (i.e. 63% of the total ice reserve in the basin), and the second and the third largest ones had ice reserves of 3.32 km^3 and 1.84 km^3 respectively. The remaining 21 glaciers had altogether only 10% of the whole ice reserve in the basin indicating that the majority of the glaciers were very small.

Figure 5.8: Average glacier mass balance with altitudes



The accumulation and ablation of the glaciers within the Langtang valley were calculated for each month and for every 100 m altitude level from 3900 to 7218 masl by applying an empirical relation. The temperatures and subsequently the glacier mass balance varied with the altitudes and the months. The precipitation for the whole study basin was assumed to be uniform over the whole study basin and taken as the same as recorded by the meteorological station at Langtang (Kyangjing) located at 3920 masl. Though it may not be true for the mountain topography of the study area, there were no other meteorological stations within the basin to verify the assumption. As far as temperature data were concerned, the adiabatic lapse rate (i.e. the rate of temperature change with altitude) was taken as -0.6ºC per 100 m of altitude. The lapse rate was assumed to be the same for all altitude levels and for all months. The total accumulation, ablation and glacier mass balance for each 100 m altitude level were calculated by summing up all monthly values. The lower altitudes were dominated by ablation whereas the upper ones by accumulation (see Figure 5.8, Annex 5.7). The equilibrium line altitude, the altitude at which the accumulation and ablation of the glacier is equal, was found at 5367 masl.

Figure 5.9: Monthly glacier mass balance at Langtang in m w.e./yr



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yr
Ac	0.04	0.04	0.05	0.05	0.07	0.11	0.14	0.20	0.12	0.03	0.02	0.01	0.87
Ab	0.02	0.02	0.03	0.03	0.13	0.38	0.53	0.51	0.30	0.04	0.01	0.00	1.98
Bl	0.02	0.02	0.03	0.02	-0.06	-0.27	-0.39	-0.31	-0.18	0.00	0.01	0.00	-1.11

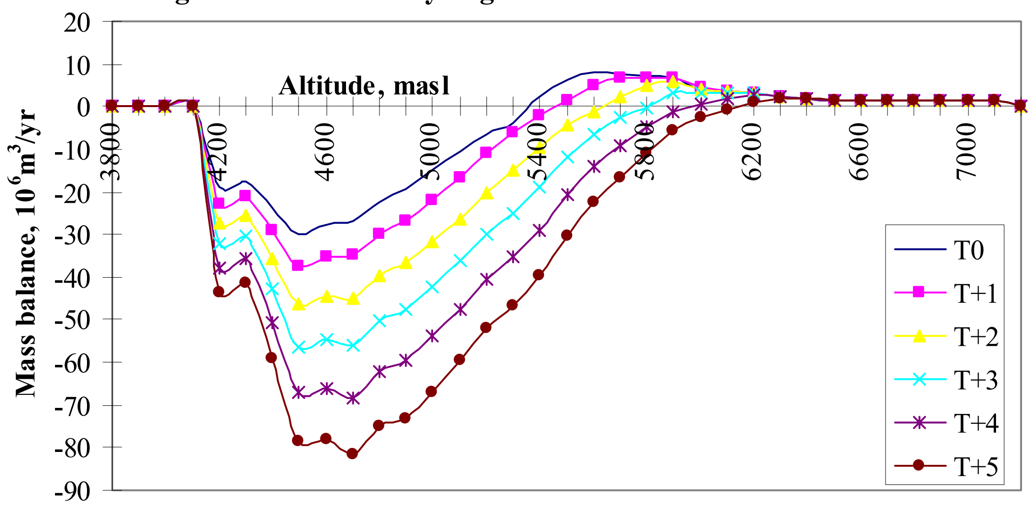
Note: Ac= Accumulation; Ab = Ablation; Bl = Balance;
Values are the averages of 1988-2000 and expressed in metres of water equivalent

There was wide a variation in glacier mass balance among the months. The total volume of the glacier mass balance over the whole glaciers was obtained by summing up all glacier mass balances of each altitude level. The total glacier mass balance in terms of volume of water equivalent (w.e.) was further divided by the glacier area in order to get a specific mass balance (see Figure 5.9). The calculated monthly specific mass balance of the glaciers shows that there was a substantial negative glacier mass balance during the study period of 1988-2000 in the Langtang Valley. The summer months (June-September) had substantial glacier ablation despite some accumulation.

5.3.2 Sensitivity Analysis of Glacier Mass Balance to Temperature Rise

As the precipitation data during the past did not show any significant trends, a sensitivity analysis of glacier mass balance and glacier-contributed runoff was carried out only for the temperature change scenarios from T_{+1} to T_{+5} (i.e. temperature rise from 1ºC to 5ºC). Then, the calculated values were compared with the T_0-scenario (no temperature change). The equilibrium line altitude (ELA) would move up to 6142 masl at T_{+5}-scenario, whereas the ELA at present (i.e. at T_0-scenario) is located at 5367 masl (see Figure 5.10; Annex 5.9; Annex 5.10).

Figure 5.10: Sensitivity of glacier mass balance in altitudes



A temperature increase will not only impact the annual glacier mass balance, but will also change the precipitation pattern. Even without any change in total annual precipitation, more precipitation will occur in a liquid form (i.e. rainfall) instead of a solid form (i.e. snowfall) with warmer temperatures. Rainfall, unlike snowfall, will not be stored, but will immediately be drained out from the basin resulting in more floods downstream during the monsoon. The impact of a temperature rise could easily be visible in the sensitivity analysis through snow-to-rain ratio, glacier mass balance rate or life of glacier ice reserve. For example, the snow-to-rain ratio would decrease from 1.6 to 0.5, the life of ice reserves would decrease from 110 to 25 years and the glacier mass balance would decrease from -1.114 to -4.850 m.w.e.yr^{-1} with a warming of 4ºC (see Table 5.7). In order to assess the accuracy of the calculation of the glacier mass balance, a theoretical runoff (Q_T) at the Langtang hydrological station was compared with the measured runoff (Q_M). The theoretical runoff (Q_T) at the Langtang station was calculated by the relation:

$$Q_T = P + Abl - Acc - E \qquad (5.1)$$

Where,

Q_T = Theoretical runoff, 10^6 m^3 yr^{-1}

P = Precipitation, 10^6 m^3 yr^{-1}

Abl = Glacier Ablation, 10^6 m^3 yr^{-1}

Acc = Glacier Accumulation, 10^6 m^3 yr^{-1}

E = Total evaporation, 10^6 m^3 yr^{-1}

Therefore, $Q_T = (199+279-122.6-138.0)\ 10^6\ m^3\ yr^{-1} = 217.4 \times 10^6\ m^3\ yr^{-1}$. The observed annual average runoff (Q_M) at the Langtang hydrological station (Kyangjing) for the period of 1988-2000 was $218 \times 10^6\ m^3\ yr^{-1}$, which gave an error of less than 1% level for the calculation.

Likewise, the results showed that even without any changes in the precipitation amount, a warming of 5ºC would cause a decrease in snowfall of 55.6% and an increase in rainfall of 89.2% simultaneously. The analysis further revealed that glaciers in the Langtang valley were already melting so rapidly that even without any further warming they would disappear in 11 decades from 2001, if the present rate of melting continues. With a warming of 2ºC, all the glaciers with a present ice reserve of 19.14 km^3 would disappear within less than half a century (see Table 5.7). A further calculation was done in order to quantify a glacier mass balance rate for a particular warming rate instead of the total amount of warming.

Table 5.7: Summary of sensitivity analysis of glaciers at Langtang (1988-2000)

Parameters	Unit	Temperature Change Scenarios					
		T_0	T_{+1}	T_{+2}	T_{+3}	T_{+4}	T_{+5}
Precipitation	$10^6\ m^3\ yr^{-1}$	199.0	199.0	199.0	199.0	199.0	199.0
Snowfall	$10^6\ m^3\ yr^{-1}$	122.6 (0)	108.6 (-11.4)	93.5 (-23.7)	79.0 (-35.5)	66.6 (-45.7)	54.4 (-55.6)
Rainfall	$10^6\ m^3\ yr^{-1}$	76.4 (0)	90.4 (18.2)	105.5 (38.1)	120.0 (57.0)	132.4 (73.3)	144.6 (89.2)
Snow-to-rain ratio		1.60	1.20	0.89	0.66	0.50	0.38
Evaporation	$10^6\ m^3\ yr^{-1}$	138.0 (0)	142.8 (3.5)	147.7 (7.0)	152.6 (10.6)	157.6 (14.2)	162.7 (17.9)
Ablation	$10^6\ m^3\ yr^{-1}$	279.0	351.6	463.6	596.9	750.8	925.7
Accumulation	$10^6\ m^3\ yr^{-1}$	122.6	108.6	93.5	79.0	66.6	54.4
Total mass balance	$10^6\ m^3\ yr^{-1}$	-156.8	-242.8	-369.5	-516.7	-683.0	-870.5
Specific mass balance*	m w.e yr^{-1}	-1.114	-1.724	-2.623	-3.668	-4.850	-6.181
Life of ice reserve	year	110	71	47	33	25	20

Note: * Specific glacier mass balance is the mass balance of the studied glaciers over the unit surface area expressed in meters of water equivalent (m w.e.).
- Values in subscription with T indicate an increase in temperature in ºC
- Values in the parentheses show a percentage change from the T_0-scenario

The regression analysis between an increase in temperature and a glacier mass balance revealed the empirical relation given in Equation 5.2 ($p<0.001$; $R^2=1.0$)

$$\Delta B = -0.6087*\Delta T^{1.3117} \qquad (5.2)$$

Where,

ΔB = Change in glacier mass balance in m.w.e.yr^{-1}

ΔT= Change in temperature in ºC

Using the relation, glacier mass balance rates for the next 20 decades from 2001 were calculated (see Table 5.8). The mass balance rates were calculated using the output values from Table 5.7 for different scenarios of temperature rise and then converted to the rate of warming using the Equation 5.2. For example, the negative glacier mass balance rate for the T_0-scenario was taken as the same as the average calculated value for the period of 1988-2000. The negative glacier mass balance rates for the warming rates of 0.03ºC yr^{-1} to 0.15ºC yr^{-1} (i.e. $T+_{0.03}$, $T+_{0.06,}$…, $T_{+0.15}$-scenarios) for every decade were calculated by:

$$B_{Tx,n} = B_{T0,n} + \Delta B_{x,n} \qquad (5.3)$$

Where,

$B_{Tx,n}$ = Glacier mass balance rate for n-decade with a warming rate of x

(Here, x = 0, 0.03, 0.06, 0.09, 0.12 , 0.15 ºC/yr; n=0,1,2,…, 20)

$B_{T0,n}$ = Glacier mass balance rate for n-decade without a further warming

$\Delta B_{x,n}$ = Change in glacier mass balance rate for n-decade with a warming rate of x

Then, all values of the specific glacier mass balance for every temperature rise scenario and for each decade were calculated (see Table 5.8). The decades were counted from 2001, e.g. decade-0 means 2000, decade-1 means 2010, decade-3 means 2030…, and so on. The calculated specific glacier mass rates given in Table 5.8 were applied to all the existing glaciers in the Nepal Himalayas in order to carry out a sensitivity analysis of the total glacier ice reserve of 480.6 km^3 to a temperature rise (see Table 5.9). The glacier-ice reserve of each glacier was calculated by:

$$V_{x,n} =V_{x,n-1} + B_{x,n} * A_n \qquad (5.4)$$

Where,

$V_{x,n}$ = Volume of glacier-ice reserve in n-year for a warming rate of x [m^3]

$V_{x,n-1}$ = Volume of glacier-ice reserve in n-1 year for a warming rate of x [m^3]

$B_{x,n}$ = Specific glacier mass balance in n-year for a warming rate of x [m w.e./yr]

A_n = Surface area of the particular glacier in n-year [m^2]

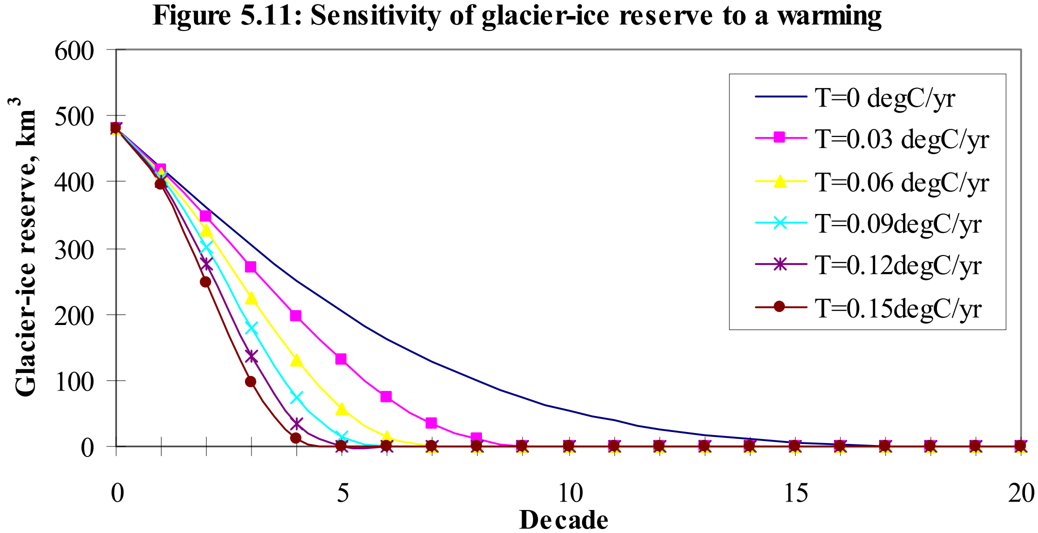
Table 5.8: Glacier mass balance rates with different temperature change scenarios

Decade	Specific glacier mass balance, m.w.e./year					
	ΔT = 0ºC/yr	ΔT = 0.03ºC/yr	ΔT = 0.06ºC/yr	ΔT =0.09ºC/yr	ΔT =0.12ºC/yr	ΔT =0.15ºC/yr
0	-1.114	-1.114	-1.114	-1.114	-1.114	-1.114
1	-1.114	-1.239	-1.425	-1.644	-1.887	-2.150
2	-1.114	-1.425	-1.887	-2.430	-3.033	-3.685
3	-1.114	-1.644	-2.430	-3.353	-4.380	-5.491
4	-1.114	-1.887	-3.033	-4.380	-5.878	-7.498
5	-1.114	-2.150	-3.685	-5.491	-7.498	-9.669
6	-1.114	-2.430	-4.380	-6.674	-9.223	-11.980
7	-1.114	-2.724	-5.112	-7.920	-11.040	-14.415
8	-1.114	-3.033	-5.878	-9.223	-12.940	-16.961
9	-1.114	-3.353	-6.674	-10.577	-14.916	-19.609
10	-1.114	-3.685	-7.498	-11.980	-16.961	-22.350
11	-1.114	-4.028	-8.348	-13.427	-19.072	-25.178
12	-1.114	-4.380	-9.223	-14.916	-21.243	-28.087
13	-1.114	-4.742	-10.120	-16.444	-23.471	-31.074
14	-1.114	-5.112	-11.040	-18.009	-25.754	-34.132
15	-1.114	-5.491	-11.980	-19.609	-28.087	-37.260
16	-1.114	-5.878	-12.940	-21.243	-30.470	-40.453
17	-1.114	-6.272	-13.919	-22.909	-32.900	-43.709
18	-1.114	-6.674	-14.916	-24.606	-35.375	-47.025
19	-1.114	-7.082	-15.930	-26.332	-37.893	-50.400
20	-1.114	-7.498	-16.961	-28.087	-40.453	-53.830

Note: decades are counted from 2001

The total glacier-ice reserve in the Nepal Himalayas for a particular year was obtained by summing up the ice reserve of all existing glaciers for the same year. The summary of the results (see Table 5.9, Figure 5.11) shows that the glacier-ice reserve will substantially be decreasing and the rate of reduction will increase with the rate of warming.

Figure 5.11: Sensitivity of glacier-ice reserve to a warming



Even without any further warming, there will be only 54.8 km^3 of glacier-ice reserve left by the year 2100, which is only 11.4% of the present glacier-ice reserve of 480.6 km^3. Even if the temperature stops rising and the current rate of melting continues, there will be no glacier-ice reserve left by the year 2180. Temperatures in the Nepal Himalayas are increasing by at least 0.06ºC/year (Shrestha, 1999, p.2775), which would further accelerate the glacier melt. If the temperature further rises at this rate (i.e. 0.06ºC/year), there will be no glacier-ice reserve left in the Nepal Himalayas by the year 2070.

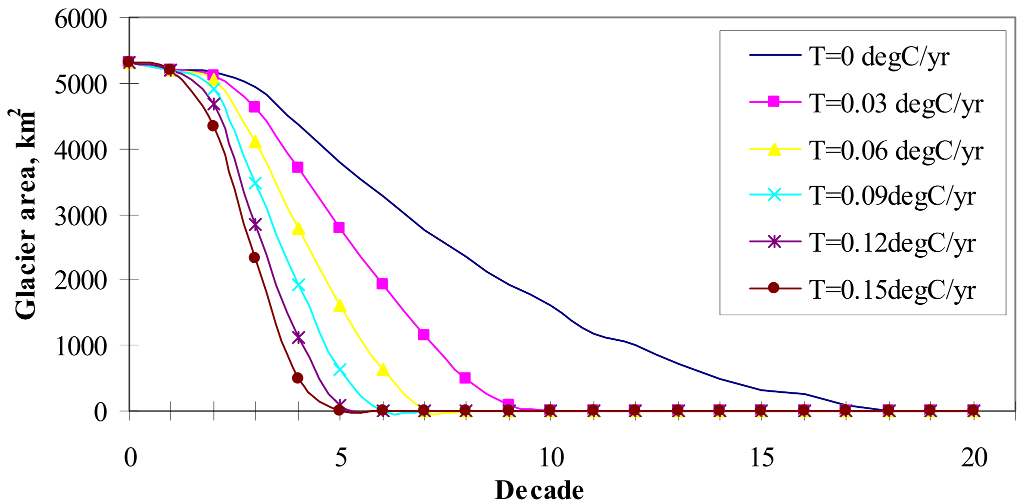
Table 5.9: Sensitivity of glacier ice-reserve to a temperature rise in Nepal

Decade	Glacier ice-reserve, km^3					
	ΔT = 0ºC/yr	ΔT = 0.03ºC/yr	ΔT = 0.06ºC/yr	ΔT =0.09ºC/yr	ΔT =0.12ºC/yr	ΔT =0.15ºC/yr
0	480.6	480.6	480.6	480.6	480.6	480.6
1	421.1	417.8	413.0	407.3	400.9	394.0
2	361.6	347.1	325.8	301.3	275.0	248.3
3	303.6	270.0	224.7	178.3	135.3	97.0
4	250.2	195.3	130.4	74.4	34.8	11.2
5	203.3	129.4	56.3	14.1	0.0	0.0
6	163.0	74.5	13.3	0.0	0.0	0.0
7	128.8	35.1	0.0	0.0	0.0	0.0
8	99.4	11.0	0.0	0.0	0.0	0.0
9	74.8	0.6	0.0	0.0	0.0	0.0
10	54.8	0.0	0.0	0.0	0.0	0.0
11	39.0	0.0	0.0	0.0	0.0	0.0
12	26.8	0.0	0.0	0.0	0.0	0.0
13	16.8	0.0	0.0	0.0	0.0	0.0
14	10.1	0.0	0.0	0.0	0.0	0.0
15	5.6	0.0	0.0	0.0	0.0	0.0
16	2.2	0.0	0.0	0.0	0.0	0.0
17	0.2	0.0	0.0	0.0	0.0	0.0
18	0.0	0.0	0.0	0.0	0.0	0.0

Note: decades are counted from 2001

The value of Equation 5.4 for a particular glacier would become negative, when the existing glacier-ice reserve is less than the melt potential for the particular year. If that happened, the particular glacier would be considered as disappeared. The areas of the remaining glaciers were summed up for the total glacier areas (see Figure 5.12 and Annex-5.1)

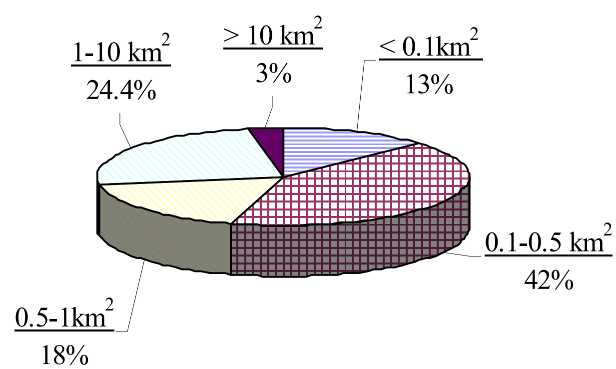
Figure 5.12: Sensitivity of glacier surface area to a warming



The Figure 5.12 shows that the current glacier-cover will be reduced by 70% even without any further warming in 2100. If the rate of temperature rise is 0.06ºC/year, the glacier areas will be reduced by 70% by the year 2050.

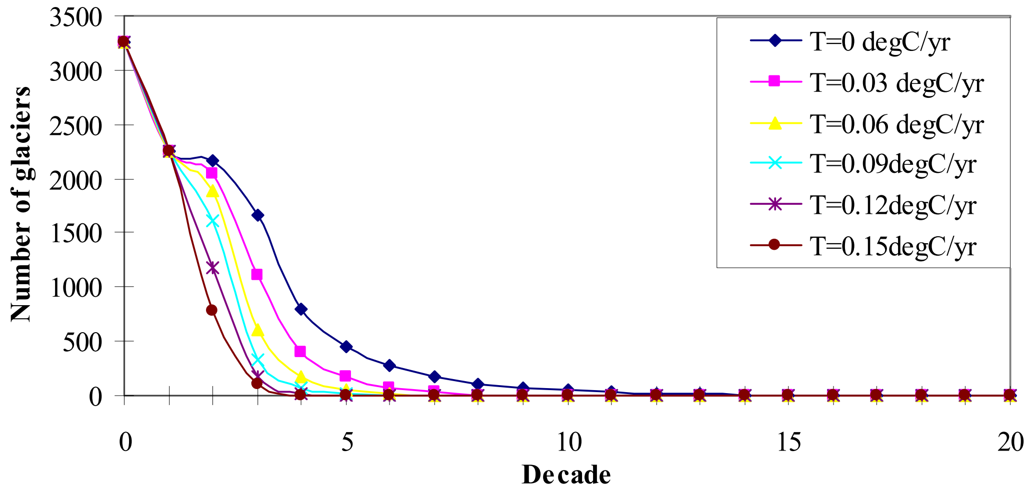
Figure 5.13: Distribution of glaciers with areas in Nepal (2001)

(Source: Mool et al., 2001a, pp.210-292)



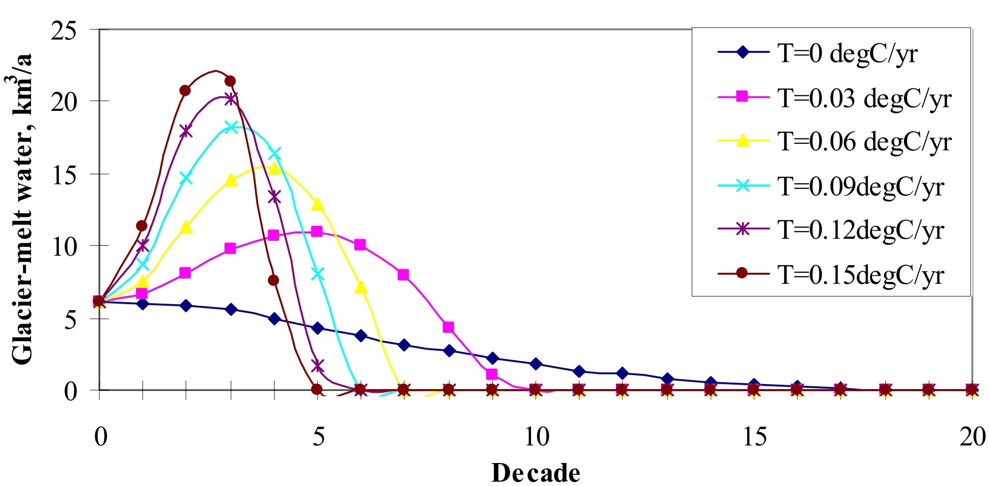
Currently, there are 3252 glaciers in the Nepal Himalayas. About 72.6% of them are with surface areas less than 1 km^2 (see Figure 5.13). The sensitivity analysis shows that about 86% of the glaciers in the Nepal Himalayas will disappear by 2050 even without any further warming. If there is a warming of 0.06ºC/year, about 98.5% of the glaciers will disappear by 2050 and there will be no glacier left by 2070 (see Figure 5.14 and Annex 5.2).

Figure 5.14: Sensitivity of glaciers to a warming in Nepal



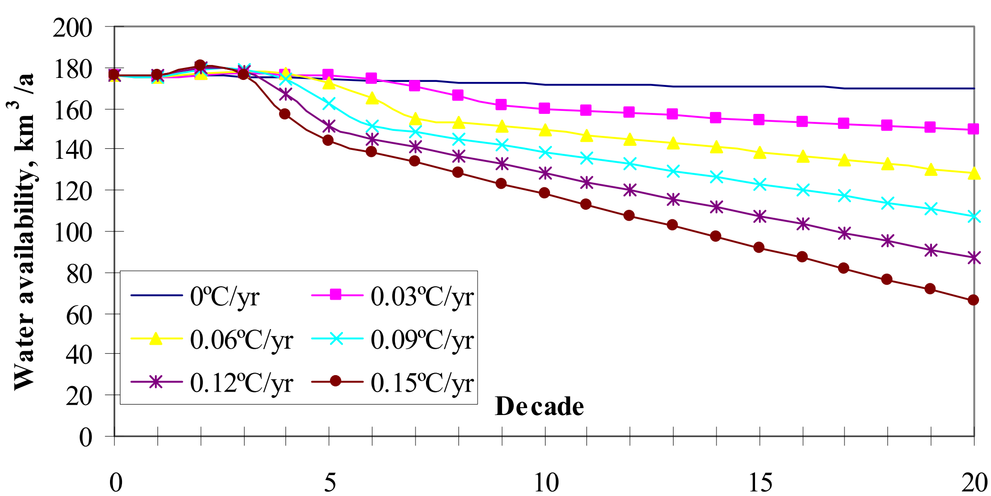
The projected disappearance of the glaciers in the Nepal Himalayas will undoubtedly reduce the contribution of glacier-melt water to the total water availability. Currently, glacier-melt water amounts to 4% of the total surface runoff of 176.08 km^3. The glacier-melt contribution will be higher for a higher rate of warming. For example, glacier-melt water will reach its maximum of 15.32 km^3/year in 2040, if the warming rate is 0.06ºC/year. Likewise, it will reach its maximum of 20.21 km^3/year in 2030, if the warming rate is 0.12ºC/year. The glacier-melt contribution will be substantially reduced after its maximum because there will be fewer glaciers left to melt (see Figure 5.15, Annex 5.3). As the contribution of glacier-melt decreases, the total water availability of Nepal will decrease accordingly.

Figure 5.15: Sensitivity of glacier-melt water to a warming



Total water availability depends not only on the glacier-melt contribution, but also on the evapotranspiration losses. Increasing temperatures may further reduce the total water availability even after the glacier-disappearances because of a possible increase in evapotranspiration associated with the rising temperatures. The total water availability in Nepal will decrease by 2.4% in 2100 even without any further warming (see Figure 5.16, Annex 5.4). If there is warming rate of 0.06ºC/year, the total water availability may decrease by 15% in 2100 and by 27% in 2200 from the level in 2001. A greater rate of warming might cause an accelerated decrease in the total water availability. For example, if there is a warming rate of 0.12ºC/year, the total water availability in Nepal may decrease by 27% in 2100 and by 51% in 2200 (see Annex 5.4).

Figure 5.16: Sensitivity of total water availability to a warming



5.3.3 Discussion about the Impacts of Climate Change on Snow and Glaciers

Higher temperatures will increase the ratio of rain to snow, accelerate the rate of snowmelt and shorten the overall snowfall (Frederick and Gleick, 1999, p.9). Changes in the snow cover of the earth affect both daily weather and long-term climate (Walsh, 1984, p.50). However, the feedback of the snow cover to the atmosphere is difficult to accurately quantify due to the complex air-sea-land interactions (ibid, p.56). The most significant feedback is the surface albedo or the reflectivity. Fresh snow has up to 85% of albedo that can reduce the solar energy available to the surface and lower atmosphere by more than 50% (ibid, p.50). Decrease in snow-to-rain ratio reduces the glacier accumulation even without any changes in total precipitation. A decrease in snowfall accelerates the ablation due to a lowered albedo at the glacier surface (Ageta and Kadota, 1992, p.89). Therefore, a decreasing snow cover and an increasing ratio of rain-to-snow ratio due to warming may have an amplifying effect on warming.

The Himalayas have a strong influence on the climate of the Indian subcontinent. It acts as a climate divide between the north and south. Monsoon rain in the Indian subcontinent mostly occurs due to the orographic influence of the Himalaya on the monsoon winds (Mani, 1981, p.8). The Himalayan range obstructs the passage of extremely cold continental air from the north into the subcontinent in the winter. In summer, it forces the rain-bearing monsoonal winds to ascend and thereby give up most of their moisture as rain and snow on the south side before crossing the range northward causing arid conditions in Tibet (ibid). Any changes in temperature and thereby changes in snow cover affect the whole monsoon system. Khandekar (1991, p. 644) reported that there existed a connection between the Eurasian snow cover, the Indian monsoon and the El Niño/ Southern Oscillation phenomenon. Likewise, Dey and Bhanu Kumar (1983, p. 5473) revealed an inverse relationship between the Himalayan snow cover and the Indian summer monsoon rainfall.

Currently, about 10% of total annual precipitation in Nepal occurs as snowfall (UNEP, 2001, p.129). Snow, glaciers and permafrost contribute about 10% to the annual stream flows in Nepal (MOPE, 2004, p.95; Shrestha, 2005, p.76). There are currently 3,252 glaciers covering a total surface area of 5,323 km^2 with an estimated ice reserve of 481 km^3 in the Nepal Himalayas (Mool et al. 2001a, p.13). With a temperature increase of 1ºC, there will be a 20% reduction in the present snow and glacier areas (MOPE, 2004, p. 96). The surface area of a small glacier AX010 in the Shorong region of eastern Nepal decreased from 0.57 km^2 in 1978 to 0.42 km^2 in 1999 with an average shrinkage rate of 71 m^2/yr (Fujita et al., 2001b, p.52). The annual shrinkage rate of the glacier during 1978-91 was 50 m^2/yr and increased to 200 m^2/yr in 1996-99. The glacier was retreating by 50.9 m annually in 1998-99 (ibid). Asahi and Watanabe (2000, p.481) reported after examining 57 glaciers in Kanchenjunga Himal, eastern Nepal that most of them were retreating from 1958 to 1992. The net annual mass balance of the glacier AX010 was -1.328 m w.e. in 1998, while that of the Rikha Sambha Glacier in 1999 was -0.732 m w.e. (WGMS, 2005, p.175). The calculated value of the average mass balance rate of 24 glaciers in the Langtang Valley in the current study was -1.114 m w.e. (see

Table 5.7), which was within the range of the mass balance rates of other Himalayan glaciers as mentioned before.

Recently, Brown (2006, p.68) reported that most of the glaciers in the world are shrinking including the Himalayan glaciers. A study by a team of more than 50 US and Chinese scientists over 26 years has reported that the glaciers in China are melting so rapidly that two thirds of them will disappear by 2060, if the current melting rate continues (ibid, p.70). This finding on the other side of the Himalayas has reinforced the findings of the present study that the glaciers in the Nepal Himalayas are rapidly shrinking and will not last for a long, if the current rate of melting continues.

As the warming continues, the volume of glaciers becomes smaller. This will result in the decreased storage of fresh water in the mountains, which is vital for domestic use, irrigation and hydropower for the people living not only in the mountains and but also far downstream in the plains (Becker and Bugmann, 2001, p.63). An accelerated melting of glaciers on the one hand and a decreasing snow-to-rain ratio on the other are two major impacts of warming that may create additional liquid water in the mountains and may lead to the creation glacier lakes in the mountain valleys. Many of these lakes are supported by loose moraines not capable of resisting ever-increasing hydrostatic pressures caused by a rising lake-water level. Therefore, a rising temperature will increase the likelihood of these lakes collapsing and creating devastating flood disasters along a long stretch of the river valley downstream of the lake, which is termed as Glacier Lake Outburst Flood (GLOF). A GLOF is a sort of debris flow with great devastating power. The floodwater carries the debris from the collapsed dam, erodes both banks and bed of the river and causes landslides from the steep slopes along the river channel (Yamada, 1998, p.13). The damaging impacts of such debris flows may extend even more than 100 km downstream causing substantial loss of lands, lives and properties. However, damage magnitude of a GLOF depends on the volume of released water, rate of water release, natural feature of the river channel and the status of infrastructure and habitation in the likely-to-be-affected areas downstream (Yamada, 1998, p.14).

5.4 Conclusion

5.4.1 Summary of Findings

The analyses carried out in this chapter revealed that climate change would have a significant impact on the atmospheric and soil moisture balance, the river runoff and the snow- and glacier-regime causing a possible reduction on the total water availability in the Nepal Himalayas. For example, the annual atmospheric moisture deficit will rise from 323 mm at present to 413 mm under a temperature rise of 5ºC assuming no change in precipitation at Kathmandu Airport. Likewise, the soil moisture storage for shallow- and deep-rooted crops will drop by 6.2% and by 10.8% respectively at a temperature rise of 5ºC, and the crop-growing season will also be shortened without an artificial irrigation. Similarly, a change in climate will change the runoff regime of both glacier-fed and rain-fed rivers. The impact on the runoff was found to be more pronounced for the rain-fed river, at least on a short-term, because of the melt-water component existing in the runoff of the glacier-fed river. The seasonal effect would be more serious than the annual effect due to domination of the monsoon climate in Nepal. Climate change could cause an increased wet season runoff and a decreased dry season runoff resulting in an increased seasonal variation in runoff.

A more remarkable impact of warming could be seen on the snow and glacier regime and on the total water availability in the Nepal Himalayas. A warming could reduce the snow-to-rain ratio, accelerate the glacier melt and increase the evaporation losses. For example, a 5ºC rise in annual temperature in the Langtang Valley could reduce the snow-to-rain ratio from 1.6 to 0.38, increase the evaporation losses by 17.9% and shorten the estimated life of the glaciers from 110 years to 20 years. The glaciers in the Nepal Himalayas are currently retreating so rapidly that even without any further warming about 86% of the glaciers will disappear and about 58% of the ice-reserve will be gone by 2050. If there is a warming of 0.06ºC/year, there will be no glacier left in the Nepal Himalayas by 2070. Such a situation will substantially reduce the total water availability in the Nepal Himalayas from 176.08 km^3/year to 128.44 km^3/year by 2200 at an assumed warming rate of 0.06ºC/year.

Such projected physical impacts on the water availability, moisture balance and runoff variability will have a serious impact on the socio-economic development in Nepal.

5.4.2 Open Questions

The *WatBal* model, which was used in this study in order to identify the sensitivity of river runoff to climate change, has used the average values of monthly precipitation, temperature and runoff data, but not the extreme values. Therefore, further research is necessary to model the extreme flows under the climate change. In addition, the effect of change in precipitation pattern on the river runoff also could not be identified during the present study.

The determination of the impact of global warming on the glacier extent of the Nepal Himalayas in this study was based on the assumption that all glaciers in the Nepal Himalayas would be affected in the same way as in the Langtang valley. How accurate is this assumption? Is the negative mass balance rate calculated in the Langtang valley representative for the entire Nepal Himalayas? More studies covering other Himalayan stations, which was beyond the scope of this study, are necessary to answer these questions. In addition, the calculation of glacier mass balance in the Langtang valley was based on the assumption that the precipitation data recorded at the Langtang (Kyangjing) station were representative for the whole study basin of 340 km^2. Because the mountain orography highly influences the precipitation, this assumption needs to be verified by the future research.

Chapter VI: Empirical Findings on the Socio-economic Impacts of Climate Change

6.0 General

After quantifying the physical impacts of climate change in Nepal with reference to water resources as discussed in chapter 5, the possible socioeconomic impacts of climate change associated to these physical impacts are determined in this chapter. In particular, sensitivity analyses of: 1. the irrigation water requirement, 2. the water balance situation, 3. the agricultural production and the food security, 4. the hydropower potential, and 5. the water-induced extreme events are carried out. At the end of this chapter, some conclusions and open questions related to this chapter are presented.

6.1 Impacts on the Water Balance, Agriculture and Food Security

6.1.1 Impacts on the Irrigation Water Requirement

The existing irrigation water requirement was determined for the whole basin area upstream of Chovar in the Bagmati river basin. The calculation was based on the information from the water use inventory study carried out by the Water and Energy Commission Secretariat, Nepal (WECS, 1997, Annex A-Table 5.1; WECS, 2000a, p.18). The specific irrigation water requirement for each month was calculated by dividing the total water requirement with the irrigated area inside the basin. The change in the irrigation water requirement due to factors other than temperature rise was ignored during the analysis. The change in the irrigation water requirement was assumed equivalent to the change in the potential evapotranspiration. A sensitivity analysis of potential evapotranspiration in relation to a temperature rise for each month at Kathmandu Airport was carried out using the FAO Penman-Monteith equation (see Equation 3.14) for different temperature rise scenarios from T_{+1} (i.e. temperature change by +1ºC) to and T_{+5} (i.e. temperature change by +5ºC) for each month (see Table 6.1).

Table 6.1: Sensitivity of potential evapotranspiration to a temperature rise, $10^3 m^3/km^2$						
	T_0	T_{+1}	T_{+2}	T_{+3}	T_{+4}	T_{+5}
Jan	45.2	46.7	48.2	49.7	51.2	52.8
Feb	59.3	61.3	63.2	65.2	67.3	69.4
Mar	94.1	96.6	99.1	101.6	104.2	106.8
Apr	120.3	123.2	126.2	129.1	132.1	135.1
May	127.4	130.5	133.6	136.7	139.9	143.1
Jun	116.3	119.0	121.6	124.3	127.0	129.8
Jul	102.7	104.9	107.1	109.3	111.6	113.8
Aug	106.4	108.9	111.3	113.7	116.2	118.8
Sep	95.4	97.6	99.9	102.2	104.6	107.0
Oct	86.1	88.5	90.8	93.2	95.7	98.2
Nov	60.1	61.9	63.8	65.7	67.7	69.7
Dec	43.8	45.3	46.7	48.2	49.7	51.3
Annual	1057	1084	1111	1139	1167	1196
Absolute Change		27.0	54.3	82.0	110.1	138.6
Relative Change, %		2.6	5.1	7.8	10.4	13.1

Note: The numbers in the subscriptions with T denote the change in temperature in ºC.

The results shown in Table 6.1 reveal that an increase in temperature of 5ºC would cause an increase in the annual potential evapotranspiration of 13.1%. Such an increase in the potential evapotranspiration due to a temperature rise would increase the overall irrigation water requirement. A sensitivity analysis of the irrigation water requirement (see Table 6.1) in relation to a temperature rise has been calculated for the different temperature change scenarios (T_{+1}, T_{+2},…, T_{+5}) by adding the extra potential evapotranspitation amount to the original irrigation water requirement (i.e. with T_0- scenario). During the analysis, the influence of other non-climatic factors on the change in the irrigation water requirement was not included (see Table 6.2).

The average specific annual water requirement for the irrigation at present (i.e. for T_0-scenario) has been calculated as 3,658,000 m^3/km^2 or 36,580 m^3/ha. Generally, there are three cropping seasons per year in most of the area within the basin. Rice is cultivated in the biggest part of the irrigated area, even twice a year in most of the land. Maize, wheat and vegetables are the other crops grown in the areas.

Table 6.2: Sensitivity of the irrigation water requirement to a warming, $10^3m^3/km^2$						
	T_0	T_{+1}	T_{+2}	T_{+3}	T_{+4}	T_{+5}
Jan	111	118	126	133	141	149
Feb	148	157	167	177	187	198
Mar	112	125	138	150	163	176
Apr	58	73	87	102	117	132
May	35	50	66	81	97	113
Jun	790	803	816	830	843	857
Jul	401	412	423	434	445	457
Aug	171	183	195	207	220	232
Sep	240	251	262	274	286	298
Oct	621	633	644	657	669	681
Nov	896	905	915	924	934	944
Dec	76	83	91	98	106	114
Annual	3658	3793	3930	4068	4209	4352
Absolute Change		135	272	410	551	694
Relative Change, %		3.7	7.4	11.2	15.1	19.0

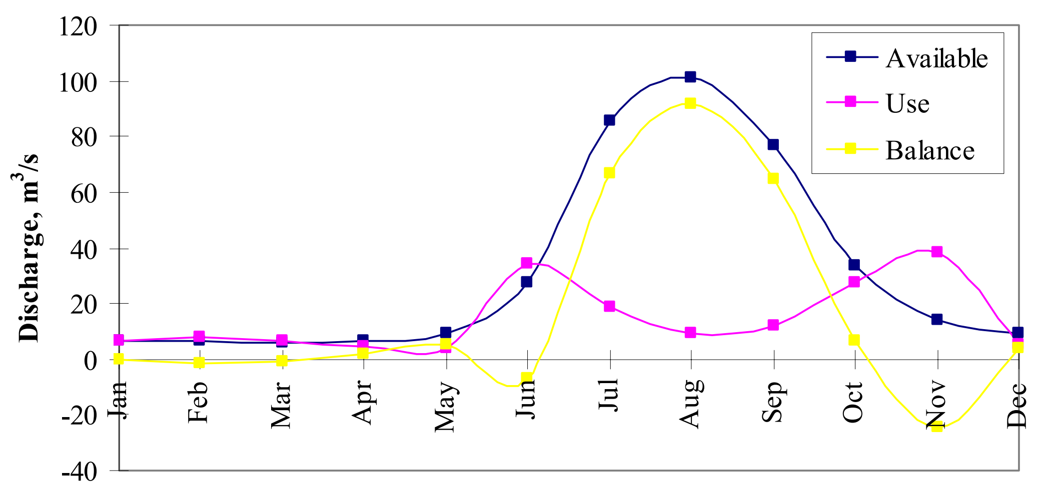
Note: The numbers in the subscriptions with T denote the change in temperature in ºC.

The results in Table 6.2 show that a 5ºC warming will increase the irrigation water demand from 3.658 million $m^3/km^2/yr$ to 4.352 million $m^3/km^2/yr$, i.e. a rise in demand of 19%.

6.1.2 Impacts on the Water Balance Situation

The existing water balance situation upstream of Chovar was determined based on the demographic information and meteorological data within the basin. Available mean monthly flows in the Bagmati river at Chovar were calculated using WECS approach and derived from the publication of the WECS (1997, Table 3.4.1-b). The total irrigation water demand was obtained for the total irrigated area of 105.6 km^2 multiplying the values of specific irrigation water demand from Table 6.2. The total domestic and industrial water demand was identified according to the information about the rural and urban population within the basin. Due to the lack of data on the actual water demand, the municipal water demand including the industrial one for the urban area was assumed as 150 litres per capita per day (lpcd) (WECS, 2000c, p.56). Similarly, rural water supply requirement including livestock demand was assumed as 72 lpcd (ibid, p.46). The total rural and urban water supply requirement at Chovar was then calculated for the current population of 1.48 million within the basin, comprising of 509,446 rural and 975,645 urban residents (ISRSC, 2002, pp.228-256). The municipal water demand was assumed to be uniform throughout the year. The irrigation water demand was determined according to the crop water requirements and varied among the months. The existing water supply and demand situation at Chovar clearly shows a seasonal imbalance in the availability of water (see Figure 6.1).

Figure 6.1: Water Balance at Chovar (2001)

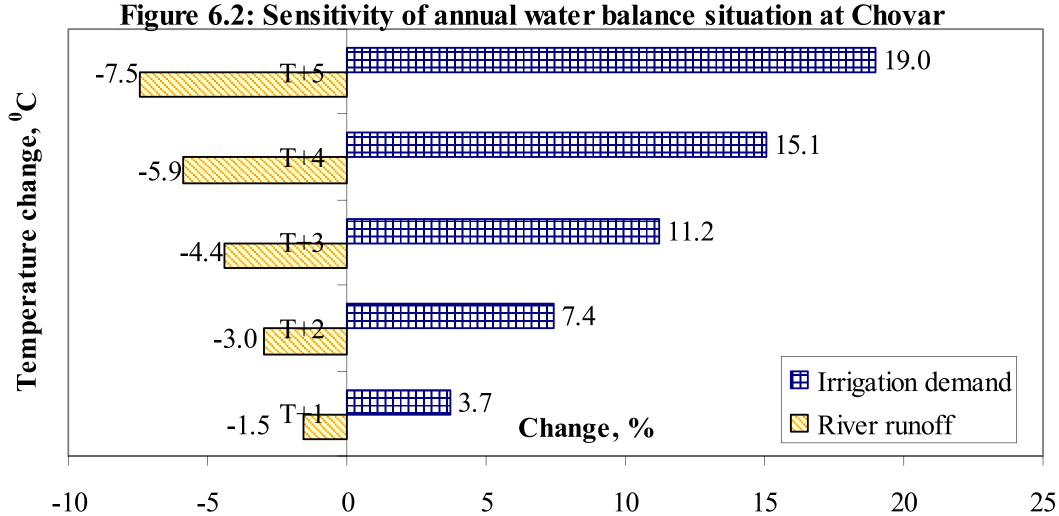


As shown in Figure 6.1, five months of the year, namely January, February, March, June and November already have a water deficit despite a sufficient surplus and a positive annual water balance during the summer monsoon months from July to September (see Table 6.3). A possible rise in temperature would further worsen the situation widening the gap between the supply of and the demand for water, especially during the non-monsoon seasons. The effect of climate change on the municipal water demand is relatively smaller than the effect of economic development (IPCC, 2001b, p.211). Industrial water demand for processing purposes is insensitive to climate change but it is defined by technologies and modes of use (ibid). Irrigation water demand is considerably more sensitive to climate change. The irrigation water use is the biggest factor (i.e. 96%) in the total annual water withdrawal in Nepal (UNEP, 2001, p.122). Therefore, the municipal and industrial water demands were assumed constant, the economic or population growth factors were excluded from the analysis and only the irrigation water demand component of the total water balance was considered sensitive to a temperature rise for the current analysis.

Table 6.3: Water supply and demand situation at Chovar in m^3/s (2001)					
Month	Water supply	Water demand			Water balance
		Irrigation	Municipal	Total	
Jan	6.52	4.45	2.28	6.73	-0.21
Feb	6.42	5.93	2.28	8.21	-1.79
Mar	5.91	4.52	2.28	6.80	-0.89
Apr	6.45	2.33	2.28	4.61	1.84
May	9.19	1.40	2.28	3.68	5.51
Jun	27.41	31.75	2.28	34.03	-6.63
Jul	85.28	16.13	2.28	18.41	66.87
Aug	100.99	6.87	2.28	9.15	91.84
Sep	76.61	9.64	2.28	11.92	64.69
Oct	33.70	24.97	2.28	27.25	6.45
Nov	14.07	36.02	2.28	38.31	-24.24
Dec	9.13	3.06	2.28	5.35	3.78
Year	31.81	12.26	2.28	14.54	17.27

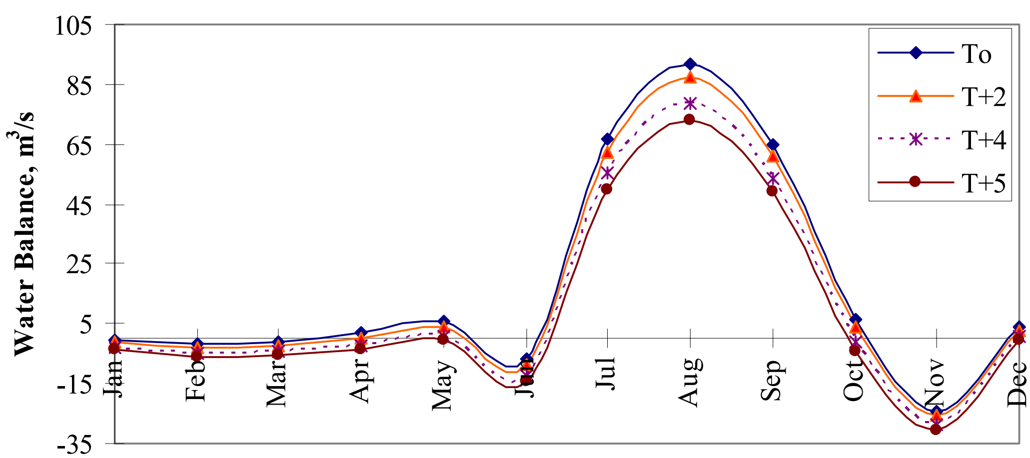
The change in temperature will change both the water supply and water demand. The sensitivity of the river runoff was calculated through the *WatBal* Model in Chapter 5 (see Table 5.4). An increase in temperature will result in a decrease in river discharge and an increase in the water demand simultaneously, which ultimately widens the gap between the river runoff and the water demand (see Figure 6.2). For example, a 5ºC rise in temperature would cause an increase of the annual water demand of 19% and a reduction of the annual river runoff of 7.5% at the same time.

Figure 6.2: Sensitivity of annual water balance situation at Chovar



Five months out of twelve are already facing water stress at Chovar. A temperature rise would prolong the water deficit period and would further deteriorate the water balance situation during the dry seasons despite enough surpluses during the rainy season. For example, the number of months in a year with a water deficit would rise from five to nine and the total annual water balance at Chovar will drop from 0.54 to 0.27 km^3/year; if the temperature increases by 5ºC (see Figure 6.3, Annex 6.1).

Figure 6.3: Change in Water Balance at Chovar



6.1.3 Impacts on the Agricultural Production, Food Security and Poverty

An increased irrigation water demand and a decreased river runoff due to warming would have a substantial impact on the agricultural production. Agriculture is one of the sectors most vulnerable to climate changes. Moreover, agriculture is one of the most important sectors for Nepal's socio-economic paradigm. About 81% of Nepal's households have agriculture as a major occupation (CBS, 2002, p.10). Agriculture currently occupies about 21% of Nepal's land area (CBS, 2004a, p.41). The share of the agriculture in the gross domestic product (GDP) of Nepal in 2004 was 39% (MOF, 2005, p.13). The agricultural sector in 2002 provided 93% of the total labour force in Nepal (FAO, 2004a, p.1).

About 86% of Nepal's population live in rural areas (ICRSC, 2002, p.20), where the agricultural income contributes the largest share of household income. However, agriculture remains predominately at subsistence level so far and is still largely non-commercialised. In many of the rural mountain areas, agriculture income provides up to 90.4% of the total family income (FAO, 2004b, p. 23). Export and import of the agricultural products provided only 14% and 16% of the total foreign trade in 2002 (FAO, 2004a, p.2). Therefore, foreign trade will most likely have less effects of the reduction in agricultural products. In contrary, any small changes on water supply and demand situations may have large impacts on the livelihoods of the subsistence farmers although it may not be clearly visible in terms of the GDP. Such a change in the water balance will disproportionately affect the poor because they have less diversified sources of income and less knowledge and capacity to cope with the changes.

The recent survey results on the status of poverty in Nepal revealed that nearly 31% of Nepal's population were currently living below the poverty line (MOF, 2005, p.150). The definition of the poverty line was based on a minimum calorie requirement of 2144 kcal/day for an average person. About 34.6% of rural and 9.6% of the urban population were under the poverty line (ibid, p.154). Moreover, the distribution of the poor was also disproportionately concentrated into the rural areas. Out of the total poor, about 95.3% were living in the rural areas and only 4.7 % in the cities (ibid) (see Table 6.4). Poverty was found to be more serious in rural areas than in urban areas, in terms of not only the number of poor people but also the poverty gap (i.e. the distance below the poverty line) and the squared poverty gap (i.e. the income disparity among the poor).

Table 6.4: Poverty analysis and measurement in Nepal (2003/04)

	Population distribution	People below poverty	Distribution of poor	Poverty gap	Squared poverty gap
	%	%	%	%	%
Nepal	100	30.8	100	7.55	2.7
Urban	15	9.6	4.7	2.18	0.71
Rural	85	34.6	95.3	8.50	3.05

Source: MOF, 2005, pp.153-154

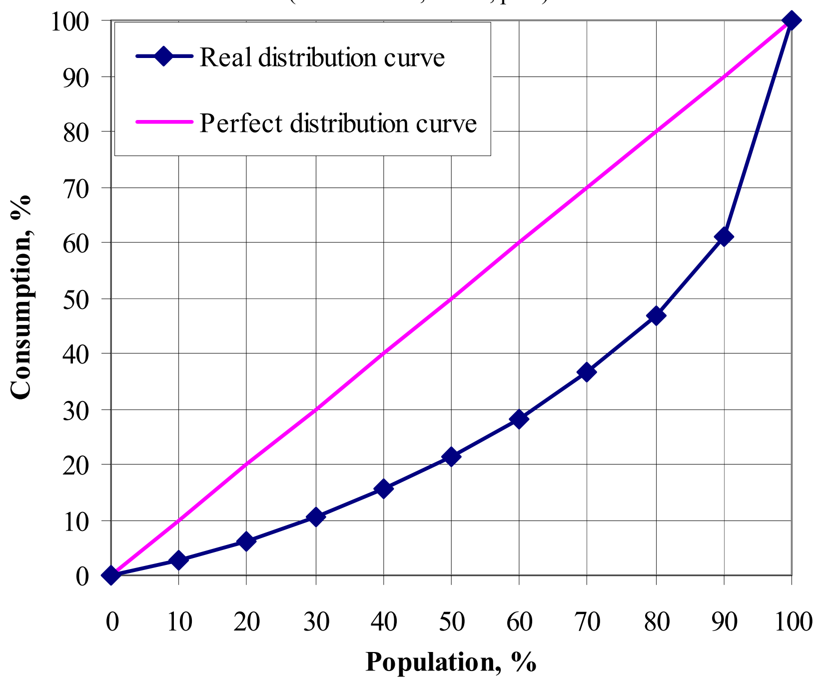
Average per capita dietary energy supply in 2002 was about 2440 kcal/day (FAO, 2004a, p.1) but the level of consumption between the rich and the poor varied widely - the Gini coefficient[3] was 0.41 (MOF, 2005, p.166). The top 20% of the population (the richest) shared about 53.3% of the total consumption while the bottom 20% (the poorest) shared only 6.2%

[3] The Gini coefficient is the measure of inequality between the rich and the poor

of the total consumption (CBS, 2004b, p.27), which has resulted in a large inequality in the consumption pattern among the people (see Figure 6.4).

Figure 6.4: Consumption pattern in Nepal (2003/04)

(Source: CBS, 2004b, p.27)



Cereal crops like rice, maize and wheat predominantly make up a major share of the total dietary energy supply required for the household food consumption in Nepal. For example, in 2002, the contributions to the total dietary energy supply by rice, maize and wheat were 38%, 17% and 14% respectively (FAO, 2004a, p.2). Rice has not only the first place in the dietary energy supply but also plays a very important role in religious and cultural activities. It is almost impossible to conduct any religious or cultural activities without having rice not only as a meal but also as a holy material. Rice may become even more important than now in the national food security system because rice can give high yields under a wider range of growing conditions (Swaminathan, 2002, p.203). Therefore, an attempt was made to quantify possible impacts of climate change through the reduction in rice production due to an increased irrigation demand caused by the increased temperatures.

A sensitivity analysis was carried out to quantify the impact of the increased water demand and the decreased rice production on poverty and food security. The following data and assumptions were taken for the analysis:

Statistics:

Population (2002) = 24.6 million (FAO, 2004a, p.1)

Per capita calorie supply =2440 kcal/day/capita (ibid)

Poverty line = per capita consumption of 2144 kcal/day (MOF, 2005, p.150)

Rice statistics for 2002 (ibid, p 48):

Production = 4,132,000 metric tonnes; Cultivated area = 1,545,000 ha;

Yield= 2.67 metric tonnes/ha

Water requirement for rice cultivation: 15000 m^3/ha (Subba, 2001, p.97)

The top 20% population consume 53.3% and the bottom 20% consume 6.2% of the total consumption (CBS, 2004b, p.27)

Edible rice supply = Total rice production (1-wastage rate)* (1-seed requirement)* extraction rate * (1-other losses) (FAO, 2000b, p.11)

Where,

Extraction rate for rice = 65%

Wastage rate = 10%

Other losses = 1.75%

Seed requirement = 55 kg / hectare

Total calorie-supply from the edible rice = Edible rice supply * energy content

Where,

Energy content for rice = 3.45 kcal/gm (FAO, 2000b, p.31)

Assumptions:

Two scenarios were considered for the analysis:

A. There will be no functioning international market and the top 20% will consume the same amount of calories taking the share from the bottom 20%.

B. There will be a functioning international market and the top 20% will import the required food and will not take the share from the bottom 20%.

1. Scenario A: There will be no possibility of food import.

- The top 20% will continue to consume the same amount of calories as they have better access to food.

- The middle 60% of population will share the consumption by the relation

$$C_{mid60\%} = OS/100 * P_{new\text{-}total} \quad (6.1)$$

Where,

$C_{mid60\%}$	= consumption for the middle 60% of the population
OS	= original share in the consumption, %
$P_{new\text{-}total}$	= Total reduced production due to warming

Per capita daily consumption for the middle 60% ($PC_{mid60\%}$)

$$PC_{mid60\%} = C_{mid60\%} /0.6 * population*365) \quad (6.2)$$

- The bottom 20% will share the remaining consumption left by others

$$C_{bottom20\%} = P_{total} - C_{top20\%} - C_{mid60\%} \quad (6.3)$$

Where,

$C_{bottom20\%}$	= consumption for the bottom 20% of population
$C_{top20\%}$	= consumption for the top 20% of population
$C_{mid60\%}$	= consumption for the middle 60% of population

Per capita daily consumption for the bottom 20% ($PC_{bottom20\%}$)

$$PC_{bottom20\%} = C_{bottom20\%} /(0.2 * population*365) \quad (6.4)$$

2. Scenario B: The food import from the international market will be possible:

- The top 20% will import the food equivalent to the decreased production from the international market, as they can afford it.
- The middle 60% of population will continue to consume the same per capita calories as at present because the level of consumption at present is already 23% below the minimum required level. They will maintain their level of consumption by taking the share of the bottom 20%.
- The Bottom 20% will share the remaining consumption left by others

$$C_{bottom20\%} = P_{total} - C_{top20\%} - C_{mid60\%} \quad (6.5)$$

Where,

$C_{bottom20\%}$	= consumption for the bottom 20% of population
$C_{top20\%}$	= consumption for the top 20% of population
$C_{mid60\%}$	= consumption for the middle 60% of population

Per capita daily consumption for the bottom 20% ($PC_{bottom20\%}$)

$$PC_{bottom20\%} = C_{bottom20\%} /(0.2 * population*365) \quad (6.6)$$

A decrease in rice production due to temperature rise was calculated by hypothetically reducing the equivalent land area of increased irrigation water demand (i.e. 1 m^3 of increased water demand = 1/15000 ha of rice field* 2.67 metric tonnes/ha of rice yield = 0.18 kg of rice). The findings of the calculation of per capita calorie supply for the average population are given in Table 6.5.

Table 6.5: Sensitivity of calorie supply to a warming for average population						
Particulars	Temperature Change Scenarios					
	T_0	T_{+1}	T_{+2}	T_{+3}	T_{+4}	T_{+5}
Rice water demand, m^3/ha (Change, %)	15,000 (0)	15,554 (3.7)	16,114 (7.4)	16,682 (11.2)	17,259 (15.1)	17,844 (19.0)
Rice production, 1000 metric tonnes /year	4132	3979	3825	3669	3510	3349
Edible rice supply, 1000 metric tonnes /year	2441	2351	2260	2168	2074	1979
Per capita average calorie supply, kcal/day	2440	2406	2371	2336	2300	2264

Because of an uneven distribution of income and unequal access to food, any impact of decrease in calorie-supply will be different for various income groups. The top 20% of the population, who are currently consuming about 53.3% of the total calorie-supply, may not have significant impact of the decreased food supply. In contrary, the impact may be very severe for the bottom 20% of the population, who are currently consuming only 6.2% of the total calorie supply. Their current daily calorie consumption is already only 35% of the minimum daily calorie requirement to carry out normal physical activities. In addition, the impact will depend on whether the rich people can import the food from the international market or not. If the rich cannot import any food from the international market, the poor will suffer more because, they will have poorer access to available food.

The outputs of the calculation for 2 different scenarios for different income groups (see Table 6.6) show that the impact of reduced agricultural production will be disproportionately greater for the poorer population because they are already undernourished. For example, a 5ºC rise in temperature would cause a decrease in the average per capita supply of 176 kcal/day (from 2440 kcal/day to 2264 kcal/day). Because of the large disparity in consumption patterns among the population, such a decrease would have different effects on the various income groups.

Table 6.6: Sensitivity of calorie supply to a warming for different income groups						
Particulars	Temperature Change Scenarios					
	T_0	T_{+1}	T_{+2}	T_{+3}	T_{+4}	T_{+5}
Scenario A: Without consideration of import possibilities of food from the international market						
Per capita calorie supply for the top 20% population , kcal/day	6503	6503	6503	6503	6503	6503
Per capita calorie supply for the mid 60% population , kcal/day	1647	1624	1601	1577	1553	1528
Per capita calorie supply for the bottom 20% population, kcal/day	756	655	552	447	341	233
Population with 756 kcal/day per capita calorie supply, million	4.92	5.58	6.25	6.93	7.62	8.32
Scenario B: With consideration of import possibilities of food from the international market						
Per capita calorie supply for the top 20% population , kcal/day	6503	6411	6319	6225	6131	6034
Per capita calorie supply for the mid 60% population , kcal/day	1647	1647	1647	1647	1647	1647
Per capita calorie supply for the bottom 20% population, kcal/day	756	676	596	514	430	346
Population with 756 kcal/day per capita calorie supply, million	4.92	5.44	5.97	6.50	7.04	7.59

A 5ºC warming would cause an increase of the poorest part of the population with an average per capita calorie consumption of less than 756 kcal/day from 4.92 million today to 8.32 million for scenario A and to 7.95 million for scenario B as analysed above. The minimum calorie requirement to carry out normal physical activities for an average person in Nepal is 2144 kcal/day (MOF, 2005, p.150). The poorest 20% of the population are currently living on only about 35% of that minimum level. A further decrease in the calorie consumption would result in the possible starvation of these people. The top 20% of the population are currently consuming about three times more than the minimum required level and would not suffer significantly from the marginal reduction in the calorie supply.

The availability of the required amount of water at the right moment is very important in order to secure the expected agricultural production. Agricultural production may be affected by the seasonal water deficit even without any changes in the annual water availability simply due to the lack of the right amount of water at the right time. Due to lack of seasonal data on agricultural production, the impact of the seasonal water stress on the agricultural production could not be analysed during the present research. Nevertheless, the increased water stress during the dry seasons due to the increased temperature was visible in the sensitivity analysis of seasonal irrigation demand (see Table 6.2).

6.1.4 Discussion of the Impacts of Climate Change on Water Balance, Agriculture and Food Security

Because of the monsoon-dominated climate, which includes large inter-seasonal variations of river flows, average annual values of river flows are a poor indicator of the amount of water resources available for use (FAO, 2000a, p.178). About 75% of the annual runoff in the Nepalese rivers leaves the respective watershed during the monsoon season from June to September (Mool et al., 2001a, p.19), which cannot be readily available for use during the non-monsoon seasons without storage. The amount of water readily available for use at present is between 10 and 20 percent of the total annual runoff in the south Asian region (FAO, 2000a, p.179). Higher temperatures would create more atmospheric water demand, which could lead to greater water stress (Rosenzweig and Hillel, 2005, p. 252) and shorter crop growing periods (see Table 5.2). Shallow unconfined aquifers along flood plains are generally recharged by seasonal streamflow and can be depleted directly by evaporation (IPCC, 2001b, p.199). Higher evaporation may mean that soil moisture deficits persist for longer and commence earlier (ibid). Currently, the total supply of drinking water has met only 79% of the total demand in Kathmandu (UNEP, 2001, p.178). The total sustainable withdrawal of groundwater from the Kathmandu valley's aquifers is approximately 26.3 million litres per day (mld), but the total ground water currently extracted is about 58.6 mld (ibid, p.123). Because of such overexploitation, the ground water table in the Kathmandu valley has been lowered significantly in the recent decades. For example, the static water level at Baluwatar in Kathmandu declined by 22.4 m in 24 years from 1976 to 1999 (ibid). Any further warming would increase the moisture deficit and decrease the water balance, which could exacerbate the problem of the water stress.

Agricultural water demand, particularly for irrigation is considerably more sensitive to climate change and it becomes more critical for crop production as conditions become hotter and drier (Frederick and Gleick, 1999, p.18; IPCC, 2001b, p.211). Climate variability directly affects agricultural production, as agriculture is one of the most vulnerable sectors to the risks and impacts of global climate change and water shortages (Ziervogel et al., 2006, p.4; Frederick and Gleick, 1999, p.25, Becker and Bugmann, 2001, p.61). Any further decreases in water resources, especially during the non-monsoon seasons, would adversely affect agricultural production. The lack of water, in association with higher temperatures, is the most limiting factor for agricultural productivity (Ziervogel et al., 2006, p.13).

A warmer temperature would exacerbate the problem of absolute food shortages. The marginalized and the poorest-of-the-poor section of the community would be hardest hit by this problem (McGuigan et al., 2002, p.6). The inequitable distribution of resources, unequal access to food and inadequate capacity to cope with the weather hazards would make the poorer section more vulnerable to climate change. Climate change would worsen not only the food distribution problem but also the absolute food shortages (Hohmeyer and Gärtner, 1992, p.28) and even deaths might be caused by both poor distribution and absolute shortages of food in places of possible grain deficits (ibid, p.31). Food security is not only a food self-sufficiency (FAO, 2003, p.23), rather it is a combination of food availability, food access and food utilization (ibid, p.7). Food availability is a function of resources and production. Food access is constrained by the income while food utilization is a factor of nutrition, which in turn is largely determined by food access. Ultimately, poverty is the most basic cause of food insecurity (see Gill et al., 2003, Annex-7, p.3). Poverty is much more prevalent, intense and severe in rural areas in Nepal (MOF, 2005, p.154). In most mountains and remote hills of Nepal, due to the rugged terrain and lack of roads, people cannot access food even if they could afford to buy it (FAO, 2004c, p.7). The losses in domestic food production due to climate change will further worsen the prevalence and intensity of hunger and this burden will undoubtedly fall disproportionately on the poorest (Shah, 2002, p.12). A decrease in food availability will mean greater competition for what is left (Hohmeyer and Gärtner, 1992, p.30) and the poor will certainly lose the competition because of the lower capacity in terms of economic, social and political aspects.

The principal groups of poor and food insecure people in Nepal are subsistence farmers (Gill et al., 2003, Annex-7, p.1). Mountain crop production, practised close to the margins of viable production, can be highly sensitive to climate change (Carter and Parry, 1994, p.420). Small changes in climate can induce large changes in agricultural risk in the mountains because risk levels often increase exponentially with altitude (ibid, p.421). Out of the total cultivable area of 2.64 million hectares in Nepal, only 1.14 million hectares (i.e. 43%) had modern irrigation facilities at the end of 2004 (MOF, 2005, p.176). Subsistence farmers, non-irrigated lands and the crops already at their maximum temperature tolerance are the most vulnerable to climate change (IPCC, 2001b, p.270). Marginal farm households account for approximately 28% of Nepal's total population (FAO, 2004c, p.15). Subsistence agriculture contributes 43% to the total household income in Nepal (FAO, 2004b, p.23) and the majority of the population are subsistence farmers. An optimum range of temperatures for rice cultivation in Nepal is 22-30ºC (MOPE, 2004, p.76). Most of the southern Terai plains of Nepal, where most of the rice is cultivated, have already an annual average temperature near or above 30ºC (Yogacharya, 1998, pp.188-190; CBS, 2004a, p13). Any further increase in temperature beyond this optimum range will adversely affect the rice production in these areas in addition to the reduced production caused by the increased water stress due to warming.

6.2 Impacts on the Hydropower Potential

6.2.1 Empirical Findings of the Impacts on the Hydropower Potential

Nepal's total available surface water is 224 billion m^3 (UNEP, 2001, p.128), of which about 53.96 km^3 (i.e. 24%) comes from the territory outside Nepal and 170.04 km^3 from Nepal's own territory. The annual total amount of precipitation inside the territory of Nepal is 267 km^3, of which about 10% occurs as snowfall and 90% as rainfall (ibid). The permanent snowline in the Nepal Himalayas lies at about 5000 masl (meters above sea level) and about 23% of Nepal's total area lies above this line(CBS, 2004a, p.15; MOPE, 2004, p.96). Increasing temperatures will shift the permanent snowline upward and will reduce the snow-to-rain ratio.

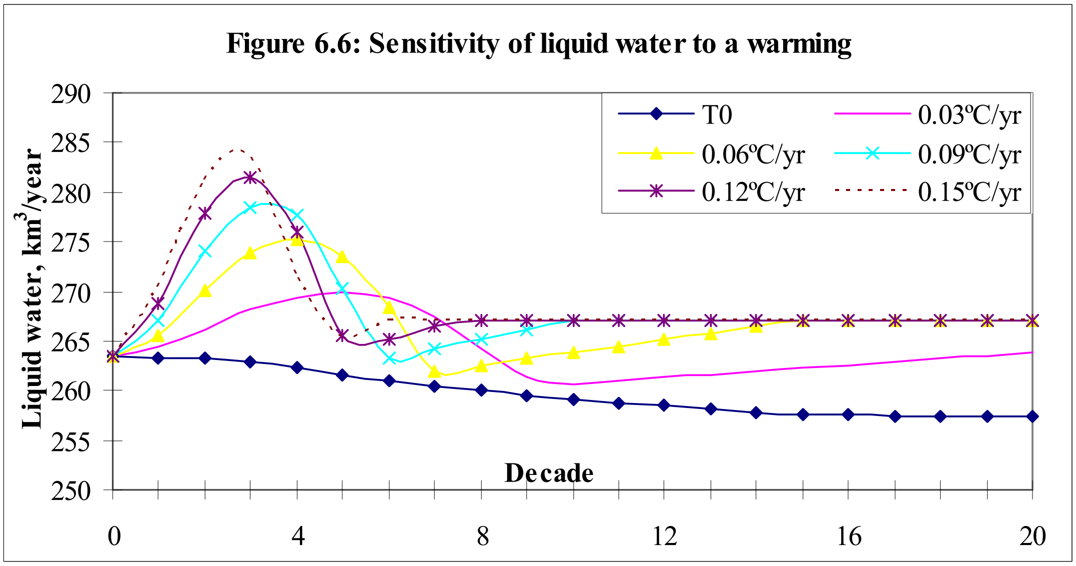
Nepal's current theoretical hydropower potential is 83 GW including the potential of the runoff collected outside the territory of Nepal (Shrestha, 1985, p.33). The information of the basin areas located outside the territory of Nepal was not available for the present study. Therefore, the present study was limited to the analysis of the the theoretical hydropower potential of the runoff generated inside the country, which was assumed to be directly proportional to the basin areas inside Nepal and taken as 63 GW (i.e. 76% of the total hydropower potential). The long-term average runoff data observed at 50 hydrological stations by the Department of Hydrology and Meteorology of Nepal (Yogacharya and Shrestha, 1998, pp. 214-217) and the snow and glacier melt rate determined by the present study at Langtang were used in order to generate an all-Nepal average monthly hydrograph. Melt-water contribution to the total monthly flow was at a minimum in December (3.9%) and at a maximum in April and May (32.3%). During the monsoon and the post-monsoon seasons, the rivers receive significant flow from the monsoon rain. Therefore, the melt-water contribution during these seasons is relatively lower than during the pre-monsoon season (see Table 6.7).

The annual and the monthly hydrographs of Nepal are generally influenced by monsoon rain. There is a significant contribution of melt water during the dry season (March-May). In the present analysis, melt water contributed about 13% to the total annual runoff whereas it contributed about 32% to the dry season runoff in Nepal. Most of Nepal's hydropower plants are the run-of-river type, which are designed for the dry season flows (i.e. minimum flows). Therefore, the hydropower potential from melt-water for the present analysis was assumed as 32% of the total hydropower potential in Nepal and the rest from the rainwater.

Table 6.7: All-Nepal average monthly and annual hydrograph

Months	Rainwater, km^3	Melt water , km^3			Total, km^3	Melt-water,%
		Snow	Glacier	Subtotal		
January	3.40	0.75	0.05	0.8	4.20	19.0
February	2.83	0.78	0.05	0.83	3.66	22.7
March	2.49	1.07	0.08	1.15	3.64	31.6
April	2.56	1.12	0.10	1.22	3.78	32.3
May	3.67	1.36	0.39	1.75	5.42	32.3
June	10.88	2.18	1.17	3.35	14.23	23.5
July	32.63	2.60	1.62	4.22	36.85	11.5
August	37.96	3.69	1.55	5.24	43.20	12.1
September	31.05	2.31	0.93	3.24	34.29	9.4
October	13.20	0.65	0.11	0.76	13.96	5.4
November	6.18	0.35	0.02	0.37	6.55	5.6
December	4.18	0.16	0.01	0.17	4.35	3.9
Annual	153.00	17.00	6.08	23.08	176.08	13.1

The expected future warming might change not only the melt-water contribution but also the total water availability in Nepal due to increased evapotranspiration. A sensitivity analysis of total water availability in Nepal to temperature rise was carried out earlier (see Chapter 5.3.2) and a similar analysis has been carried out here in order to determine the sensitivity of hydropower potential. Hydropower potentials for melt-water and rainwater were separately calculated and added together to get the total hydropower potential of the runoff from the territory inside Nepal (see Table 6.8, Figure 6.5).



Generally, the hydropower potential is a function of the average flow and the vertical drop available for the particular flow. In the present sensitivity analysis, the change in hydropower potential was assumed to be directly proportional to the change in the total water availability. All other factors like technological advancement, site alterations were assumed constant.

Table 6.8: Sensitivity of hydropower potential in Nepal with temperature rise

Decade*	Hydropower potential, GW					
	ΔT = 0	ΔT = 0.03ºC/yr	ΔT = 0.06ºC/yr	ΔT =0.09ºC/yr	ΔT =0.12ºC/yr	ΔT =0.15ºC/yr
0	63.0	63.0	63.0	63.0	63.0	63.0
1	62.9	62.8	63.0	63.4	63.8	64.4
2	62.9	63.4	65.0	66.7	68.3	69.4
3	62.7	64.3	66.6	67.9	67.8	66.8
4	62.1	64.4	66.0	64.4	59.3	51.7
5	61.5	64.0	62.6	55.3	46.6	41.9
6	61.0	62.7	56.3	46.3	42.6	38.9
7	60.5	60.1	48.8	44.5	40.1	37.4
8	60.1	56.4	47.6	42.6	38.3	36.0
9	59.6	52.9	46.3	40.7	37.1	34.5
10	59.3	51.3	45.1	38.9	36.0	33.0
11	58.9	50.7	43.8	38.0	34.8	31.6
12	58.7	50.1	42.6	37.1	33.6	30.1
13	58.4	49.5	41.3	36.3	32.5	28.7
14	58.2	48.8	40.1	35.4	31.3	27.2
15	58.0	48.2	38.9	34.5	30.1	25.8
16	58.0	47.6	38.3	33.6	29.0	24.3
17	57.8	47.0	37.7	32.8	27.8	22.8
18	57.7	46.3	37.1	31.9	26.6	21.4
19	57.7	45.7	36.5	31.0	25.5	19.9
20	57.7	45.1	36.0	30.1	24.3	18.5

Note: Decades have been counted from 2001.

The results of the analysis (see Table 6.8, Figure 6.5) show that the hydropower potential initially increases with a temperature increase due to increased glacier-melt. However, further warming will add no more hydropower potential but reduce it at later stages due to reduced glacier-ice reserves. The glaciers in the Nepal Himalayas have been retreating so fast in recent decades that there will be a 6% decrease in hydropower potential at the end of this century even without any further warming. In the case of a warming of 0.06ºC/year, the theoretical hydropower potential of Nepal will rise by 5.7% by 2030 but will decrease by 28% by the end of this century. An analysis of installed capacity and annual energy generation of 10 existing hydro power plants of Nepal showed that the actual annual average energy generation from these plants for the period of 1990-2003 was about 58% of the theoretical available energy based on installed capacity (NEA, 2003b, p.48). So, the sensitivity of hydro-energy potential was calculated using the same coefficient of 0.58 (see Table 6.9).

Table 6.9: Sensitivity of hydroenergy potential in Nepal with temperature rise

Decade*	Hydroenergy potential, TWh/a					
	ΔT = 0	ΔT = 0.03ºC/yr	ΔT = 0.06ºC/yr	ΔT =0.09ºC/yr	ΔT =0.12ºC/yr	ΔT =0.15ºC/yr
0	320.3	320.3	320.3	320.3	320.3	320.3
1	319.7	318.9	320.0	321.9	324.4	327.3
2	319.5	322.3	330.1	339.0	347.0	352.8
3	318.4	326.5	338.3	344.9	344.4	339.6
4	315.5	327.3	335.3	327.3	301.3	262.9
5	312.6	325.3	318.1	280.9	236.7	213.1
6	309.8	318.4	286.1	235.4	216.3	197.5
7	307.3	305.5	248.1	225.8	203.6	190.1
8	305.2	286.3	241.8	216.3	194.6	182.7
9	303.0	268.7	235.4	206.7	188.6	175.3
10	301.4	260.9	229.0	197.5	182.7	167.9
11	299.2	257.7	222.7	193.1	176.8	160.5
12	298.4	254.5	216.3	188.6	170.9	153.1
13	296.8	251.3	209.9	184.2	164.9	145.7
14	295.7	248.1	203.6	179.8	159.0	138.3
15	294.9	244.9	197.5	175.3	153.1	130.9
16	294.6	241.8	194.6	170.9	147.2	123.5
17	293.7	238.6	191.6	166.4	141.3	116.1
18	293.2	235.4	188.6	162.0	135.3	108.7
19	293.2	232.2	185.7	157.5	129.4	101.3
20	293.2	229.0	182.7	153.1	123.5	93.9

Note: decades are counted from 2001

6.2.2 Discussion of Impacts on the Hydropower Potential

Stream-flow in most of the rivers in Nepal is at a minimum in early spring because flows recede rapidly after the summer rains. This period of minimum flow is problematic for the run-of-river hydroelectric facilities (Kattelmann, 1993, p.103). Snow-fed rivers provide sustained flow even during this critical period through the melt-water contribution. The melt-water contribution may exceed 30% of average flows of Nepalese rivers in May (Sharma, 1993, p.121), which has reinforced the findings of the present study. A possible decrease in river runoff, as indicated by most projections, would reduce not only the electricity generation of existing plants but also the total hydropower potential of Nepal (Agarawala et al., 2003, p.32). In addition, there might be significant declines in the dry season flows and an increasing trend in the number of flooding days because of climate change, which is critical for hydropower generation (ibid). The flows of glacier-fed rivers first increase due to warming, as more water is released by the melting of snow and glaciers. As the glaciers get smaller and the volume of melt water reduces, the dry season flows will no longer be supported by melt-water and will decline (Shrestha, 2005, p.77). Therefore, the reduced dry season flow caused by a temperature rise could result in reduced hydropower potential.

The hydropower potential will be affected not only by the increased seasonal variability but also by the decreased water availability due to climate change. The current hypothetical value of the total hydroenergy potential in Nepal excluding the runoff collected outside the country is equivalent to about US \$ 15 x 10^{12} per year using a current energy charge of 0.047 US \$/kWh (i.e. NRs 3.5/kWh) of the Nepal Electricity Authority for wholesale consumers (NEA, 2003a, p.40)[4]. The monetary value of the annual hydroenergy potential would rise to about US \$ 16.2x10^{12} in 2030 and would decrease to about US \$ 7.2x10^{12} in 2200, if the temperature rises by 0.09ºC/year. The glaciers in the Nepal Himalayas are already melting so rapidly that there will be no glaciers left in 2180 even without any further warming. The equivalent annual hydroenergy potential in Nepal in 2200 would decrease to US \$ 13.8x10^{12} even without any further temperature rise and to US \$ 8.6x 10^{12}, if the temperature rises by 0.06ºC/year. Unfortunately, this potential cannot be trapped without appropriate infrastructures, functioning energy markets and the sustainable development of water resources.

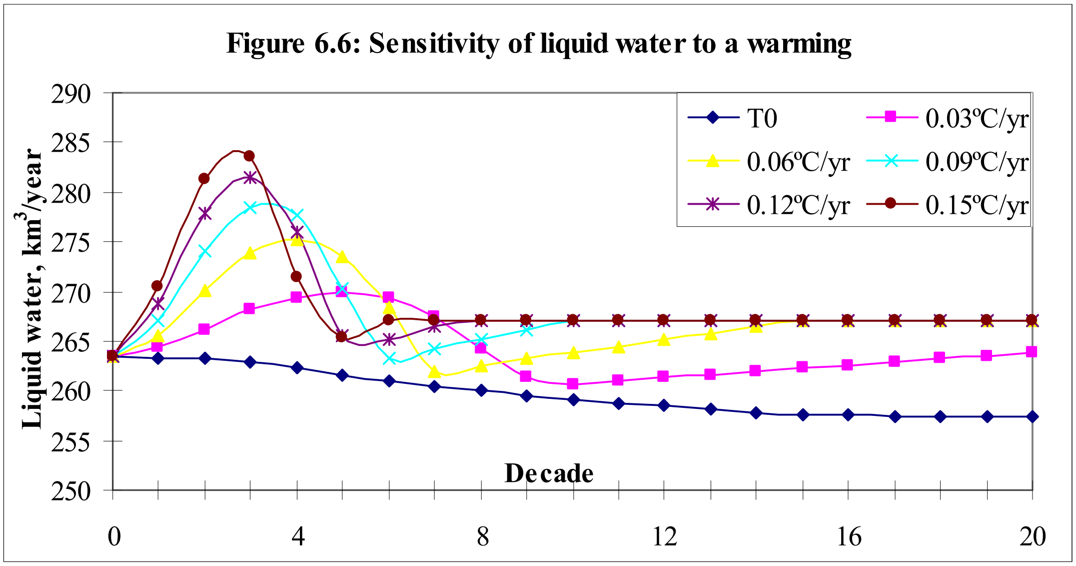
[4] Assuming an exchange rate of 1 US \$ = NRs 74

6.3 Impacts on the Extreme Events

6.3.1 Impacts on the Glacier Lake Outburst Flood

Rising temperature that causes retreat of mountain glaciers is one of the main factors responsible for the formation and expansion of glacier lakes (Mool et al., 2001a, p.121). Almost all glaciers in the Himalayas have been retreating since the Little Ice Age (1400-1650 AD) and on average they have retreated about 1 km since then (ibid, p.122). Such a retreat has provided a large space for retaining melt water that has led to the formation of glacier lakes. A rising water level in these lakes makes them vulnerable to collapse. The collapse of such lakes may result in the instantaneous release of the stored lake water that may create devastating floods. Such floods are termed as Glacier Lake Outburst Floods.

Glacier Lake Outburst Floods became one of the most disastrous events in Nepal in the second half of the last century. Increasing temperatures would accelerate the glacier melt on the one hand and reduce the snow-to-rain ratio on the other, which could result in the formation and expansion of glacier lakes in the mountain valleys. The supporting dams of these lakes generally consist of loose moraines, which are not strong enough to resist the growing hydrostatic pressure on them caused by rising water level in the lakes. An increasing volume of liquid precipitation (i.e. rainwater) and accelerated melting of glaciers are the main causes for the rising water level in glacier lakes in the Nepal Himalayas. Both of these events jointly and simultaneously may create an additional volume of liquid water in the high mountains. This may have a direct impact on the creation of new glacier lakes and the rapid expansion of existing ones in the Nepal Himalayas. Such newly formed and expanded glacier lakes face growing hydrostatic pressures on their supporting dams and ultimately these lakes will collapse. Sensitivity analysis of glacier-melt and rainwater to temperature rises revealed that the liquid water volume would increase in all temperature rise scenarios (see Figure 6.6).



The rate of the formation and growth of glacier lakes depends among other factors on the rate of increase in liquid water. For example, the annual liquid water volume will reach its maximum after 5 decades at a warming rate of 0.03ºC/year while it will reach its maximum even within 3 decades at a warming rate of 0.09ºC/year (see Table 6.10).

Table 6.10: Sensitivity of melt- and rainwater to temperature change in Nepal

Decade*	Volume of melt- and rainwater, km^3/year					
	ΔT = 0	ΔT = 0.03ºC/yr	ΔT = 0.06ºC/yr	ΔT =0.09ºC/yr	ΔT =0.12ºC/yr	ΔT =0.15ºC/yr
0	263.38	263.38	263.38	263.38	263.38	263.38
1	263.25	264.33	265.64	267.11	268.72	270.43
2	263.21	266.15	270.01	274.03	277.91	281.34
3	262.96	268.14	273.86	278.50	281.54	283.54
4	262.30	269.39	275.30	277.70	275.96	271.44
5	261.65	269.99	273.52	270.33	265.55	265.41
6	261.03	269.39	268.43	263.25	265.17	267.00
7	260.46	267.53	261.90	264.16	266.42	267.00
8	260.00	264.28	262.57	265.17	267.00	267.00
9	259.50	261.36	263.25	266.08	267.00	267.00
10	259.13	260.65	263.82	267.00	267.00	267.00
11	258.64	260.99	264.50	267.00	267.00	267.00
12	258.46	261.33	265.17	267.00	267.00	267.00
13	258.11	261.56	265.74	267.00	267.00	267.00
14	257.86	261.90	266.42	267.00	267.00	267.00
15	257.67	262.24	267.00	267.00	267.00	267.00
16	257.60	262.57	267.00	267.00	267.00	267.00
17	257.41	262.91	267.00	267.00	267.00	267.00
18	257.30	263.25	267.00	267.00	267.00	267.00
19	257.30	263.49	267.00	267.00	267.00	267.00
20	257.30	263.82	267.00	267.00	267.00	267.00

Note: decades are counted from 2001.

The central message from the findings (see Table 6.10, Figure 6.6) is that the formation and growth of glacier lakes in the Nepal Himalayas will be most significant during the next three to five decades. The formation and growth of glacier lakes will continue, though at a slower speed, even after the annual volume of liquid water stops increasing because cumulative volumes of these lakes generally continue to increase. The growth of lakes and subsequent rise in water levels will generally increase the risks of the Glacier Lake Outburst Floods (GLOFs).

The Glacier Lake Outburst Floods (GLOFs) occurred more frequently during the last 3 decades of the last century (Mool et al., 2001a, p.128). There have been more than 12 reported GLOF events in Nepal since 1964. Among them, some glacier lakes collapsed more than twice during the last 40 years. The Zhangzangbo Glacier Lake at the headwater of the Sunkoshi River collapsed twice (in 1964 and 1981) and the Ayaco Glacier Lake at the head of the Arun River collapsed thrice (in 1968, 1969 and 1970) in the recent past (ibid, p. 129). The Zhangzangbo GLOF (11^{th} of July 1981) caused substantial damage to the diversion weir of the Sunkoshi Hydropower plant, the Friendship Bridge at the Nepal-China border, two other bridges and extensive road sections of the Arniko Highway amounting to a total loss of more than US $ 3 million (ibid, p. 132). Similarly, the Dig Tsho GLOF (4^{th} of August 1885) in the Khumbu Region of east Nepal destroyed the Namche small hydroelectric plant with an estimated loss of US $ 1.5 million, 14 bridges, 30 houses, trails and cultivation lands, properties of many families including 3 human lives over a distance of 42 km (Yamada, 1998, p.11; Ives, 1986, p. 30). On 3^{rd} of September 1998, the Tam Pokhari GLOF in the Dudh Koshi Basin, eastern Nepal destroyed 6 bridges and farm lands (estimated total loss of US $ 2 million) including 2 human lives (Mool et al., 2001a, p.135).

Mool et al. (2001a, p.176) identified 20 potentially dangerous glacier lakes in the Nepal Himalayas. Among them, Tsho Rolpa is one of the biggest glacier lakes (ibid, p.177). The lake is located at 4,580 metres above sea level and is just about 50 years old. Its surface area increased more than seven fold in 40 years from 0.23 km^2 in 1957 to 1.65 km^2 in 1997 (DHMN, 2000, p.3) (see Figure 6.7).

A potential outburst of the Tsho Rolpa glacier lake could instantaneously release about 30 million cubic metres of water (i.e. about 3-5 times more than that in the case of Dig Tsho

GLOF) and would cause serious damage to about 10,000 human lives, thousands of livestock, agricultural land, forest, bridges, road and Ramechhap Airport including the Khimti Hydroelectric Plant (Horstmann, 2004, p.4; DHMN, 2001, p.4). The potential damage cost to the Khimti Hydroelectric Plant alone would be more than US $ 22 million (Horstnamm, 2004, p.4). The estimated peak discharge would be about 7000 m^3/s, the flood would rise up to 17 metres from normal flood levels and the damage impacts would reach farther than 100 km downstream (Rana et al., 2000, p.566).

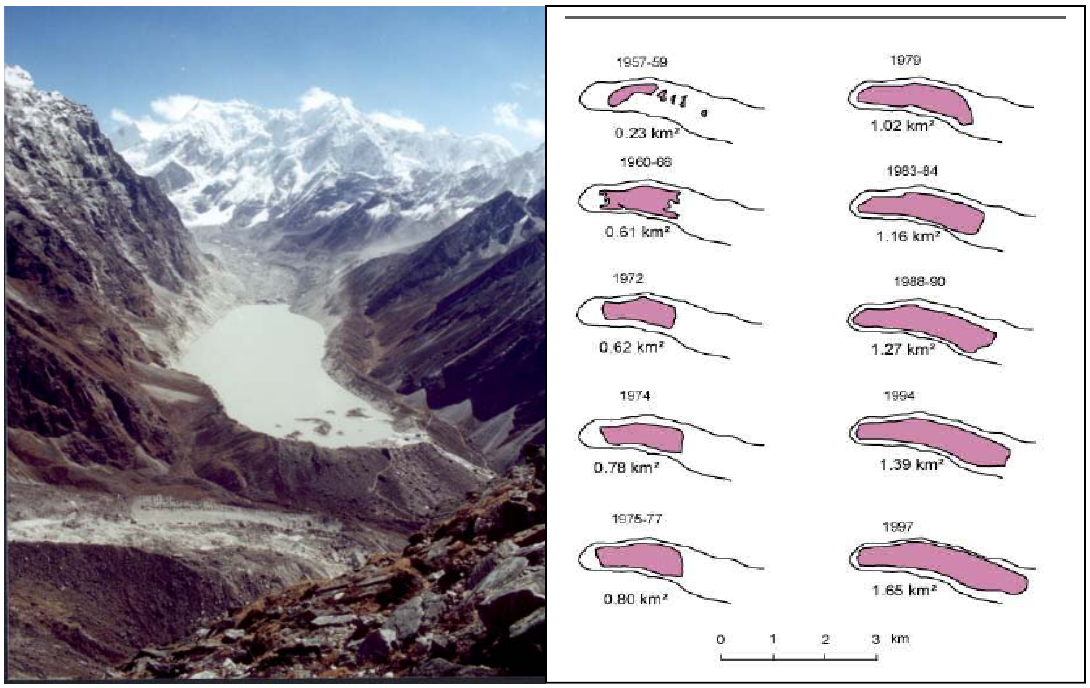


Figure 6.7: Tsho Rolpa Glacier Lake and its development (after Mool et al, 2001a, p.146; DHMN, 2000, p.3)

Due to such a substantial risk of GLOF, the flood risk reduction system was installed in 1998 to warn the people living downstream of Tsho Rolpa. Additionally, the water level of the lake was reduced by 3 m by constructing an open channel across the moraine dam-crest in June 2000 and thereby the flood risk was reduced by 20% (Rana et al., 2000, p.563). The total project costs were about US $ 3 million and were financed by the government of the Netherlands (DHMN, 2001, p.6).

The conclusion of the studies of past GLOF events and applied risk reduction measures in Nepal is that the threats of potential damage by GLOFs in Nepal are imminent and the costs of possible risk reduction measures are extremely high for a country like Nepal. The GLOFs are the new threats of climate change in the Nepal Himalayas (Horstmann, 2004, p.2). Empirical and model studies suggest that there will be more new glacier lakes and existing glacier lakes will grow rapidly in the Nepal Himalayas in the future because of climate change. Historical records of past GLOFs suggest that the frequency of these events appears to be increasing (Agrawala et al., 2003, p.28). The damage magnitude depends not only on the lake characteristics like volume and surface area of the lakes and the rate of water-release from the lake, but also on the natural features of the river channel and the status of infrastructure and habitation (Yamada, 1998, p.14). Therefore, it was difficult to quantify the total damage of potential GLOFs in Nepal without having detailed studies of all individual glacier lakes and the risk prone areas, which was beyond the scope of the current study.

6.3.2 Impacts on Droughts, Floods and Landslides

6.3.2.1 Snow-covered Area and the Extreme Floods

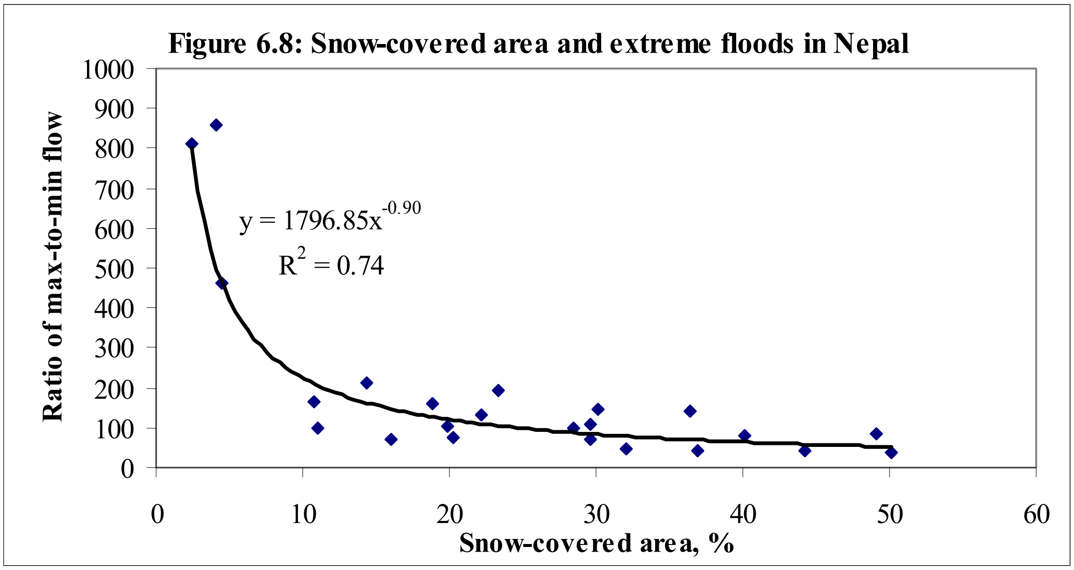
An analysis of the observed river flows from 50 hydrological stations across Nepal has shown that the ratio of maximum to minimum instantaneous flows increases with a decrease in snow-covered areas (Yogacharya and Shrestha, 1998, pp. 214-217; WECS/DHMN, 1996, Annex A). This is because snow acts as a balancing reservoir and plays an important role in the hydrologic cycle (LRMP, 1984, p.15). The fully rain-fed hydrological stations (i.e. without snow-covered areas) had a maximum-to-minimum discharge ratio of 2422 while those with a snow-covered area of more than 30% of the total basin areas had only 78 (see Table 6.11)

Table 6.11: Snow-covered areas and the ratio of maximum to minimum instantaneous flows in some selected hydrological stations across Nepal (1962-93)

Snow covered area [%]	Ratio of maximum to minimum flows	Number of stations
0	2422	20
<10	1103	4
10-30	137	13
>30	78	8

Source: Yogacharya and Shrestha, 1998, pp.214-217; DHMN/WECS, 1996, Appendix A

A correlation analysis between snow-covered areas within the basin and maximum-to-minimum discharge ratios of 24 hydrological stations across Nepal for the period of 1962-93 showed a strong negative correlation between them (correlation coefficient - Spearman's ρ-rho =-0.724). The correlation was significant at the 0.01 level (see Annex 6.3). The correlation coefficient clearly indicated that decreasing snow-covered area would result in an increasing ratio of maximum-to-minimum discharges indicating an increasing likelihood of extreme floods (see Figure 6.8, Annex 6.2).



The regression analysis of the data revealed an equation of inverse function as following (R^2=0.74, significance level <0.001):

$$E= 1796.85*A^{-0.9} \qquad (6.3)$$

Where,

E= Ratio of extreme maximum-to-minimum flows

A= Snow-covered area, %

The relationship given by Equation 6.3 indicates that increasing temperatures not only reduce water storage in the mountains but also increase the likelihoods of extreme floods.

6.3.2.2 The Flood Frequency Analysis

Cloudburst-induced floods will also rise due to an increase in the intense precipitation events. Maximum instantaneous floods of the Bagmati River at Chovar for the period of 1963-1980 were used for the flood frequency analysis. A return period for each flood was determined using the Weibull distribution (Chow, 1964, p.8.20):

$$T= (N+1)/m \qquad (6.4)$$

Where,

T= Return period, year

N= Total number of record

m= Rank of peak floods from the highest

The relation between the return period and the peak floods were found as (R^2= 0.95; $p<0.001$):

$$Q= 218.64 \ln(T)+246.64 \quad (6.5)$$

Where,

Q= Maximum instantaneous annual flood in m^3/s

T= Return period in years

The same peak floods were hypothetically increased by 20% and the new relation between the peak floods and the return period was found as (R^2= 0.95; $p<0.001$):

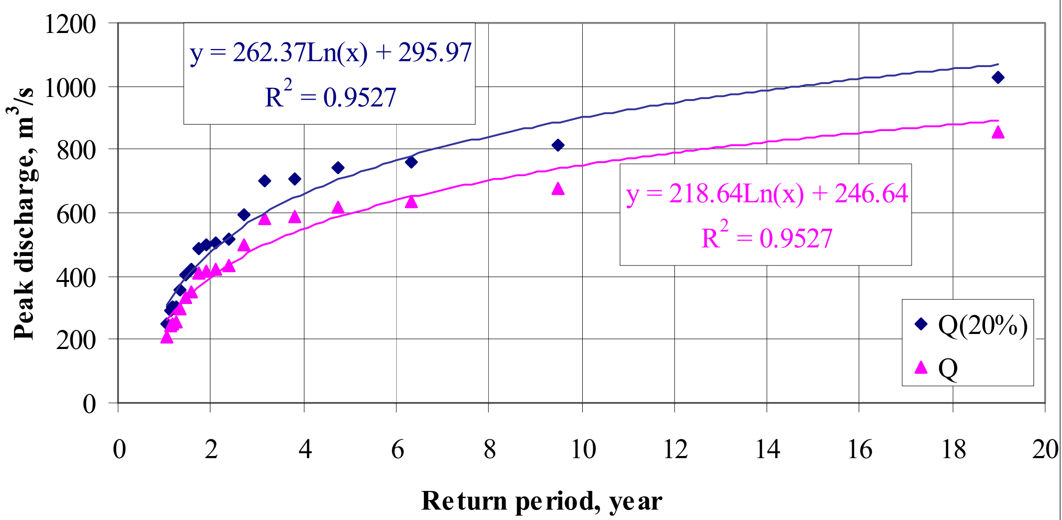
$$Q_{20\%}= 262.37 \ln(T)+295.97 \quad (6.6)$$

Where,

$Q_{20\%}$= hypothetically 20% increased peak flood in m^3/s.

In the past, a flow of 450 m^3/s occurred every 2.54 years on average. When each of the instantaneous peak flood magnitudes increased by 20%, the incidence of the same flood levels would drop to 1.8 years. Thus, in any given year, the probability that a flood of the magnitude 450 m^3/s would occur increases from 39.3% to 55.6% when peak floods increase by 20% (see Figure 6.9).

Figure 6.9: Hypothetical changes in peak discharges of the Bagmati River at Chovar



Currently, about 80% of the total annual precipitation in Nepal occurs during the summer months (June-September) and only 20% over the rest of the year (Chailse and Khanal, 2001, p.64). Due to such an uneven distribution of precipitation in Nepal, there is substantial damage caused by water-induced disasters like landslides and floods almost every year in the summer. Model studies suggest that there will be about 22.9% increase in summer precipitation with only 12.6% increase in annual precipitation (Agrawala et al., 2003, p.13), which indicates a more pronounced seasonal imbalance of precipitation due to climate change.

6.3.2.3 Droughts, Floods and Landslides caused by the Changing Precipitation Pattern

Though there was no significant trend in the annual precipitation at the selected stations (see Table 4.3), there was a significantly increasing trend in July-August precipitation and a decreasing trend in the annual number of rainy days. At the same time, the number of rainy days with higher intensity of precipitation was increasing in the study period (see Table 4.5). A decreasing number of rainy days indicated an expanding drought period. The monsoon rain is very important for agriculture in monsoon Asia and failure in monsoon can cause serious droughts leading to a decreased agriculture production and even famine (Chalise, 1994, p.398). Furthermore, an increasing number of days with higher intensity of precipitation and increasing July-August precipitation indicated an increasing likelihood of monsoon floods and landslides.

Even without any changes in total annual precipitation, there will be significant changes in snowfall and rainfall amounts due to warming. Increasing temperatures will result in decreasing snow-to-rain ratios. For example, a 2ºC warming in Langtang will result in a decrease in snow-to-rain ratio from 1.61 to 0.89 (see Table 5.7). Currently, about 26.7 km^3 of precipitation falls as snowfall every year in the Nepal Himalayas. If the temperature increases by 0.06ºC/yr, the volume of precipitation as snowfall will decrease to 8.7 km^3 in 2100 and there will be no snowfall in 2150. If the temperature increases by 0.09ºC/yr, there will be no snowfall in 2100 (see Table 6.12).

Table 6.12: Sensitivity of snowfall to temperature increases in the Nepal Himalayas

Decade*	Amount of snowfall in water equivalent, km^3/year					
	ΔT = 0	ΔT = 0.03ºC/yr	ΔT = 0.06ºC/yr	ΔT =0.09ºC/yr	ΔT =0.12ºC/yr	ΔT =0.15ºC/yr
0	26.7	26.7	26.7	26.7	26.7	26.7
1	26.7	25.5	24.6	23.7	22.8	21.9
2	26.7	24.6	22.8	21.1	19.3	17.5
3	26.7	23.7	21.1	18.4	15.7	13.1
4	26.7	22.8	19.3	15.7	12.2	8.7
5	26.7	21.9	17.5	13.1	8.7	4.3
6	26.7	21.1	15.7	10.4	5.1	0
7	26.7	20.2	14.0	7.8	1.6	0
8	26.7	19.3	12.2	5.1	0	0
9	26.7	18.4	10.4	2.5	0	0
10	26.7	17.5	8.7	0	0	0
11	26.7	16.6	6.9	0	0	0
12	26.7	15.7	5.1	0	0	0
13	26.7	14.9	3.4	0	0	0
14	26.7	14.0	1.6	0	0	0
15	26.7	13.1	0	0	0	0
16	26.7	12.2	0	0	0	0
17	26.7	11.3	0	0	0	0
18	26.7	10.4	0	0	0	0
19	26.7	9.6	0	0	0	0
20	26.7	8.7	0	0	0	0

Note: decades are counted from 2001.

The permanent snowline in Nepal Himalayas lies close to 5000 m elevation (MOPE, 2004, p. 95) but the snowline comes down to about 2400 m in January (LRMP, 1984, p.17). About 43% of the total area in Nepal lies above 3000 masl (CBS, 2004a, p.15), where a significant amount of precipitation currently occurs as snowfall. A decrease in the snow-to-rain ratio due to warming may have a substantial effect on the river runoff not only in the high mountain areas but also in the plains downstream. An increase in rainfall due to a decrease in snow-to-rain ratio, even without any change in total precipitation will ultimately increase the likelihoods of landslides and floods. Currently, the total amount of average annual rainfall in Nepal is 240.3 km^3 (UNEP, 2001, p.129). The total annual rainfall will rise to 267 km^3 in 2150, if the temperature rises by 0.06ºC/yr only due to an increase in rain-to-snow ratio caused by increased temperatures. Likewise, if the temperature increases by 0.09ºC/yr, the total annual rainfall will reach to 267 km^3 by 2100 (see Table 6.13). The total precipitation was assumed constant during the sensitivity analysis of rainfall and snowfall. If there is an increase in precipitation in the Himalayas as indicated by some studies, the likelihoods of landslides and floods will be even more.

Table 6.13: Sensitivity of rainfall to temperature increases in the Nepal Himalayas

Decade*	Amount of rainfall, km^3/year					
	ΔT = 0	ΔT = 0.03ºC/yr	ΔT = 0.06ºC/yr	ΔT =0.09ºC/yr	ΔT =0.12ºC/yr	ΔT =0.15ºC/yr
0	240.3	240.3	240.3	240.3	240.3	240.3
1	240.3	241.5	242.4	243.3	244.2	245.1
2	240.3	242.4	244.2	245.9	247.7	249.5
3	240.3	243.3	245.9	248.6	251.3	253.9
4	240.3	244.2	247.7	251.3	254.8	258.3
5	240.3	245.1	249.5	253.9	258.3	262.7
6	240.3	245.9	251.3	256.6	261.9	267.0
7	240.3	246.8	253.0	259.2	265.4	267.0
8	240.3	247.7	254.8	261.9	267.0	267.0
9	240.3	248.6	256.6	264.5	267.0	267.0
10	240.3	249.5	258.3	267.0	267.0	267.0
11	240.3	250.4	260.1	267.0	267.0	267.0
12	240.3	251.3	261.9	267.0	267.0	267.0
13	240.3	252.1	263.6	267.0	267.0	267.0
14	240.3	253.0	265.4	267.0	267.0	267.0
15	240.3	253.9	267.0	267.0	267.0	267.0
16	240.3	254.8	267.0	267.0	267.0	267.0
17	240.3	255.7	267.0	267.0	267.0	267.0
18	240.3	256.6	267.0	267.0	267.0	267.0
19	240.3	257.4	267.0	267.0	267.0	267.0
20	240.3	258.3	267.0	267.0	267.0	267.0

Note: decades are counted from 2001

Nepal has the highest number of annual deaths caused by natural disasters among the countries of the Hindu Kush- Himalayan region in terms of its total area and population (Khanal, 2005, p.181). The number of average annual deaths per million populations in Nepal during 1990-1998 was 35 whereas those in India, China, Bhutan/Myanmar and Pakistan were 6, 3, 2 and 7 respectively (ibid). About 30% of the total annual deaths of people and about 54% of total annual property losses from various disasters in Nepal are caused by water-induced disasters like floods, landslides and avalanches (DWIDP, 2002, p.16). For example, the number of annual average deaths from all types of disaster from 1983 to 2001 was 1077, whereas that only from water-induced disasters was 322. Similarly, the annual average loss of property from various natural disasters was US $ 19 million and that from water-induced disasters was US $ 10 million (ibid). Water-induced disasters are caused by extreme weather events associated with heavy rainfall, which result in floods, landslides and debris flows causing substantial damages almost every monsoon (Chalise and Khanal, 2001, p.63). Particular types of water-induced disasters are common for specific elevation zones. For example, snow avalanches and glacier lake outburst floods (GLOFs) occur in high mountain areas normally above 3500 m, while landslides, debris flow, mudflow, flash floods and landslide-dammed floods are common between 500 m and 3500 m elevation zones (Chalise, 2001, p.51). Likewise, floods are very common in the plains below 500 m. Although the GLOFs originate in the high mountain areas, their damage effect may exceed 100 km downstream to the plains along the river valley.

Droughts: The analysis of the past precipitation records revealed a decreasing trend in the number of rainy days. In addition, the days with more intense precipitation were increasing i.e. more precipitation occurred in fewer days. This changing precipitation pattern indicated that the drought period was becoming longer, though there was no definite trend in the annual precipitation amount.

Landslides and floods: The combination of weak Himalayan geology and the monsoon climate makes the hills and mountains of Nepal vulnerable to landslides (Upreti, 2001, p.31). Intense precipitation is one of the principal triggering factors for landslides, debris flows and slope failures in the hills and mountains of the Himalayan region above 500 m (Chalise, 2001, p.58). A very dry spring accompanied by heavy precipitation in late summer is favourable for most of the landslides in Nepal (Manandhar and Khanal, 1988, p.41). In Nepal, the most extreme precipitation on record was observed on July 20, 1993 in Tistung, near Kathmandu Valley with a maximum hourly precipitation of 70 mm and 24-hour precipitation of 539.5 mm, which created catastrophic landslides and floods causing substantial damage to the central hills and plains of Nepal. About 500-800 km^2 of land were damaged affecting about 69000 families including 975 deaths by that event (Khanal, 2005, p.184). Increasing events of intense precipitation, as concluded in Chapter 4 and indicated by other research, would increase the likelihoods of landslide events in the future due to climate change.

6.3.3 Discussion of the Impacts of Climate Change on the Extreme Events

Climate change will lead to increased climatic variability, which would lead to increased frequency and magnitude of weather-related extreme events (Becker and Bugmann, 1997, p.29). Because the period of the maximum melting season of snow and glaciers coincides with the monsoon rainy season, any intensification of the monsoon or any further warming is likely to contribute to flood disasters in the Himalayan catchments (IPCC, 2001b, p. 565). An extreme climatic event will result in higher losses of life in a developing country than in a developed country because of a different adaptive capacity (IPCC, 2001b, p.895). An extreme climatic event combined with the socio-political characteristics of the region can become a social catastrophe in the developing countries (ibid). In Nepal, the normal daily life of a large section of the population is already not so different from the living conditions of those hit by a disaster (Dixit, 2003, p.167). Climate change brings additional threats to the livelihoods of these people (McGuigan et al, 2002, p.6).

The intensity of rainfall is the most important landslide-triggering factor in Nepal. The precipitation threshold (i.e. the minimum daily precipitation that could initiate a landslide, debris flow or similar event) generally depends on geology, vegetation and slope. In Nepal, a daily precipitation of 100 mm could initiate a landslide, debris flow or similar event (Chalise and Khanal, 2001, p. 65). A daily precipitation of 50-100 mm was enough to create small-scale shallow landslides in China, whereas shallow landslides could be observed when 24-hour rainfall exceeded 130-150 mm in Darjeeling, India (ibid). Earlier, Chalise and Khanal (2001, p.64) analysed the number of 24-hour rainfall events (June-October) for 1971-90 across Nepal with different categories of rainfall amount and reported that the number of days with higher intensity of rainfall was increasing. The results of the current analysis of daily precipitation from three different meteorological stations in Nepal for 1971-2000 have confirmed these findings (see Table 4.6).

Chaulagain (2005, p.124) earlier reported that extreme flood flows were increasing faster than the annual river runoff of the Tamakoshi river at Busti in eastern Nepal. For example, the maximum instantaneous flows of the river were increasing by about 3.4% per year, while its annual runoff was increasing by 1.5% per year during 1971-2000. Increasing trend of the average summer monsoon (June-September) runoff of the Tamakoshi river, which is currently contributing 79% to the annual runoff, would indicate a growing likelihood of extreme floods in the future. An earlier study by Chaulagain (2004, p.37) reported that the maximum temperatures at Jiri near the Busti station were increasing by 0.09ºC annually during 1971-2000. Such a rapid increase in the region has most probably resulted in the accelerated melting of glaciers in the headwater of the Tamakoshi river upstream of the station and the increase in the river runoff.

6.4 Conclusion

6.4.1 Summary of the Findings

A warming will affect the water balance by increasing the water demand and reducing the water supply. The temperature rise will be critical for the water availability, especially during the non-monsoon seasons in Nepal, although there will be water surpluses during the monsoon season (July-September). Decreased water availability will have substantial adverse effects on the agricultural production. The subsistence farmers and the poor will face the most severe problems including possible famine and starvation because of decreased agricultural production. In addition, decreased water availability will cause a reduction in the hydropower potential.

A decreasing number of rainy days and increasing number of intense precipitation i.e. a changing precipitation pattern, would increase the likelihoods of floods, landslides and droughts. Likewise, accelerated glacier melt and a decreased snow-to-rain ratio would increase the likelihood of formation and expansion of the glacier lakes in the Nepal Himalayas. The supporting dams, mostly the moraines, may not be able to resist a growing hydrostatic pressure of the lake water and would collapse, which could create a devastating flood called 'glacier lake outburst flood'. Such floods can cause substantial damages to the property, people and the environment for a large section along the river valley downstream of the lake.

6.4.2 Open Questions

The present study was limited to the sensitivity analysis of irrigation water demand in relation to only temperature change but not to precipitation change. The analysis of extreme floods and landslides requires sub-daily precipitation data, which were not available during this study. Likewise, the risk estimation of the GLOFs in the Nepal Himalayas is difficult without a study of each dangerous lake. Each GLOF may have its own damage magnitude, which is difficult to compare with others because the damage magnitude of any GLOF depends not only on the physical characteristics of the lakes, but also on the socioeconomic conditions and on geo-morphological characteristics along the river channel. Due to the lack of such information, sensitivity of risks of GLOFs to climate change could not be determined in this study.

There may be a number of effects of a temperature rise on the agricultural production. However, this study was limited to the determination of the impacts of increased irrigation demand. Nevertheless, there are still open questions how CO_2-fertilization effect or photosynthesis will be affected under a temperature rise and how such effects in combination with moisture deficit will influence agricultural production. The analysis for determining the impacts of reduced agricultural production on the poor population was only preliminary and qualitative, and therefore, needs further research.

The sensitivity of the hydropower potential of Nepal to a temperature rise was analysed only based on the total water availability. Run-of-river hydropower plants, the dominant existing hydropower plants in Nepal, are very sensitive to the low flows but not so much to the annual flows. The detailed impact of climate change on the potential hydropower generation during dry months could not be measured in the present sensitivity analysis.

In addition, expected future socioeconomic impacts of climate change depend also on the societal response and the preparedness to the changes as well. However, the present research could not include possible future economic development, future demographic projection and probable human response to climate change. Therefore, further research is required in order to more accurately quantify the socio-economic impacts of climate change with reference to water resources in Nepal. Application of appropriate socioeconomic models and theories, which was beyond the scope of this study, might be helpful in order to quantitatively define socioeconomic impacts of climate change with higher degree of accuracy.

Chapter VII: Conclusions and Recommendations

7.0 General

This chapter aims to summarise the results of the analysis, to check whether the established objectives have been achieved, and to conclude whether the developed hypotheses can be accepted or should be rejected. It also aims to prepare recommendations, to pose open questions and suggest areas of future research regarding the findings of this dissertation.

7.1 Conclusions

The analysis of temperature data revealed that there has been a clear warming trend in the past temperature records. The maximum temperatures were increasing faster than the minimum temperatures indicating a widening temperature range. Similarly, the analysis of precipitation data did not show a clear trend but the number of rainy days showed a decreasing trend. Out of the annual rainy days, the number of rainy days with lower intensities of precipitation was decreasing whereas that with higher intensities of precipitation was increasing, which supports the hypothesis of a changing precipitation pattern.

The hypothesis that there is an increasing trend in temperature and a decreasing trend in the number of rainy days can be accepted. The trends of temperature and precipitation were different for different seasons but this seasonal influence showed no uniformity at different stations. Therefore, the hypothesis that the change in precipitation or temperature will be different depending on seasons can be partially accepted. In addition, the hills and mountains were warming faster than the plains i.e. the warming rate was increasing with altitude. Therefore, the hypothesis that higher altitudes are warming faster than the lower altitudes could be clearly accepted. Likewise, the hypothesis that the temperature range (i.e. the difference between the maximum and minimum temperatures) has been increasing was found to be true.

A rise in temperature will have a substantial impact on the water balance including soil moisture, atmospheric water and surface runoff. Likewise, a temperature increase will reduce the glacier-ice reserves and ultimately could reduce the total water availability in Nepal. The hypothesis that the climate change will have a substantial impact on the water resources of

Nepal could be accepted. The hypothesis of increasing likelihoods of weather related extreme events as a result of climate change could not be rejected, but it could be accepted largely qualitatively. Due to a lack of sub-daily data on precipitation records, the analysis of cloudburst-induced extreme events remained incomplete. The hypothesis that climate change will result in more water shortages could be accepted because of the increasing gaps between the water supply and the water demand due to warming.

The analysis of the impact of decreasing water availability due to a rise in temperature on agricultural production, food security and poverty could support the hypothesis that the poor people and the subsistence farmers will be hardest hit by a temperature rise. Similarly, the hydropower potential of Nepal will also be reduced due to reduced water availability in the Nepal Himalayas. The hypothesis regarding the possible reduction in the hydropower potential due to climate change, therefore, could not be rejected.

7.2 Recommendations

The conclusions regarding the climate change in the Himalayan region of Nepal were based on the meteorological records observed at only one Himalayan station and for only 13 years. Therefore, a longer data period and more observation stations should be used for analysis. More empirical studies regarding the impact of climate change on water resources are required in order to segregate the climatic impacts from non-climatic impacts on the river runoff in Nepal. Because of the diverse topographical, physical and environmental characteristics of the basins, the impact may vary from basin to basin. Therefore, more representative basins should be studied for the identification of possible impacts of climate change on water resources including physical and socioeconomic dimensions.

The higher altitude areas are more sensitive to climate change but there are less information on climate, environment and resources due to difficult accessibility, particularly in the Nepal Himalayas. Because of the rugged topography, remoteness, severe weather conditions and little economic development, the Nepal Himalayas are generally a poor region. More field-based studies should be conducted in the remote hills and mountains in order to collect more physical and socioeconomic information. The information on snow and glaciers should cover the wider temporal and spatial scale, so that a more accurate analysis about their sensitivity to climate change could be made. The possible adaptation options for minimizing the damage magnitude of climate change should be determined through scientific studies and participatory assessments. The detailed identification of such adaptation options was beyond the scope of present study. However, the possible areas of adaptation may be as follows.

Adaptation to water shortages

- Deeper and more detailed studies on the possible impacts of climate change on water resources
- A holistic and integrated development approach for water resources development
- Understanding and management of the water resources system
- Promotion of indigenous and sustainable water efficiency technologies
- Rainwater harvesting
- Promotion of regional and international cooperation

Adaptation to water-induced extreme events

- Development of water-induced disaster mitigation measures
- Identification of the sites and the risks of potential glacier lake outburst floods
- Regular monitoring and applying possible risk reduction measures at the most risk-prone sites of glacier lake outburst floods (GLOFs).
- Due attention to the GLOF risk during the planning and implementation of water resources projects including hydropower plants.
- Preparation for possible relocation / resettlement from the most risk prone areas
- Application of both structural and non-structural measures for flood prevention and flood relief efforts. This is because adaptation to flood is not a purely technical or engineering question; rather it is a social, political and economic solution that requires multidisciplinary and multi-facet approaches.
- Establishment of hydrological and rain-gauge stations to collect the rain and flood information along with capacity building of local people to operate and maintain the stations.
- Identification of the most flood prone areas and establish a flood early warning system in those areas with clear demarcation of dangerous levels.
- Development of a functioning network for information dissemination and cooperation to cope with flood disaster among the communities.

7.3 Propositions for Future Research

The propositions for future research consist of three areas as divided in this research:

- Climate change in Nepal,
- Physical impacts of climate change in Nepal and
- Socioeconomic impacts of climate change

Do the other Himalayan regions have the same trend in temperature and precipitation as the Langtang region? How big is the gap between the climate change in the lower altitudes and the higher altitudes in the Himalayas? How can these gaps in the climatic, physical and environmental information in the Himalayan regions be filled? How can the uncertainties in defining the climate change be reduced? In order to get answers to these questions, more analyses of climatological data including daily and sub-daily observations are necessary using different tools and models. Nepal's rugged topography, especially wide altitudinal variation within a relatively short horizontal distance makes it difficult to apply the General Circulation Models (GCMs). Therefore, the development of a regional circulation models appropriate for Nepal's orographic characteristics by scaling down the GCM is necessary in order to model the future climate of Nepal.

Are the climatological data from the Langtang valley, which have been used during the analysis of the impacts of climate change on water resources of Nepal, representative for the entire Nepal Himalayas? How do the climatological data in the Langtang Valley differ from those in other Himalayan stations? Do the results of the sensitivity analysis of glacier extent in the Langtang Valley represent the whole glacier system in the Nepal Himalayas? In order to be able to answer these question, the glacier mass balance model should be applied in other glaciological stations (i.e. at least in the other 5 glaciological stations under the Department of Hydrology and Meteorology, Nepal, which could not be included in the present research) and the values of the glacier mass balance should be compared with those obtained in the Langtang valley. Furthermore, the river runoff modelling in this study has used average monthly hydrological and meteorological records, but not extreme values. How can the extreme flows be modelled in order to identify the impacts of climate change on extreme flows? Some other suitable models should be explored in order to answer these questions.

Finally, determining the socioeconomic impacts of climate change in relation to water resources is more complex and consists of more assumptions and uncertainties than determining the physical impacts. Therefore, more empirical studies covering larger areas are necessary in order to reduce the uncertainties. In some cases, direct field study may also be necessary in order to collect primary data regarding the likely impact of climate change on agricultural production, food security and poverty with respect to water resources. Impact of the seasonal water shortages due to monsoon failure or long drought, despite adequate surpluses in annual water balance could not be analysed in the present research. Such an analysis will be necessary in order to reduce the uncertainties in determining the impacts of climate change on agricultural production and food security.

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Annex

Annex 4.1: Temperature trend calculation

Station	Data period	Type of data	Trend	Coeff.	Const.	t-statistic	Stand. error	error in beta	Signifi-cance	Actual signifi-cance
RP	1971-00	Annual-mean	0.04	0.04	23.38	64.92	13.47	0.001	<0.05	0.036
RP	1971-00	mean-premo	0.01	0.01	25.64	4.25	22.22	0.002	>0.1*	0.235
RP	1971-00	mean-mon	0.06	0.06	27.22	40.03	14.17	0.001	<0.05	0.025
RP	1971-00	mean postmon	0.06	0.06	22.02	18.52	30.62	0.003	<0.05	0.050
RMP	1971-00	mean winter	0.02	0.02	15.97	8.04	23.52	0.002	>0.1*	0.125
KTM	1971-00	Annual-mean	0.05	0.05	17.52	60.15	7.86	0.001	<0.05	0.017
KTM	1971-00	mean-premo	0.05	0.05	18.35	22.68	20.84	0.002	<0.05	0.044
KTM	1971-00	mean-mon	0.04	0.04	22.97	49.04	7.71	0.001	<0.05	0.020
KTM	1971-00	mean postmon	0.05	0.05	16.44	17.70	26.71	0.002	<0.05	0.037
KTM	1971-00	mean winter	0.08	0.08	9.97	46.57	16.24	0.002	<0.05	0.021
DMN	1973-00	Annual-mean	0.07	0.07	12.23	33.65	16.05	0.002	<0.05	0.030
DMN	1973-00	mean-premo	0.08	0.08	12.63	20.69	29.83	0.004	<0.05	0.048
DMN	1973-00	mean-mon	0.06	0.06	15.98	24.99	18.52	0.002	<0.05	0.040
DMN	1973-00	mean postmon	0.08	0.08	11.73	24.17	25.53	0.003	<0.05	0.041
DMN	1973-00	mean winter	0.06	0.06	6.55	20.08	23.04	0.003	<0.05	0.050
LTG	1988-00	Annual-mean	0.26	0.26	1.03	21.56	10.02	0.012	<0.05	0.047
LTG	1988-00	mean-premo	0.34	0.34	-0.03	20.85	13.27	0.016	<0.05	0.047
LTG	1988-00	mean-mon	0.27	0.27	6.39	26.85	8.35	0.010	<0.05	0.036
LTG	1988-00	mean postmon	0.30	0.30	-0.46	16.21	15.25	0.018	<0.1	0.060
LTG	1988-00	mean winter	0.15	0.15	4.08	9.45	12.99	0.016	<0.1	0.105
RMP	1971-00	annual-max	0.05	0.05	29.80	30.56	15.46	0.002	<0.05	0.032
RMP	1971-00	annual-min	0.03	0.03	16.92	26.87	17.59	0.002	<0.1	0.060
KTM	1971-00	annual-max	0.09	0.09	23.42	83.48	10.19	0.001	<0.05	0.012
KTM	1971-00	annual-min	0.01	0.01	11.52	8.32	11.35	0.001	>0.1*	0.120
DMN	1973-00	annual-max	0.10	0.10	16.87	42.84	17.10	0.002	<0.05	0.023
DMN	1973-00	annual-min	0.04	0.04	7.61	9.68	31.88	0.004	<0.1	0.100
LTG	1988-00	annual-max	0.32	0.32	5.47	24.76	10.58	0.013	<0.05	0.040
LTG	1988-00	annual-min	0.27	0.27	-2.17	21.95	10.07	0.012	<0.05	0.046
Trend calculation for 1988-2000										
RMP	1988-00	Annual	-0.01	-0.01	24.423	55.124	4.010	0.005	>0.4*	-0.476
KTM	1988-00	Annual	0.06	0.06	18.357	60.915	3.628	0.004	<0.1	0.074
DMN	1988-00	Annual	0.12	0.12	12.857	48.775	4.532	0.006	<0.05	0.046
LTG	1988-00	Annual	0.27	0.27	1.046	22.021	10.037	0.012	<0.05	0.045

Note: RMP= Rampur; KTM= Kathmandu; DMN= Daman; LTG= Langtang
* = not significant even at the given levels

Annex 4.2: Precipitation trend calculation

Stn	Data period	Type of data	Trend	Coeff.	Const.	t-statistic	Stand. error	error in beta	Signifi-cance	Actual signifi-cance
DMN	1973-00	AAP	-9.988	-9.988	1951.7	-2.95	26110	3.38	>0.3*	-0.338
DMN	1973-00	MP	-5.445	-5.445	1465.1	-4.56	9201	1.19	>0.2*	-0.219
DMN	1973-00	NMP	-4.540	-4.54	486.61	-10.36	3380	0.438	<0.1	-0.096
DMN	1973-00	ARD	-0.430	-0.43	125.08	-10.61	312.5	0.04	<0.1	-0.093
DMN	1973-00	RD<10	-0.122	-0.122	66.095	-4.03	233.5	0.03	>0.2*	-0.246
DMN	1973-00	RD10-25	-0.220	-0.22	37.476	-9.99	169.8	0.02	<0.1	-0.091
DMN	1973-00	RD 25-50	-0.126	-0.126	16.214	-10.13	95.92	0.012	<0.1	-0.095
DMN	1973-00	RD>50	0.058	0.058	4.087	4.95	93.43	0.012	>0.2*	0.207
DMN	1973-00	MRD	-0.006	-0.006	85.27	-0.25	183		>0.9*	>0.9
DMN	1973-00	RD-NM	-0.423	-0.423	39.81	-14.67	222.35	0.029	<0.1	-0.069
RMP	1971-00	AAP	-0.315	-0.3145	1999.2	-2.47	8617.48	0.91	>0.9*	-2.893
RMP	1971-00	MP	-3.706	-3.706	1680.8	-4.64	7548.6	0.8	>0.2*	-0.216
RMP	1971-00	NMP	1.455	1.455	338.4	4.69	2933.6	0.31	>0.2*	0.213
RMP	1971-00	ARD	-0.023	-0.023	105.86	-0.79	275.6	0.03	>0.9*	-1.304
RMP	1971-00	MRD	0.093	0.093	75.425	4.088	215.07	0.02	>0.2*	0.215
RMP	1971-00	NMRD	-0.116	-0.1164	30.437	-6.73	163.5	0.017	<0.15	-0.146
RMP	1971-00	RD<10	0.069	0.069	52.101	2.62	248.5	0.026	>0.35*	0.377
RMP	1971-00	RD 10-25	-0.140	-0.14	29.306	-8.19	161.66	0.017	<0.15	-0.121
RMP	1971-00	RD 25-50	0.078	0.078	14.586	5.99	123.08	0.013	<0.2	0.167
RMP	1971-00	RD>50	-0.040	-0.04	9.7908	-3.3	113.56	0.012	<0.3	-0.3
KTM	1971-00	AAP	4.219	4.219	1373.4	-0.524	5669.8	0.6	<0.15	0.142
LTG	1988-00	AAP	4.746	4.746	553.32	2.556	1519.76	1.856	>0.3*	0.391
RMP	1971-00	RD <25	-0.071	-0.0714	81.407	-2.39	282	0.03	>0.4*	-0.420
DMN	1973-00	RD<25	-0.342	-0.342	103.57	-9.2764	284.38	0.037	<0.1	-0.108
KTM	1971-00	ARD	-0.041	-0.0409	111.17	-1.528	253.09	0.026	>0.6*	-0.636
KTM	1971-00	RD <25	-0.198	-0.1976	96.8	-7.24	258.1	0.027	<0.15	-0.137
KTM	1971-00	RD 25-50	0.159	0.1591	10.634	14.64	102.78	0.01	<0.1	0.063
KTM	1971-00	RD>50	0.011	0.0109	3.398	575.199	55.85	0.0059	>0.5*	0.541
KTM	1971-00	JA RD	0.160	0.16	42.82	9.49	159.33	0.0168	<0.1	0.105
KTM	1971-00	JA P	3.300	3.3	625.04	5.66	5509.44	0.58	<0.2	0.176
RMP	1971-00	JA RD	0.086	0.086	43.602	6.65	122.19	0.0129	<0.15	0.150
RMP	1971-00	JA P	4.226	4.2256	919.51	6.183	6461.3	0.13	<0.05	0.031
DMN	1973-00	JA RD	0.020	0.0203	49.849	1.64	95.2	0.012	>0.5	0.591
DMN	1973-00	JA P	2.940	2.94	805.1	3.31	6826.6	0.88	<0.3	0.299
LTG	1988-00	JA P	3.625	3.625	260.17	3.18	934.12	1.14	>0.3*	0.314
LTG	1988-00	ARD	0.445	0.445	93.58	2.47	147.31	0.18	>0.4*	0.404
LTG	1988-00	RD<25	0.335	0.335	93.27	1.90	144.36	0.18	>0.5	0.526
LTG	1988-00	RD 25-50	0.077	0.077	0.46	4.92	12.81	0.02	<0.2	0.203
LTG	1988-00	JA RD	1.181	1.1813	35.423	8.99	107.51	0.13	<0.1	0.111

Note: RMP= Rampur; KTM= Kathmandu; DMN= Daman; LTG= Langtang

* = not significant even at the given levels

RD= rainy days; ARD= annual rainy days; AAP= annual average precipitation; MP= monsoon precipitation; NMP= non-monsoon precipitation; JA RD= July-August rainy days; JAP= July-August precipitation; MRD= monsoon rainy days; NMRD= non-monsoon rainy days;

RD> 50= number of rainy days with precipitation of 50 mm/day or more.

Annex 4.3: Modelling of the Bagmati River runoff at Chovar (1976-1980) [mm]

Months	1	2	3	4	5	6	7	8	9	10	11	12
Modelled	8.1	7.3	5.7	8.2	19.9	150.8	217.2	210.3	117.1	47.0	28.8	20.7
Observed	15.6	13.6	4.0	12.0	26.4	166.6	186.8	257.8	150.6	65.0	29.1	16.0

Months	13	14	15	16	17	18	19	20	21	22	23	24
Modelled	17.0	13.3	10.3	16.6	19.1	73.0	177.0	229.8	72.9	40.8	27.9	22.0
Observed	12.5	9.6	3.2	9.5	16.1	98.8	208.3	160.2	86.4	49.4	28.0	24.7

Months	25	26	27	28	29	30	31	32	33	34	35	36
Modelled	16.8	13.3	16.3	13.6	25.3	101.1	192.9	287.4	117.6	77.7	37.2	26.2
Observed	14.8	5.6	6.4	11.6	24.2	105.9	281.6	366.7	174.6	145.1	42.5	21.6

Months	37	38	39	40	41	42	43	44	45	46	47	48
Modelled	19.6	18.8	11.8	11.1	9.4	48.2	269.3	224.5	82.0	44.4	27.9	31.8
Observed	12.6	15.1	5.5	8.3	6.7	15.7	157.0	214.7	86.0	44.1	23.1	22.2

Months	49	50	51	52	53	54	55	56	57	58	59	60
Modelled	21.1	16.8	15.8	10.0	18.1	116.0	172.5	148.4	115.4	59.4	32.6	23.9
Observed	10.9	4.8	6.0	2.3	8.1	72.7	189.1	207.4	106.8	42.8	19.3	10.9

Annex 4.4: Modelling of the Langtang Khola runoff at Langtang (1993-1998), [mm]

Months	1	2	3	4	5	6	7	8	9	10	11	12
Modelled	17.2	16.8	23.0	30.5	55.8	39.4	59.5	97.4	114.2	45.7	18.4	15.2
Observed	24.6	20.5	17.6	19.8	39.4	70.5	109.9	116.0	80.2	33.5	28.6	24.0

Months	13	14	15	16	17	18	19	20	21	22	23	24
Modelled	15.2	15.2	15.3	15.3	25.1	26.1	85.2	118.0	99.2	40.9	16.2	15.3
Observed	17.8	15.2	16.5	16.1	26.5	94.5	109.9	116.0	81.4	46.3	39.6	25.2

Months	25	26	27	28	29	30	31	32	33	34	35	36
Modelled	27.9	42.5	55.4	46.2	35.9	63.2	99.1	122.1	100.4	41.4	19.8	15.3
Observed	16.0	14.5	15.9	16.6	21.9	119.8	121.1	119.9	89.0	43.3	28.1	27.6

Months	37	38	39	40	41	42	43	44	45	46	47	48
Modelled	20.0	15.3	15.2	15.3	15.8	56.4	105.8	146.3	98.8	79.0	31.7	15.3
Observed	25.2	21.7	20.1	18.4	53.8	111.7	124.2	120.4	85.2	43.5	27.8	20.6

Months	49	50	51	52	53	54	55	56	57	58	59	60
Modelled	15.2	15.3	17.1	21.5	26.4	81.3	123.4	115.4	84.7	44.0	38.7	15.7
Observed	16.5	14.0	41.5	27.1	28.6	84.5	120.4	109.9	108.1	79.0	34.1	11.4

Months	61	62	63	64	65	66	67	68	69	70	71	72
Modelled	21.5	15.3	15.2	15.3	15.9	56.3	105.8	148.8	99.7	79.3	31.8	15.3
Observed	25.2	21.7	20.3	17.9	53.8	111.7	124.2	120.1	85.2	43.5	27.8	20.6

Annex 5.1: Sensitivity of glacier surface area to temperature changes in Nepal

Decade	Glacier surface area, km^2					
	ΔT = 0ºC/yr	ΔT = 0.03ºC/yr	ΔT = 0.06ºC/yr	ΔT =0.09ºC/yr	ΔT =0.12ºC/yr	ΔT =0.15ºC/yr
0	5322.5	5322.5	5322.5	5322.5	5322.5	5322.5
1	5207.5	5207.5	5207.5	5207.5	5207.4	5207.4
2	5167.2	5118.3	5055.9	4917.2	4666.3	4343.8
3	4950.8	4614.5	4101.0	3468.7	2838.7	2326.4
4	4372.3	3690.4	2798.6	1921.6	1124.5	489.3
5	3803.3	2780.7	1597.0	627.0	94.5	0
6	3259.4	1921.6	627.0	0	0	0
7	2768.5	1149.9	0	0	0	0
8	2362.6	489.3	0	0	0	0
9	1921.6	94.5	0	0	0	0
10	1597.0	0	0	0	0	0
11	1173.6	0	0	0	0	0
12	1019.0	0	0	0	0	0
13	706.1	0	0	0	0	0
14	489.3	0	0	0	0	0
15	327.0	0	0	0	0	0
16	259.0	0	0	0	0	0
17	94.5	0	0	0	0	0
18	0	0	0	0	0	0

Note: decades are counted from 2001

Annex 5.2: Sensitivity of glacier number to temperature changes

Decade	Number of glaciers in Nepal Himalayas					
	ΔT = 0ºC/yr	ΔT =0.03ºC/yr	ΔT =0.06ºC/yr	ΔT =0.09ºC/yr	ΔT =0.12ºC/yr	ΔT =0.15ºC/yr
0	3252	3252	3252	3252	3252	3252
1	2259	2259	2259	2259	2258	2258
2	2169	2050	1896	1607	1177	773
3	1671	1109	605	329	178	107
4	795	407	171	70	25	7
5	454	168	48	10	1	0
6	269	70	10	0	0	0
7	166	26	0	0	0	0
8	111	7	0	0	0	0
9	70	1	0	0	0	0
10	48	0	0	0	0	0
11	27	0	0	0	0	0
12	21	0	0	0	0	0
13	12	0	0	0	0	0
14	7	0	0	0	0	0
15	4	0	0	0	0	0
16	3	0	0	0	0	0
17	1	0	0	0	0	0
18	0	0	0	0	0	0

Note: decades are counted from 2001

Annex 5.3: Sensitivity of glacier-melt water to temperature changes in Nepal

Decade	Glacier-melt water in the Nepal Himalayas, km^3/year					
	ΔT = 0ºC/yr	ΔT =0.03ºC/yr	ΔT =0.06ºC/yr	ΔT =0.09ºC/yr	ΔT =0.12ºC/yr	ΔT =0.15ºC/yr
0	6.08	6.08	6.08	6.08	6.08	6.08
1	5.95	6.61	7.58	8.72	9.99	11.36
2	5.91	8.09	11.28	14.72	17.93	20.69
3	5.66	9.75	14.56	18.18	20.21	21.30
4	5.00	10.65	15.32	16.37	13.39	7.62
5	4.35	10.92	12.86	8.10	1.73	0
6	3.73	10.08	7.11	0	0	0
7	3.16	7.89	0	0	0	0
8	2.70	4.30	0	0	0	0
9	2.20	1.04	0	0	0	0
10	1.83	0	0	0	0	0
11	1.34	0	0	0	0	0
12	1.16	0	0	0	0	0
13	0.81	0	0	0	0	0
14	0.56	0	0	0	0	0
15	0.37	0	0	0	0	0
16	0.30	0	0	0	0	0
17	0.11	0	0	0	0	0
18	0	0	0	0	0	0

Note: decades are counted from 2001

Annex 5.4: Sensitivity of total water availability to temperature changes in Nepal

Decade	Total water availability in Nepal, km^3/yr					
	ΔT = 0ºC/yr	ΔT =0.03ºC/yr	ΔT =0.06ºC/yr	ΔT =0.09ºC/yr	ΔT =0.12ºC/yr	ΔT =0.15ºC/yr
0	176.08	176.08	176.08	176.08	176.08	176.08
1	175.95	175.64	175.57	175.67	175.90	176.23
2	175.91	176.08	177.19	178.55	179.68	180.35
3	175.66	176.70	178.39	178.89	177.80	175.76
4	175.00	176.56	177.07	173.95	166.80	156.87
5	174.35	175.79	172.53	162.56	150.99	144.05
6	173.73	173.91	164.69	151.34	145.09	138.85
7	173.16	170.68	155.50	148.21	140.93	133.64
8	172.70	166.05	153.42	145.09	136.76	128.44
9	172.20	161.75	151.34	141.97	132.60	123.23
10	171.83	159.66	149.26	138.85	128.44	118.03
11	171.34	158.62	147.17	135.72	124.27	112.82
12	171.16	157.58	145.09	132.60	120.11	107.62
13	170.81	156.54	143.01	129.48	115.95	102.41
14	170.56	155.50	140.93	126.35	111.78	97.21
15	170.37	154.46	138.85	123.23	107.62	92.00
16	170.30	153.42	136.76	120.11	103.45	86.80
17	170.11	152.38	134.68	116.99	99.29	81.59
18	170.00	151.34	132.60	113.86	95.13	76.39
19	170.00	150.30	130.52	110.74	90.96	71.18
20	170.00	149.26	128.44	107.62	86.80	65.98

Note: decades are counted from 2001

Annex 5.4: Sensitivity of the Bagmati River runoff to temperature at Chovar

ΔT, ºC	Change in runoff, %												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
+1	-1.8	-2.2	-2.5	-2.7	-2.5	-1.9	-1.7	-1.2	-1.1	-1.4	-1.7	-1.9	-1.5
+2	-4.9	-5.4	-5.8	-5.6	-4.6	-2.7	-2.4	-2.3	-2.5	-3.5	-4.7	-5.1	-3.0
+3	-7.2	-8.0	-8.6	-8.4	-6.9	-4.1	-3.5	-3.4	-3.7	-5.2	-7.0	-7.6	-4.4
+4	-10.1	-11.0	-11.7	-11.0	-8.7	-4.8	-4.5	-4.6	-5.1	-7.4	-10.0	-10.7	-5.9
+5	-12.2	-13.4	-14.3	-13.7	-11.3	-6.9	-6.3	-5.6	-6.2	-9.0	-12.0	-12.9	-7.5

Annex 5.5: Sensitivity of the Bagmati River runoff to precipitation at Chovar

ΔP, %	Change in runoff, %												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
+15	2.6	3.1	3.9	5.2	7.2	8.5	9.3	7.8	3.2	3.5	2.9	3.2	5.0
+10	4.7	5.8	7.5	10.2	13.9	17.3	28.5	9.0	5.3	6.2	5.3	5.7	10.0
+5	7.1	8.8	11.6	16.0	22.1	27.7	38.5	15.5	9.1	9.8	8.0	8.5	15.2
-5	-5.4	-5.3	-5.1	-4.5	-4.0	-4.2	-6.2	-6.3	-5.0	-5.8	-6.8	-6.7	-5.4
-10	-7.5	-7.7	-8.4	-9.4	-11.0	-12.5	-13.6	-12.7	-9.4	-9.4	-9.1	-9.0	-10.0

Annex 5.6: Sensitivity of runoff of the Langtang Khola and the Bagmati River to climate change (T_{+2}, P_{-10} scenario)

Basin	Change in runoff, %												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
A	-5.6	-3.6	-4.8	-5.5	-8.3	-4.3	-7.3	-7.3	-7.6	-9.9	-9.3	-0.5	-6.2
B	-20.0	-19.9	-19.3	-17.3	-14.2	-10.1	-12.2	-14.1	-15.5	-19.0	-22.8	-22.6	-17.2

Note: A= Glacier-fed Langtang Khola, B= Rain-fed Bagmati River

Annex 5.7: Glacier mass balance status with altitudes in Langtang, 10^6 m^3 w.e./a

	Altitude level, masl									
	3800	3900	4000	4100	4200	4300	4400	4500	4600	4700
Acc	0.30	0.35	0.89	0.88	0.86	0.85	1.05	1.74	1.79	1.92
Abl	-0.30	-0.35	-0.89	-0.88	-19.89	-18.22	-24.75	-31.54	-29.45	-28.76
Bal	0.00	0.00	0.00	0.00	-19.03	-17.37	-23.70	-29.80	-27.65	-26.84
	Altitude level, masl									
	4800	4900	5000	5100	5200	5300	5400	5500	5600	5700
Acc	2.13	3.10	5.68	7.414	8.30	8.96	9.35	9.62	9.11	8.00
Abl	-24.60	-22.28	-20.43	-17.78	-14.75	-12.91	-7.01	-3.13	-1.14	-0.30
Bal	-22.47	-19.17	-14.75	-10.36	-6.44	-3.95	2.34	6.48	7.96	7.70
	Altitude level, masl									
	5800	5900	6000	6100	6200	6300	6400	6500	6600	6700
Acc	7.41	6.83	4.29	3.71	3.12	2.53	1.95	1.61	1.50	1.50
Abl	-0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Bal	7.37	6.83	4.29	3.71	3.12	2.53	1.95	1.61	1.50	1.50

	Altitude level, masl				
	6800	6900	7000	7100	7200
Acc	1.50	1.44	1.44	1.44	0.26
Abl	0.00	0.00	0.00	0.00	0.00
Bal	1.50	1.44	1.44	1.44	0.26

Annex 5.8: Inventory of studied glaciers of Langtang Basin during the analysis
Total number: 24; Total area: 140.86 km^2; Ice reserve: 19.14 km^3

Glacier Number	Area (km^2)	Mean Length (m)	Elevation Highest (masl)	Elevation Mean (masl)	Elevation Tongue (masl)	Thick-ness (m)	Reserve of ice (km^3)
Gtri_gr 40	16.46	11590	5852	4991	4130	111.97	1.84
Gtri_gr 41	2.11	1260	5951	5627	5304	55.25	0.12
Gtri_gr 42	2.09	1645	5951	5448	4945	55.06	0.12
Gtri_gr 43	4.69	4050	5950	5230	4511	73.28	0.34
Gtri_gr 44*	67.93	17740	7218	5834	4450	177.31	12.04
Gtri_gr 45	4.39	2150	6568	5738	4907	71.61	0.31
Gtri_gr 46	0.01	150	5715	5585	5456	2.05	0
Gtri_gr 47	0.07	315	6157	6050	5944	12.64	0
Gtri_gr 48	25.65	1580	6279	5243	4206	129.52	3.32
Gtri_gr 49	0.79	760	5886	5625	5364	38.26	0.03
Gtri_gr 50	0.84	880	6892	6494	6096	39.18	0.03
Gtri_gr 51	0.18	410	6248	6020	5791	20.49	0
Gtri_gr 53	0.14	750	6279	6096	5913	18.18	0
Gtri_gr 54	0.38	1070	5364	5075	4785	28.48	0.01
Gtri_gr 55	0.18	410	6145	5983	5822	20.49	0
Gtri_gr 56	0.41	760	5334	5144	4953	29.4	0.01
Gtri_gr 57	0.38	500	5288	5113	4938	28.48	0.01
Gtri_gr 58	1.17	2850	5791	5334	4877	44.46	0.05
Gtri_gr 59	0.42	4050	6172	5433	4694	29.7	0.01
Gtri_gr 60	6.55	5130	5563	5128	4694	82.19	0.54
Gtri_gr 61	0.25	820	5563	5433	5304	23.79	0.01
Gtri_gr 62	0.55	1580	5669	5380	5090	33.15	0.02
Gtri_gr 63	3.82	3735	5486	5037	4587	68.22	0.26
Gtri_gr 64	1.4	2340	5685	5204	4724	47.54	0.07
Total	**140.86**						**19.14**

Source: Mool et al., 2001a, pp.224-225
Note : * - Langtang Glacier

Annex 5.9: Altitudinal distribution of glacier area and expected glacier mass accumulation within the study basin at Langtang

Altitude, masl	Total area, km^2	Glacier area, km^2	Accumulation, 10^6 m^3 w.e/yr					
			T_0	T_{+1}	T_{+2}	T_{+3}	T_{+4}	T_{+5}
3800	5	0	0.30	0.30	0.25	0.20	0.15	0.10
3900	6	0	0.35	0.30	0.25	0.20	0.15	0.10
4000	8	0	0.89	0.72	0.60	0.48	0.36	0.24
4100	10	0.67	0.88	0.77	0.66	0.55	0.44	0.33
4200	10	2.12	0.86	0.80	0.70	0.50	0.50	0.30
4300	11	2.19	0.85	0.72	0.63	0.54	0.45	0.36
4400	12	3.42	1.05	0.90	0.80	0.70	0.60	0.50
4500	12.32	4.99	1.74	1.53	1.23	1.07	0.92	0.77
4600	13.32	5.45	1.79	1.58	1.29	1.15	1.00	0.86
4700	13.32	6.30	1.92	1.60	1.33	1.20	1.07	0.93
4800	14.32	6.42	2.13	1.60	1.36	1.11	0.99	0.86
4900	15.32	7.00	3.10	2.00	1.60	1.47	1.20	1.07
5000	18.98	7.22	5.68	3.61	2.66	2.09	1.90	1.52
5100	19.38	7.30	7.41	5.30	3.26	2.65	2.24	1.83
5200	20.38	7.29	8.30	6.20	4.07	2.71	2.33	1.94
5300	18.38	7.56	8.96	7.17	5.15	3.12	2.39	2.02
5400	17.38	7.54	9.35	7.82	5.91	4.00	2.61	2.09
5500	16.64	6.86	9.62	8.49	6.82	4.99	3.16	1.83
5600	15.53	6.27	9.11	8.54	7.30	5.59	4.04	2.48
5700	13.64	6.07	8.00	7.91	7.09	5.87	4.36	2.86
5800	12.64	5.56	7.41	7.46	7.20	6.19	4.93	3.54
5900	11.64	4.56	6.83	6.87	6.87	6.29	5.24	3.96
6000	7.32	4.15	4.29	4.32	4.32	4.25	3.73	3.00
6100	6.32	4.20	3.71	3.73	3.73	3.73	3.48	2.97
6200	5.32	3.85	3.12	3.14	3.14	3.14	3.09	2.77
6300	4.32	2.82	2.53	2.55	2.55	2.55	2.55	2.46
6400	3.32	2.82	1.95	1.96	1.96	1.96	1.96	1.96
6500	2.74	2.74	1.61	1.62	1.62	1.62	1.62	1.62
6600	2.56	2.56	1.50	1.51	1.51	1.51	1.51	1.51
6700	2.56	2.56	1.50	1.51	1.51	1.51	1.51	1.51
6800	2.55	2.55	1.50	1.51	1.51	1.51	1.51	1.51
6900	2.45	2.45	1.44	1.45	1.45	1.45	1.45	1.45
7000	2.45	2.45	1.44	1.45	1.45	1.45	1.45	1.45
7100	2.45	2.45	1.44	1.45	1.45	1.45	1.45	1.45
7200	0.44	0.44	0.26	0.26	0.26	0.26	0.26	0.26
	340.0	140.86	122.82	108.65	93.49	79.06	66.6	54.41
Specific accumulation, m w.e./yr			**0.87**	**0.77**	**0.66**	**0.56**	**0.47**	**0.39**

Annex 5.10: Altitudinal distribution of expected glacier mass ablation and balance within the study basin at Langtang

Altitude, masl	Glacier mass ablation, 10^6 m^3 w.e/yr						Glacier mass balance, 10^6 m^3 w.e/yr					
	T_0	T_{+1}	T_{+2}	T_{+3}	T_{+4}	T_{+5}	T_0	T_{+1}	T_{+2}	T_{+3}	T_{+4}	T_{+5}
3800	0.30	0.30	0.25	0.20	0.15	0.10	0.00	0.00	0.00	0.00	0.00	0.00
3900	0.35	0.30	0.25	0.20	0.15	0.10	0.00	0.00	0.00	0.00	0.00	0.00
4000	0.89	0.72	0.60	0.48	0.36	0.24	0.00	0.00	0.00	0.00	0.00	0.00
4100	0.88	0.77	0.66	0.55	0.44	0.33	0.00	0.00	0.00	0.00	0.00	0.00
4200	19.89	23.79	28.16	32.79	38.24	44.04	-19.03	-22.99	-27.46	-32.29	-37.74	-43.74
4300	18.22	21.95	26.31	30.92	36.02	41.86	-17.37	-21.23	-25.68	-30.38	-35.57	-41.50
4400	24.75	30.04	36.54	43.59	51.08	59.60	-23.70	-29.14	-35.74	-42.89	-50.48	-59.10
4500	31.54	38.88	47.56	57.34	67.87	79.30	-29.80	-37.34	-46.33	-56.27	-66.95	-78.53
4600	29.45	36.97	45.78	55.92	67.00	78.72	-27.65	-35.39	-44.49	-54.78	-65.99	-77.86
4700	28.76	36.57	46.38	57.21	69.43	82.59	-26.84	-34.97	-45.05	-56.01	-68.36	-81.66
4800	24.60	31.59	41.10	51.32	63.14	76.05	-22.47	-29.99	-39.75	-50.21	-62.16	-75.19
4900	22.28	28.94	38.34	49.19	60.82	74.19	-19.17	-26.94	-36.74	-47.72	-59.62	-73.12
5000	20.43	25.55	34.34	44.38	55.88	68.50	-14.75	-21.94	-31.68	-42.29	-53.99	-66.98
5100	17.78	21.80	29.48	38.80	49.71	61.50	-10.36	-16.50	-26.22	-36.15	-47.47	-59.66
5200	14.75	17.28	24.26	32.75	42.78	54.06	-6.44	-11.08	-20.19	-30.03	-40.46	-52.12
5300	12.91	13.37	20.11	28.30	37.69	48.82	-3.95	-6.20	-14.97	-25.17	-35.30	-46.80
5400	7.01	10.08	15.48	23.00	31.63	41.66	2.34	-2.26	-9.57	-19.00	-29.02	-39.58
5500	3.13	7.16	11.14	16.93	24.01	32.15	6.48	1.33	-4.32	-11.94	-20.85	-30.32
5600	1.14	3.42	8.30	12.24	18.21	25.00	7.96	5.12	-1.00	-6.65	-14.18	-22.52
5700	0.30	1.36	4.77	8.60	13.60	19.69	7.70	6.55	2.32	-2.73	-9.23	-16.82
5800	0.04	0.51	2.15	6.36	9.49	14.54	7.37	6.95	5.06	-0.17	-4.56	-11.00
5900	0.00	0.12	0.81	3.26	6.61	9.75	6.83	6.75	6.05	3.03	-1.37	-5.79
6000	0.00	0.00	0.15	0.95	3.15	5.62	4.29	4.32	4.17	3.29	0.59	-2.62
6100	0.00	0.00	0.00	0.32	1.39	3.64	3.71	3.73	3.73	3.41	2.09	-0.67
6200	0.00	0.00	0.00	0.11	0.53	1.86	3.12	3.14	3.14	3.03	2.55	0.90
6300	0.00	0.00	0.00	0.00	0.17	0.73	2.53	2.55	2.55	2.55	2.38	1.73
6400	0.00	0.00	0.00	0.00	0.03	0.23	1.95	1.96	1.96	1.96	1.93	1.73
6500	0.00	0.00	0.00	0.00	0.00	0.05	1.61	1.62	1.62	1.62	1.62	1.56
6600	0.00	0.00	0.00	0.00	0.00	0.00	1.50	1.51	1.51	1.51	1.51	1.51
6700	0.00	0.00	0.00	0.00	0.00	0.00	1.50	1.51	1.51	1.51	1.51	1.51
6800	0.00	0.00	0.00	0.00	0.00	0.00	1.50	1.51	1.51	1.51	1.51	1.51
6900	0.00	0.00	0.00	0.00	0.00	0.00	1.44	1.45	1.45	1.45	1.45	1.45
7000	0.00	0.00	0.00	0.00	0.00	0.00	1.44	1.45	1.45	1.45	1.45	1.45
7100	0.00	0.00	0.00	0.00	0.00	0.00	1.44	1.45	1.45	1.45	1.45	1.45
7200	0.00	0.00	0.00	0.00	0.00	0.00	0.26	0.26	0.26	0.26	0.26	0.26
Total	279.4	351.5	462.9	595.7	749.6	924.9	-156.6	-242.8	-369.4	-516.6	-683.0	-870.5
Specific, m w.e.	**1.98**	**2.50**	**3.29**	**4.23**	**5.32**	**6.57**	**-1.11**	**-1.72**	**-2.62**	**-3.67**	**-4.85**	**-6.18**

Annex 5.11: Altitudinal distribution of monthly glacier mass balance within the study basin at Langtang (average of 1988-2000)

Altd., masl	Glacier mass balance, 10^6 m^3 w.e/yr												
	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Year
3800	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
3900	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
4000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
4100	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
4200	-4.327	-4.144	-3.300	-0.882	0.020	0.016	0.074	0.076	0.107	-0.334	-2.182	-3.731	-18.61
4300	-4.119	-3.929	-3.055	-0.573	0.029	0.014	0.066	0.069	0.098	-0.156	-1.884	-3.502	-16.94
4400	-5.862	-5.566	-4.204	-0.522	0.034	0.016	0.074	0.076	0.108	-0.076	-2.356	-4.899	-23.18
4500	-7.737	-7.305	-5.316	-0.363	0.053	0.024	0.113	0.117	0.166	0.063	-2.452	-6.332	-28.97
4600	-7.545	-7.073	-4.871	-0.135	0.049	0.023	0.106	0.109	0.155	0.128	-1.711	-6.012	-26.78
4700	-7.696	-7.150	-4.536	-0.008	0.046	0.021	0.098	0.102	0.144	0.147	-1.170	-5.909	-25.91
4800	-6.789	-6.232	-3.509	0.063	0.042	0.020	0.091	0.094	0.134	0.141	-0.598	-4.896	-21.44
4900	-6.196	-5.492	-2.350	0.095	0.046	0.021	0.098	0.102	0.144	0.152	-0.203	-4.109	-17.69
5000	-5.021	-4.202	-1.230	0.139	0.065	0.030	0.140	0.145	0.206	0.217	0.153	-2.614	-11.97
5100	-3.690	-2.544	-0.390	0.149	0.070	0.032	0.150	0.156	0.221	0.233	0.308	-1.425	-6.729
5200	-2.078	-1.214	0.166	0.141	0.067	0.031	0.143	0.148	0.210	0.222	0.341	-0.557	-2.380
5300	-1.027	-0.269	0.467	0.134	0.063	0.029	0.136	0.140	0.199	0.210	0.332	0.026	0.442
5400	-0.187	0.467	0.590	0.127	0.060	0.028	0.128	0.133	0.188	0.199	0.314	0.413	2.460
5500	0.452	1.007	0.630	0.121	0.057	0.027	0.123	0.127	0.180	0.190	0.301	0.583	3.798
5600	0.741	1.124	0.601	0.113	0.053	0.025	0.114	0.119	0.168	0.178	0.281	0.617	4.134
5700	0.758	1.059	0.528	0.100	0.047	0.022	0.101	0.104	0.148	0.156	0.247	0.559	3.828
5800	0.750	1.005	0.489	0.092	0.043	0.020	0.093	0.097	0.137	0.145	0.228	0.519	3.620
5900	0.700	0.928	0.450	0.085	0.040	0.019	0.086	0.089	0.126	0.133	0.210	0.478	3.345
6000	0.441	0.584	0.283	0.053	0.025	0.012	0.054	0.056	0.079	0.084	0.132	0.301	2.104
6100	0.380	0.504	0.245	0.046	0.022	0.010	0.047	0.048	0.069	0.072	0.114	0.260	1.816
6200	0.654	0.866	0.420	0.079	0.037	0.017	0.080	0.083	0.118	0.124	0.196	0.446	3.120
6300	0.531	0.703	0.341	0.064	0.030	0.014	0.065	0.067	0.096	0.101	0.159	0.362	2.534
6400	0.408	0.540	0.262	0.049	0.023	0.011	0.050	0.052	0.073	0.078	0.122	0.278	1.947
6500	0.337	0.446	0.216	0.041	0.019	0.009	0.041	0.043	0.061	0.064	0.101	0.230	1.607
6600	0.314	0.416	0.202	0.038	0.018	0.008	0.039	0.040	0.057	0.060	0.094	0.215	1.501
6700	0.314	0.416	0.202	0.038	0.018	0.008	0.039	0.040	0.057	0.060	0.094	0.215	1.501
6800	0.313	0.415	0.202	0.038	0.018	0.008	0.038	0.040	0.056	0.060	0.094	0.214	1.496
6900	0.301	0.399	0.194	0.037	0.017	0.008	0.037	0.038	0.054	0.057	0.091	0.206	1.439
7000	0.301	0.399	0.194	0.037	0.017	0.008	0.037	0.038	0.054	0.057	0.091	0.206	1.439
7100	0.301	0.399	0.194	0.037	0.017	0.008	0.037	0.038	0.054	0.057	0.091	0.206	1.439
7200	0.301	0.399	0.194	0.037	0.017	0.008	0.037	0.038	0.054	0.057	0.091	0.206	1.439
Total	**-54.28**	**-43.44**	**-25.88**	**-0.53**	**1.25**	**0.59**	**2.74**	**2.84**	**4.02**	**2.93**	**-8.46**	**-37.65**	**-155.9**
Spec., m w.e	**-0.385**	**-0.308**	**-0.184**	**-0.004**	**0.009**	**0.004**	**0.019**	**0.020**	**0.029**	**0.021**	**-0.060**	**-0.267**	**-1.11**

Annex 6.1: Sensitivity of the water balance at Chovar, m^3/s						
	T_0	T_{+1}	T_{+2}	T_{+3}	T_{+4}	T_{+5}
January	-0.21	-0.62	-1.23	-1.98	-2.87	-3.81
February	-1.79	-2.32	-3.05	-3.93	-4.94	-6.01
March	-0.89	-1.54	-2.39	-3.37	-4.46	-5.61
April	1.84	1.08	0.13	-0.96	-2.15	-3.41
May	5.51	4.66	3.62	2.40	1.07	-0.40
June	-6.63	-7.66	-8.92	-10.53	-12.28	-14.49
July	66.87	64.98	62.48	59.18	55.14	49.95
August	91.84	90.17	87.41	83.56	78.68	73.14
September	64.69	63.43	61.10	57.90	53.80	49.16
October	6.45	5.51	3.87	1.70	-1.05	-4.07
November	-24.24	-24.85	-25.87	-27.19	-28.82	-30.55
December	3.78	3.32	2.58	1.63	0.49	-0.74
Annual discharge, m^3/s	17.27	16.35	14.98	13.20	11.05	8.60
Annual volume, km^3	**0.54**	**0.52**	**0.47**	**0.42**	**0.35**	**0.27**

Annex 6.2: Snow-covered area and extreme instantaneous flows of major rivers in Nepal								
Name of River	Station		Basin Area	Snow covered area		Extreme flows, m^3/s		Data period
	No	Location	km^2	km^2	%	Max.	Min.	
Karnali	240	Asara Ghat	19,260	8528	44.3	3430	81	1962-93
Karnali	250	Benighat	21,240	8528	40.2	7190	89	1963-93
Seti	260	Banga	7460	1744	23.4	6400	33	1963-93
Bheri	270	Jamu	12,290	2447	19.9	5120	50	1963-90
Karnali	280	Chisapani	42,890	12,719	29.7	14,700	214	1962-93
Kaligandaki	410	Seti Beni	7130	2150	30.2	2600	18	1964-90
Kaligandaki	420	Kotagaun	11,400	2150	18.9	5790	36	1964-90
Seti	430	Phoolbari	582	166	28.5	599	6	1964-84
Marsyangdi	439.7	Bimalnagar	3774	1890	50.1	1160	31	1987-93
Marsyangdi	439.8	Goplingghat	3850	1890	49.1	2340	28	1974-85
Chepe Khola	440	Garam besi	308	14	4.5	460	1	1964-93
Buri Gandaki	445	Arughat	4270	1574	36.9	855	21	1964-90
Phalankhu Khola	446.8	Betrawati	162	9	5.6	168	0.1	1971-85
Trisuli	447	Betrawati	4640	941	20.3	1850	25	1967-93
Tadi Khola	448	Tadipul	653	16	2.5	812	1	1969-85
Narayani	450	Narayanghat	31,100	6895	22.2	22,500	169	1963-93
Arun River	604.5	Turkeghat	28,200	2334	8.3	2560	80	1976-90
Bhotekoshi	610	Barhabise	2410	260	10.8	1840	11	1965-92
Balephi Khola	620	Jalbire	629	186	29.6	662	6	1964-93
Sunkoshi	630	Pachwarghat	4920	541	11.0	2710	27	1964-90
Tamakoshi	647	Busti	2753	881	32.0	803	17	1971-85
Khimti Khola	650	Rasnatu	313	13	4.2	1460	1	1979-93
Sunkoshi	652	Khurkot	10,000	1435	14.4	8200	39	1968-90
Likhu	660	Sangutar	823	5	0.6	482	7	1964-89
Dudhkoshi	670	Rabuwabazar	3780	1377	36.4	2870	20	1964-90
Sunkoshi	680	Kampughat	17,600	2817	16.0	7690	108	1966-85
Tamor	690	Mulghat	5640	1610	28.5	5400	26	1965-90
Saptakoshi	695	Chatara	54,100	6782	12.5	9450	173	1977-87

Source: Yogacharya and Shrestha, 1998, pp. 214-217; DHMN/WECS, 1996, Appendix A

Annex 6.3: Sensitivity of calorie supply to a warming (without import option)						
Particulars	Temperature Change Scenarios					
	T_0	T_{+1}	T_{+2}	T_{+3}	T_{+4}	T_{+5}
Annual discharge at Chovar, m^3/s (Change, %)	15.52 (0)	15.28 (-1.5)	15.06 (-3.0)	14.84 (-4.4)	14.61 (-5.9)	14.36 (-7.5)
Rice water demand, m^3/ha (Change, %)	15,000 (0)	15,554 (3.7)	16,114 (7.4)	16,682 (11.2)	17,259 (15.1)	17,844 (19.0)
Rice production, 1000 metric tonnes /year	4132	3979	3825	3669	3510	3349
Edible rice supply, 1000 metric tonnes /year	2441	2351	2260	2168	2074	1979
Per capita average calorie supply, kcal/day	2440	2406	2371	2336	2300	2264
Per capita calorie supply for the top 20% population , kcal/day	6503	6503	6503	6503	6503	6503
Per capita calorie supply for the mid 60% population , kcal/day	1647	1624	1601	1577	1553	1528
Per capita calorie supply for the bottom 20% population, kcal/day	756	655	552	447	341	233
Population with 756 kcal/day per capita calorie supply, million	4.92	5.58	6.25	6.93	7.62	8.32

Annex 6.4: Sensitivity of calorie supply to warming (with import option)						
Particulars	Temperature Change Scenarios					
	T_0	T_{+1}	T_{+2}	T_{+3}	T_{+4}	T_{+5}
Annual discharge at Chovar, m^3/s (Change, %)	15.52 (0)	15.28 (-1.5)	15.06 (-3.0)	14.84 (-4.4)	14.61 (-5.9)	14.36 (-7.5)
Rice water demand, m^3/ha (Change, %)	15,000 (0)	15,554 (3.7)	16,114 (7.4)	16,682 (11.2)	17,259 (15.1)	17,844 (19.0)
Rice production in Nepal, 1000 metric tonnes /year	4132	3979	3825	3669	3510	3349
Edible rice supply in Nepal, 1000 metric tonnes /year	2441	2351	2260	2168	2074	1979
Per capita average calorie supply, kcal/day	2440	2406	2371	2336	2300	2264
Per capita calorie supply for the top 20% population , kcal/day	6503	6411	6319	6225	6131	6034
Per capita calorie supply for the mid 60% population , kcal/day	1647	1647	1647	1647	1647	1647
Per capita calorie supply for the bottom 20% population, kcal/day	756	676	596	514	430	346
Population with 756 kcal/day per capita supply, million	4.92	5.44	5.97	6.50	7.04	7.59

Annex 6.5: Correlations between snow-covered area and the ratio of maximum-to-minimum extreme flows in rivers in Nepal

			Snow covered area, %	Extreme max to min discharge
Spearman's rho	Snow covered area, %	Correlation Coefficient	1.000	-.724**
		Sig. (2-tailed)	.	.000
		N	23	23
	Extreme max to min discharge	Correlation Coefficient	-.724	1.000
		Sig. (2-tailed)	.000	.
		N	23	23
Pearson Correlation	Snow covered area, %	Pearson Correlation	1.000	-.663**
		Sig. (2-tailed)	.	.001
		N	23	23
	Extreme max to min discharge	Pearson Correlation	-.663	1.000
		Sig. (2-tailed)	.001	.
		N	23	23

** Correlation is significant at the .01 level (2-tailed).

Annex 6.6: Flood frequency analysis of the Bagmati River at Chovar (1963-80)

Return period (T), year	Normal flood (Q), m^3/s	Hypothetically 20% increased flood (Q_{20}), m^3/s	Probability of exceedence (P),%
19.0	856.0	1027.2	5.3
9.5	680.0	816.0	10.5
6.3	633.0	759.6	15.8
4.8	617.0	740.4	21.1
3.8	591.0	709.2	26.3
3.2	582.0	698.4	31.6
2.7	497.0	596.4	36.8
2.4	431.0	517.2	42.1
2.1	420.0	504.0	47.4
1.9	416.0	499.2	52.6
1.7	407.0	488.4	57.9
1.6	350.0	420.0	63.2
1.5	335.0	402.0	68.4
1.4	299.0	358.8	73.7
1.3	254.0	304.8	79.0
1.2	251.0	301.2	84.2
1.1	245.0	294.0	89.5
1.1	206.0	247.2	94.7

Selbstständigkeitserklärung

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Flensburg, 2006

Narayan Prasad Chaulagain

Curriculum Vitae

Family Name	:	Chaulagain
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ACADEMIC QUALIFICATION

1984-1987	:	Certificate in Civil Engineering from the Tribhuwan University, Nepal
1990-1995	:	Master of Science (MSc) in Water Resource Engineering with honours from the Odessa State Academy of Civil Engineering and Architecture, Ukraine.
2001-2003	:	Master of Science (MSc) in Energy Systems and Management from the University of Flensburg, Germany

JOB EXPERIENCES

1. From September 1995 to June 1996
   As a **Regional Site Engineer** of the Basic and Primary Education Project of the Government of Nepal, I was responsible for design, estimate and construction supervision of office buildings in different districts of Nepal.

2. From July 1996 to July 1998
   As a **Senior Hydropower Engineer** of **Masina Continental Associates**, an engineering consulting company in Kathmandu, I was responsible for field survey, hydrological study, design, report preparation and construction supervision of various hydropower projects, irrigation, water supply, and rural electrification projects

3. From August 1998 to July 2001
   As an **Energy Advisor** of the **Rural Energy Development Programme (REDP)** of the **United Nations Development Programme Nepal,** I was responsible for overall management of all district level activities of REDP including successful implementation of more than 10 micro hydro projects, 800 solar home systems, 250 family-sized biogas plants and 900 improved cooking stoves, which have provided renewable energy technologies for more than 3000 rural households in Nepal.

PUBLICATIONS

Many scientific research papers published in the international conference proceedings and in other publications.

EXTRA ACTIVITIES

Life member Nepal Engineers' Association, life member of Society of Hydrologists and Meteorologists of Nepal, member of Nepal Hydropower Association and member of Flensburg Association for Energy Management Nepal and other organizations.