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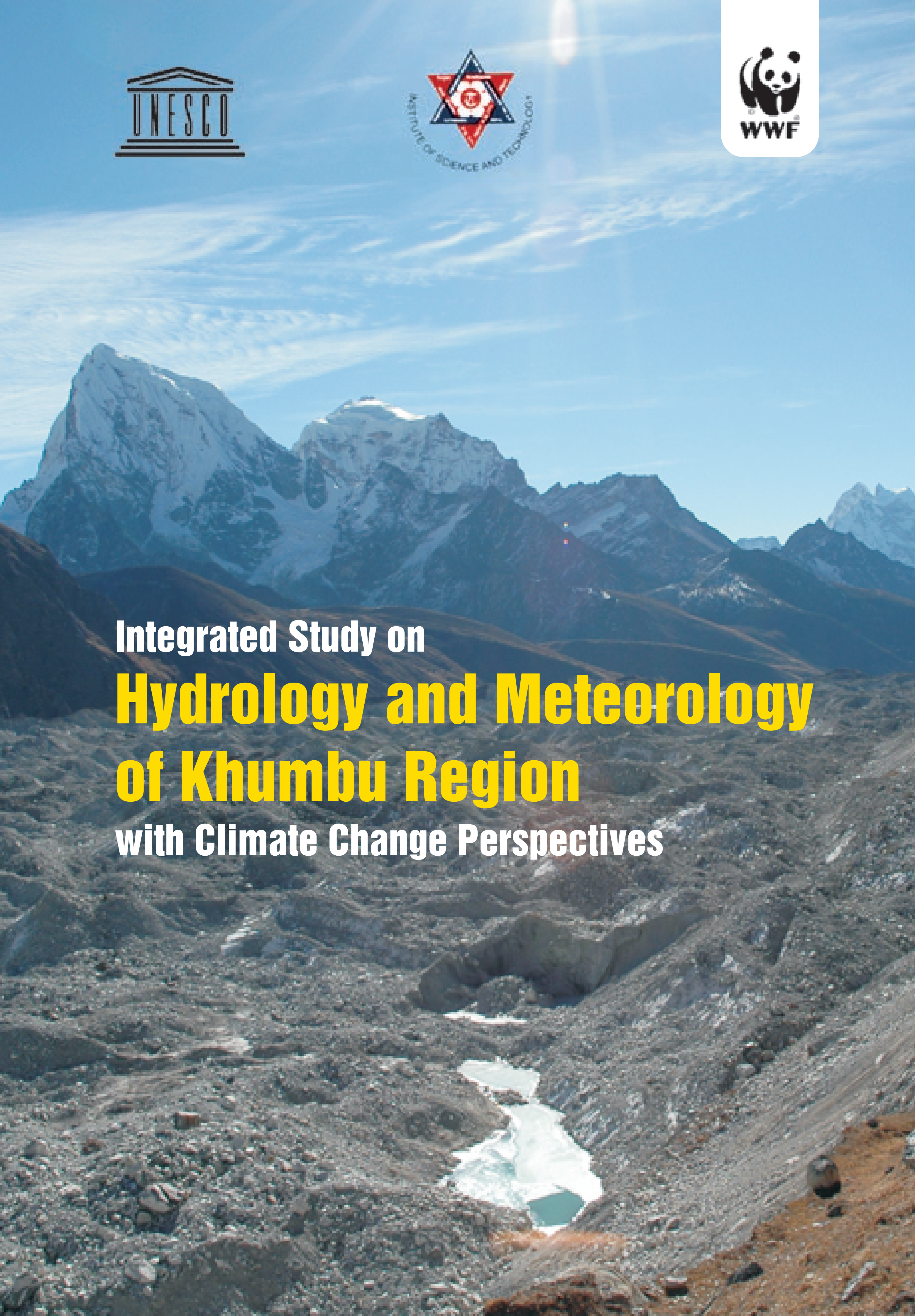

Integrated Study on

Hydrology and Meteorology of Khumbu Region

with Climate Change Perspectives

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Hydrology and Meteorology of Khumbu Region

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Research undertaken by

Central Department of Hydrology and Meteorology

Tribhuvan University (TU)

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PREFACE

Climate change and global warming are the key issues facing the global community today. Due to global warming there will be an increased incidence of flash floods, prolonged droughts and vector borne diseases, as well as a reduction in agricultural productivity and the extinction of species.

According to the Intergovernmental Panel on Climate Change (IPCC) report, the global mean surface temperature increased by 0.6 ^{0}C during the 20th Century. Many analyses have confirmed that the temperature increase in the 20th Century was greater than in previous centuries. The IPCC estimates that approximately 20-30 per cent of plant and animal species are likely to be at increasingly high risk of extinction as global mean temperatures exceed a warming of 2-3 ^{0}C above pre-industrialization levels.

Many aspects of climate change need further understanding, and this research is an attempt to enhance the understanding of the impacts of climate change in the Kumbhu Region of Nepal and its subsequent impact on natural disasters, biodiversity and local communities. This publication highlights the hydrological and meteorological aspects of climate change and the climate change impacts in the Kumbhu Region. We are confident that the information generated by this research will be beneficial to local communities as well as to various organizations implementing adaptation measures in the area.

One interesting component of this research is the involvement of postgraduate students. They have been an integral part of this research, and we believe that this has enhanced their capacities in this sector.

I would like to thank Professor K.B. Thapa, Dr. Binod Shakya and team for their sincere efforts in compiling this report. I would also like to take this opportunity to thank UNESCO for providing the financial support to undertake this research and the European Union for its support towards publishing this report. I believe the findings of the study will be equally helpful to researchers, students and policymakers in understanding the impacts of climate change in the Khumbu Region.

Anil Manandhar
Country Representative
WWF Nepal

ABBREVIATIONS AND ACRONYMS

BOD	Biological Oxygen Demand
CBS	Central Bureau of Statistic
CDHM	Central Department of Hydrology and Meteorology
COD	Chemical Oxygen Demand
DEM	Digital Elevation Model
DHM	Department of Hydrology and Meteorology
DO	Dissolved Oxygen
GCM	General Circulation Model
GeoSFM	GeoSpatial Stream Flow Modeling
GIS	Geographical Information System
GLOF	Glacial Lake Outburst Flood
ICIMOD	International Centre for Integrated Mountain Development
IHP	International Hydrological Programme
IPCC	Intergovernmental Panel on Climate Change
IUCN	The World Conservation Union
Landsat	Land Resources Satellite
masl	meters above sea level
MPN	most probable number
MSS	Multi Spectral Scanner (Landsat)
NTU	nephelometric turbidity
PMS	Pyramid Meteorological Station
SNP	Sagarmatha National Park
SPCC	Sagarmatha Pollution Control Committee
SPOT	Système Probatoire Pour l'Observation de la Terre/Satellite Pour l'Observation de la Terre
TM	Thematic Mapper (Landsat)
TU	Tribhuvan University
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
VDC	Village Development Committee
WECS	Water and Energy Commission Secretariat
WHO	World Health Organization
WMO	World Meteorological Organization
WWF	World Wide Fund for Nature

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1

INTRODUCTION

1.1 Background

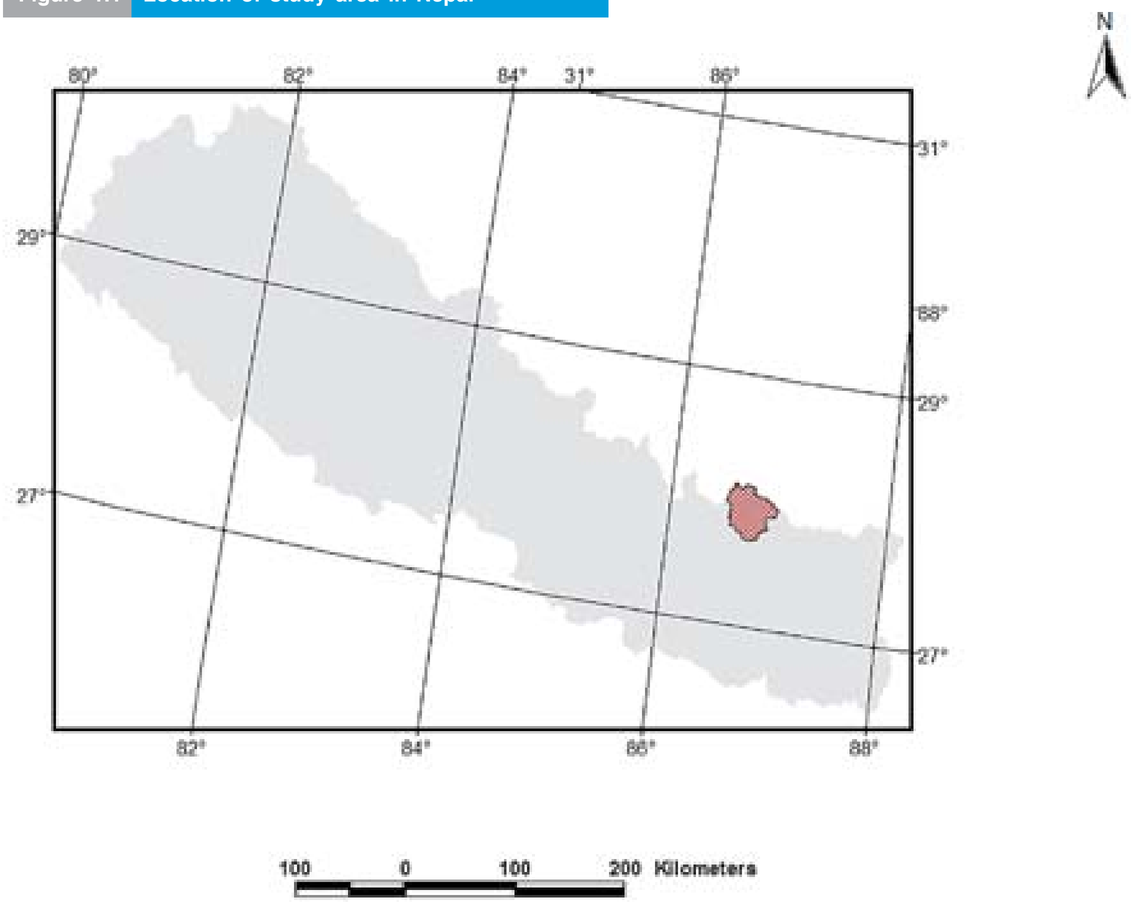
Changing climate and a warming world are the key issues today and the global community faces many risks from climate change. It is now believed that large flash floods, frequent flooding, prolonged drought, increases in vector borne diseases and rapid glacier melt are some important impacts of climate change. The global mean surface temperature has increased by 0.6 ^{0}C during the 20th Century (IPCC 2001a). Many analyses confirm that temperature increase in the 20th Century has been greater than in previous centuries. According to Douglos (1995), the magnitude of warming was more rapid in the 19th Century than in the 17th and 18th Centuries in Nepal. In recent times, many studies have confirmed that there is a large variability in climate. Deviations in the variability of the climate apparently have significant impacts on food production and livestock, water scarcity, flood disaster risk etc., particularly in developing regions. The Third Assessment Report of the Intergovernmental Panel for Climate Change (IPCC 2001b) indicates that warming in the Asian region is projected to be 3 ^{0}C by 2050. Also, the annual warming of the Himalayan region of Nepal, between 1977 and 1994, was found to be 0.06 ^{0}C/year (Shrestha et al. 1999). These changes could have large effects on Himalayan glaciers by shrinkage of glaciated areas. Also, there will be substantial increases in the aerial extent of glacier lakes, which may cause catastrophic Glacial Lake Outburst Floods (GLOFs).

In Nepal, climate change studies have been carried out by different institutions including government organizations, non-governmental organizations, international non-governmental organizations, academic institutions and the private sector. The Central Department of Hydrology and Meteorology, Tribhuvan University conducted a glacier lake assessment project of the Eastern Himalayas (1997-1998, ESCAPE-NASDA). The report showed the growth of glacier lakes and the formation of new glacier lakes in the Eastern Himalayas with liable threats of GLOF. The Climate Change and Energy Program of WWF Nepal is implementing the Himalayan Glacier Project to establish an unambiguous relationship between glacier shrinkage and the degree of climate change. This regional scale project covers three countries – Nepal, China and India. In Nepal, the study area of the project is the Khumbu and Ngozumpa glaciers of the Khumbu Region, in the Solukhumbu District. The project's aim is to examine the specific threat posed by the rapidly retreating glaciers upon the important river systems and the people who depending on them. In addition, the project focuses on the establishment of a relationship between glacier retreat, flow patterns and freshwater availability. The project also aims to suggest some adaptation strategies for concerned communities and ecosystems. To achieve these goals, a detailed analysis of the available hydrological and meteorological data is necessary. The averages of meteorological data will provide the basic climatic pattern and its change over the region, which could be further related to other relevant aspects. Under the agreement of CZ 65 with WWF Nepal, the Central Department of Hydrology and Meteorology, Tribhuvan University has carried out an integrated study on hydrology and meteorology with special reference to climate change over the Khumbu (Upper Dudh Koshi Basin). The study includes field investigations regarding social and hydro-meteorology analysis to determine the extent of climate change impacts on different aspects.

1.2 Study area

The Upper Dudh Koshi Basin lies in the Solukhumbu District in the Eastern Region of Nepal. The northern boundary of the Dudh Koshi Basin (Khumbu Region) is defined by the main divide of the Great Himalayan Range, which follows the international border with the Tibet Autonomous Region of China. The Upper Dudh Koshi Basin with an area, of 1440 km^2 has been considered for the study area, which extends from 27°412 4" to 28°082 06" North latitudes and 86°302 04" to 86°572 19" East longitudes. The location of the study area is shown in Figure 1.1. The landscape of the study area is mountainous with very sparse settlement and the area is dominated by the Sherpa people. The area is covered with temperate forests, sub-alpine forests, tundra vegetation, barren land and water bodies. The rivers in the area are perennial as they are fed by snow and glaciers.

Figure 1.1 Location of study area in Nepal



1.3 Topography

The topographic features of the Upper Dudh Koshi Basin are very rugged and steep with its terrain cut by valleys, deep river gorges and glaciers. The general topographic features are depicted in Figure 1.2a. The region includes three peaks higher than 8,000 meters above sea level (masl). Some of the world's highest peaks, such as Mt. Everest (8,848 masl), Lhotse (8,501 masl) and Cho Oyu (8,153 masl), are within the Khumbu's boundaries. The mountain landscape of this region is very young and the main uplift occurred some 500,000–800,000 years ago. Evidence indicates that uplift is still continuing at a slower rate. The mountains in the upper part of the Khumbu Region contain many glaciers and glacier lakes. Around 296 glacier lakes exist in this region, and some of them are considered potentially dangerous (Bajracharya et al. 2007). The prevalent winds and insolation associated with aspect features can influence the vegetation and snow line. The aspect features are depicted in Figure 1.2b.

Figure 1.2a Topographic features in Upper Dudh Koshi Basin

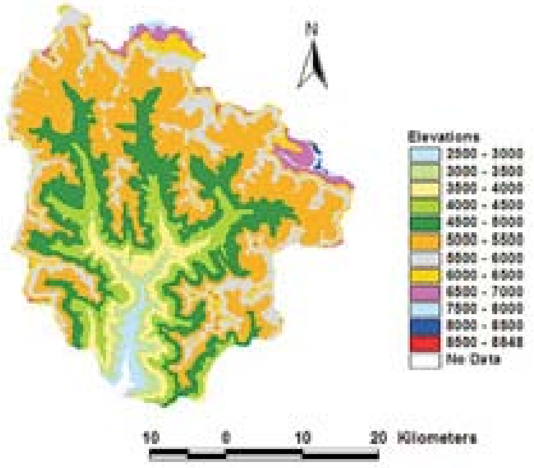
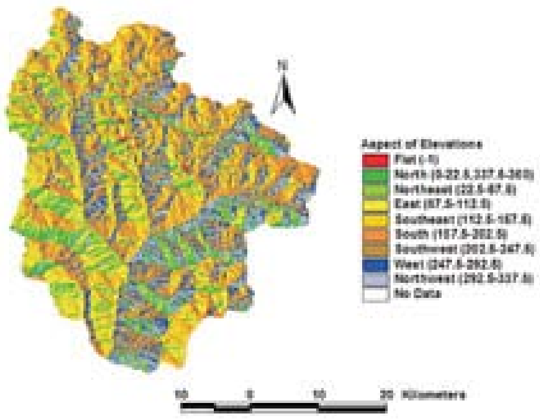


Figure 1.2b Aspects of elevation in Upper Dudh Koshi Basin



1.4 Settlement

The study area consists of scattered villages. Lukla and Namche Bazaar are the main villages in the region. Lukla is an important settlement located at an altitude of 2,850 masl. To the north of Lukla is the Khumbu Region. In the Khumbu Region, Pangboche is the highest settlement. Namche Bazaar is a village lying at the junction of the Dudh Koshi and a lateral valley that leads to the frontier pass of Nangpa La (5480 masl). Most of the houses in Namche Bazaar are associated with cottage industries producing carpets and thick sweaters from yak wool. Namche Bazaar is the major regional trading center, and hosts the headquarters of the Sagarmatha National Park.

1.5 Population

The Khumbu consists of three VDCs namely: Khumjung, Namche and Chaurikharka. The main ethnic group living in the Khumbu Region is the Sherpas. The Sherpas are living in 63 settlements with a population of about 3,300 (CBS 1990). The population statistics as presented in Table 1.1 show that the population is falling in Namche VDC. The population of VDCs according to last census is presented in Figure 1.3d. Each VDC contains 9 wards. The population distribution of each ward is presented in Figures 1.3a through 1.3c.

Table 1.1 Population statistics for Khumbu Region

	VDC 1990	Population 2001	Growth Rate
Khumjung	1809	2010	1.05%
Namche	1647	1325	-0.47%
Chaurikharka	2422	3080	2.4%

Source: Nepal CBS Census 2001

Figure 1.3a Ward population in Chaurikharka VDC (2001)

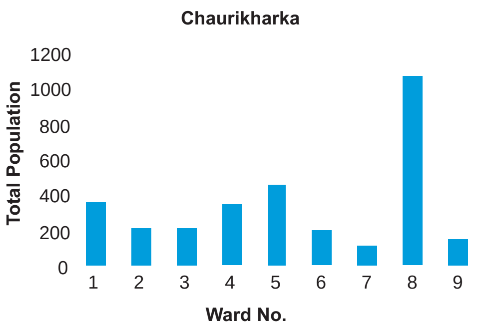


Figure 1.3b Ward population in Khumjung VDC (2001)

Figure 1.3c Ward population in Namche VDC (2001)

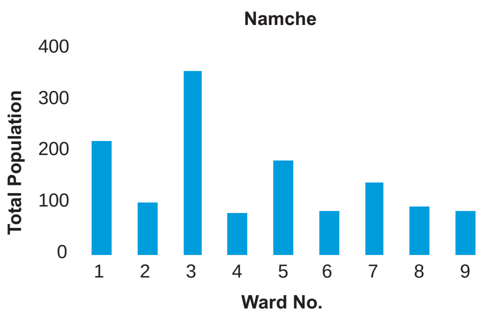
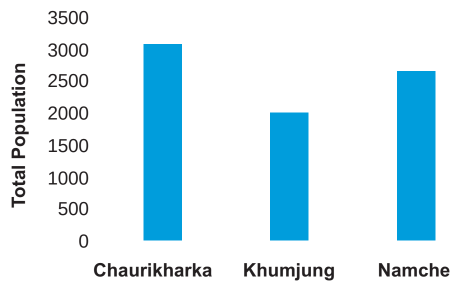


Figure 1.3d Total VDC population (2001)



Chapter 2

GENERAL HYDROLOGY AND METEOROLOGY

2.1 Meteorology and hydrology

Exposure and altitude influence the climate on elevated land masses. An enclosed valley or upland is climatically very different from an exposed peak. Weather conditions on windward sides and flanks inclined towards the sun are unlike those lying in the sun and wind shadows. The Himalayan region has diverse climatic features due to elevated lands, rugged topographic features and exposure, etc. Besides the physiographic features, the climate of the Himalayan region is dominated by the monsoon circulation, which results in high precipitation from June through September, and relatively little precipitation for the rest of the year. Four characteristic periods of the year can be recognized in place of the conventional seasons (Rao 1981): winter (December to February), the pre-monsoon period (March to May), the monsoon period (June to September) and the post-monsoon period (October and November). The Sagarmatha National Park in the Khumbu Region, with altitudinal variation between 3,000 to 8,848 masl, experiences different types of climate. In this area, precipitation fluctuates in relation to windward/leeward slopes with the prevailing winds as well as with the local wind circulation (Barry 1981).

2.2 Precipitation

The precipitation in the Khumbu Region may be considerably greater on the upper slopes than in the valleys. Post-monsoon, skies are typically cloud free and precipitation is unusual (Yasunari 1976). The average annual precipitation is about 2,100 mm at elevations between 2,500 to 3,000 masl. Between the altitudes 3,500 and 4,500 masl, precipitation is around 1,000 mm, and around 500 mm above 4,500 masl (Figure 2.1a-1). The non-monsoon precipitation is around 150 mm at altitudes above 3,500 masl. At 3,000 masl, precipitation is around 250 mm (Figure 2.1b). Likewise, monsoon precipitation varies from 300 to 1,900 mm in the study area (Figure 2.1a-2). The rainfall analysis is based on interpolation of point rainfall data available in and around the study area. At the Pyramid Meteorological Station (5050 masl), the monsoon precipitation is about 87 per cent of annual total. Whereas, at Chaurikharka Meteorological Station (2613 masl), monsoon precipitation is 81 per cent of the annual total. At Syangboche Meteorological Station the contribution of the monsoon is the lowest at about 74 per cent of the annual total. The wettest and driest months for the region are July and December respectively. The monthly rainfall distribution is presented in Table 2.1.

Table 2.1 Monthly precipitation at meteorological stations in Khumbu Region (mm)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Pyramid	3	4	10	10	17	68	132	147	57	10	6	1
Chaurikharka	16	28	51	80	106	310	566	531	303	92	14	9
Namche Bazaar	14	14	34	30	52	158	257	277	159	108	8	8
Chiasla	12	10	35	51	93	302	527	496	251	101	9	13
Syangboche	21	23	29	43	52	135	213	191	145	47	8	9
Tengboche	13	13	23	35	48	210	307	309	209	113	10	2

Source: Tartari et al. 1998, Climatological Records of Nepal, DHM

Figure 2.1a-1 Annual average precipitation

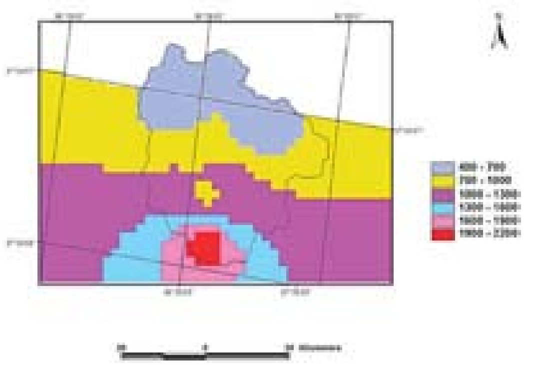


Figure 2.1a-2 Annual average monsoon precipitation

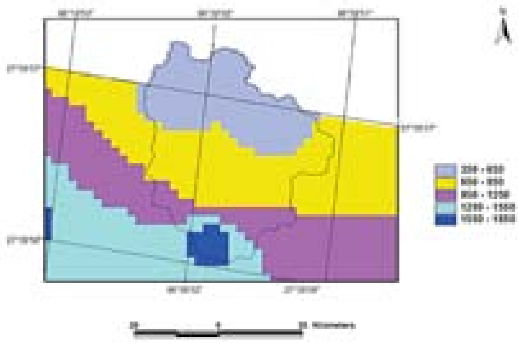
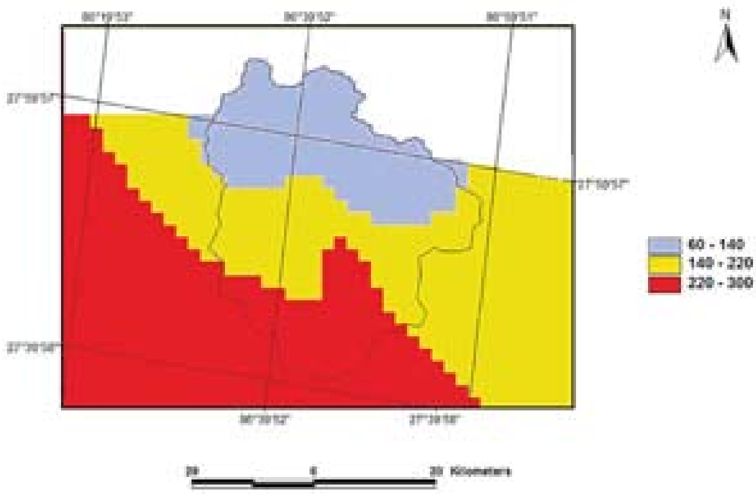


Figure 2.1b Non-monsoon average precipitation



2.3 Air temperature

The Pyramid Meteorological Station is the highest station in the study area at an elevation of 5,050 masl. During the monsoon period, the diurnal thermal range is always low because of cloudiness, which does not allow strong heating during the day or strong cooling at night (Tartari et al. 1998). In contrast, the range is very high from the end of the post-monsoon period to the end of winter because the sky is usually cloud free (Tartari et al. 1998).

The average temperature at the Pyramid Meteorological Station is below zero for the months October to April. The annual mean temperature at the Pyramid Meteorological Station is -2.38 ^{0}C. February is the coldest month with an average temperature of -9.2 ^{0}C, and July the warmest with average temperature of 4.2 ^{0}C. The mean monthly temperature distribution is presented in Figure 2.2a. The temperature is quite comfortable (>0 ^{0}C) for at least five months (Table 2.3). However, the minimum air temperature drops below freezing for at least 9 months (Table 2.2). The minimum temperature distribution is presented in Figure 2.2b.

A “jump” in mean temperature characterizes the onset of a new season (Figure 2.2a). The most evident inter-seasonal jump is between winter and the pre-monsoon season with a difference of 4.3 ^{0}C (Tartari et al. 1998).

The other meteorological stations are located below 5,000 masl and their mean monthly temperature data are tabulated in Table 2.3. Meteorological Stations at Namche, Syangboche and Tengboche have mean monthly temperatures below sub freezing during winter only (Table 2.3). Except for the Pyramid Meteorological Station, January is the coldest month for all the stations, but July is the warmest month for all meteorological stations.

Table 2.2 Minimum and maximum monthly temperature at Pyramid Meteorological Station (degrees celsius)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Max temp	-2.8	-3.7	0.8	1.2	6	8.1	8	6.8	5.6	3	0.3	0.2
Min temp	-13.6	-14.2	-9.7	-8.9	-3.8	0.7	1.5	0.5	-1.2	-6.2	-10.9	-11.7

Source:Tartari et al. 1998

Table 2.3 Mean monthly temperature at meteorological stations (degrees celsius)

Meteoro-logical Station	Elevation (masl)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Pyramid	5050	-8.6	-9.2	-4.9	-4.3	0.5	3.8	4.2	3	1.4	-1.9	-5.8	-6.8
Namche	3450	-0.7	0.6	3.5	7.2	9.2	11.4	12.4	12.1	11.0	7.6	4.0	0.8
Chailsa	2770	2.4	3.9	7.6	9.9	12.1	14.3	15.0	14.9	13.7	10.7	6.6	3.4
Syangboche	3700	-3.5	-2.3	0.7	4.0	6.4	8.6	9.4	9.2	7.5	4.4	1.4	-1.2
Tengboche	3857	-1.7	-0.9	2.5	5.6	7.4	10.0	10.5	10.0	8.6	6.3	1.6	0.0

Source:Tartari et al. 1998, Climatological Records of Nepal, DHM

Figure 2.2a Mean monthly temperature distribution at Pyramid Meteorological Station

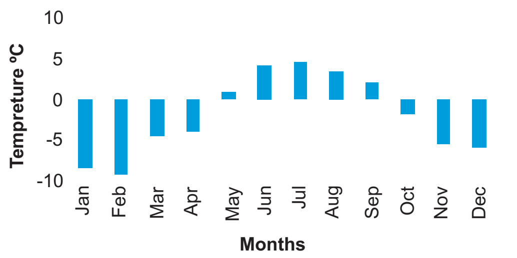
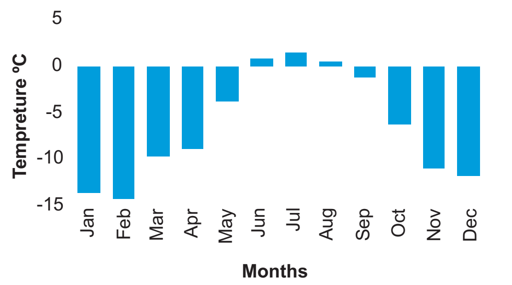


Figure 2.2b Minimum monthly temperature distribution at Pyramid Meteorological Station



2.4 Wind

The monthly mean wind speed at the Pyramid Meteorological Station is not high, with a monthly mean of about 127 km/day. However, the maximum monthly wind speed has a high variation in wind run (Table 2.4). On average, the post-monsoon period is the least windy. Wind speed is very high in winter, and gusts can exceed 140 km/h. During the monsoon season the wind declines and gusts are at their minimum strength, particularly in August with an average of 31 km h-1 (Tartari et al. 1998). At Pyramid Meteorological Station, the wind speed is highest during January and lowest during November (Figure 2.3a).

The hourly wind speed at Dingboche Meteorological Station is at a maximum in the early afternoon and minimum during the early morning in both monsoon and non-monsoon seasons (Table 2.5). The monsoon average wind speed is greater than the non-monsoon wind speed during the morning, but it is the reverse in the evening at Syangboche Meteorological Station. The variation in wind speed in the monsoon and non-monsoon season is shown in Figure 2.3b.

Table 2.4 Monthly wind run at Pyramid Meteorological Station

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average wind run (km/day)	183	152	157	125	148	145	125	109	105	94	89	98	127
Maximum wind run (km/day)	762	783	557	264	258	243	226	187	182	147	465	400	783

Source: Tartari et al. 1998

Table 2.5 Average October wind speed in m/s (1997) at Syangboche

Hours	1	2	3	4	5	6	7	8	9	10	11	12
non-monsoon	2.6	2.4	2.4	2	2.1	2.2	2.3	3.2	5.2	6.8	7.4	7.7
monsoon	3	3	3.1	3.2	3.2	3.3	3.4	3.9	5	6.4	7.4	8.1
Hours	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
non-monsoon	7.9	7.8	7.5	6.5	5.4	4.3	3.3	3.1	3.1	3	3.2	3.1
monsoon	8.7	8.4	7.8	6.5	4.8	3.5	2.8	2.7	2.5	2.6	2.7	2.9

Source: DHM Nepal

Figure 2.3a Monthly wind run at Pyramid Meteorological Station

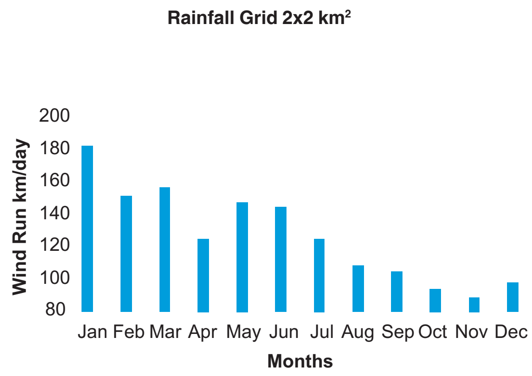
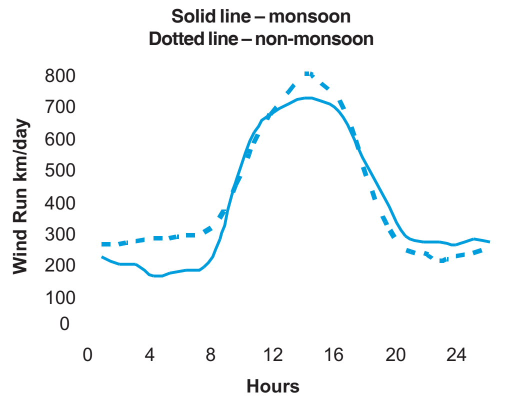


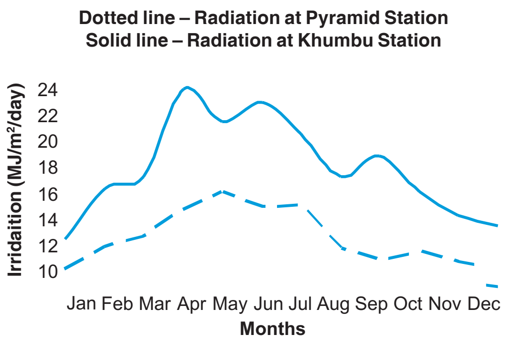
Figure 2.3b Hourly wind run at Dingboche Meteorological Station



2.5 Solar radiation

The average solar radiation is 12.4 MJ/m^2/day at Pyramid Meteorological Station (altitude 5,050 masl). The monthly average solar radiation reaches its maximum in the month of May (15.6 MJ/m^2/day). Solar radiation decreases at the beginning of the rainy season and is at its minimum in the month of January (10.4 MJ/m^2/day). The radiation at the Khumbu Meteorological Station is relatively higher than at Pyramid Meteorological Station. The monthly distribution of radiation at both stations is presented in Figure 2.4. The average solar radiation at Khumbu Meteorological Station (altitude 4,355 masl) is 17.6 MJ/m^2/day. The minimum radiation is recorded in January (13.3 MJ/m^2/day) for Khumbu Meteorological Station, and the maximum monthly average radiation is found in the month of April. Solar radiation for Pyramid and Dingboche Meteorological Stations is presented in Table 2.6. The Pyramid Meteorological Station is located 700 m higher than the Khumbu Meteorological Station and, hence, it gets less radiation.

Figure 2.4 Average monthly solar radiation



2.6 Humidity

The yearly average range of humidity at Pyramid Meteorological Station is 45 per cent (Table 2.7a). The humidity range is quite high for all months except from June to September. Records in March and April show great variations in humidity and this also causes great variations in weather during these months. The diurnal range of relative humidity drops in the monsoon period reaching its lowest value in August (22 per cent). Humidity for December is the lowest with an average mean of 30 per cent, and August is the highest with an average mean of 93 per cent.

The annual average relative humidity is 64 per cent (Table 2.7b). The monthly average from May to October is higher than the annual average. A sudden drop in humidity in October depicts the end of the rainy season, but the sudden rise of humidity in the month of May can be due to sublimation of ice and snow as radiation is highest in this month. The monthly humidity at the Pyramid Meteorological Station is shown in Figure 2.5.

Table 2.6 Monthly mean solar radiation for Pyramid and Khumbu Meteorological Station

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
Pyramid	12.4	15.7	16.6	22.5	20.2	21.5	19.4	16.6	17.9	15.6	14.0	13.3	17.6
Khumbu	10.4	11.9	12.6	14.4	15.6	14.6	14.7	11.8	11.0	b11.6	10.9	10.5	12.5

Source:Tartari et al. 1998, Climatological Records of Nepal, DHM

Table 2.7a Monthly mean humidity at Pyramid Meteorological Station

Humidity	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Maximum mean humidity %	63	78	86	90	96	98	99	99	99	88	65	46	84
Mean humidity %	35	45	49	58	75	88	92	93	91	66	45	30	64
Minimum mean %	14	16	16	24	42	67	75	77	72	31	19	12	39
Mean humidity range	49	62	70	66	54	31	24	22	27	57	46	34	45

Source:Tartari et al. 1998, Climatological Records of Nepal, DHM

Table 2.7b Annual average relative humidity

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean humidity %	35	45	49	58	75	88	92	93	91	66	45	30	64

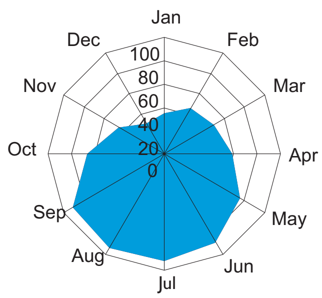
Source:Tartari et al. 1998, Climatological Records of Nepal, DHM

Table 2.8 Monthly flow of Imja river

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Flow m^3/s	1.03	1.02	1.11	1.44	2.49	4.66	7.93	8.72	7.40	4.50	2.58	1.65

Source: DHM, Nepal

Figure 2.5 Monthly humidity at Pyramid Meteorological Station



2.7 River flow

The discharge data of some upstream reaches of the Dudh Koshi River network is available from 1988. The discharge data is measured by the Department of Hydrology and Meteorology (DHM). The mean monthly discharge of Imja river at Khumbu is presented in Table 2.8. The river has the highest flow in August and minimum flow in February (Table 2.8). However, the river has discharge greater than 1 m^3/s for all months.

2.8 Extreme weather

The disastrous avalanche that occurred in the Gokyo area of Khumbu Region on 9-10 November 1995 was due to an extreme weather event in the recent past. A low depression system developed in the Bay of Bengal on 7 November 1995 and the system shifted northward with the surface pressure of 996 mb over Bihar in India during the morning on 9 November (Shakya 1998). The system brought heavy rain and snow over east and central Nepal. The precipitation gauges at lower elevations in the Khumbu Region recorded 50-200 mm of rain. About 30-50 cm of snow was observed at 3,800 masl, 50-100 cm of snow at about 4,000 masl, 100-200 cm above 5,000 masl (local observer), This weather event led to a catastrophic avalanche near the village of Pangkha in Gokyo, which killed 24 people and over 100 livestock.

Chapter 3

CLIMATE CHANGE IMPACTS

3.1 Change in climatic type

Koppen's method is most widely used for climatic classification. His first classification in the year 1900 was largely based on vegetation zones, and later, in 1918, it was revised with temperature, rainfall and seasonal characteristics (Critchfield 1999). The classification includes five major categories designated by capital letters as:

A –Tropical forest
B – Dry climates
C – Warm temperate rainy climates; mild winters.
D – Cold forest climates; severe winters
E – Polar climates

Records from meteorological stations at Chailsa, Namche Bazaar, Syangboche and Pyramid have been considered for climatic classification. A regional regression analysis was carried out to find out the wettest and coldest month's temperature distribution over the region and the analysis is shown in Figures 3.1a and 3.1b.

At elevations between 2,000 and 3,000 m, the average temperature of the warmest month observed is greater than 10 ^{0}C and the coldest month between 0 and 18 ^{0}C. The temperature of the warmest month is less than 22 ^{0}C and the average temperature of each of the four warmest months is above 10 ^{0}C. The precipitation in the driest month of the winter-half of the year is less than 1/10 the amount in the wettest summer month. Thus, the climatic type for that region is **Cwb** type (Tropical upland: mild winter; dry winter, short summer).

Between elevations 3,000 and 4,000 m, the average temperature of the warmest month is greater than 10 ^{0}C and the coldest month about 0 ^{0}C or less. The average temperature from one to three months is 10 ^{0}C or above and temperature of the warmest month is below 22 ^{0}C. In this belt, the precipitation in the driest month of the winter-half of the year is less than 1/10 amount of the wettest summer month. Thus, the climatic type for the region is **Dwc** type (Subarctic: severe winter; dry winter, short cool summer).

Between elevations 4,000 and 6,000 m, the average temperature of the warmest month is below 10 ^{0}C, but not less than 0 ^{0}C. Thus, the climatic type for the region is **ET** type (Tundra: very short summer).

Above 6,000 m, the average temperature of warmest month is 0 ^{0}C or below. Thus, the climatic type for the region is **EF** type (Perpetual ice, glacier and snow).

According to IPCC, by 2050, the average temperature is predicted to be 3 ^{0}C higher. In such circumstances, a change in climatic type across the region is certain. A summary of climatic types is shown in Table 3.1. The summary of the present climatic types and their possible shift due to global warming in 2050 are shown in Figures 3.1c and 3.1d respectively. The climatic type along with vegetation is shown in Table 3.2.

Figure 3.1a Present wettest and coldest month temperature distribution with altitude

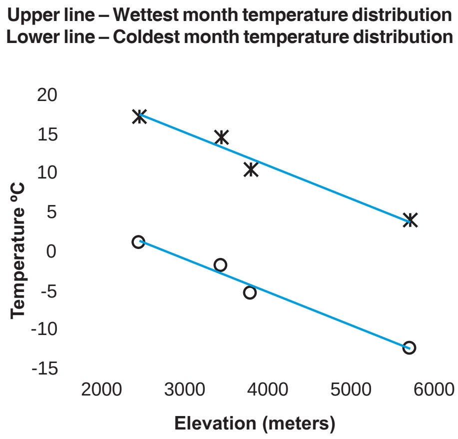


Figure 3.1b Wettest and coldest month temperature distribution with altitude on the basis of IPCC projected temperature, 2050

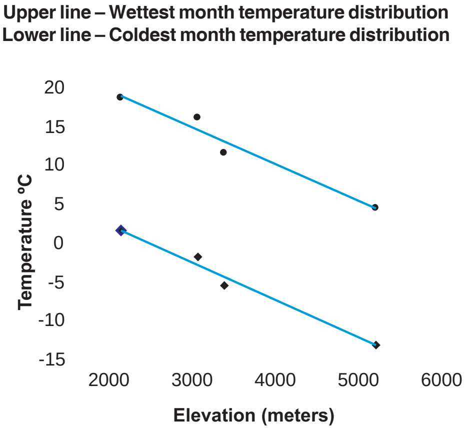


Table 3.1 Climatic type over Upper Dudh Koshi Basin

Elevation (meters)	Climatic Type (recent)		Climatic Type (2050 AD)	
2000-3000	**Cwb**	Tropical upland: mild winter; dry winter, short summer	**Cwa/Cwb**	Mild winter but short warm summer/Tropical upland: mild winter; dry winter, short summer
3000-4000	**Dwc**	Subarctic: severe winter;	**Cwb**	Tropical upland: mild winter; dry winter, short cool summer dry winter, short summer
4000-6000	**ET**	Tundra: very short summer	**Dwc**	Subarctic: severe winter; dry winter, short cool summer
6000-above	**EF**	Perpetual ice, glacier	**ET**	Tundra: very short and snow summer

Table 3.2 Vegetation type and climate

Elevation (masl)	Vegetation	Climatic Type
<3000	Forest blue pine	Cwb
Above 3600	Rhododendron forest	Dwc
4500 5500	Grassland and dwarf shrubs	ET
5500-6000	Sub-nival zone with cushion plants	ET
6000 above	Permanent snow line	EF

Figure 3.1c Recent climate type and its distribution (Koppen Classification)

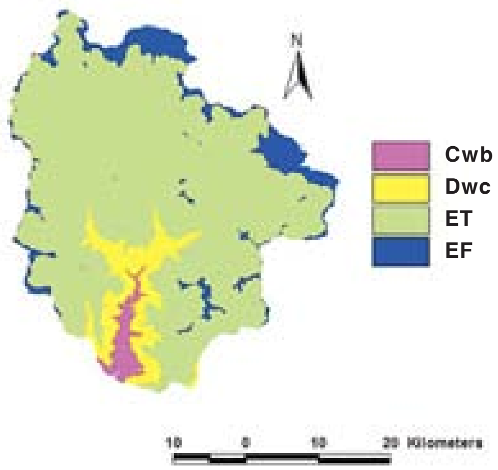
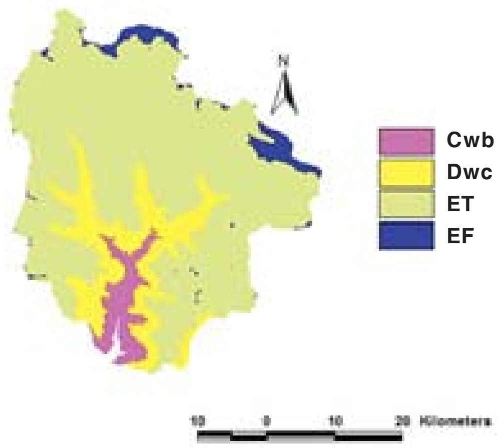


Figure 3.1d Climate type and its distribution (projected Koppen Classification, 2050)



3.2 Impact on glaciers and glacier lakes

The warming rate of the Himalayan climate in Nepal is 0.06 ^{0}C/year (Shrestha et al. 1999). According to Douglos (1995), the magnitude of warming was more rapid in the 19th Century than in the 17th and 18th Centuries. His analysis is based on 250 year tree ring data at Kalinchok in Nepal. Over the Himalayan region, the warming impacts have caused the glaciers to retreat to form potentially dangerous glacier lakes. The growing rate and formation of new glacier lakes are rapid in the Eastern Himalayan region of Nepal (Shakya 2001). This warming will cause an upward shift in the snow line.

Between 1960 and 2000, moraine dammed lakes increased from 33 to 89 in number in the Khumbu Region. However, only 3 valley glacier lakes were created between 1960 and 2000. The area of total moraine dammed lakes reached 7.254 km^2 from 2.291 km^2 (Bajracharya et al. 2007). The glacier lake statistics are shown in Table 3.3.

Table 3.3 Glacier lake statistics for Khumbu Region

Type of Glacier Lake	Number		Area (km^2)	
	1960's	2000	1960's	2000
Moraine dammed	33	89	2.291	7.254
Valley	13	16	1.706	2.706

Source: Bajracharya et al. 2007

Table 3.4 Retreat of glaciers in Khumbu Region

Glacier Name	Mean Length (m/year)		Average Retreat Rate (m/year)
	1960's	2000/2001	1960-2000
Imja	10,770	8,430.0	59
Lumding	6,015.0	4,700.0	33
Lanmuche	3,160.0	2,388.0	19
Bhote Koshi	17,100	16,455	16
Ngojumba	22,500	21,625	22
Khumbu	12,040	11,198	21
Lhotse	8,870.0	8,453.0	10
Inkhu	10,770	9,786.0	25

Source: Bajracharya et al. 2007

Average glacier retreat rate (m/year) in the region between 1960 and 2000 as shown in Table 3.4 indicates a high rate of retreat at Imja Glacier and a low retreat rate at Lhotse Glacier (Bajracharya et al. 2007).

3.3 Imja Glacier Lake

Dig Tsho Glacier Lake was considered a 'potentially dangerous' glacier lake and it burst in August 1985. Imja Glacier Lake is a similar type of potentially dangerous lake, but it is much larger and a rapidly expanding glacier lake in the Khumbu Region (Bajracharya et al. 2007). The estimated volume of water stored in the lake was around 28 million cubic meters in 1992 and 35.8 million cubic meters in 2002 (Bajracharya et al. 2007). The aerial growth of Imja Lake is shown from Figure 3.2b through 3.2i.

The growth rate of Imja Lake is $\frac{dv}{dt} = 0.709$ million m^3/year.

Thus, it is estimated that lake volume will grow to be around 40.1 million cubic meters (Mm^3) in 2008 (Figure 3.2a).

Models of glacier lakes are subject to many difficulties and uncertainties. Clague and Mathews (1973) developed a relationship especially for glacier lake outburst as:

$$Q_{max} = 113V_0^{0.64} \quad [i]$$

Where Q_{max} is maximum discharge (m^3/s) at the outlet of the lake and V_0 is the outburst volume in Mm^3.

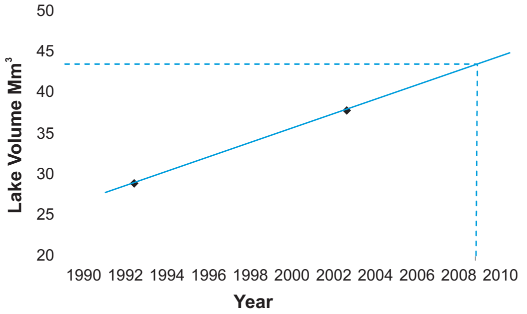
Walder and Costa (1996) did corrections over Clague and Mathews. On the basis of 26 lakes and they developed the formula:

$$Q_{max} = 46V^{0.66} \quad [ii]$$

Where V is total lake volume, Mm^3.

Shakya (2001) further developed a similar relationship for Nepalese Himalayan conditions using 11 glacier lakes including

Figure 3.2a Growth rate of Imja Glacier Lake



records of the Zhangzangbo and Dig Tsho outbursts. The developed modified formula is:

$$Q_{max} = 137.08\, V_o^{1.1745} \qquad [iii]$$

Where Q_{max} is peak GLOF discharge (m^3/s) at the outlet of the lake and V_0 is outburst volume in Mm^3.

$$\frac{Q_D}{Q_{max(D=o)}} = 0.5(D+1)^{-0.557} + 0.5e^{-0.0325D} \qquad [iv]$$

Shakya (2001) has also developed a formula for downstream attenuation. On the basis of 11 lake outbursts he found:

Where Q_{max} and Q_D are peak GLOF discharge (m^3/s) at the outlet of the lake (D=0) and at distance (D km) downstream respectively.

Assuming a 50 per cent lake volume outburst (20 Mm^3), the peak discharge of Imja Lake using equation [iii] works out to be 4,757 m^3/s at the outlet of Imja Lake.

The downstream attenuation from the outlet of the lake using equation [iv] is presented in Figure 3.3. However, the total volume of flood downstream depends on the season during which it bursts. If it bursts during the monsoon, the flood will be more catastrophic. Shakya (2001) developed a regional average monsoon flow empirical formula over eastern Himalayan rivers as:

$$Q_{mon} = 0.0927A^{1.0092} \qquad [v]$$

Where Q_{mon} is average monsoon flow in m^3/s and A is area of basin below the outlet of the lake. The total flood volume from Imja GLOF in case of burst during monsoon season is presented in Table 3.5.

Table 3.5 Downstream attenuation of estimated flood incase of Imja GLOF

Distance D, downstream in km	0	5	10	20	30	40	50
GLOF discharge, Q_D, m^3/s (using equation [iv])	4757	2900	2344	1678	1249	949	735
Monsoon average flow, m^3/s (using equation [v])	0	6.7	23.9	62	116	124	151
Total Flood Q, m^3/s	4757	2906.7	2367.9	1740	1365	1073	886

Figure 3.2b Aerial extent of Imja Lake, Landsat MSS, 29 Dec 1976

Figure 3.2c Aerial extent of Imja Lake, Space Shuttle, panchromatic, 02 Dec 1983

Figure 3.2d Aerial extent of Imja Lake, SPOT HRV1, 23 Mar 1986

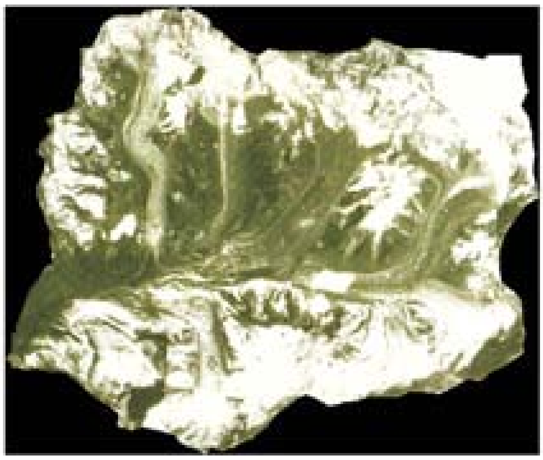


Figure 3.2e Aerial extent of Imja Lake, Landsat MSS, 25 Apr 1991

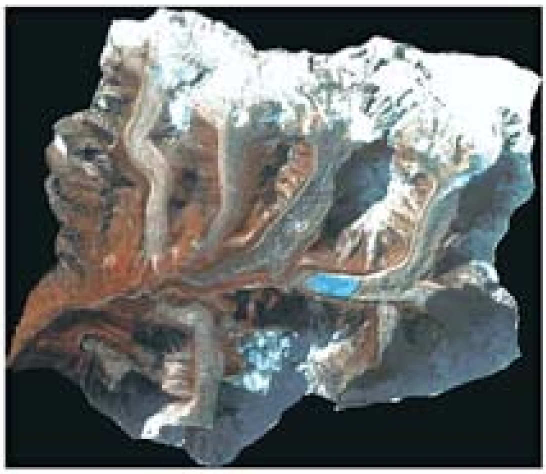


Figure 3.2f Aerial extent of Imja Lake, Landsat TM, 29 Nov 1999

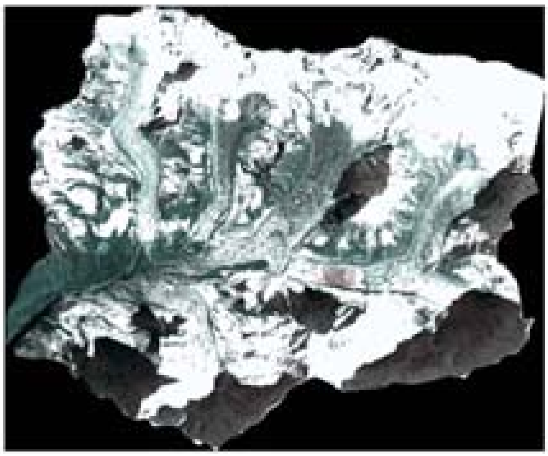
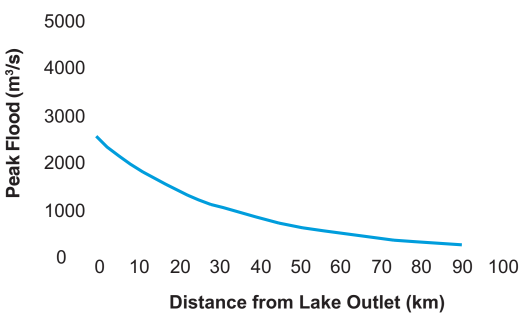


Figure 3.2g Aerial extent of Imja Lake, Landsat TM, 17 Nov 1992

Figure 3.2h Aerial extent of Imja Lake, Landsat TM, 30 Oct 2000

Figure 3.2i Aerial extent of Imja Lake, Google Earth 2007, Image Terra Metric

Figure 3.3 Downstream attenuation of GLOF after the breach of Imja Lake



3.4 Impact on evaporation and precipitation

Results from General Circulation Models (GCMs) indicate there is a possibility of changes in precipitation and evapotranspiration losses the in future. On the basis of doubled CO_2, as predicted by GISS GCM, Mirza (1997) developed coefficients a and β for future precipitation and evapotranspiration respectively for the Koshi Basin of Nepal. He gave the following relations.

$P_1 = a P_0$ [vi-a]

$E_1 = \beta E_0$ [vi-b]

Where P_0 denotes the present precipitation and P_1 is future precipitation. Similarly E_0 denotes the present evapotranspiration and E_1 is future evapotranspiration. Mirza (1997) estimated a =1.26 and β=0.99 for the Koshi Basin.

Increases in atmospheric CO_2 concentration may reduce plant evapotranspiration. His results depict a 26% increase in precipitation and 1% decrease in evapotranspiration in 64 years in the Koshi Basin. Increases in precipitation have already been observed by local people (Field Visit 2007).

3.5 Impact on river flow

The river flow data for upstream of the Dudh Koshi River network is limited. The flow duration curve from 1988 to 1998 of the Imja River is presented in Figure 3.4. It is difficult to study the climate change impact on flow if data is limited. However, daily flow data for the Dudh Koshi at downstream Station No 670, at Rabuwa Bazaar is available from 1964. The flow duration curve plotted on a daily basis from 1964-1973, 1974-1993 and 1999-2006 is shown in Figure 3.5. The curve from 1999-2006 shows a strong rise in flow from 33 per cent of time and less (four months) compared to 1964-1973 and 1974-1993 curves; whereas, flow curves from year 1964-1973 and 1974-1993 are almost identical. The rise in flow curve produced by 1999-2006 seems to be the synchronization of high rainfall and excess snowmelt.

3.6 Effect on river quality

The main sources of drinking water for local people and animals are the natural streams. Hotels on the tourist trails use drinking water tapped from upstream sources using pipes. However, in most places, people carry water from springs and streams to meet their needs. The quality of water from upstream sources is pure and safe (Appendix IV and V). Local people do not use the main river water because they believe that the river is polluted due to settlement waste. Nevertheless, analysis of Dudh Koshi water sampled between Larja Dobhan and Phakdin falls found the water to be within the safe limits of the WHO guidelines, but parameters like BOD and COD indicate the start of slight contamination (Appendix III). From field studies, it has been found that neither the people nor the animals have been affected by any kind of waterborne diseases. The main health problems faced were coughs and nasal congestion.

Figure 3.4 Flow duration curve of Imja River

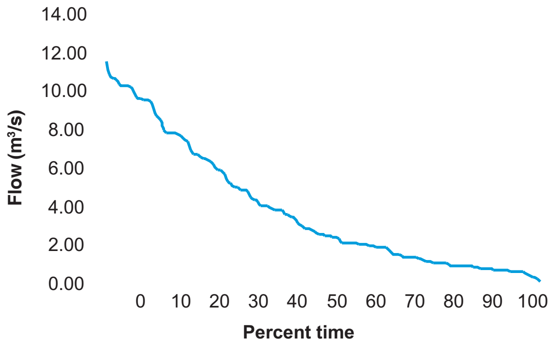
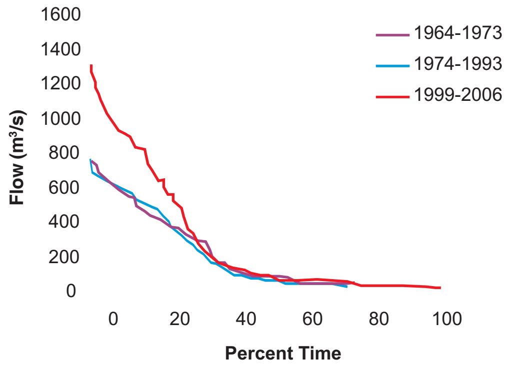


Figure 3.5 Flow duration curve of Dudh Koshi River at Rabuwa Bazaar



Chapter 4

FIELD INVESTIGATION

4.1 Introduction

The field study was carried out at Lukla, Phakdin, Namche, Syangboche and their vicinities. Two field visits from 23rd to 30th March and 17th to 24th November 2007 were carried out in the Khumbu Region. The field study area is presented in Figure 4.1a. During the field investigation various hydrological, climatic, hydraulic and socioeconomic data related to climate change were collected. Data was collected on river runoff, snow, water quality, river hydraulic properties, population, energy, livestock, agroproducts and vegetation. These field data were correlated to understand the climate change and its impacts. In addition, one of the objectives of the field visits was to train the graduate students in field measurement and field survey. The observation of weather during the March field visit is presented in Appendix VII. The measurement at Syangboche Meteorological Station and cloud observation at Phakdin and its vicinity are presented in Figures 4.1b and 4.1c. Short field visits to neighboring areas, namely, Kodari and Jiri, were carried out to canvas the opinion of local people on climate change. This will indeed lend support to a detailed study on the Khumbu Region. The GLOF affected area near the Friendship Bridge at the China and India border is shown in Figure 4.1d.

During the field visit a difference of 35 per cent was observed between daytime and evening humidity at Phakdin and Lukla. The atmospheric pressure dropped from 928 to 585 mb between Lukla and Namche. The minimum pressure of 566 mb was observed at Syangboche. On general observation, the sky is clear during the daytime and overcast during the evening.

Figure 4.1a **Field study area at Khumbu**

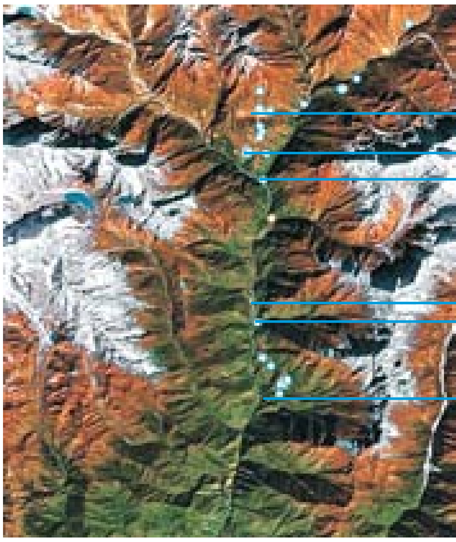


Figure 4.1b **Meteorological measurement at Syangboche**

Figure 4.1c Cloud observation at Phakdin and its vicinity

Figure 4.1d Measuring discharge at Khumbu Khola

4.2 Discharge measurement

On the way to Namche during March 2007, the team measured the essential hydrological parameters. The measured hydrological parameters are given in Appendix I. Discharge measurement by float method was carried out on Dudh Koshi River near Larja Dobhan. The mean discharges were calculated as 8.60 m^3/s and are presented in Appendix I. Two marks were labeled on heavy rocks close to the river, 1m and 2m above the water surface. A second discharge measurement was carried out 4 km upstream from Larja Dobhan (at Phungi Thenga). Discharges were measured using the float and tracer technique. The results from the float method are given in Appendix I. The mean discharge by float method is calculated as 4.8m^3/s, and by tracer method as 4.37m^3/s, with an average of 4.5m^3/s. The time of concentration of tracer is shown in Figure 4.1e and the measurement is presented in Figure 4.1f. The details of tracer concentration are presented in Appendix VIII. The tracer calculation is presented in Table 4.1a.

During the second field visit (17 to 24 November 2007), a substantial decrease in snow area was found compared to the first field visit. The water level was 38 cm above the marked water level during the first field visit at Larja Dobhan and the corresponding discharge was estimated at around 16 m^3/s.

Figure 4.1e Time of concentration of tracer at Dudh Koshi River

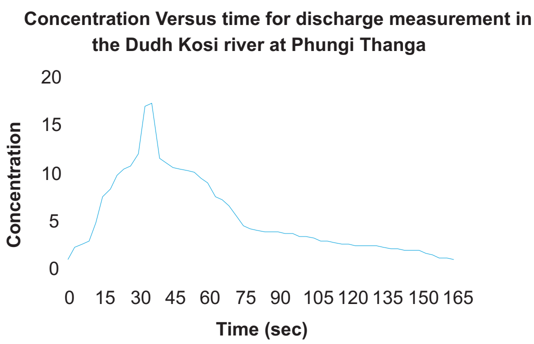


Figure 4.1f Tracer preparation for discharge measurement

Table 4.1a **Discharge measurement by tracer**

Parameter	Unit
Mass of tracer (M)	3.9 gm
Sum of all concentrations (C)	297.53 µg/l
Time interval (ΔT)	3 sec
Discharge (Q) = $\frac{M}{C \times \Delta T}$	4369.31 l/s Or 4.37 m^3/s

Table 4.1b **Snow measurement at Syangboche**

Parameter	Unit
Area of the tube (A)	13.203 cm^2
Mean height of snow depth (h)	16 cm
Mean weight of snow (W)	72.21gm
Snow density (D) = $\frac{W}{h \times A}$	0.342 gm/cm^3
Mean water equivalent (WE) =10 x h x D	54.72 mm

4.3 Snow measurement

In 2007, the heaviest snowfall was observed on 14th February, of about 1.5 m, at Syangboche (4050 masl), according to a local snow gauge reader. After 14th February 2007 there was no snow fall and most of the snow had melted. A maximum of only 60 cm of snow was observed in the area during the March field visit. North-east of Syangboche, behind the yak farm at altitudes of 3,950, 3,970 and 4,050 masl, a snow survey was carried out. The maximum depth of snow was found to be 60 cm at an altitude of 3,970 masl. Three snow pits were dug for snow measurement at different depths (47cm, 55cm and 42cm) at different altitudes. Each pit consisted of three different observation levels, as given in Appendix II. The grain size in the first pit was found to be very coarse; in the second pit as coarse, medium and very coarse; and in the third pit medium and very coarse, according to the International Hydrological Programme (IHP) classification. The moisture condition of the measured snow was wet in the upper portion and very wet and dripping in the bottom portion. The mean density of the three pits was calculated as 0.342 gm/cm^3 and water equivalent as 54.72 mm. During the second field visit (17 to 24 November 2007) snow was not found at the previous measuring sites. The summary of snow equivalent calculation is presented in Table 4.1b.

During the second field visit (17 to 24 November 2007) snow was not found at the previous measuring sites. The snow examination during field visits is presented in Figures 4.2a and 4.2b.

Figure 4.2a **Snow examination on the way to Phakdin**

Figure 4.2b **Snow depth measurement at Syangboche**

4.4 Local environment (field survey)

During both field visits, altogether sixty local people were interviewed. From the survey, it was found that the main source of drinking water for the local people and animals is the natural streams. The quality of water looks pure and safe. The interview-survey revealed that neither the people nor the animals had been affected by any kind of waterborne diseases. The local community from Lukla to Namche meets their water needs from small upstream sources, but there is scarcity in Syangboche. The main health problems faced were coughs and nasal conjestion. Some major animals found in the Sagarmatha National Park are musk deer, red panda and the Himalayan thar.

The main vegetables grown are cabbage, potato, radish, carrot and Chinese green vegetable. Rice is imported from villages further down the valley or directly from the capital, Kathmandu. Energy is the main problem in the area. Kerosene and cooking gas costs more than double the actual price. The majority of the population uses fodder and wood for cooking and for heating their houses. Due to a lack of energy sources, deforestation is becoming a problem in the area. As the local people rely on forest wood for cooking, the number of trees in the forest is decreasing. This might be a major threat causing soil erosion, landslides and other disasters in the area. However, the installation of a micro-hydro electricity plant in the region is a potentially good source of energy in the future.

4.5 Measurement of hydraulic parameters

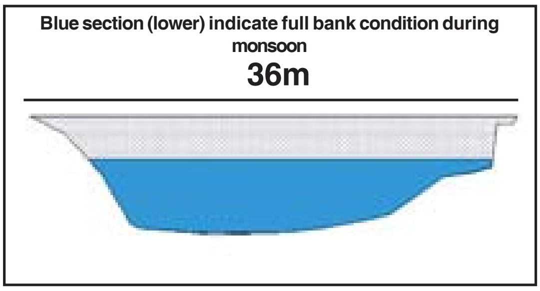
The hydraulic parameters of the Dudh Koshi River were measured at Dukdinma to study the future GLOF impact. A cross-section of the river up to the existing bridge height was measured to calculate floods. Some settlements in Phakdin are just above the bridge and are highly vulnerable to flooding. The cross-section of the river is shown in Table 4.2. The corresponding picture and cross-section are presented in Figures 4.2c and 4.2d respectively. The flow during the field visit (November 2007) was measured and Manning's roughness coefficient estimated.

Table 4.2 Cross-section measurement of Dudh Koshi at Dukdinma

Distance from bank (m)	Depth of bed right from bridge (m)
0	0
2.5	1.2
5	3.9
7.5	8.4
19	8.4
21.5	8.4
24.5	7.5
26.5	7.1
30.5	4.3
32.5	4
34	3.5
34.5	0.45
35	0.45
35.5	0.45
36	0

Figure 4.2c Cross-section measurement

Figure 4.2d Cross-section of Dukdinma River



The summary of hydraulic parameters measured and results calculated are presented in Table 4.3.

During the Dig Tsho GLOF the water level was observed up to the bridge level (Field Investigation 2007). The hydraulic parameters of the cross-section up to bridge level are presented in Table 4.4.

A lake burst during peak monsoon season could be more severe. The average monsoon high flow of the Dudh Koshi River is estimated as 660 m^3/s at Dukdinma (at the edge of Phakdin). The hydraulic parameters of the flow channel are presented in Table 4.5.

4.6 Vegetation

The Khumbu Region (Upper Dudh Koshi Basin) can generally be divided into three vegetation zones by altitude. The lower altitudinal belt (below 3,800 masl) consists of temperate forests and woodlands; the middle belt (3,800–4,200 masl) of sub-alpine forests and shrub land; and the upper belt (above 4,200 masl) of tundra vegetation (Byers 1987). Furthermore, there is a small area of lower mixed temperate forest between 2,800–3,200 masl. Forests of pine and hemlock are found in lower elevations up to 3,500 masl, and above that, forests of silver fir, birch, rhododendron and juniper trees are found (IUCN 1979).

Table 4.3 Hydraulic parameters and flow (Dudh Koshi at Dukdinma)

Hydraulic Parameter	Value
Flowing water area (A), m^2	15.4
River velocity (V), m/s	1.8
Measured discharge(Q), m^3/s	27.8
Wetted perimeter (P), m	15.2
Hydraulic radius (R), m	1.01
Estimated Manning's coefficient (n) (equation [vii])	0.09

Table 4.4 Hydraulic parameters and GLOF (Dudh Koshi at Dukdinma)

Hydraulic Parameter	Value
Flood water area (A), m^2	219
Wetted perimeter (P), m	44.30
Hydraulic radius(R), m	4.94
Manning's coefficient (n) (equation [vii])	0.09
Energy slope (S), m/m	0.029
Discharge (Q), m^3/s	1200

Table 4.5 Hydraulic parameters and flow from monsoon (Dudh Koshi at Dukdinma)

Hydraulic Parameter	Value
Flood water area (A), m^2	120
Wetted perimeter (P), m	44.3
Hydraulic radius(R), m	4.94
Manning's coefficient (n) (equation [vii])	0.09
Energy slope	0.029
Discharge (Q), m^3/s	660

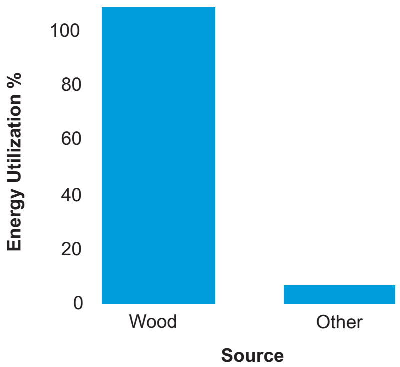
Chapter 5

RESULTS

5.1 Energy

The growing settlements in the Khumbu and the harsh topography have made local people reliant on forest wood for energy. The comparative prices of forest wood, kerosene and cooking gas in the Khumbu and in the capital, Kathmandu, are presented in Table 5.1. The rising price of energy may lead to a harsh life in the future. Under such circumstances, an alternative clean energy source would be fruitful for the local people. A micro-hydroelectricity plant is being developed in the area, but this will not be sufficient to provide enough energy for heating and lighting for houses. Energy utilization in the Khumbu Region is presented in Figure 5.1. Alternative energy sources feasible in the area are wind and solar energy. The wind and solar radiation given in Tables 2.4 and 2.6 would be useful in obtaining the wind and solar radiation potential. As the climate warms (IPCC 2001b), a decrease in the utilization of energy is anticipated.

Figure 5.1 **Energy utilization in the Khumbu Region**



5.2 Vegetables

Potato is the main food grown in the region, and few vegetables were grown in the past. During the field visit in November 2007, various vegetables were observed on the way from Lukla to Manjo. Vegetables such as carrots, coriander, Chinese palung saag, barela (Nepalese name), radish, onions, cauliflower, cabbage, Chinese salad, and white beans, etc. were seen growing in the local farms. Greenhouse tomato, chilli and cucumber farming was observed, which indicates the promotion of agriculture in the region. However, the growing of vegetables and fruit such as pumpkin and watermelon reflects the climate. Pumpkin and watermelon are generally found in warm temperate climates. The vegetables grown are shown in Figures 5.2a through 5.2f.

Table 5.1 **Energy source price rate**

Energy	Average Price (Lower Khumbu)	Kathmandu
Firewood	15 Rs/kg	*
Kerosene	100 Rs/litre	50 Rs/litre
Cooking gas	2700 Rs/14kg cylinder	1100 Rs/14kg cylinder

** unknown*
Source: Market prices 2007

Figure 5.2a Chinese salad at Ghat

Figure 5.2b Watermelon at Phakdin

Figure 5.2c Pumpkin at Phakdin

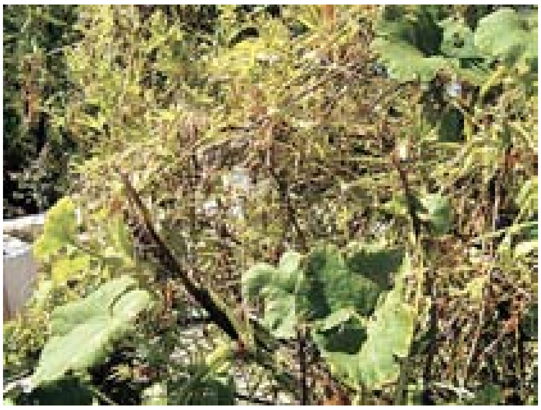


Figure 5.2d Chinese palung saag at Dukdinma

Figure 5.2e Onion near Thado Koshi

Figure 5.2f Greenhouse tomatoes at Ghat

5.3 River flow

The rapid snow and glacier melt has increased the flow rate across the Khumbu Region. According to local people, river flows are higher than in the past 10 years (Field Investigation 2007). In the future this flow rate will decrease as the snow bound area and number of glaciers reduces. However, some peak flows are expected due to increases in rainfall (Mirza 1997) over the Koshi Region. The flow hydrograph of the Imja River from USGS GeoSFM flow modeling (Figure 5.3) depicts fluctuations in flows with several low flows less than 1m^3/s. This model does not take into account the snow and glacier melt component. Whereas, observed flow at the same river site shows a minimum of 1 m^3/s (Table 2.8).

Figure 5.3a **Hydrograph from USGS GeoSFM model of Imja River (2003)**

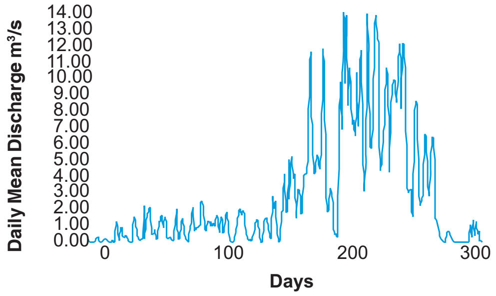
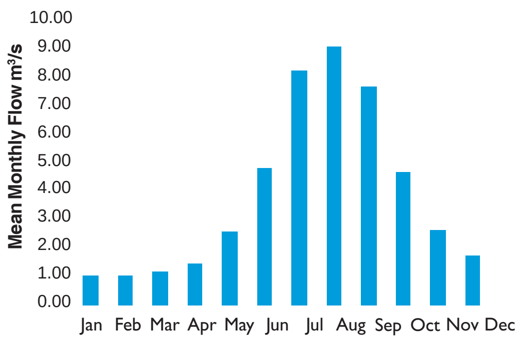


Figure 5.3b **Mean monthly flow of Imja River**



5.4 GLOF impact

Phakdin and Larja Dobhan lie about 25 and 32 km downstream from the outlet of Imja Lake. Phakdin is a highly vulnerable place as the settlements and hotels lie on the banks of the Dudh Koshi. The flood during the Dig Tsho Lake outburst was observed up to bridge level at Phakdin. Two suspension bridges and settlements at Phakdin are highly exposed to floods. The cross-section area of the Dudh Koshi at Dukdinma (at the edge of Phakdin) is shown in Figures 4.2c and 4.2d.

As the average flow velocity of the Dudh Koshi River near Phakdin is 1.8 m/s and flowing water cross-section area is 15.4 m^2, the flowing water discharge is 27.8 m^3/s (Table 4.3). Manning's roughness coefficient (n) is obtained by slope area method (equation [vii]) as 0.09 (Table 4.3).

$$n = \frac{AR^{2/3}S^{1/2}}{Q} \qquad \text{[vii]}$$

The flood up to bridge level using slope area method with n=0.09 is

$$Q = \frac{AR^{2/3}S^{1/2}}{n} \qquad \text{[viii]}$$

$$Q = \frac{219 \times 4.94^{2/3} 0.029^{1/2}}{0.09} = 1200 \text{ m}^3\text{/s}$$

The anticipated flood near Phakdin using the attenuation curve (Figure 3.3) is 1,230 m^3/s, which could overtop the bridge and most likely hit the nearby settlements. It could have downstream impact below the Khumbu Region as well. The downstream track from the outlet of Imja Lake is presented in Figure 5.4a. The vulnerable areas are presented in Figure 5.4b through 5.4d. A lake burst during peak monsoon season could be more severe. The average monsoon high flow of the Dudh Koshi River is estimated at 660 m^3/s as given in Table 4.5.

Figure 5.4a Downstream track from Imja Lake

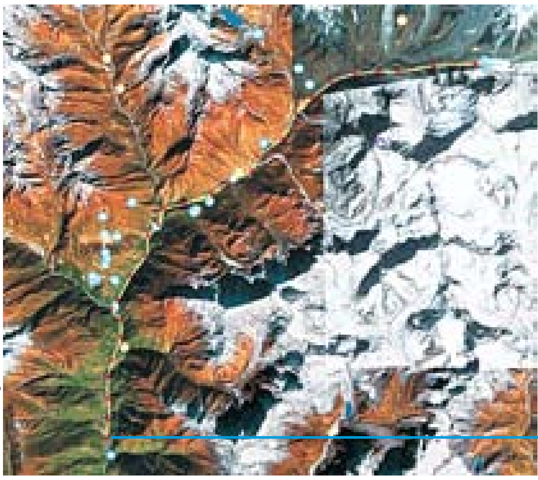


Figure 5.4b Vulnerable area at Dukdinma

Distance (D) = 32 km from Imja Lake outlet (Dukdinma)

Figure 5.4c Vulnerable area at Phakdin

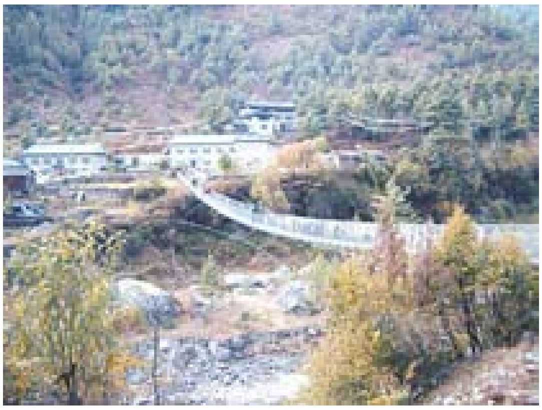
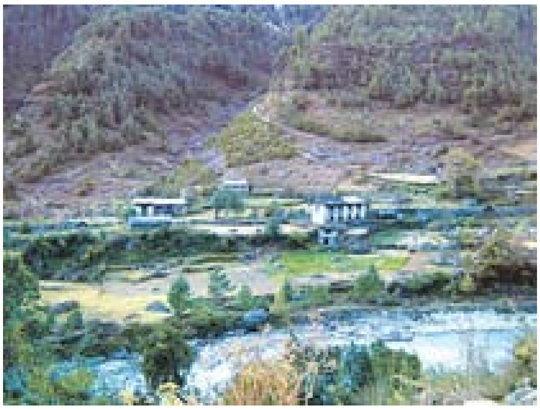


Figure 5.4d Vulnerable area at Dukdinma



5.5 Water quality

The water quality at upstream sources is clear and pure. However, growing settlements and direct sewage connections to the river down-stream may cause river pollution in the future. The waste water from the settlements disposed in the river was tested in the laboratory. As there are not many houses, a high degree of pollution is not found. Ammonia was detected in the small river at Lukla (Appendix IV), but it lies within the safe limits according to WHO guidelines (WHO 1998). Similarly, ammonia is found in the river at Namche, where waste is disposed, but it too falls within the safe limits of the WHO guidelines. Total coliform from waste water disposed in the river at Lukla and Namche sampling sites both exceeded 100 in number. But turbidity of more than 5 NTU was found, which exceeds the WHO guidelines. However, for local people, drinking water sources from upstream are still pure and clear (Appendix IV and V)). Coliform is seen in all Dudh Koshi river water samples. The sampling and analysis of river water are shown in Figures 5.5a and 5.5b respectively.

Figure 5.5a Collecting water sample at Lukla

Figure 5.5b Water sample testing in the laboratory

Figure 5.6a Landslide at Dukdinma

Figure 5.6b Flood exposed settlement at Dukdinma

5.6 Vulnerability

During the field visits, a calm environment was experienced in the Khumbu Region, but due to global warming, a high threat of glacier lake outburst in the future is anticipated. Some settlements are highly exposed to GLOF, but such settlements are still growing despite the threat of GLOF. Deforestation along with high rainfall may cause heavy floods, soil erosion and landslides. The landslide and flood exposed areas are presented in Figures 5.6a and 5.6b respectively. A reduction in snow and glacier melt area is anticipated in the future. Thus, during the non-rainy season, a reduction in drinking water supply from upstream sources is likely. Consequently, the limited flow from upstream will force people to rely on polluted downstream water in the future.

The main income of the local people is directly and indirectly related to tourism and a reduction in tourist flows due to environmental risks from climate change would significantly affect their livelihoods. In such circumstances old people, children and women will be the most vulnerable groups in the region.

5.7 Adaptation

Hydro-electricity, windmills, solar energy and bio-gas will be the main sources of energy in the future. Among them, hydro-electricity is perceived as the most effective in the area. There are no windmills in the region, but local people believe that it would be one of the alternatives (Field Investigation 2007). Roof-top rainwater harvesting could alleviate the shortage of water. The annual rainwater harvesting potential of the region is 400 l/m^2 in the upper part and 2,000 l/m^2 in the lower part of the region (Figure 2.1a-1). Some vegetables/fruits such as pumpkin and watermelon are seen in the lower part of the Khumbu Region (Chaurikharka to Monjo), which is a good sign for the local people. Proper land utilization for more agriculture is possible in the region and this would be one of the greatest advantages for the region in the future. As the greatest threat in the region is flooding, settlements should be kept away from the main riverbanks.

CONCLUSION

Both primary and secondary hydrological and meteorological data were analyzed for this study, and many important results obtained. The secondary data were collected from the DHM, scientific papers and from different organizations. Students and teachers from the Central Department of Hydrology and Meteorology, as well as from Tribhuvan University, were involved in the field visits. Field visits were conducted in March and November 2007 to collect the primary data. The study focused on integrated studies of hydrology and meteorology in the Khumbu Region related to climate change.

The topography of the Khumbu Region (Upper Dudh Koshi Basin) is very rugged and steep with its terrain cut by valleys, deep river gorges and glaciers, with three peaks higher than 8,000 meters above sea level (masl). The study area consists of scattered villages located in three VDCs, namely, Khumjung, Namche and Chaurikharka. The main ethnic group living in the Khumbu Region is the Sherpas.

February is the coldest month and July the warmest month in the region. The minimum air temperature drops below freezing for at least 9 months of the year at about 5,000 masl. Low rainfall is observed in the northern part and higher rainfall over the southern part of the Khumbu Region. The variation in monthly temperature is high over all meteorological stations. At the Pyramid Meteorological Station (5,050 masl), the wind speed is highest during January and lowest during November**.** A sudden drop in humidity over the region in October indicates the end of the rainy season, but the sudden rise in humidity in the month of May can be due to the sublimation of ice and snow, as solar radiation is highest during this month.

At elevations between 2,000-3,000 masl, the climate type **Cwb** is found (i.e., Tropical upland: mild winter; dry winter and short summer). Between elevations 3,000-4,000 masl, the climate type for the region is **Dwc** (i.e., Subarctic: severe winter; dry winter and short cool summer) and between elevations 4,000- 6,000 masl, the climate type is **ET** (i.e., Tundra: very short summer). Above 6,000 masl, the climate type is **EF** (i.e., perpetual ice, glaciers and snow). Taking into considering the IPCC's projected temperature rise, these climatic types will shift to higher altitudinal zones in the future.

The sharp rise in the flow duration curve (1999-2006) of the Dudh Koshi River indicates higher snow/glacier melt than in the previous years. Consequently, 33 to 89 moraine dammed lakes were created between 1960 and 2000 and the volume of existing lakes, such as Imja Lake, has also increased. At 50 per cent lake volume outburst, a peak discharge of 4,757 m^3/s is estimated for Imja Lake at its outlet. In case of lake outburst, the settlements of Phakdin, Dukdinma and Ghat are highly vulnerable.

During the second field visit (17 to 24 November 2007), less snow area was found in comparison to the first field visit (23 to 30 March 2007). The water level of the Dudh Koshi River was found to be 38 cm above the water level observed during the first field visit.

The main vegetables grown by the local people are cabbage, potato, radish, carrot and Chinese green vegetables. Rice is imported from villages situated at lower elevations downstream from the Khumbu and from Kathmandu. Energy is the main problem in the area because kerosene and cooking gas are carried or air-lifted to the Khumbu, hence they cost more than double the actual price. The majority of the population uses fodder and wood for cooking and to heat their houses. Due to a lack of alternative clean energy sources, deforestation is becoming a major problem in the area. This might be a major threat causing soil erosion, landslides, floods and other environmental disasters. However, the install-ation of micro-hydro plants in the region will provide a good alternative energy source in the future.

The main source of drinking water for the local people and animals is the natural streams. Local people do not use the main river water because they believe it is polluted by settlement waste. The field study found that neither the people nor the animals have been affected by waterborne diseases. The main health problems faced are coughs and nasal conjestion. However, ammonia was found in the water sample from the river at Namche and Lukla, because waste is deposited into the river at these places.The concentration of ammonia in the river falls within the safe limits set by the WHO guidelines. However, the turbidity value and bacteria content in the river exceeds the WHO guidelines. These observations indicate that local river pollution has just begun at Namche and Lukla.

Hydro-electricity is considered the most effective energy source in the area. There are no windmills in the region, but the local people believe that wind power would be one of the best sources of alternative energy.

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