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THREE DECADES
FOR MOUNTAINS AND PEOPLE

# Glacier Status in Nepal and Decadal Change from 1980 to 2010 Based on Landsat Data

NORWEGIAN MINISTRY
OF FOREIGN AFFAIRS

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# Contents

# Foreword

I am pleased to present this report on the status of glaciers in Nepal and the decadal change since 1980. The study represents a major advance on ICIMOD's first publication on the glaciers of Nepal in 2001 and complements the basin-wise description of basins in the Himalayan region published in 2011. Use of the remote sensing images that are now available has enabled the preparation of a comprehensive assessment of the status of Nepal's glaciers in 2010 and the changes since approximately 1980, 1990, 2000, and 2010. A small case study in the Langtang and Imja sub-basins provided a more detailed snapshot view of the changes in individual glaciers and small sub-basins and the possible parallels with changes in average temperatures over the past two decades.

The Himalayan region contains some of the most dynamic, fragile and complex mountain ranges in the world. These magnificent mountain ranges play an important role in global atmospheric circulation, the hydrological cycle, and water resources availability, provide a wide range of ecosystem services, and are a source of many hazards. Mountain areas are particularly vulnerable to climate change, and Nepal's Himalayan mountains are no exception. A number of noticeable impacts related to climate change have already been documented.

The high Himalayan region contains solid freshwater reserves in the form of snow and glaciers that benefit both the mountain people and the downstream riparian areas. However, these glaciers are showing signs of shrinking, thinning, and retreating. Among others, this is leading to the formation and expansion of glacial lakes, which could lead to an increase in the number of glacial lake outburst floods (GLOFs). If the present trends persist, the glacier ice mass will gradually be reduced, which will impact on the availability of water resources as well as glacial hazards. Climate and glacier changes cannot be generalized across the region, however; and the consequences of any change for glaciological hazards and water resources are complex and thus difficult to predict. The general trend appears to be one of glacial retreat, as in many mountain areas in the world, but observations of individual glaciers indicate that the annual retreat rates vary from basin to basin. In some cases the rate has doubled in recent years compared to the early seventies. Notwithstanding the importance of the cryosphere, there is a lack of data on the snow and glacial resources of these mountains, and especially of the long-term information on glaciers required for a credible scientific assessment. Glacier inventories have been compiled for some parts of the region using different approaches, but there has been no comprehensive coordinated assessment. A long term consistent glacier database is needed to support assessments of glacier status across the region and understanding of climate change impacts on glaciers, as well as for climate and hydrological monitoring.

ICIMOD has been working with partner institutes in the region to build a regional database of HKH glaciers since the late 1990s, and prepared an inventory of the status of glaciers in the major river basins of the Hindu Kush Himalayan region in 2011. The data will be very useful as a basis for modelling studies of future water availability. For Nepal, however, it is important for future planning to have detailed information on the glaciers within the country boundary. This publication aims to meet this need, with a detailed account of glacier status in 2010 and changes over the past thirty years. The decadal glacier trends will help in understanding the scenario for future water availability and glacial hazards.

We particularly thank the Royal Norwegian Embassy, Kathmandu for its financial support for the HKH Cryosphere Monitoring Project and the inspiration provided during this work, as well as HIMALA and SERVIR Himalaya of NASA and USAID who provided additional support. We are especially pleased that the project has enabled us to further strengthen our collaboration and cooperation with national partners. I would like to express my thanks and appreciation to the ICIMOD colleagues and national partners for their efforts in undertaking this comprehensive and painstaking study. I am confident that the information contained in this publication and presewnted on ICIMOD's online Mountian GeoPortal will be a useful resource for the country, as well as for scientists worldwide studying the processes, potential impact, and implications of climate change.

**David Molden**
Director General
ICIMOD

# Foreword

The Department of Hydrology and Meteorology (DHM) of Nepal initiated organized hydrological and meteorological activities in 1962. Since then, it has installed meteorological stations across the country for continuous monitoring of temperature and precipitation, including in the higher mountain regions. DHM has also been working in glaciology for many years, with a recent focus on the monitoring and mitigation of glacial lakes, and collaborating with and supported by ICIMOD and other agencies.

Glaciers have been thinning and retreating in many parts of the world. Changes in glaciers provide some of the clearest evidence for climate change, and glacier shrinkage, and in some cases disappearance, indicates the speed of the present change on a global scale. These changes have implications locally and regionally for water resources, and globally for sea level rise. The associated increase in regional and local hazards is also increasing risk for communities. In view of this, extensive efforts have been made internationally to improve our understanding of the ongoing changes in glaciers and the pattern of global warming, as well as projecting future scenarios using global and regional climate models.

In Nepal, detailed study and monitoring of glaciers started after a catastrophic glacial lake outburst flood (GLOF) event in 1985. DHM collaborated closely with ICIMOD in the preparation of the first inventory of glaciers, glacial lakes, and glacial lake outburst floods in Nepal, published in 2001, and the two organizations have continued to work together closely since then in the field of glaciology. DHM was pleased to provide technical and advisory support for the preparation of the present updated inventory, which provides an overview of the current status of Nepal's glaciers as well as the changes over the preceding decades based on an analysis of satellite images. The datasets will provide an important basis to the scientific community in formulating further research needs.

We thank ICIMOD for the opportunity to work on and contribute to this publication, and I sincerely thank the many DHM colleagues for their generous support and involvement during the preparation. We are confident that our collaboration will continue to strengthen following this project.

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We thank Mr Pradeep Mool of ICIMOD for his encouragement to undertake the crucial task of investigating the status and decadal change of the glaciers in the Nepal Himalayas, and Mr Basanta Shrestha, and Dr Manchiraju Sri Ramachandra Murthy for their indispensable support in undertaking the project.

We also wish to express our gratitude to all the officials and staff members who helped contributed to the Cryosphere Monitoring Project supported by the Norwegian Ministry of Foreign Affairs. The present study was partially supported by the HIMALA project of the United States Agency for International Development (USAID)/Office of US Foreign Disaster Assistance (OFDA), and the National Aeronautics and Space Administration (NASA) and SERVIR-Himalaya initiative of USAID and NASA. Landsat data were provided courtesy of NASA and the United States Geological Survey (USGS). The Shuttle Radar Topography Mission (SRTM) elevation model version was provided courtesy of NASA's Jet Propulsion Laboratory and further processed by the Consultative Group for International Agriculture Research (CGIAR).

Last but not least we wish to take this opportunity to express our gratitude to our immediate colleagues in the Geospatial Solutions, MENRIS, and Cryosphere Initiative groups for their support, strength, and cooperation which played an essential role in the successful completion of this work.

# Acronyms and Abbreviations

| | |
|---|---|
| ASTER | Advanced Spaceborne Thermal Emission and Reflection Radiometer |
| CGIAR | Consultative Group for International Agricultural Research |
| CI | clean-ice |
| CV | coefficient of variation |
| DC | debris cover |
| DEM | digital elevation model |
| DHM | Department of Hydrology and Meteorology |
| ELA | equilibrium line altitude |
| ENVI | environment for visualizing images |
| ERTS | Earth Resources Technology Satellite |
| ETM | enhanced thematic mapper |
| FCC | false colour composite |
| GEN | Japanese Glaciological Expedition to Nepal |
| GIS | geographic information system |
| GLIMS | Global Land Ice Measurements from Space |
| GLOF | glacial lake outburst flood |
| HKH | Hindu Kush Himalayas |
| ICIMOD | International Centre for Integrated Mountain Development |
| ID | identity |
| IDL | interactive data language |
| IPCC | Intergovernmental Panel for Climate Change |
| Landsat | land resources satellite |
| LIGG | Lanzhou Institute of Glaciology and Geocryology |
| LWM | land and water mask |
| masl | metres above sea level |
| MSS | multi spectral scanner (Landsat) |
| NASA | National Aeronautics and Space Administration |
| NDSI | normalized difference snow index |
| NDVI | normalized difference vegetative index |
| NEA | Nepal Electricity Authority |
| OBIC | object based image classification |
| OFDA | Office of U.S. Foreign Disaster Assistance |
| RGB | red green blue |
| RMSE | root mean square error |
| SD | standard deviation |
| SLC | scan line corrector |
| SPOT | Système Probatoire d'Observation de la Terre /Satellite Pour l'Observation de la Terre |
| SRTM | Shuttle Radar Topography Mission |
| TM | thematic mapper (Landsat) |
| TTS | Temporary Technical Secretary |
| US | United States |
| USAID | United States Agency for International Development |
| USGS | United States Geological Survey |
| UTM | universal transverse mercator |
| WECS | Water and Energy Commission Secretariat |
| WGI | World Glacier Inventory |
| WGMS | World Glacier Monitoring Service |
| WGS | World Geographic System |
| WMO | World Meteorological Organization |

# Executive Summary

This report provides a comprehensive account of the status of glaciers of Nepal in approximately 1980, 1990, 2000, and 2010 based on a semi-automatic standardized analysis of satellite images with post-processing database management in ArcGIS. The methodology is an improved version of methods developed by global initiatives like the World Glacier Monitoring Service (WGMS), Global Land Ice Measurement from Space (GLIMS), and GlobGlacier. The customized methodology of semi-automatic glacier mapping provides a rapid delivery of glacier attributes. The semi-automatically derived glacier outlines from 2010 were overlain separately on the images used to approximate 1980, 1990, and 2000, and the glacier outlines were modified manually for the respective years and used for change analysis. Clean-ice and debris-covered glaciers were mapped separately for 2010 to support studies of water resources assessment and climate change impact. In an additional case study, glacier outlines for the four decades in the Langtang sub-basin in central Nepal and Imja sub-basin in eastern Nepal were analysed and compared with decadal temperature change.

The inventory is a much-needed follow up to the inventory of glaciers and glacial lakes in Nepal published in 2001, which used a variety of data sources with considerable temporal differences, including Indian Survey topographic maps (1962–1975), aerial photos (1957–1959), and field survey findings, and must thus be considered essentially as indicative. The present single country inventory complements the survey published in 2011 of glaciers in the individual river basins of the Hindu Kush Himalayan region, which was based on data from a single source (Landsat images) with a short temporal range (2005±3 years) and also analysed semi-automatically.

The inventory for Nepal was supplemented by a case study in Langtang valley in central Nepal and Imja valley in eastern Nepal showing the changes over 30 years in individual glaciers. The changes were compared with the changes in temperature recorded at nearby hydrometeorological stations; the loss of glacier area was paralleled by a steady increase in average annual temperature, and especially average minimum temperature. Changes in rainfall patterns over 20 years were also analysed.

The results provide information on the change in glacial extent over the past decade and quantitative data to support discussion of climate change impacts in the Nepal Himalayas. The major findings were as follows:

In 2010, a total of 3,808 glaciers were identified with a total area of 3,902 km$^2$ and estimated ice reserves of 312 km$^3$. The average area of individual glaciers was 1 km$^2$. The Ngojumba glacier in the Dudh Koshi sub-basin was the largest single glacier with an area of 79 km$^2$.

About 90% of the glacier area lay between 4,500 and 6,500 masl; with 65% between 5,000 and 6,000 masl.

The contribution of estimated ice reserves is higher for a large glacier than for the same cumulative area from a number of smaller ones. Thus the estimated ice reserves were higher in basins with larger glaciers and larger glaciers are the most important reserves of freshwater.

The total glacier area decreased by 24% between 1977 and 2010, and the estimated ice reserves by 29% (129 km$^3$). The number of glaciers increased by 11%, a result of fragmentation following shrinkage. The lowest losses of glacier area (and in some cases gains) were observed from glaciers with a north or northwest aspect (of which there were very few) and slopes of less than 20°. Mountain basin type and valley glaciers also showed a lower proportional loss of area.

The glaciers receded on average by 38 km$^2$ per year.

The rate of loss of glacial area between ~1980 and 1990 was almost twice that in the subsequent two decades (1990–2000 and 2000–2010). Further study is needed to determine whether this reflects a slowing in the rate of change or an anomalous situation in the first period.

The average annual mean temperature in the Langtang and Imja (Khumbu) sub-basins rose at an average rate of 0.12°C/year and 0.09°C/year, respectively, between 1988 and 2008. Moving average analysis showed that the rate of increase in average mean minimum temperature was significant and higher than the increase in average mean maximum temperature.

# 1 Introduction

Glaciers are natural renewable solid reserves of freshwater. They are sensitive to changes in temperature and considered to be one of the best indicators of climate variation. Glacier meltwater contributes to river flow, and in the central and eastern part of the Himalayan region people living downstream benefit especially from glacier meltwater during the pre-monsoon dry season. Overall, the meltwater from snow and glaciers contributes about 10% of the annual stream flow in Nepal (DHM 2008).

Mountain areas are particularly vulnerable to climate change, and the Nepal Himalayas are no exception. The average annual temperature in the Nepal Himalayas between 1971 and 1994 increased by between 0.15 and 0.6°C per decade (Shrestha et al. 1999), which is two to eight times higher than the global mean warming of 0.74°C over the last 100 years (IPCC 2001a, b). Warming can affect the glacier distribution and seasonal snow cover spatially and temporally both by increasing the melting rate and by reducing snowfall in favour of rain. The lack of appropriate glacier data in Nepal has prevented a comprehensive assessment of current glacier mass balance and of any change. In recent years, however, people in the high mountain regions of Nepal have noticed that the snow line is receding and that glacial lakes are growing at the termini as glaciers retreat (Fushimi et al. 1985). These changes are thought to result from global climate change, and in particular rising temperatures.

Globally, 11 of the 12 years from 1995–2006 ranked among the 12 warmest years in the instrumental record of global surface temperature since 1850. The temperature increase is widespread over the globe and is greater at higher northern latitudes (IPCC 2007). The third assessment report of the Intergovernmental Panel for Climate Change (IPCC 2001b) indicated a projected warming in the Asian region of 3.0°C by 2100. These changes cannot be generalized across the region, and the implications for glaciological hazard events and changes in water resources are difficult to predict (ICIMOD 2011). However, the changes could have large effects on Himalayan glaciers with the retreat of the glaciated areas and an increase in the area of glacial lakes. The annual retreat rates that have been observed vary from basin to basin; in some cases the rate has doubled in recent years compared to the early seventies (Bajracharya et al. 2007). Glacier retreat can lead to variations in river runoff, with an initial increase in discharge as a result of the higher rate of melting, followed by a decrease as the ice mass is depleted. It can also lead to the formation and expansion of glacial lakes with increased risks of glacial lake outburst floods (GLOF).

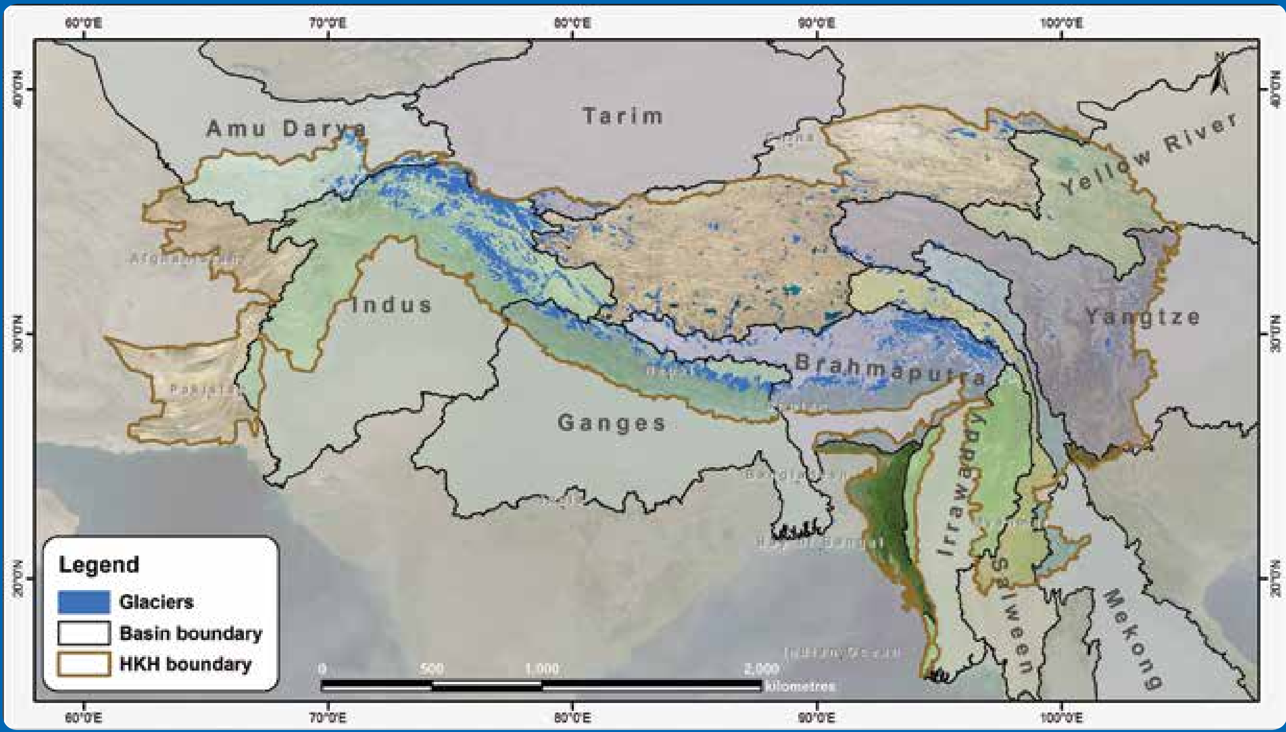
A study on the rate of glacier retreat in the major mountain systems of the world showed that the glaciers in the Himalayan region were retreating at a rate of 0.3 to 1 m per year, the highest among all regions (Dyurgerov and Meier 2005). In order to understand these changes and project future scenarios, it is necessary to know the present status of glaciers and have an indication of the extent and rate of ongoing change. This report describes an assessment of the status and recent rates of change of the glaciers in Nepal.

## Glacier Inventories of the Hindu Kush Himalayan Region

The Hindu Kush Himalayan region (HKH) has the largest concentration of snow and glaciers outside the polar regions (Kulkarni 1991, 1994). Notwithstanding this, there is a marked lack of information and data on the snow and glacial resources of these mountains, and especially of the long-term data required for scientific assessment, with only sporadic reports before 2000. A first attempt was made by ICIMOD and its partner institutions to map the glaciers of Nepal, Bhutan, Pakistan, some selected basins in India, and the Ganges basin in China between 1999 and 2004 (Mool et al. 2001a, 2001b; ICIMOD 2005). A new report released in December 2011 by ICIMOD offered the first consistent and comprehensive account of the glacier coverage of the entire Hindu Kush Himalayan (HKH) region based on the river basins (Figure 1.1) (Bajracharya and Shrestha 2011). Although Nepal's glaciers were included in the inventory, they were not collated on a country basis.

The 2011 inventory was based on analysis of Landsat satellite images from 2005±3 years. It identified 54,252 glaciers in the HKH region with a total area of 60,054 km$^2$ and estimated ice reserves of 6,127 km$^3$ (Table 1.1); 1.4% of the total area of the HKH region was found to be glaciated. Significant glaciated areas were identified in the Indus, Ganges, Brahmaputra, and Tibetan Interior basins; one-third of the total was mapped in the Indus basin

Figure 1.1: **Distribution of glaciers in the major river basins of the Hindu Kush Himalayan (HKH) region**




Source: Bajracharya and Shrestha 2011

(Figure 1.2). Very few glaciers were mapped from the Irrawaddy, Mekong, and Yellow River basins. About 62% of the glaciated area was at an elevation 5,000–6,000 masl (Figure 1.3).

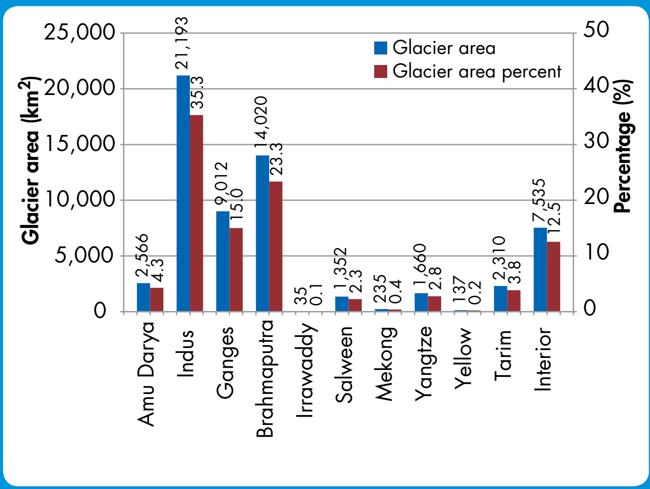
The 2011 report and database represented a significant first step in filling the information gap on the glaciers of the HKH region. The database is expected to support regional level assessments and the development of strategies and policies in the context of climate change. It will also contribute to increased understanding of the impacts of climate change on glaciers and the implications for mountain ecosystems and water availability downstream.

Table 1.1: **Glaciers and glaciated area in the major basins of the Hindu Kush Himalayan region**

| Basins | Glacier number | Glacier area (km$^2$) | Estimated ice reserves (km$^3$) | Average area per glacier (km$^2$) |
|---|---|---|---|---|
| Amu Darya | 3,277 | 2,566 | 162.6 | 0.78 |
| Indus | 18,495 | 21,193 | 2,696.1 | 1.15 |
| Ganges | 7,963 | 9,012 | 793.5 | 1.13 |
| Brahmaputra | 11,497 | 14,020 | 1,302.6 | 1.22 |
| Irrawaddy | 133 | 35 | 1.3 | 0.27 |
| Salween | 2,113 | 1,352 | 87.7 | 0.64 |
| Mekong | 482 | 235 | 10.7 | 0.49 |
| Yangtze | 1,661 | 1,660 | 121.4 | 1.00 |
| Yellow | 189 | 137 | 9.2 | 0.73 |
| Tarim Interior | 1,091 | 2,310 | 378.6 | 2.12 |
| Qinghai-Tibetan Interior | 7,351 | 7,535 | 563.1 | 1.02 |
| **Total** | **54,252** | **60,054** | **6,126.9** | **1.11** |

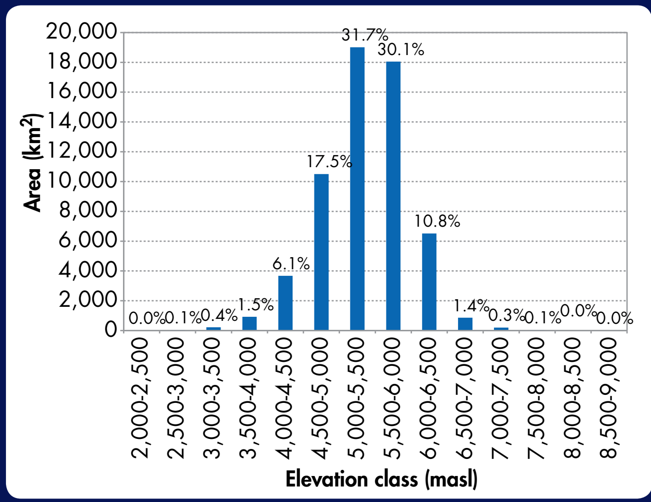
Source: Bajracharya and Shrestha 2011

Figure 1.2: **Glacier area and percentage in the major river basins of the Hindu Kush Himalayan region**




Source: Bajracharya and Shrestha 2011

Figure 1.3: **Distribution of glaciated area with elevation in the Hindu Kush Himalayan region**

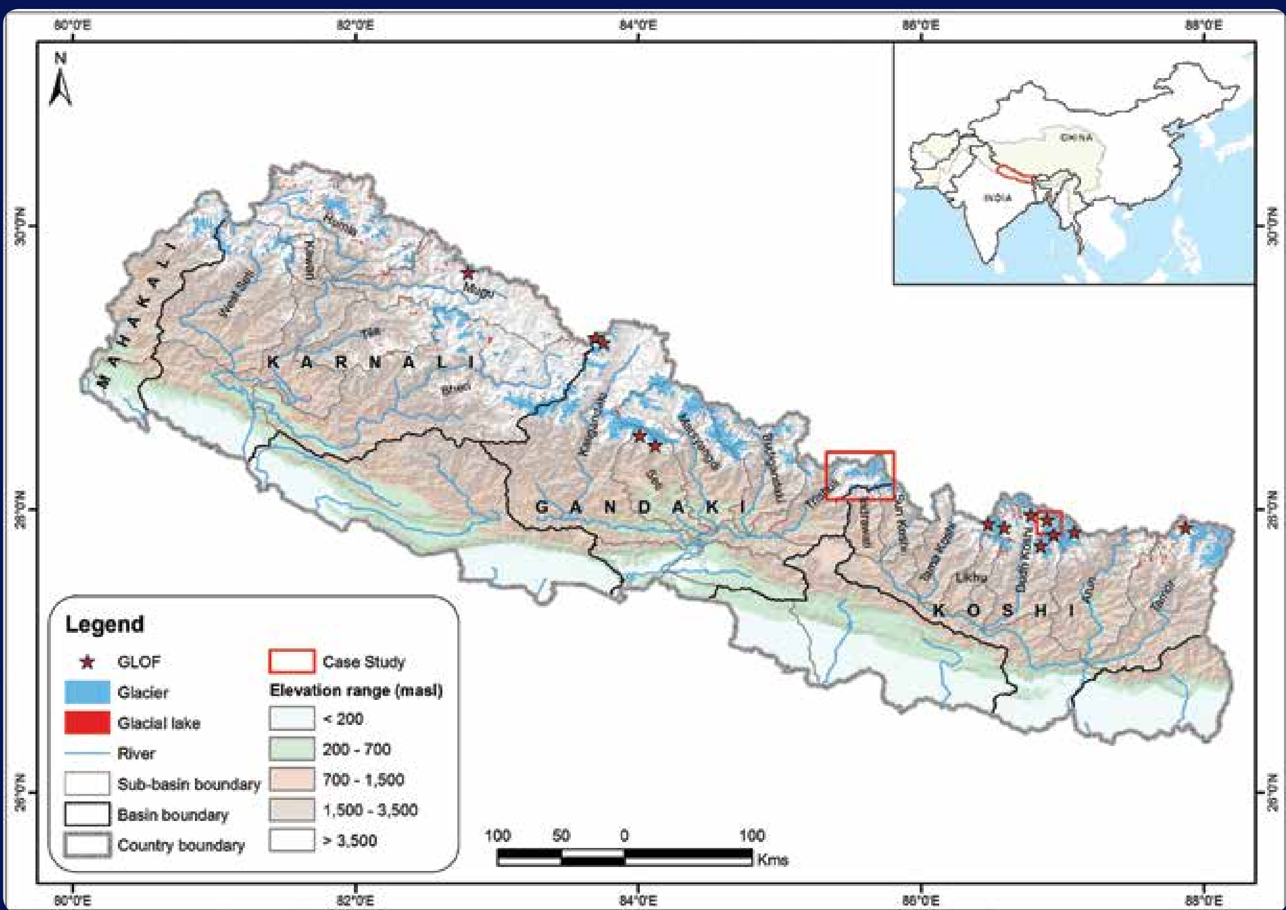



Source: Bajracharya and Shrestha 2011

## Nepal

Nepal is a predominantly mountainous country, lying between 26°12′ and 30°27′ N and 80°04′ and 88°12′ E in the central Himalayas (Figure 1.4). The country extends for 840 km from east to west and between 90 and 230 km (average 180 km) from north to south, with a total area of 147,181 km². The altitudinal variation is extreme, from 64 masl in the southeast to 8,848 masl in the northeast, the greatest land-based relief in the world. Approximately 83% of the total land area consists of mountains and high hills, with the remainder comprising the foothills and Terai

Figure 1.4: **Glaciers, glacial lakes, and glacial lake outburst floods (GLOFs) in Nepal**




Modified from ICIMOD 2011

plains to the south. The country is vulnerable to numerous hazards as a result of the fragile geological conditions, great elevation differences and steeply sloping terrain, soft soil cover, steep river gradients, and poor vegetation cover, combined with frequent earthquakes and high intensity seasonal rainfall. Monsoon rainfall commonly triggers a variety of slope movements, many of which cause extensive damage to life and property.

## Glaciers and Glacial Lakes in Nepal

Nepal was first opened to foreign scientists in 1950. The first glaciologist to visit Nepal was Fritz Müller, a participant in the Swiss Everest Expedition of 1956. In the following years, the number of scientific expeditions gradually increased, but there are still no glaciers under long-term observation in the country, although individual studies have been made of the AX010, Khumbu, Mera, Yala, Lirung, and Rikha Samba glaciers. The Nagoya and Kyoto Universities of Japan organized the first systematic investigation of Nepal's glaciers in the form of the Glaciological Expedition of Nepal (GEN), led by Higuchi, which carried out a series of field studies (Higuchi 1976, 1977, 1978, and 1980). The first detailed study of the AX010 glacier was conducted in 1978/79 (Ageta et al. 1980; Ageta and Kadota 1992). Yala Glacier has been studied since the 1980s, and Rikha Samba Glacier has been surveyed intermittently since 1974 (Nakawo et al. 1976; Fugii et al. 1996; Fujita et al. 1997). The AX010 has the densest observations in terms of glacier extent, mass balance, and ice flow (Fujita et al. 2001).

The first inventory of glaciers and glacial lakes in Nepal was published by ICIMOD in 2001. It was based on 1 inch to 1 mile (1:63,360 ) and 1:50,000 blueprint topographic maps published by the Survey of India from 1963 to 1982, satellite images from 1999 and 2000, aerial photos taken from 1957 to 1959 for areas for which no topographic maps were available, and supplementary field work (Mool et al. 2001a). The study identified 3,252 glaciers with a total area of 5,324 km$^2$, almost 3.6% of the land area of Nepal. The inventory provided a first overview of the glaciers in the country, but the data were based on a wide temporal range and derived from different sources, and the values should be considered as indicative only. The 2001 inventory also mapped all lakes at elevations higher than 3,500 masl and classified them as erosion, valley trough, blocked, cirque, supra-glacial, or moraine dammed lakes. A total of 2,323 lakes were identified with an area of 75 km$^2$. A new inventory of glacial lakes was published by ICIMOD in 2011 based on an analysis of Landsat satellite images from 2005/6; 1,466 lakes were identified with a total area of 65 km$^2$ (ICIMOD 2011).

Several glacial lake outburst flood (GLOF) events have been documented in the Hindu Kush Himalayan region in recent years; these have sometimes caused loss of life and property and the destruction of valuable forest and pasture resources, farmland, and costly mountain infrastructure. Some GLOFs are reported to have created long-term secondary environmental degradation, with both physical and socioeconomic impacts locally and in neighbouring downstream countries (Ives 1986). In Nepal, at least 24 GLOF events have been identified to date, of which ten took place in the Tibet Autonomous Region of China but had an impact in Nepal (Bajracharya et al. 2007; Ives et al. 2010; ICIMOD 2011). On average, one GLOF event is recorded every three to ten years in the Himalayan region.

## River Basins and Sub-basins in Nepal

The glaciated area in Nepal contains the upper reaches of four major river basins with 19 sub-basins, all of which are part of the Ganges basin system: the Mahakali, Karnali, Gandaki, and Koshi (Figure 1.4). The glacier-fed river basins have a total area of 89,457 km$^2$, or about 61% of the total land area of Nepal. All of the river basins have one or more sub-basins with transboundary sections. The mapping processes were limited to the sections within Nepal and the data refer only to the Nepal area of the basins.

### Mahakali basin

The Mahakali River basin lies in the far western region of Nepal between longitudes 80°22′ and 80°52′ E and latitudes 28°32′ and 30°10′ N (Figure 1.4). The river runs along the border between Nepal and India and only about a third of the catchment area of this comparatively small basin lies in Nepal; hence it is not divided further into sub-basins in this report.

## Karnali basin

The Karnali River basin is the largest river basin in Nepal and lies in the western and far northwestern regions between longitudes 83°30′ and 81°00′ E and latitudes 30°24′ and 28°48′ N (Figure 1.4). It has six sub-basins – the West Seti, Kawari, Humla, Mugu, Tila and Bheri – of which the Humla Karnali originates in Tibet Autonomous Region (TAR) of China and the remainder originate in Nepal. The major part of the Mugu Karnali flows from east to west, and the Humla Karnali from west to east, unlike most rivers in Nepal, which generally flow from north to south. In the lower reaches in India, the Karnali River is called the Ghaghara.

## Gandaki basin

The Gandaki River basin lies in central Nepal between longitudes 82°55′ and 85°50′ E and latitudes 29°15′ and 28°05′ N (Figure 1.4). It has seven major sub-basins, five of which originate in glaciated areas – the Kali Gandaki, Seti, Marsyangdi, and Budhi Gandaki, all of which originate in Nepal, and the Trishuli, which originates in TAR/China. The river is also known as the Sapta Gandaki and, in the lower reaches, the Narayani.

## Koshi basin

The Koshi River basin lies in eastern Nepal between longitudes 85°30′ and 88°12′ E and latitudes 26°50′ and 28°15′ N, and is the smallest of the three main basins (Figure 1.4). It has seven major sub-basins – the Indrawati, Sun Koshi, Tama Koshi, Likhu, Dudh Koshi, Arun, and Tamor. The Arun, Tama Koshi, and Sun Koshi rivers originate in TAR/China; the remaining rivers originate within Nepal.

# About This Report

The study described here was designed to develop a comprehensive inventory of the glaciers of Nepal in 2010, to compare the results with the status in approximately 1980, 1990, and 2000, and to use these results to describe the trends. The inventory was prepared using semi-automatic standardized analysis of Landsat satellite images. A detailed case study was also made of the change over time of selected glaciers in the Langtang and Imja valleys. The results were compared with the patterns of change identified from meteorological data from two local hydromet stations.

The methodology used, country and basin-wise results, and case study results are presented in the following chapters. The detailed data will be made available in an online database.

# 2 Methodology – Data Collection and Glacier Mapping

## Introduction

Ideally, field-based mapping is required to gain precise information about a glacier, such as extent, depth, total mass, and mass balance. However, this is extremely challenging, labour intensive, and time consuming, and not possible for more than a handful of glaciers. The rugged terrain, extremely high altitude, harsh climatic conditions, lack of logistical support, and remoteness of the high Himalayan region mean that in most places field studies are impossible and where they have been carried out, they focus on a few lower altitude and more accessible glaciers. However, in recent years, the increased availability of satellite data in combination with advanced remote sensing tools and techniques have significantly facilitated mapping and monitoring of glaciers in these otherwise inaccessible regions, and this methodology was used to prepare the current inventory. The inventory used a combination of automated and manual interpretation of satellite images, complemented by limited field studies. The methodology is described in the following sections.

## Data Collection and Preparation

### Satellite images

Satellite data were first used to map glaciers in the early 1970s, making use of the US Earth Resources Technology Satellite (ERTS), later named Landsat-1. Since then, several studies on glacier mapping have used data from a steadily improving series of satellites launched by the world's space agencies, including the Landsat Multispectral Scanner (MSS), one of the first satellites used for glacier mapping by the United States Geological Survey (USGS), ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) used by GLIMS (Global Land Ice Measurements from Space) and GlobGlacier, and SPOT (Système Probatoire d'Observation de la Terre/Satellite Pour l'Observation de la Terre), also used by GlobGlacier.

The inventory and decadal glacier change analysis described here used Landsat 5-MSS, Landsat 7, and Landsat 7-ETM+ images, which are freely downloadable. Thirteen Landsat ETM images, including full and partial scenes, cover Nepal. Among these, nine scenes cover the northern part with all of the country's glaciers. To document the recent status of glaciers, it is ideally necessary to acquire low snow and cloud-free images; however, the freely downloadable images rarely meet the ideal requirements for glacier mapping and images must be selected within a number of years rather than a single year. Decadal analysis was carried out to determine glacier status and change in approximately 1980, 1990, 2000, and 2010. Landsat 5-MSS images from 1976 to 1979 were used to approximate 1980 (hereafter referred to as ~1980); Landsat 7TM images from 1988 to 1992 for 1990; Landsat 7-ETM+ from 1999 to 2001 for 2000, and Landsat 7-ETM+ from 2009 to 2011 for 2010. In each case, the images with the least snow cover and no cloud cover were selected. The images used in the study are listed in Annex 1.

The Landsat 7-ETM+ images from June 2003 onwards have a scan line dropout. The Landsat 7-ETM+ scan line corrector (SLC) failure causes the scanning pattern to exhibit wedge-shaped scan-to-scan gaps. These SLC failed images are referred to as SLC-off images. The scan gaps vary from one pixel or less near the centre of the images to fourteen pixels along the east and west edges. Approximately 22% of the normal scene areas in SLC-off images are missing; however, the remaining spectral information maintains the same radiometric and geometric quality as images prior to the failure (Storey et al. 2005).

Various techniques are available for correcting and filling the gaps in the SLC-off images. The present study used the IDL extension in ENVI (Environment for Visualizing Images) software to fill the SLC gap. The correction is based on combining overlapping areas between preceding and subsequent imagery in those areas that show a gap. This is generally considered to be the best method.

### Digital elevation model

Topographic information such as elevation and slope play a crucial role in the identification of glaciers. This information is derived from a digital elevation model (DEM). A DEM was also used to derive crucial glacier parameters such as hypsometry, minimum/maximum/median elevation, aspect, slope, and other factors related to elevation. The study used the SRTM (Shuttle Radar Topography Mission) DEM version 4.1 from CGIAR at a spatial resolution of 90 m.

The Universal Transverse Mercator (UTM) WGS 84 projection system was used for glacier mapping because the base satellite imagery (Landsat) was provided in this projection. In the UTM WGS 84 projection system, the Nepal Himalayas fall into Zone 44N to 45N. Glacier area was analysed using this projection system.

### Climate data

Monthly and yearly air temperature data from 1988 to 2008 were obtained from the Nepal Department of Hydrology and Meteorology (DHM) for Kyanjing station (3,920 masl) in the Langtang valley and Dingboche station (4,355 masl) in the Imja valley of the Khumbu region. There are some data gaps. For the study, these were partially filled using automatic and semi-automatic weather station data; the remaining data gaps were filled by interpolating and extrapolating from the average linear trend and data patterns of the available data. The maximum, minimum, and mean annual and seasonal temperatures for Kyanjing and Dingboche were generated for a period of 21 years. The data were classified into annual, pre-monsoon (March to May), monsoon (June to September), post-monsoon (October and November), and winter (December to February). The annual, seasonal, and decadal temperature change was analysed and compared with the changes in glacier area over the different time intervals.

## Glacier Mapping and Volume Estimation

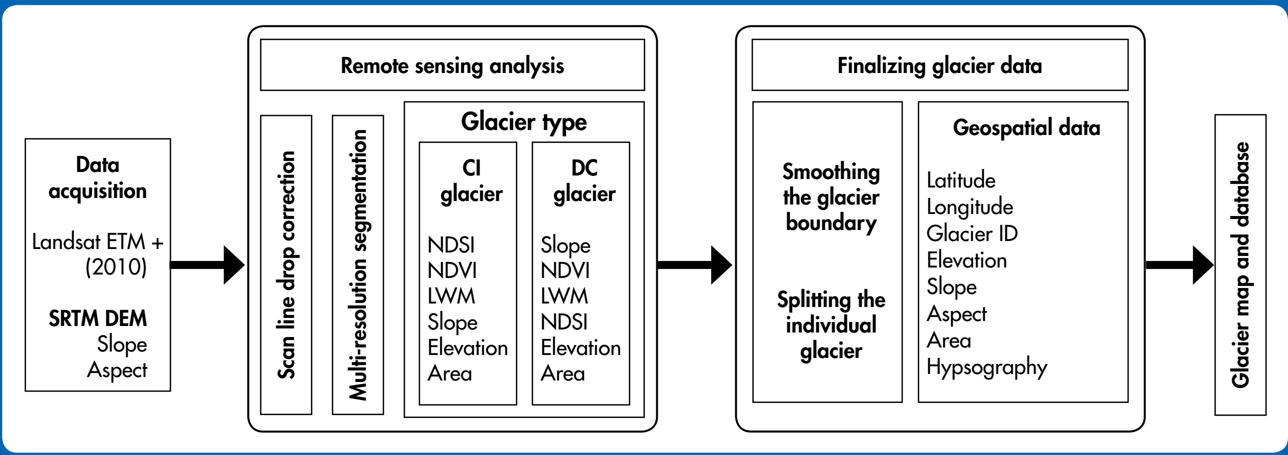
### Semi-automatic glacier mapping

Methods have been developed for the automatic delineation of glaciers in satellite images but they are only valid for clean-ice glaciers (Frey and Paul 2012; Bolch et al. 2008, 2010; Bhambri and Bolch 2009; Paul and Andreassen 2009; Racoviteanu et al. 2009; Paul and Kaab 2005; Paul 2002), whereas in most parts of the HKH, debris-covered glaciers, or debris-covered tongues, predominate. While automatic methods have been developed to map debris-covered glaciers, they always produce errors, which in the best cases require manual correction. Mapping without intensive human involvement is not yet technically feasible. Manual mapping of glaciers using satellite imagery, complemented by limited ground-based measurements for verification, is a reasonable approach but extremely labour intensive. The current inventory used semi-automatic mapping – a combination of manual and automatic methods (Bajracharya et al. 2014).

Semi-automatic glacier mapping is able to rapidly deliver glacier data consistent with established international inventory standards. In the approach used here, the glacier outlines were delineated using an object-based image classification (OBIC) approach. After the SLC-off correction, the image was segmented in Definiens Developer software using multi-resolution segmentation. This is a heuristic optimization procedure to locally minimize the average heterogeneity of image objects at a given resolution. Different algorithms were used to differentiate clean-ice (CI) and debris-covered (DC) glaciers based on their spectral characteristics. The multi-stage classification process is summarized in Figure 2.1. A detailed description is provided in Bajracharya and Shrestha (2011) and Bajracharya et al. (2014).

In order to identify the decadal changes from ~1980 to 2010, a base map of glacier outlines was established for 2010 using semi-automatic mapping. The glacier outlines for the other years (2000, 1990, and ~1980) were then generated by manual modification using overlays of the satellite images from the respective years.

Figure 2.1: **Methodology used for mapping clean-ice and debris-covered glaciers using satellite images**




Modified from Bajracharya and Shrestha 2011

## Estimation of glacier volume

Detailed field measurements are required to determine the volume of glaciers. When these are not available the volume must be estimated. Various approaches have been used for estimation, including the volume-area (V-A) relationship (e.g., Chen and Ohmura 1990; Bahr et al. 1997), slope-dependent ice-thickness estimation (Haeberli and Hoelzle 1995), and more recently a variety of spatially distributed ice-thickness models (e.g., Clarke et al. 2009; Farinotti et al. 2009; Huss and Farinotti 2012; Li et al. 2012; Paul and Linsbauer 2012). All these methods have been used to estimate glacier volume in the Himalayas and Karakoram (Frey et al. 2014), but the results are slightly different and it is not clear which method is the most reliable. The area-thickness relationship has been used by a number of organizations to estimate the volume of glaciers in the Hindu Kush Himalayan region, including the Lanzhou Institute of Glaciology and Geocryology (LIGG) (LIGG/WECS/NEA 1988); the International Centre for Integrated Mountain Development (ICIMOD) (Bajracharya and Shrestha 2011; Mool et al. 2001a, b); the Indian Space Research Organization (ISRO) (Kulkarni et al. 2007, 2014a,b), and recently by Frey et al. (2014). Therefore, glacier area-thickness relationship was chosen in this study to estimate the volume of ice reserves.

The relationship between glacier area (*F*) and mean ice thickness (*H*) was estimated using the empirical formula

$$H = -11.32 + 53.21\, F^{0.3}$$

The ice reserves were then estimated from the mean ice thickness multiplied by the glacier area.

## Glacier attributes

A variety of different attributes were identified for individual glaciers in addition to area and estimated ice reserves. They included the location, elevation, aspect, mean slope, morphological classification, and morphological type (Muller et al. 1977). The allocation of attributes is described in detail in Bajracharya and Shrestha (2011) and summarized briefly in the following pages.

The clean-ice (CI) and debris-covered (DC) components of glaciers were analysed in the 2010 images using semi-automatic delineation with 'eCognition Developer'. Generally CI glaciers have steeper slopes than DC glaciers and slope was used as one distinctive feature to help differentiate DC parts of glaciers from non-glacier rock. Many glaciers have both a higher elevation CI component and a lower elevation DC component. For the purposes of differentiation of attributes like number, area, elevation, and other features, CI and DC components were counted separately. But in the overall counts of glacier number, they were counted as one. Thus, the sum of CI and DC glacier numbers was generally higher than the total number of glaciers. This additional analysis was not performed for the earlier time periods.

The areas of individual glaciers were derived from the mapping process as described above. The glaciers were only mapped if their area was larger than 0.02 km². For the analysis, glaciers were grouped into six size classes: class 1a ≤ 0.10 km²; class 1b = 0.11 to 0.50 km²; class 2 = 0.51 to 1.00 km²; class 3 = 1.01 to 5.00 km², class 4 = 5.01 to 10.00 km², and class 5 ≥ 10.01 km².

The highest and lowest elevations were derived from the DEM for each glacier elevation and had an uncertainty of ±30–60 m depending on the pixel resolution of the DEM; the mean elevation was calculated as the averaged value of all the glacier pixels in the digital elevation model (DEM) measured in metres above sea level (masl). The calculations were carried out for CI and DC components separately. The lowest elevations (elevation of the terminus) of all mountain and all valley glaciers were also averaged separately in each individual sub-basin to facilitate analysis of overall relative recession in future inventories, since the recession of glaciers at the lowest elevation depends on the glacier type.

The latitude and longitude were derived from the central coordinates of each glacier polygon. The centroid of the glacier polygon was generated automatically. If the central point was in a rocky outcrop, the points were shifted manually to the nearest point inside the glacier polygon.

The mean aspect was derived from the DEM as the average value of all cells covered by the glacier and transformed to the eight cardinal directions as described in Bajracharya and Shrestha (2011). Glacier recession does not take place evenly around the boundaries, thus the aspect of a glacier may change as the position of its boundaries change.

The mean slope was also derived from the DEM as the average value of all cells covered by the glacier and was divided into seven classes at intervals of 10°; it was also calculated for CI and DC components separately. The mean slope is an important proxy for other parameters like mean thickness and also relates to other dynamic measures, with glaciers on steep slopes generally being more unstable. The mean slope of a glacier can also change as the glacier boundaries change.

The glaciers were classified morphologically using the World Glacier Monitoring Service classification (WGMS 1989) as described in Bajracharya and Shrestha (2011). Generally six types of glacier were observed, valley trough type and five types of mountain glacier (ice apron, cirque, niche, basin, and miscellaneous). The classes are not unique and different analysts might choose a different type, but the classification does provide a good overall indication of the type of glaciers in a basin. Again, the classification type can change as a glacier recedes and the boundaries change. Briefly, mountain glaciers commonly have a hanging profile and the major source of nourishment is snow and/or drift snow. They are characterized by steep mountain slopes and small alpine niche basins and are mostly CI type. Valley glaciers have a regular longitudinal profile from head to terminus with steeper (CI) slopes on the upper levels and less steep (DC) slopes in the lower parts. The part of the valley glacier at the head has the characteristics of a mountain glacier, but due to its continuation the whole ice mass is counted as a valley glacier. These glaciers are mainly nourished by snow and drift snow in the upper part and snow and ice avalanches in the lower part. A large accumulation area is normally needed for the glacier to extend far into the valley, thus the average area of valley glaciers is usually higher than that of mountain glaciers, the elevation differences are high, and the area and ice reserves are large.

## Accuracy rating

Images were selected that had the least snow cover and almost no cloud cover to ensure the accuracy of the glacier outlines. The glacier outlines were edited at a scale of 1:25,000, which is suitable for visualization, and published at a scale of 1:50,000.

There is an uncertainty in the glacier area associated with the accuracy with which the glacier margins are delineated, which depends on the image resolution, snow cover, and contrast between the glacier and the adjacent terrain. To minimize the uncertainty, images with the least snow cover were used and the semi-automatically delineated (OBIC derived) glacier polygons were refined by manual editing, further modified by comparing with higher resolution Google images, and finally cross-checked by a single person. The MSS images have a resolution of 79 m and the TM and ETM+ images, a resolution of 30 m. There are several suitable MSS images available for glacier terminus mapping (Vohra 2010), but with more snow coverage than those of the TM and ETM+ images, which also contributes to some uncertainty in the values.

The boundary delineation is affected by various types of obscurity. A maximum offset of the boundary of not more than half of the image resolution (i.e., ±15 m in TM and ETM+ and ±40 m in MSS) was assigned to each type of obscurity. The uncertainties in the glacier area were estimated from the difference between the glacier area determined from the glacier polygon (which depends on the projection parameters) and the area calculated from the pixel base (which depends on the image resolution).

The total uncertainty (error) in the glacier area was calculated as

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (a_i - \hat{a}_i)^2}{n}}$$

Where, $a_i$= area of glacier from glacier polygon, and $\hat{a}_i$= area of glacier calculated on the basis of pixels.

The uncertainties of the glacier area in the present study were calculated to be 2.6, 1.3, 1.6 and 1.6% for the ~1980, 1990, 2000, and 2010 values, respectively. This uncertainty is lower than previous estimates of about 3% (Andreassen et al. 2008; Bajracharya et al. 2014; Frey and Paul 2012; Bolch et al. 2010).

# 3 The Status of Glaciers in Nepal in 2010

## Status of Glaciers in Nepal

The results of the analysis of the Landsat satellite images for 2010 are summarized in Table 3.1. The table shows the area, elevation, and estimated ice reserves of Nepal's glaciers (clean-ice and debris-covered) in 2010. The geographic distribution of the glaciers is shown in Figure 3.1. A total of 3,808 glaciers were identified with an area of 3,902 km². The Ngojumba glacier in the Dudh Koshi sub-basin was the largest glacier with an area of 78.7 km².

### Number, area, and estimated ice reserves

The glacier number, area, and estimated ice reserves in the 19 sub-basins are shown graphically in Figure 3.2; the values for the sub-basins and basins overall are given in Table 3.1. The total number of glaciers was highest in the Karnali and Gandaki basins, whereas the area and ice reserves were highest in the Gandaki and Koshi basins. The number of glaciers in the sub-basins was variable. The Kali Gandaki sub-basin had the most with 504, whereas the Kawari, Tila, Seti, Sun Koshi, Tama Koshi, and Likhu sub-basins all had fewer than 100 glaciers. The estimated volume of ice reserves depends on the glacier area not the number. The average area of individual glaciers was less than 1 km² in the Mahakali and Karnali basins, greater than 1 km² in the Gandaki and Koshi basins, and just over 1 km² overall. The greatest ice reserves were contributed by the Tamor, Dudh Koshi, Marsyangdi, Budhi Gandaki, and Kali Gandaki sub-basins in the Koshi and Gandaki basins.

Figure 3.1: **Distribution of glaciers in Nepal in 2010**

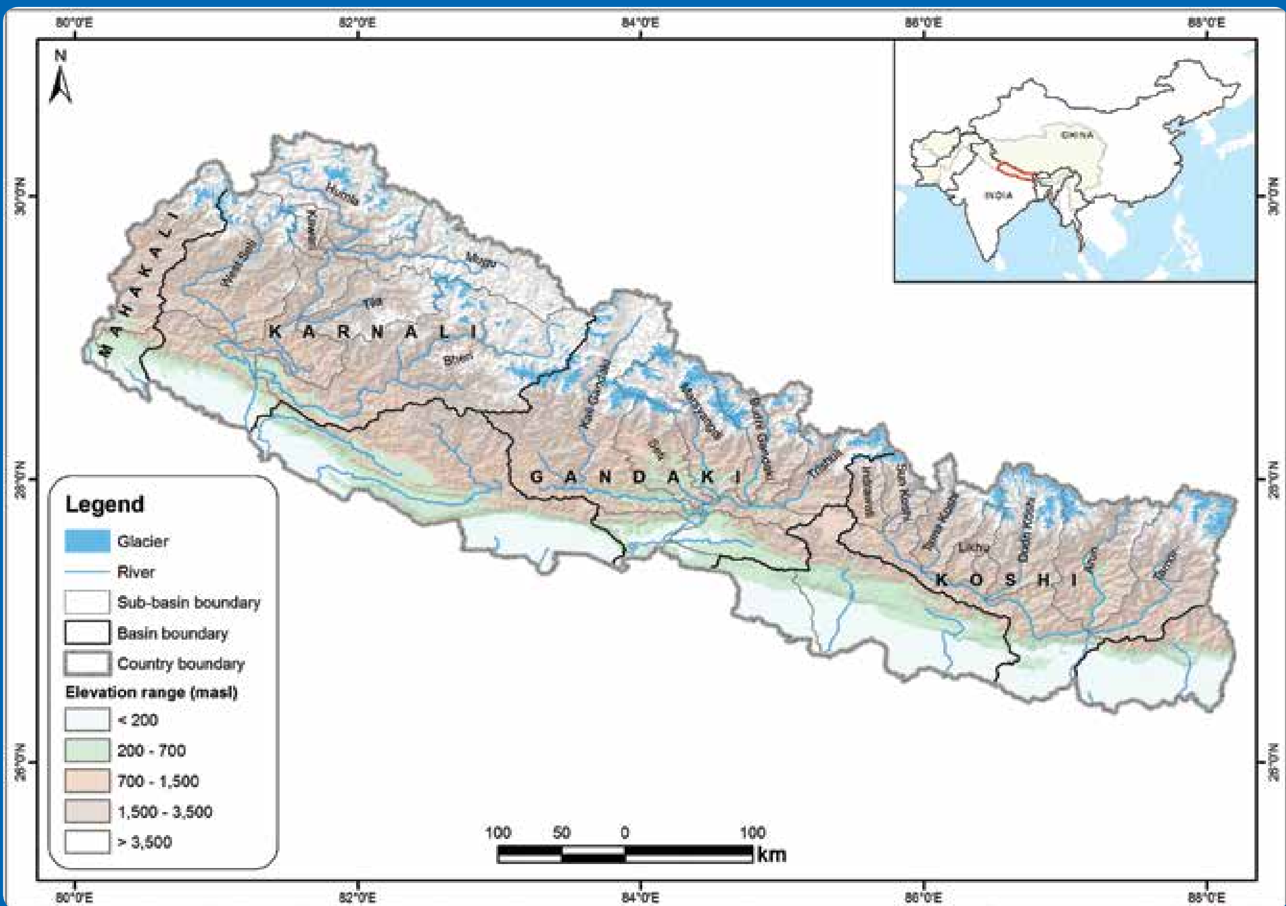


Table 3.1: **Summary of glaciers in the sub-basins of Nepal based on the satellite images of 2010**

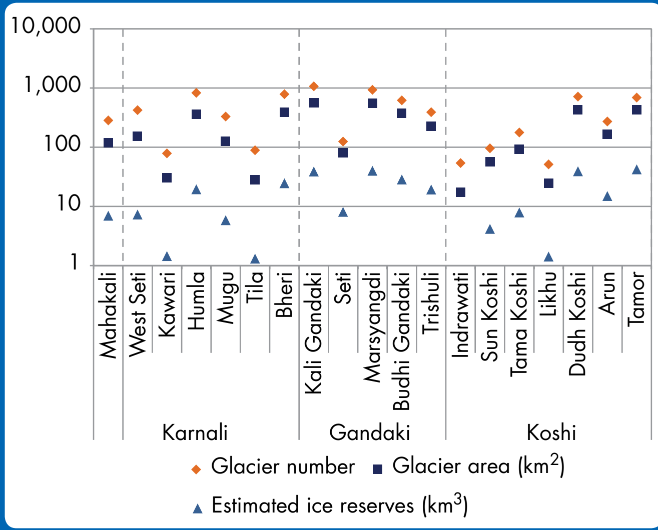
| Basin | Sub-basin (glaciated) | | Glacier number | | | Glacier area (km²) | | | | | Lowest latitude | Estimated ice reserves | Elevation (masl) | | | | | | Mean slope (deg) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Name | Area (km²) | CI | DC | Total | CI | DC | Total | Largest | Average | (degree) | (km³) | CI | | DC | | Average terminus | | CI | DC |
| | | | | | | | | | | | | | Min | Max | Min | Max | Mountain | Valley | | |
| Mahakali | Mahakali * | 5,022 | 164 | 14 | 164 | 92.6 | 19.9 | 112.5 | 11.1 | 0.69 | 29.829 | 6.97 | 4,031 | 6,850 | 3,695 | 5,299 | 5,063 | 4,077 | 35 | 13 |
| Karnali | West Seti | 7,378 | 270 | 14 | 270 | 127.9 | 18.1 | 146.0 | 12.9 | 0.54 | 29.658 | 7.28 | 4,387 | 6,982 | 4,132 | 5,329 | 5,105 | 4,484 | 30 | 12 |
| | Kawari | 822 | 48 | 1 | 48 | 26.0 | 3.2 | 29.2 | 7.0 | 0.61 | 29.677 | 1.45 | 3,874 | 6,834 | 3,631 | 4,015 | 4,974 | 3,631 | 24 | 6 |
| | Humla* | 5,983 | 474 | 33 | 474 | 309.5 | 28.4 | 337.9 | 14.3 | 0.71 | 29.679 | 19.48 | 4,340 | 6,939 | 4,271 | 5,596 | 5,182 | 4,670 | 24 | 12 |
| | Mugu | 5,374 | 203 | 16 | 205 | 99.9 | 19.3 | 119.2 | 7.6 | 0.58 | 29.108 | 5.84 | 4,650 | 6,837 | 4,507 | 5,536 | 5,300 | 4,588 | 28 | 12 |
| | Tila | 3,329 | 61 | 1 | 61 | 24.4 | 2.4 | 26.8 | 7.4 | 0.44 | 29.187 | 1.31 | 4,444 | 6,309 | 4,124 | 4,710 | 5,118 | 4,124 | 34 | 10 |
| | Bheri | 13,688 | 401 | 10 | 401 | 349.1 | 14.7 | 363.8 | 23.4 | 0.91 | 28.665 | 24.66 | 4,374 | 7,541 | 4,133 | 5,402 | 5,328 | 4,735 | 30 | 10 |
| | Sub-total | 36,575 | 1,457 | 75 | 1,459 | 936.8 | 86.1 | 1,022.8 | 23.4 | 0.70 | 28.665 | 60.04 | 3,874 | 7,541 | 3,631 | 5,596 | 5,168 | 4,372 | 28 | 10 |
| Gandaki | Kali Gandaki* | 11,862 | 504 | 16 | 504 | 512.8 | 14.6 | 527.4 | 27.0 | 1.05 | 28.477 | 38.90 | 4,187 | 8,101 | 3,846 | 5,705 | 5,640 | 4,304 | 29 | 16 |
| | Seti | 2,947 | 45 | 3 | 45 | 67.6 | 4.0 | 71.6 | 43.6 | 1.59 | 28.466 | 8.09 | 4,432 | 7,504 | 3,894 | 5,086 | 5,380 | - | 37 | 18 |
| | Marsyangdi | 4,787 | 384 | 22 | 384 | 475.3 | 33.7 | 509.0 | 28.6 | 1.32 | 28.340 | 39.97 | 4,034 | 7,761 | 3,651 | 5,653 | 5,408 | 4,481 | 30 | 11 |
| | Budhi Gandaki* | 3,642 | 243 | 17 | 242 | 313.7 | 35.3 | 348.9 | 32.2 | 1.44 | 28.266 | 28.53 | 3,753 | 8,019 | 3,282 | 5,422 | 5,187 | 4,154 | 34 | 12 |
| | Trishuli* | 2,912 | 164 | 13 | 165 | 172.1 | 35.4 | 207.6 | 50.2 | 1.26 | 28.107 | 19.26 | 3,978 | 7,184 | 3,650 | 5,520 | 5,305 | 4,377 | 33 | 12 |
| | Sub-total | 26,149 | 1,340 | 71 | 1,340 | 1,541.5 | 123.0 | 1,664.5 | 50.2 | 1.24 | 28.107 | 134.75 | 3,753 | 8,101 | 3,282 | 5,705 | 5,384 | 4,329 | 33 | 14 |
| Koshi | Indrawati | 1,229 | 37 | 0 | 37 | 16.4 | 0 | 16.4 | 4.3 | 0.44 | 28.102 | 0.73 | 4,843 | 5,911 | - | - | 5,112 | - | 23 | - |
| | Sun Koshi * | 1,437 | 39 | 6 | 39 | 48.2 | 4.3 | 52.6 | 13.9 | 1.35 | 28.046 | 4.16 | 4,136 | 6,940 | 4,047 | 5,134 | 5,164 | 4,200 | 32 | 15 |
| | Tama Koshi* | 2,716 | 85 | 8 | 85 | 71.7 | 12.7 | 84.4 | 32.2 | 0.99 | 27.776 | 7.89 | 4,455 | 6,648 | 4,363 | 5,627 | 5,222 | 4,594 | 30 | 14 |
| | Likhu | 1,051 | 27 | 5 | 27 | 20.0 | 3.0 | 23.0 | 8.9 | 0.85 | 27.707 | 1.42 | 4,576 | 6,698 | 4,357 | 5,219 | 5,157 | 4,840 | 24 | 18 |
| | Dudh Koshi | 4,065 | 286 | 43 | 287 | 281.1 | 110.0 | 391.1 | 78.7 | 1.36 | 27.638 | 39.20 | 4,390 | 8,209 | 4,367 | 5,753 | 5,410 | 4,860 | 31 | 12 |
| | Arun * | 5,156 | 108 | 5 | 108 | 133.7 | 15.4 | 149.2 | 43.3 | 1.38 | 27.651 | 14.98 | 4,470 | 7,851 | 4,200 | 5,851 | 5,328 | 4,585 | 29 | 11 |
| | Tamor | 6,056 | 262 | 29 | 262 | 314.7 | 71.2 | 385.9 | 73.1 | 1.47 | 27.528 | 42.26 | 4,633 | 8,401 | 4,161 | 5,988 | 5,466 | 4,766 | 27 | 14 |
| | Sub-total | 21,711 | 844 | 96 | 845 | 885.9 | 216.7 | 1,102.6 | 78.7 | 1.30 | 27.528 | 110.64 | 4,136 | 8,401 | 4,047 | 5,988 | 5,265 | 4,641 | 28 | 14 |
| **Nepal** | | **89,457** | **3,805** | **256** | **3,808** | **3,456.8** | **445.7** | **3,902.4** | **78.7** | **1.02** | **27.528** | **312.40** | **3,753** | **8,401** | **3,282** | **5,988** | **5,220** | **4,355** | **31** | **13** |

* Area within Nepal

## Glacier area classes

The number, area, and estimated ice reserves in each size class are summarized in Table 3.2. Close to half of the glaciers (1,739) were in class 1b, and one-fifth (781) in class 1a. However, the class 1a and class 1b glaciers contributed only 1% and 11% of the total area, respectively, and together less than 4% of the ice reserves, whereas the 62 class 5 glaciers contributed more than one-third of the total glacier area and more than half of the ice reserves. The largest glacier was the Ngojumba glacier in the Dudh Koshi sub-basin with an area of 78.7 km$^2$.

Figure 3.2: **Glacier number, area, and estimated ice reserves in Nepal in 2010**




## Glacier elevation

The maximum glacier elevation was 8,400 masl, below the elevation of the highest peaks (Mount Everest and others) because the slopes at the top of these mountains are very steep and virtually ice free. Furthermore, the glacier mapping threshold value was 0.02 km$^2$, thus any small ice patches close to the peak would not have been identified. Although the glaciers don't start at the peak, the peaks do contribute snow to the accumulation areas below in the form of wind-blown snow and snow avalanches.

The maximum glacier elevation increased from west to east (Figure 3.3). The Koshi basin had the highest glaciers overall and the Mahakali basin the lowest. Figure 3.4 shows the maximum and minimum glacier elevations in the sub-basins. The Indrawati sub-basin had the smallest range of glacier elevation; there were not many glaciers in this basin and they were all small mountain type. The greatest range of elevation was found in the Tamor and Dudh Koshi sub-basins in the Koshi basin, and the Budhi Gandaki, Kali Gandaki, and Marsyangdi sub-basins in the Gandaki basin. This geographical pattern reflects the existence of a greater number of valley glaciers in central and eastern Nepal than in western Nepal.

## Latitude and longitude

The range of latitude and longitude in the glaciers in the four basins is shown in Figure 3.5. Nepal extends along the Himalayan range with glaciers in all areas from west to east. This pattern is reflected in the greater range of longitude than of latitude among the glaciers. The decreasing latitude from west to east reflects the northwest to southeast line of the Himalayan range, and of Nepal itself.

Table 3.2: **Glacier area classes (2010)**

| Class | Area | Glacier number | | Glacier area | | Estimated ice reserves | | Mean area per glacier |
|---|---|---|---|---|---|---|---|---|
| | (km$^2$) | Number | % | km$^2$ | % | km$^3$ | % | km$^2$ |
| 1a | ≤ 0.10 | 781 | 20.5 | 50.3 | 1.3 | 0.6 | 0.2 | 0.06 |
| 1b | 0.11–0.50 | 1,739 | 45.7 | 431.4 | 11.1 | 10.8 | 3.5 | 0.25 |
| 2 | 0.51–1.00 | 556 | 14.6 | 394.2 | 10.1 | 14.6 | 4.7 | 0.71 |
| 3 | 1.01–5.00 | 606 | 15.9 | 1,234.1 | 31.6 | 70.7 | 22.6 | 2.04 |
| 4 | 5.01–10.00 | 64 | 1.7 | 444.3 | 11.4 | 37.5 | 12 | 6.94 |
| 5 | ≥ 10.01 | 62 | 1.6 | 1,348.1 | 34.5 | 178.2 | 57 | 21.74 |
| | **Total** | **3,808** | **100** | **3,902** | **100** | **312.4** | **100** | **1.02** |

Figure 3.3: **Elevation range of clean-ice and debris-covered glaciers in the major basins (2010)**

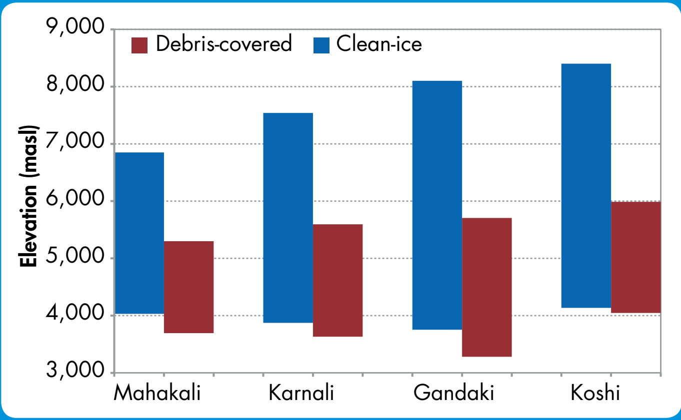



Figure 3.4: **Elevation range of glaciers in the sub-basins (2010)**

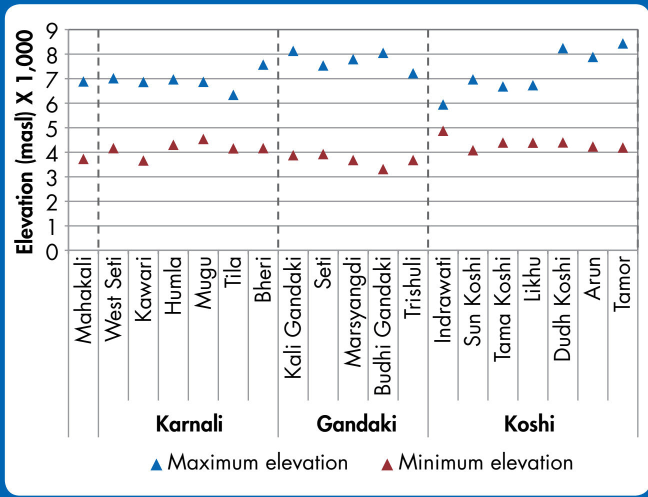
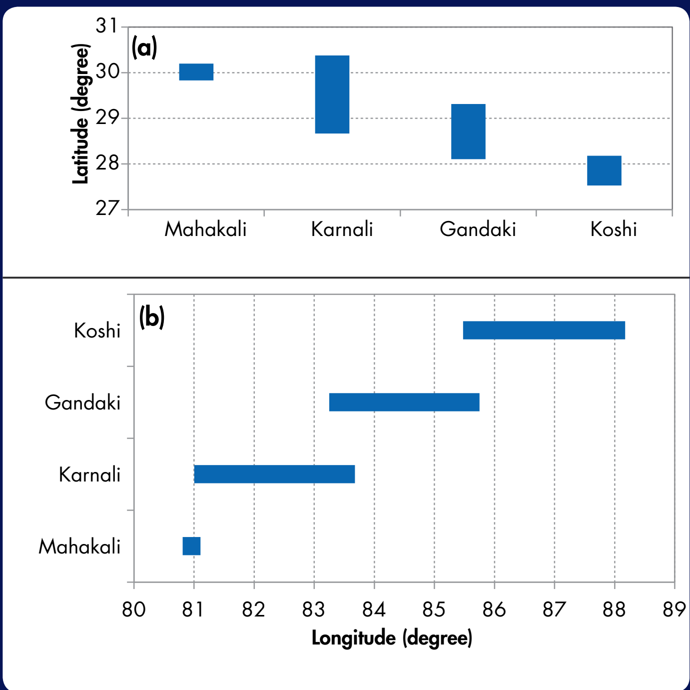



Figure 3.5: **Maximum and minimum latitude (a) and longitude (b) of glaciers in individual basins (2010)**




## Aspect

Nepal extends along the southern flank of the Himalayan range; thus the rivers that originate from the southern slopes of the mountains generally flow from north to south, while the majority of glaciers in the headwater regions have southwest to southeast aspects. The number, area, and estimated ice reserves of glaciers with different aspects is summarized in Table 3.3, and the percentage with different aspects and the proportion of these in different mean slope classes is shown in the rose diagram in Figure 3.6. Glaciers with a southwest aspect predominated in number, but those with a south aspect contributed the greatest area. Only 14 glaciers, less than 0.5%, had a north aspect (1, 8, 2, and 3 in the Mahakali, Karnali, Gandaki, and Koshi basins, respectively), and they were all very small, with a total area of only 1.7 $km^2$, or 0.12 $km^2$ per glacier on average

## Slope

The mean slope of the glaciers ranged from less than 10° to more than 60° (Figure 3.6 and Table 3.4), with slopes of 20–30° the most common in terms of both number and area. There were more glaciers with slopes of 30–40° than slopes of 10–20°, but the total area of glaciers with slopes of 10–20° was greater, indicating that the steeper glaciers were smaller on average than less steep glaciers. Mean slopes less than 10° and more than 60° were rare.

## Morphological type

The morphological classification of the glaciers is summarized in Table 3.5. Almost all the glaciers (97%) were mountain type (ice apron, cirque, niche, and basin), of which two-thirds were mountain basin type and a quarter ice apron type. Mountain basin glaciers were the largest of the mountain type glaciers with an average area of 0.9 $km^2$,

Table 3.3: **Glacier aspect (2010)**

| Aspect | N | NE | E | SE | S | SW | W | NW | Total |
|---|---|---|---|---|---|---|---|---|---|
| Number | 14 | 255 | 590 | 634 | 717 | 773 | 561 | 264 | 3,808 |
| Area (km²) | 1.7 | 89.1 | 466.6 | 754.6 | 1,078.7 | 991.3 | 412.6 | 107.8 | 3,902 |
| Estimated ice reserves (km³) | 0.03 | 3.1 | 30. 9 | 58.2 | 108.3 | 86.3 | 21.6 | 4.1 | 312.4 |

Table 3.4: **Glacier mean slope (2010)**

| Mean slope (deg) | <10 | 10–20 | 20–30 | 30–40 | 40–50 | 50–60 | >60 | Total |
|---|---|---|---|---|---|---|---|---|
| Number | 7 | 625 | 1,455 | 1,162 | 464 | 89 | 6 | 3,808 |
| Area (km²) | 18.6 | 1,031.2 | 2,056.2 | 618.4 | 152.1 | 24.9 | 1 | 3,902 |
| Estimated ice reserves (km³) | 1.7 | 89.5 | 183.3 | 31.4 | 5.6 | 0.9 | 0.02 | 312.4 |

Table 3.5: **Morphological classification of glaciers (2010)**

| Glacier type | | Glacier number | | Glacier area | | Estimated ice reserves | | Mean area per glacier |
|---|---|---|---|---|---|---|---|---|
| | | Number | % | km² | % | km³ | % | km² |
| Mountain | Miscellaneous | 18 | 0.5 | 8.2 | 0.2 | 0.3 | 0.1 | 0.45 |
| | Ice Apron | 942 | 24.7 | 243.1 | 6.2 | 8.3 | 2.7 | 0.26 |
| | Cirque | 24 | 0.6 | 4.9 | 0.1 | 0.1 | 0 | 0.20 |
| | Niche | 315 | 8.3 | 39.6 | 1 | 0.9 | 0.3 | 0.13 |
| | Basin | 2,397 | 62.9 | 2,165.9 | 55.5 | 125.4 | 40.2 | 0.90 |
| Valley | Trough | 112 | 2.9 | 1,440.8 | 36.9 | 177.3 | 56.8 | 12.86 |
| | **Total** | **3,808** | **100** | **3,902** | **100** | **312.4** | **100** | **1.02** |

and contributed 56% of the total glacier area and 40% of the estimated ice reserves. The valley glaciers were much larger with an average area of 12.9 km², and although few in number (3% of the total), they contributed 37% of the glacier area and 57% of the estimated ice reserves.

## Clean-ice and debris-covered glaciers

Almost 89% of the total glacier area in Nepal was from CI glaciers (Table 3.1). The average slope of the clean-ice (CI) and debris-covered (DC) glaciers in the separate sub-basins is shown in Figure 3.7. There was a clear demarcation, with all CI glaciers having slopes above 20° (range 23–37°, average 31°), and all DC glaciers having slopes below 20° (range 6–18°, average 13°).

DC glaciers contained 11.4% of the total glacier area, with a marked variation in the individual basins, from 7.4% in the Gandaki basin to 19.7% in the Koshi basin (Table 3.1). The difference was even more marked among the sub-basins, from zero in the Indrawati sub-basin and 2.8% in the Kali Gandaki sub-basin to 28.1% in the Dudh Koshi sub-basin

Figure 3.6: **Percentage of glaciers with different aspects and slope (2010)**

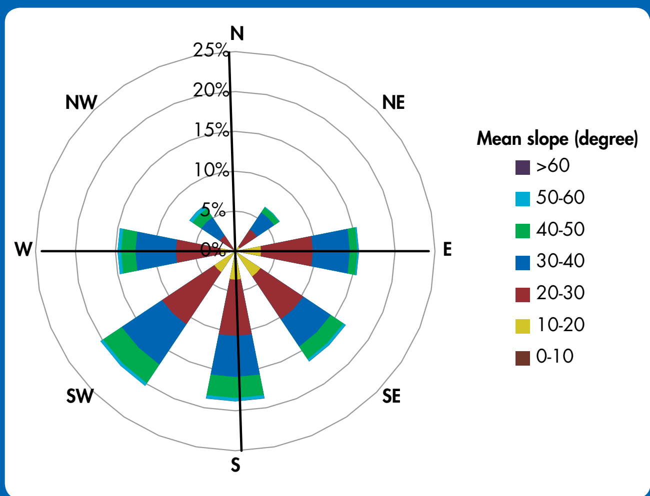


Figure 3.7: **Average slope of clean-ice and debris-covered glaciers in the sub-basins (2010)**

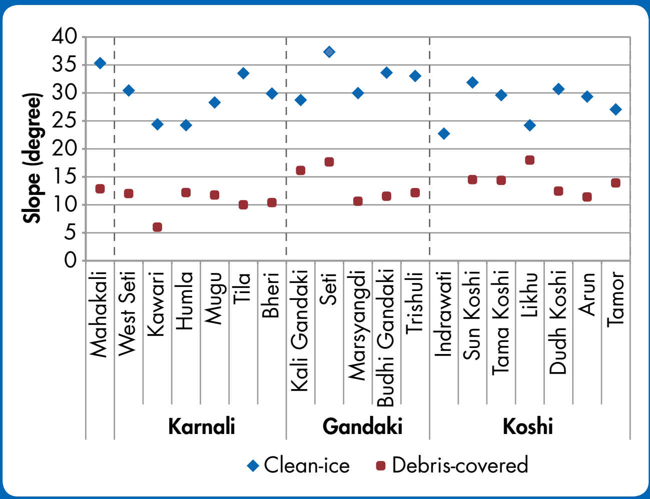



Figure 3.8: **Area of clean-ice and debris-covered glaciers in the sub-basins (2010)**

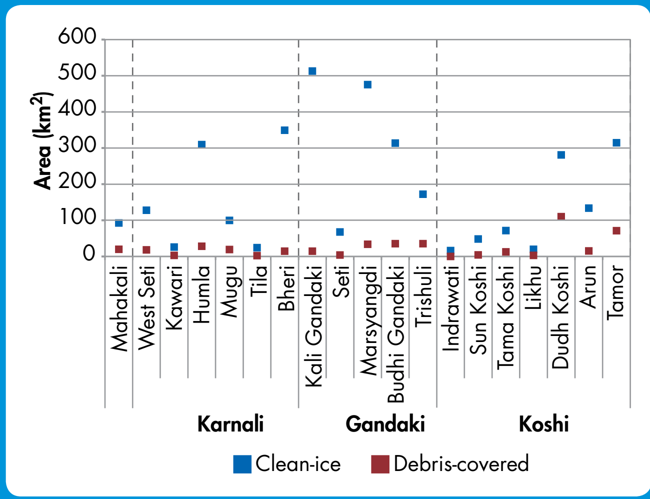
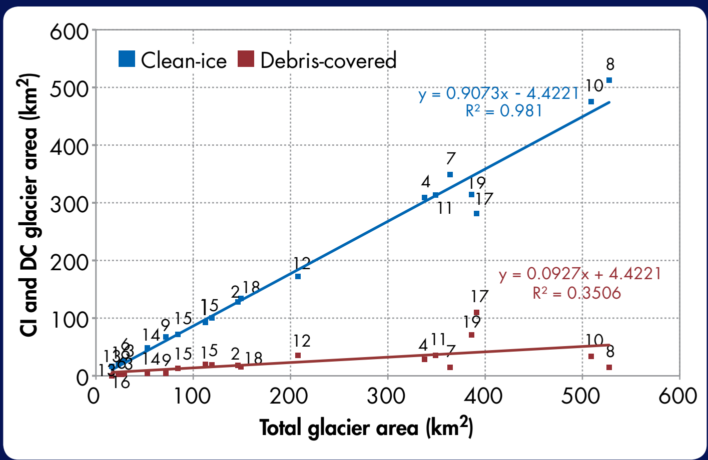
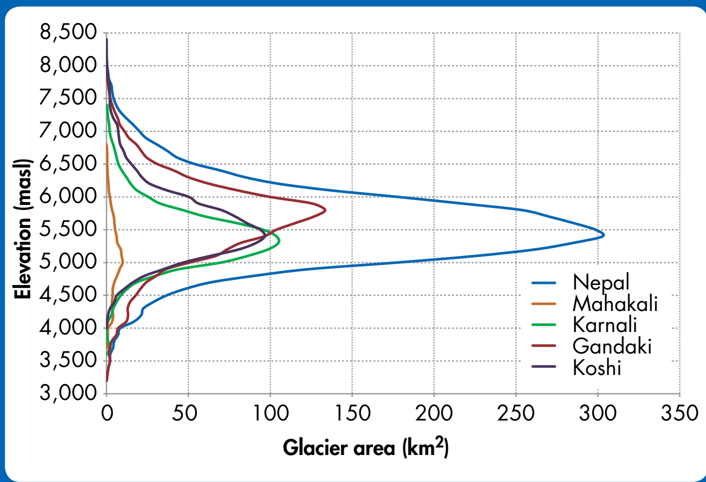



Figure 3.9: **Variation of clean-ice and debris-covered glacier area with total glacier area in the sub-basins (2010)**




| ID | Sub-basin | ID | Sub-basin | ID | Sub-basin | ID | Sub-basin |
|---|---|---|---|---|---|---|---|
| 1 | Mahakali | 6 | Tila | 11 | Budhi Gandaki | 16 | Likhu |
| 2 | West Seti | 7 | Bheri | 12 | Trishuli | 17 | Dudh Koshi |
| 3 | Kawari | 8 | Kali Gandaki | 13 | Indrawati | 18 | Arun |
| 4 | Humla | 9 | Seti | 14 | Sun Koshi | 19 | Tamor |
| 5 | Mugu | 10 | Marsyangdi | 15 | Tama Koshi | | |

Figure 3.10: **The 100 m bin area-altitude distribution of glaciers in the major basins and Nepal overall (2010)**




(Figure 3.8). The CI area increased almost proportionately with total glacier area in a sub-basin, whereas the DC area increased only slightly with overall glacier area (Figure 3.9).

## Area-elevation distribution (hypsography)

The area-elevation distribution of the glaciers in the major basins and Nepal overall is summarized in Table 3.6 based on a 500 m bin, and shown graphically in Figure 3.10 using a 100 m bin. Two-thirds of the glacier area (2,577 km²) lay between 5,000 and 6,000 masl; less than 50 km² of glacier area was found in each 100 m elevation bin above 6,500 masl and below 4,700 masl. The hypsographic curves show that the Gandaki basin had the highest elevation glaciers and the Mahakali basin the lowest (Figure 3.10).

Table 3.6: **Area elevation distribution of glaciers in the major basins of Nepal in 2010**

| Elevation zone (masl) | Mahakali | | Karnali | | Gandaki | | Koshi | | Total | |
|---|---|---|---|---|---|---|---|---|---|---|
| | km² | % | km² | % | km² | % | km² | % | km² | % |
| 3,000–3,500 | 0 | 0 | 0 | 0 | 1.9 | 0.1 | 0 | 0 | 1.9 | 0 |
| 3,500–4,000 | 1.6 | 1.4 | 3.5 | 0.3 | 15.2 | 0.9 | 0 | 0.0 | 20.2 | 0.5 |
| 4,000–4,500 | 15.2 | 13.5 | 14.3 | 1.4 | 59.7 | 3.6 | 8.4 | 0.8 | 97.7 | 2.5 |
| 4,500–5,000 | 27 | 24 | 114.9 | 11.2 | 130.1 | 7.8 | 92 | 8.3 | 364.1 | 9.3 |
| 5,000–5,500 | 40.6 | 36.1 | 463.4 | 45.3 | 369.4 | 22.2 | 379 | 34.4 | 1,252.4 | 32.1 |
| 5,500–6,000 | 20.7 | 18.4 | 315.1 | 30.8 | 604.4 | 36.3 | 384.6 | 34.9 | 1,324.8 | 33.9 |
| 6,000–6,500 | 6.1 | 5.5 | 80.5 | 7.9 | 334.2 | 20.1 | 154 | 14 | 574.8 | 14.7 |
| 6,500–7,000 | 1.3 | 1.1 | 25.4 | 2.5 | 108.9 | 6.5 | 53.7 | 4.9 | 189.3 | 4.9 |
| 7,000–7,500 | 0 | 0 | 5.4 | 0.5 | 34.6 | 2.1 | 22.7 | 2.1 | 62.8 | 1.6 |
| 7,500–8,000 | 0 | 0 | 0 | 0 | 5.8 | 0.3 | 7.5 | 0.7 | 13.3 | 0.3 |
| 8,000–8,500 | 0 | 0 | 0 | 0 | 0 | 0 | 0.6 | 0.1 | 0.6 | 0 |
| **Total** | **113** | **100** | **1,023** | **100** | **1,664** | **100** | **1,103** | **100** | **3,902** | **100** |

## Status of Glaciers in Individual River Basins

The overall glacier status in Nepal as a whole and its four major basins – the Mahakali, Karnali, Gandaki, and Koshi – are described in the previous section. The following sections describe the status within the individual basins.

### The Mahakali basin

The Mahakali River flows along the border between Nepal and India in the far western region of Nepal; only 35% of the catchment area lies in Nepal. There were 164 glaciers within the Nepal part of the basin with a total area of 113 km² and estimated ice reserves of about 7 km³ (Table 3.7). The areal distribution is shown in Figure 3.11.

The number, area, and estimated ice reserves in each size class of glacier are shown in Table 3.7. This basin had the greatest proportion of very small and small glaciers of all the basins, with close to three-quarters (124) in the smallest two classes (37% in class 1a, 39% in class 1b), but contributing only 16% of the glacier area. The five glaciers in classes 4 and 5 contributed 33% of the glacier area and close to half of the ice reserves.

The glacier elevation ranged from 3,695 to 6,850 masl (Figure 3.3) with an average of 5,063 masl for mountain type glaciers and 4,077 masl for valley type glaciers. Details of elevation, aspect, and slope of the glaciers in the Mahakali basin are provided in Annex 3 (Figure A3.1).

Table 3.7: **Glacier area classes in the Mahakali basin in 2010**

| Class | Area | Glacier number | | Glacier area | | Estimated ice reserves | | Mean area per glacier |
|---|---|---|---|---|---|---|---|---|
| | (km²) | Number | % | km² | % | km³ | % | km² |
| 1a | ≤ 0.10 | 60 | 36.6 | 3.6 | 3.2 | 0 | 0.6 | 0.06 |
| 1b | 0.11–0.50 | 64 | 39 | 14.1 | 12.6 | 0.3 | 4.8 | 0.22 |
| 2 | 0.51–1.00 | 17 | 10.4 | 11.6 | 10.3 | 0.4 | 6.1 | 0.68 |
| 3 | 1.01–5.00 | 18 | 11 | 46.2 | 41 | 2.9 | 41.9 | 2.57 |
| 4 | 5.01–10.00 | 4 | 2.4 | 25.9 | 23 | 2.2 | 30.9 | 6.48 |
| 5 | ≥ 10.01 | 1 | 0.6 | 11.1 | 9.9 | 1.1 | 15.7 | 11.13 |
| | **Total** | **164** | **100** | **112.6** | **100** | **6.97** | **100** | **0.69** |

Figure 3.11: **Distribution of glaciers in the Mahakali basin (2010)**

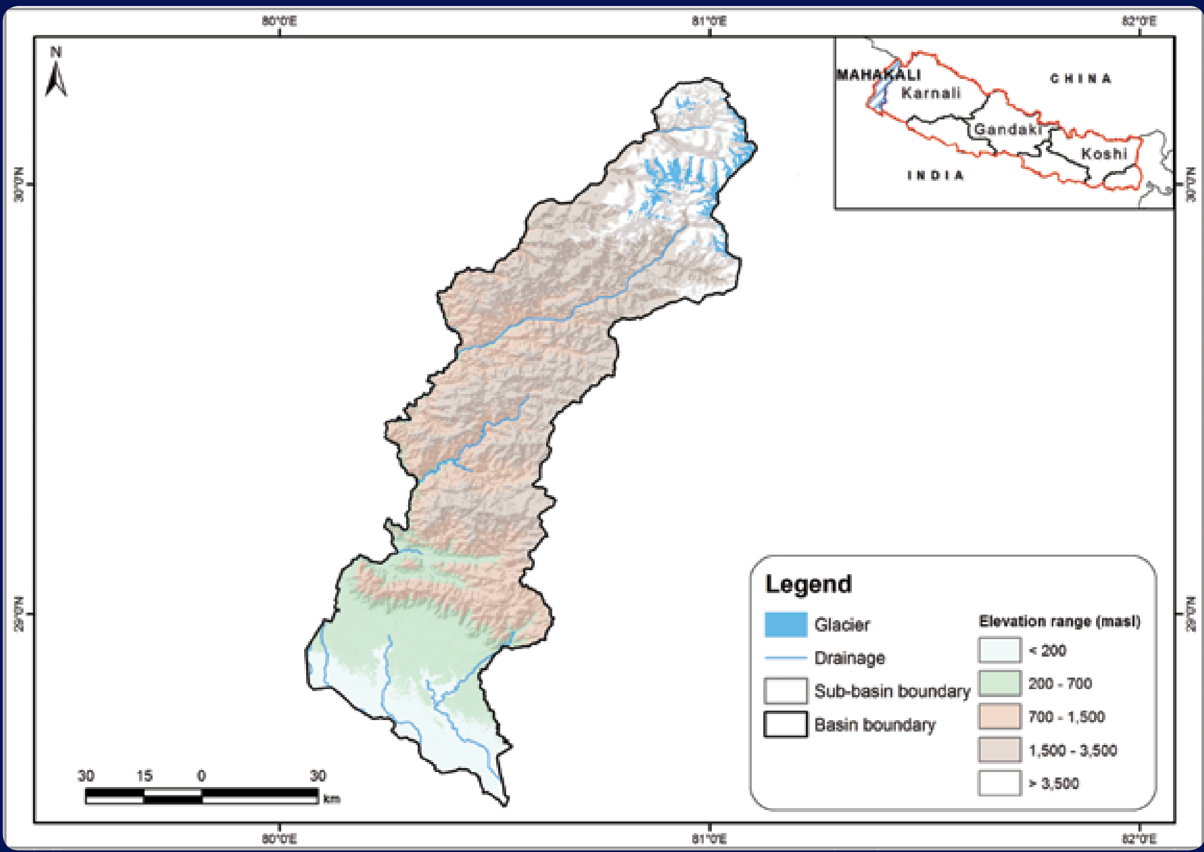



Table 3.8: **Morphological classification of glaciers in the Mahakali basin in 2010**

| Glacier type | | Glacier number | | Glacier area | | Estimated ice reserves | | Mean area per glacier |
|---|---|---|---|---|---|---|---|---|
| | | Number | % | km² | % | km³ | % | km² |
| Mountain | Miscellaneous | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Ice Apron | 58 | 35.4 | 9.7 | 8.6 | 0.3 | 3.9 | 0.17 |
| | Cirque | 2 | 1.2 | 1.4 | 1.2 | 0.1 | 0.7 | 0.68 |
| | Niche | 5 | 3 | 0.4 | 0.3 | 0.01 | 0.1 | 0.08 |
| | Basin | 88 | 53.7 | 45.4 | 40.3 | 2.2 | 31.3 | 0.52 |
| Valley | Trough | 11 | 6.7 | 55.8 | 49.6 | 4.5 | 64.1 | 5.07 |
| | **Total** | **164** | **100** | **113** | **100** | **7** | **100** | **0.69** |

The morphological classification of the glaciers is summarized in Table 3.8. The majority of glaciers (93%) were mountain type, with 54% mountain basin type and 35% ice apron type. Mountain basin type glaciers contributed 40% of the total glacier area and 31% of the estimated ice reserves, while apron type glaciers contributed 8.6% of the glacier area and 3.9% of the estimated ice reserves. Less than 7% of the glaciers were valley type, but these large glaciers (average area 5.1 km²) contributed 50% of the total glacier area and 64% of the estimated ice reserves.

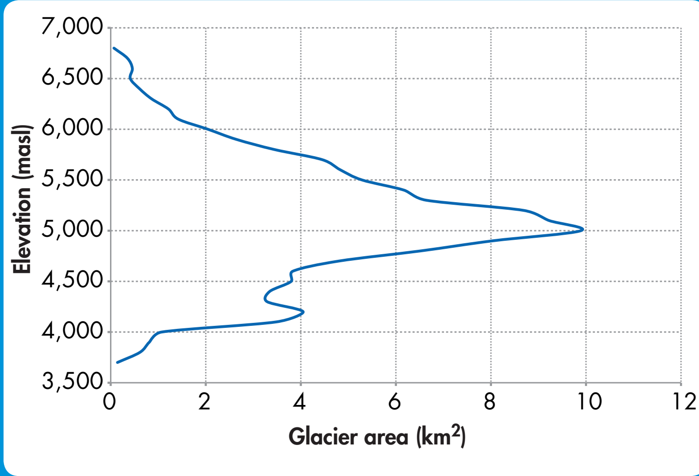
There were only 14 DC type glaciers in the basin with a total area of 19.9 km² (Table 3.1). The average slope of the clean-ice glaciers was 35°, the steepest of all the basins, which reflects the fact that these are mainly very small glaciers high in the mountains.

The area-elevation distribution of the glaciers using a 100 m bin is shown graphically in Figure 3.12. The highest value for a 100 m bin lay between 5,000 and 5,100 masl (9.9 km²).

## The Karnali basin

The Karnali basin is the largest of the four river basins and had the greatest number of glaciers (Table 3.1). The six sub-basins – the West Seti, Kawari, Humla, Mugu, Tila, and Bheri – contained 1,459 glaciers with a total glacier area of 1,023 km² and estimated ice reserves of 60 km³. The geographical distribution of the glaciers is shown in Figure 3.13. One-third of the glaciers (474) and a third of the glaciated area (338 km²) were found within the Humla sub-basin; and just over a quarter of the glaciers (401) and more than a third of the glaciated area in the Bheri sub-basin (Table 3.1). The largest single glacier (G083246E28708N) had an area of about 23.4 km², but the average area per glacier was only 0.7 km².

Figure 3.12: **The 100 m bin area-elevation distribution of glaciers in the Mahakali basin (2010)**




The number, area, and estimated ice reserves in each size class of glacier in the individual sub-basins are shown in Table 3.9. Details of the glacier area classes in the individual sub-basins are given in Annex 2 (Table A2.1). Again 70% (993) of the glaciers were in class 1a (23%) or class 1b (45%) and together these small glaciers contributed 18% of the glacier area and 7% of the ice reserves. The ten glaciers in class 5 had an average area of 15 km² and contributed 15% of the glacier area and 28% of the ice reserves.

The glacier elevation ranged from 3,631 to 7,541 masl (Figure 3.14). The lowest elevation of clean-ice glaciers was 3,874 masl and of DC glaciers 3,631 masl, both in the Kawari basin. The highest CI glacier elevation was

Figure 3.13: **Distribution of glaciers in the Karnali basin (2010)**

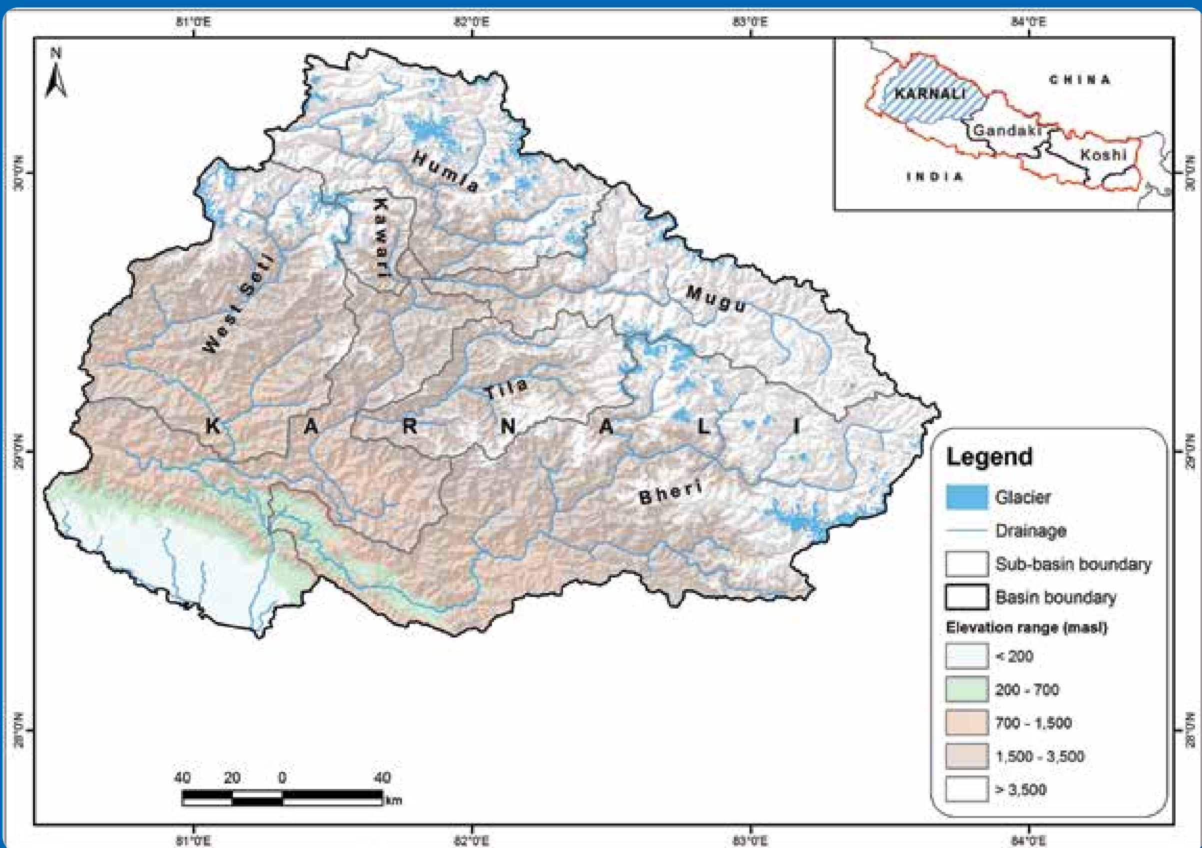


Table 3.9: **Glacier area classes in the Karnali basin (2010)**

| Class | Area | Glacier number | | Glacier area | | Estimated ice reserves | | Mean area per glacier |
|---|---|---|---|---|---|---|---|---|
| | (km²) | Number | % | km² | % | km³ | % | km² |
| 1a | ≤ 0.10 | 341 | 23.4 | 22 | 2.2 | 0.3 | 0.5 | 0.06 |
| 1b | 0.11–0.50 | 652 | 44.7 | 158.7 | 15.5 | 3.9 | 6.6 | 0.24 |
| 2 | 0.51–1.00 | 234 | 16 | 166.1 | 16.2 | 6.2 | 10.3 | 0.71 |
| 3 | 1.01–5.00 | 203 | 13.9 | 400.4 | 39.1 | 22.7 | 37.8 | 1.97 |
| 4 | 5.01–10.00 | 19 | 1.3 | 125.8 | 12.3 | 10.4 | 17.3 | 6.62 |
| 5 | ≥ 10.01 | 10 | 0.7 | 149.9 | 14.7 | 16.6 | 27.6 | 14.99 |
| | **Total** | **1,459** | **100** | **1,022.8** | **100** | **60.0** | **100** | **0.70** |

Table 3.10: **Morphological classification of glaciers in the Karnali basin in 2010**

| Glacier type | | Glacier number | | Glacier area | | Estimated ice reserves | | Mean area per glacier |
|---|---|---|---|---|---|---|---|---|
| | | Number | % | km² | % | km³ | % | km² |
| Mountain | Miscellaneous | 2 | 0.1 | 0.6 | 0.1 | 0.02 | 0 | 0.28 |
| | Ice Apron | 225 | 15.4 | 37.5 | 3.7 | 0.9 | 1.6 | 0.17 |
| | Cirque | 4 | 0.3 | 0.3 | 0 | 0 | 0 | 0.07 |
| | Niche | 149 | 10.2 | 14.6 | 1.4 | 0.3 | 0.4 | 0.1 |
| | Basin | 1,060 | 72.7 | 798.9 | 78.1 | 41.8 | 69.6 | 0.75 |
| Valley | Trough | 19 | 1.3 | 171.1 | 16.7 | 17 | 28.3 | 9 |
| | **Total** | **1,459** | **100** | **1,023** | **100** | **60** | **100** | **0.7** |

Figure 3.14: **Elevation range of clean-ice and derbris-covered in the Karnali sub-basins (2010)**

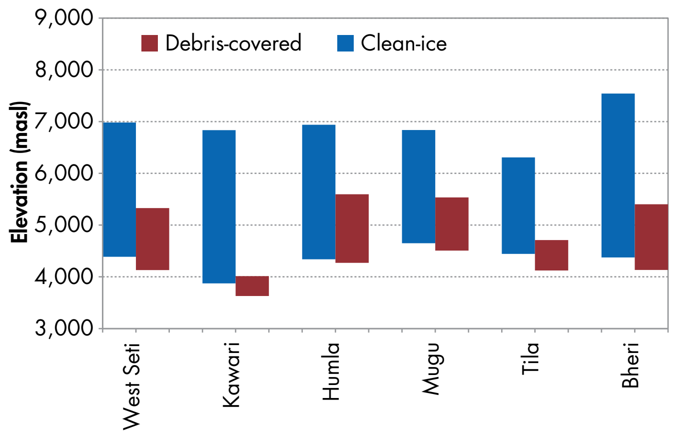
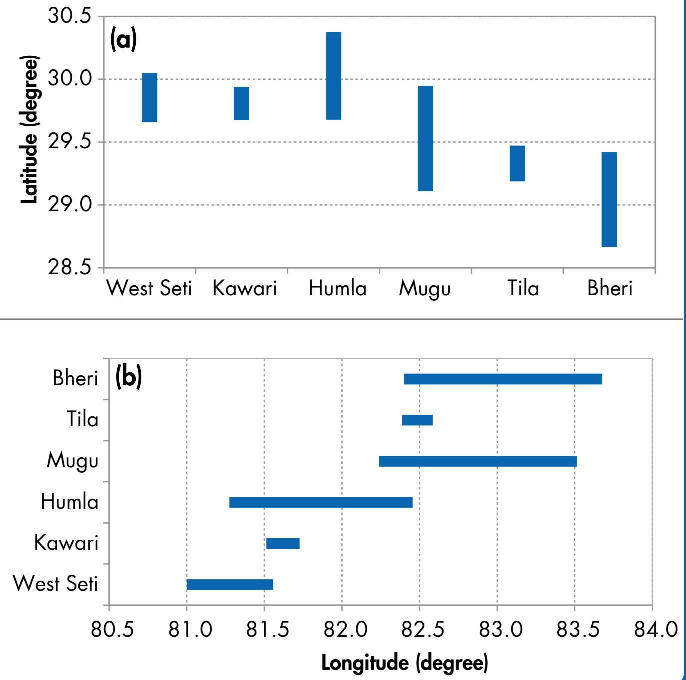



Figure 3.15: **Maximum and minimum latitude (a) and longitude (b) of glaciers in the Karnali sub-basins (2010)**

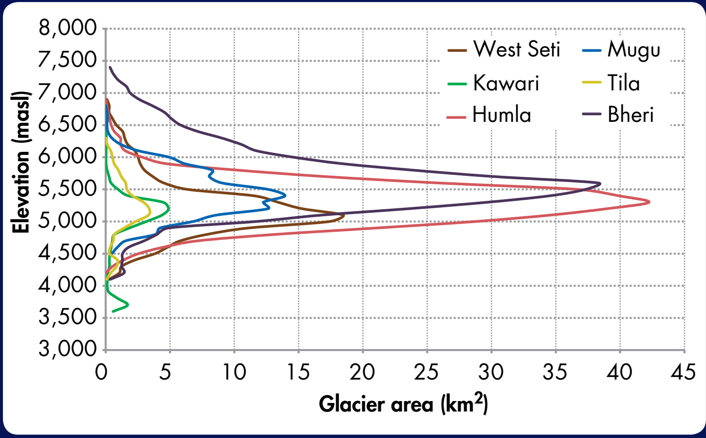


in the Bheri sub-basin and the highest DC glacier elevation in the Humla sub-basin. Details of the aspect and slope of glaciers in the Karnali sub-basins are provided in Annex 3 (Figure A3.2).

The range of latitude and longitude in the glaciers in the sub-basins is shown in Figure 3.15. The decreasing latitude from west to east reflects the northwest to southeast line of the Karnali basin.

The morphological classification of the glaciers is summarized in Table 3.10. Details for the sub-basins are provided in Annex 2 (Table A2.2). Close to 99% of glaciers (1,440) were mountain type, with 73% mountain basin type and 15% ice apron type. Mountain type glaciers contributed 83% of the total glacier area and 72% of the estimated ice reserves. Only 1% of the glaciers were valley basin type. The average area (9 km²) of the valley basin type glaciers was smaller than in the Koshi and Gandaki basins, but they still contributed 17% of the total glacier area and 28% of the estimated ice reserves.

Figure 3.16: **The 100 m bin area-elevation distribution of glaciers in the Karnali sub-basins (2010)**




The area-elevation distribution of the glaciers in the Karnali basin based on a 500 m bin is summarized in Table 3.6, and shown graphically for the individual sub-basins using a 100 m bin in Figure 3.16; the detailed values are provided in Annex 2 (Table A2.3). More than 75% of the glaciated area lay between 5,000 and 6,000 masl, with the highest value for a 100 m bin between 5,300 and 5,400 masl (105 km²). The Bheri sub-basin had the highest band of glaciated area (7,400–7,500 masl) and the Kawari sub-basin the lowest (3,600–3,700 masl).

## The Gandaki basin

The Gandaki basin has seven major sub-basins of which five are glaciated – the Kali Gandaki, Seti, Marsyangdi, Budhi Gandaki, and Trishuli. They contained 1,340 glaciers with a total area of 1,665 km² and estimated ice reserves of 135 km³, the highest in all the basins (Table 3.1). The geographical distribution of the glaciers is shown in Figure 3.17. Close to 40% of the glaciers (504) and just under a third of the glaciated area (527 km²) were found in the Kali Gandaki sub-basin, the highest number and area in any sub-basin in Nepal. The mean area of individual glaciers in the basin ranged from 1.05 km² in the Kali Gandaki sub-basin to 1.59 km² in the Seti sub-basin, with a mean value of 1.24 km². The largest glacier in the Gandaki basin (50.2 km²) was G085705E28306N in the Trishuli sub-basin. The second largest, with 43.6 km², was in the Seti sub-basin, the smallest basin in the Gandaki.

The number, area, and estimated ice reserves in each size class of glacier in the individual sub-basins are shown in Table 3.11. Details of the glacier area classes in the individual sub-basins are given in Annex 2 (Table A2.4). Close to half of the glaciers (629) were in class 1b, with an average area of 0.25 km². They contributed 10% of the glacier area and 3% of the estimated ice reserves. In contrast, the 32 glaciers in class 5 (2%) had an average area of 20 km², and contributed 38% of the glacier area and 59% of the estimated ice reserves.

The glacier elevation ranged from 3,282 masl to 8,101 masl (Figure 3.18). The lowest elevation of DC glaciers was 3,753 masl, and of DC glaciers 3,282 masl, both in the Budhi Gandaki sub-basin. The highest elevation of CI glaciers was 8,101 masl and of DC glaciers 5,705 masl, both in the Kali Gandaki basin. Details of the aspect and slope of glaciers in the Gandaki sub-basins are provided in Annex 3 (Figure A3.3).

The range of latitude and longitude in the glaciers in the sub-basins is shown in Figure 3.19. The decreasing latitude from west to east reflects the northwest to southeast line of the Gandaki basin.

The morphological classification of the glaciers is summarized in Table 3.12. Details for the sub-basins are provided in Annex 2 (Table A2.5). The majority of glaciers (97%) were mountain type, with 60% mountain basin type and 31% ice apron type. Mountain type glaciers contributed 68% of the total glacier area and 52% of the estimated

Figure 3.17: **Distribution of glaciers in the Gandaki basin (2010)**

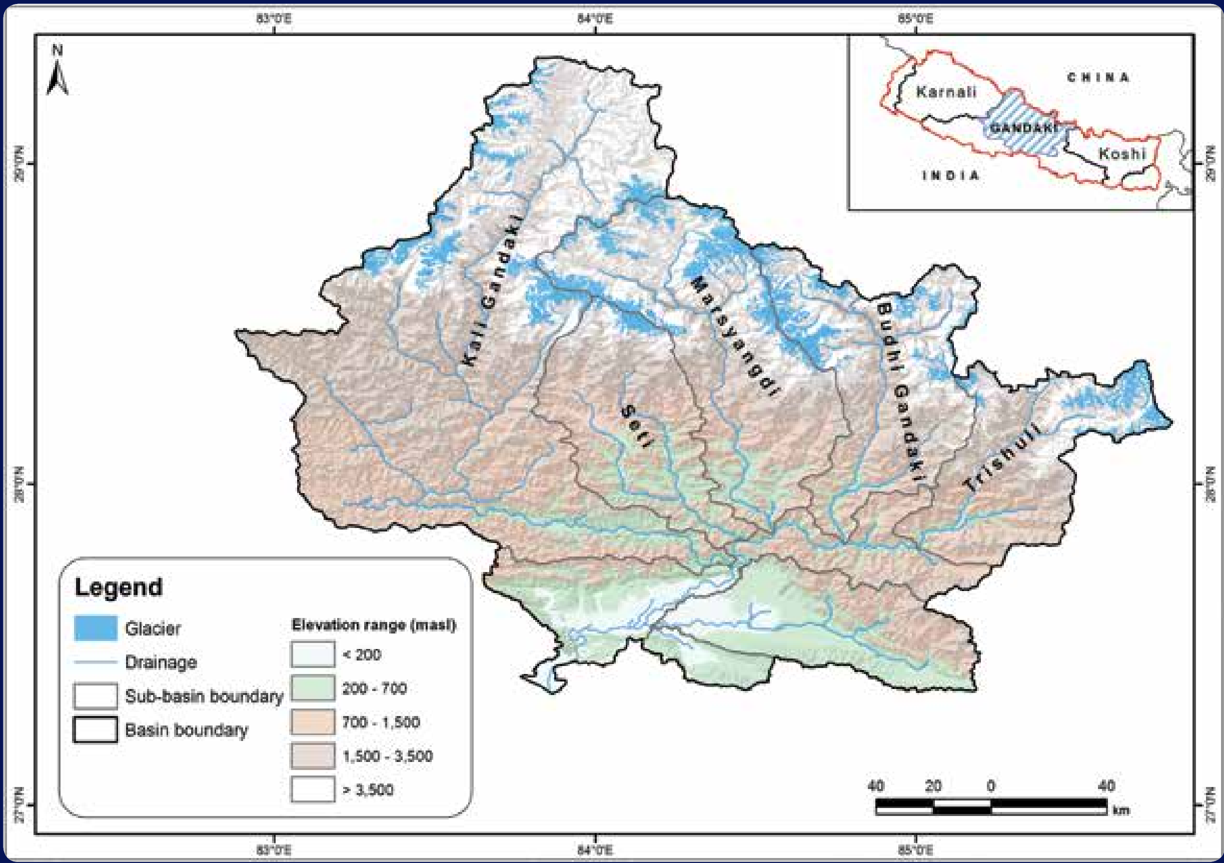



Table 3.11: **Glacier area classes in the Gandaki basin (2010)**

| Class | Area | Glacier number | | Glacier area | | Estimated ice reserves | | Mean area per glacier |
|---|---|---|---|---|---|---|---|---|
| | (km²) | Number | % | km² | % | km³ | % | km² |
| 1a | ≤ 0.10 | 199 | 14.9 | 13.6 | 0.8 | 0.2 | 0.1 | 0.07 |
| 1b | 0.11–0.50 | 629 | 46.9 | 159.5 | 9.6 | 4 | 3 | 0.25 |
| 2 | 0.51–1.00 | 195 | 14.6 | 139 | 8.4 | 5.2 | 3.8 | 0.71 |
| 3 | 1.01–5.00 | 258 | 19.3 | 522.5 | 31.4 | 29.7 | 22.1 | 2.03 |
| 4 | 5.01–10.00 | 27 | 2 | 190.9 | 11.5 | 16.2 | 12.1 | 7.07 |
| 5 | ≥ 10.01 | 32 | 2.4 | 639 | 38.4 | 79.4 | 58.9 | 19.97 |
| | **Total** | **1,340** | **100.0** | **1,664.4** | **100** | **134.8** | **100** | **1.24** |

Table 3.12: **Morphological classification of glaciers in the Gandaki basin in 2010**

| Glacier type | | Glacier number | | Glacier area | | Estimated ice reserves | | Mean area per glacier |
|---|---|---|---|---|---|---|---|---|
| | | Number | % | km² | % | km³ | % | km² |
| Mountain | Miscellaneous | 3 | 0.2 | 2.2 | 0.1 | 0.1 | 0.1 | 0.72 |
| | Ice Apron | 417 | 31.1 | 140.9 | 8.5 | 5.5 | 4.1 | 0.34 |
| | Cirque | 8 | 0.6 | 1.8 | 0.1 | 0.04 | 0 | 0.22 |
| | Niche | 81 | 6 | 14.3 | 0.9 | 0.4 | 0.3 | 0.18 |
| | Basin | 797 | 59.5 | 973.7 | 58.5 | 64.6 | 47.9 | 1.22 |
| Valley | Trough | 34 | 2.5 | 531.7 | 31.9 | 64.2 | 47.6 | 15.64 |
| | **Total** | **1,340** | **100** | **1,664** | **100** | **134.8** | **100** | **1.24** |

ice reserves. Less than 3% of the glaciers were valley basin type, but these large glaciers (average area 15.6 km²) contributed 32% of the total glacier area and 48% of the estimated ice reserves.

Only 5% of the glaciers in the Gandaki basin had a DC component, and they contributed less than 8% of the total glacier area. The mean slopes of the CI and DC glaciers were 33° and 14°, respectively.

The area-elevation distribution of the glaciers in the Gandaki basin based on a 500 m bin is summarized in Table 3.6, and shown graphically for the individual sub-basins using a 100 m bin in Figure 3.20; the detailed values are provided in Annex 2 (Table A2.6). Close to 60% of the glaciated area lay between 5,000 and 6,000 masl, with the highest value for a 100 m bin between 5,800 and 5,900 masl (133.5 km²). The Kali Gandaki sub-basin had the highest elevation band of glaciated area (8,100–8,200 masl) and the Budhi Gandaki sub-basin the lowest (3,200–3,300 masl).

## The Koshi basin

The Koshi basin has seven major sub-basins – the Indrawati, Sun Koshi, Tama Koshi, Likhu, Dudh Koshi, Arun, and Tamor. They contained 845 glaciers with a total area of 1,103 km² and estimated ice reserves of 111 km³ (Table 3.1). The geographical distribution of the glaciers is shown in Figure 3.21. One-third of the glaciers (287) and slightly more than a third of the glaciated area (391 km²) were found within the Dudh Koshi sub-basin. The mean area of individual glaciers in the basin ranged from 0.44 km² in the Indrawati sub-basin to 1.47 km² in the Tamor sub-basin, with a mean value of 1.30 km².

The number, area, and estimated ice reserves in each size class of glacier are shown in Table 3.13. Details of the glacier area classes in the individual sub-basins are given in Annex 2 (Table A2.7). Close to half of the glaciers (394) were in class 1b, with an average area of 0.25 km². They contributed 9% of the glacier area and 2.3% of the estimated ice reserves. The 19 glaciers in class 5 (2%) had an average area of 28.9 km², and contributed 50% of the glacier area and 73% of the estimated ice reserves. The Dudh Koshi sub-basin contained the largest glacier in Nepal, the Ngojumba glacier, with an area of 78.7 km².

The glacier elevation ranged from 4,040 masl to 8,400 masl (448 m below the top of Mount Everest)

Figure 3.18: **Elevation range of clean-ice and debris-covered glaciers in the Gandaki sub-basins (2010)**

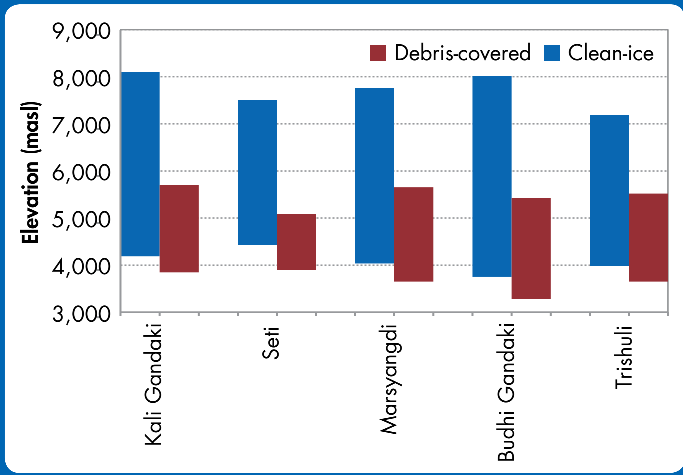



Figure 3.19: **Maximum and minimum latitude (a) and longitude (b) of glaciers in the Gandaki sub-basins (2010)**

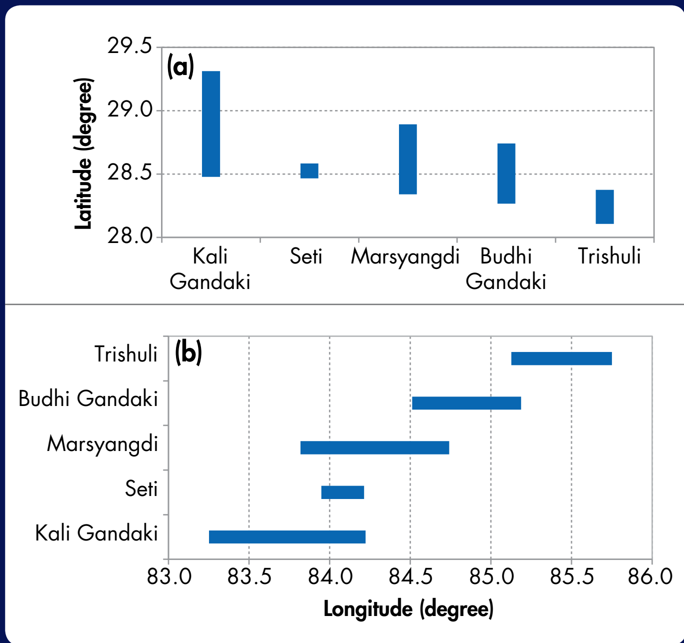



Figure 3.20: **The 100 m bin area-elevation distribution of glaciers in the Gandaki sub-basins (2010)**

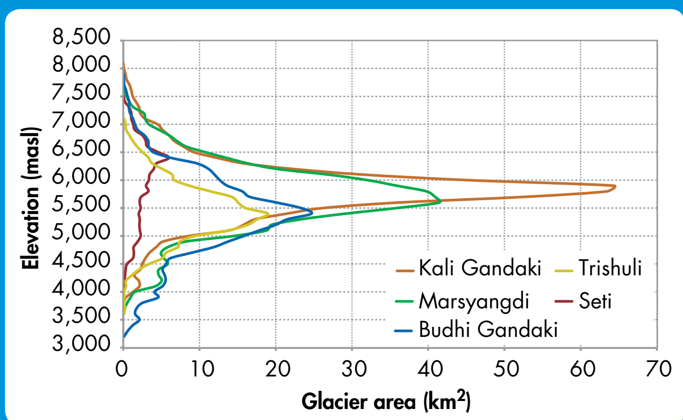


Figure 3.21: **Distribution of glaciers in the Koshi basin (2010)**

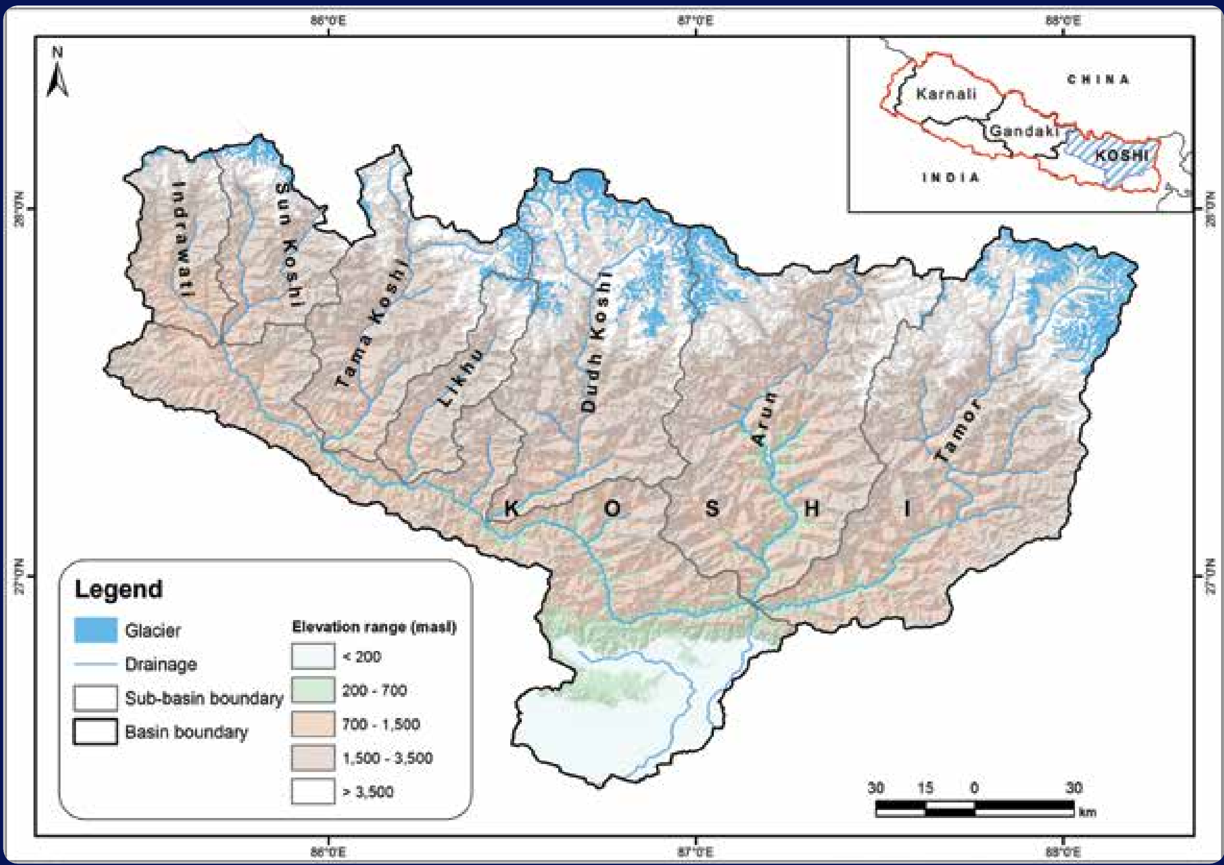



Table 3.13: **Glacier area classes in the Koshi basin (2010)**

| Class | Area | Glacier number | | Glacier area | | Estimated ice reserves | | Mean area per glacier |
|---|---|---|---|---|---|---|---|---|
| | (km²) | Number | % | km² | % | km³ | % | km² |
| 1a | ≤ 0.10 | 181 | 21.4 | 11.2 | 1 | 0.1 | 0.1 | 0.06 |
| 1b | 0.11–0.50 | 394 | 46.6 | 99.1 | 9 | 2.5 | 2.3 | 0.25 |
| 2 | 0.51–1.00 | 110 | 13 | 77.5 | 7 | 2.9 | 2.6 | 0.70 |
| 3 | 1.01–5.00 | 127 | 15 | 265.2 | 24.1 | 15.3 | 13.8 | 2.09 |
| 4 | 5.01–10.00 | 14 | 1.7 | 101.9 | 9.2 | 8.7 | 7.9 | 7.28 |
| 5 | ≥ 10.01 | 19 | 2.3 | 548.1 | 49.7 | 81.1 | 73.3 | 28.85 |
| | **Total** | **845** | **100.0** | **1,102.7** | **100.0** | **110. 7** | **100.0** | **1.30** |

(Figure 3.22). The lowest elevation of clean-ice glaciers was 4,136 masl, and of DC glaciers 4,047 masl, both in the Sun Koshi sub-basin. Details of the aspect and slope of glaciers in the Karnali sub-basins are provided in Annex 3 (Figure A3.4).

The range of latitude and longitude in the glaciers in the sub-basins is shown in Figure 3.23. The decreasing latitude from west to east reflects the northwest to southeast line of the Koshi basin. The sub-basins with a greater number of glaciers generally had a wider range of latitude and longitude of glacier area.

The morphological classification of the glaciers is summarized in Table 3.14. Details for the sub-basins are provided in Annex 2 (Table A2.8).The majority of glaciers (94%) were mountain type, with 54% mountain basin type and 29% ice apron type. Mountain type glaciers contributed 38% of the total glacier area and 17% of the estimated ice reserves. Less than 6% of the glaciers were valley basin type, but these large glaciers (average area 14.2 km²) contributed 62% of the total glacier area and 83% of the estimated ice reserves.

Figure 3.22: **Elevation range of clean-ice and debris-covered glaciers in the Koshi sub-basins (2010)**

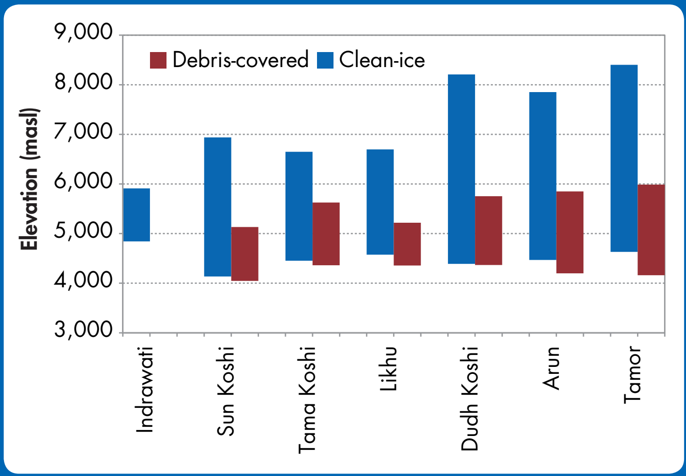



Figure 3.23: **Maximum and minimum latitude (a) and longitude (b) of glaciers in the Koshi sub-basins (2010)**

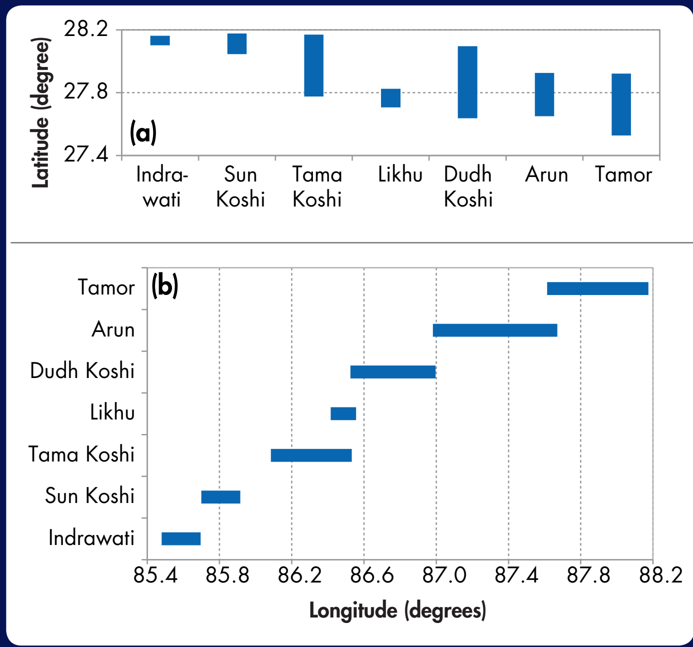


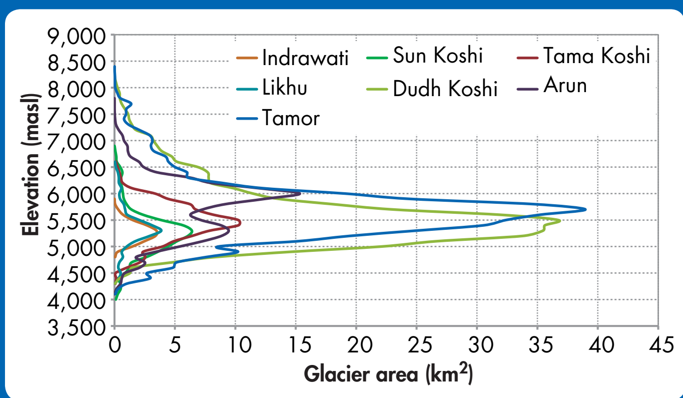

Table 3.14: **Morphological classification of glaciers in the Koshi basin (2010)**

| Glacier type | | Glacier number | | Glacier area | | Estimated ice reserves | | Mean area per glacier |
|---|---|---|---|---|---|---|---|---|
| | | Number | % | km² | % | km³ | % | km² |
| Mountain | Miscellaneous | 13 | 1.5 | 5.4 | 0.5 | 0.2 | 0.2 | 0.42 |
| | Ice Apron | 242 | 28.6 | 55.1 | 5 | 1.6 | 1.5 | 0.23 |
| | Cirque | 10 | 1.2 | 1.5 | 0.1 | 0.03 | 0 | 0.15 |
| | Niche | 80 | 9.5 | 10.4 | 0.9 | 0.2 | 0.2 | 0.13 |
| | Basin | 452 | 53.5 | 347.9 | 31.6 | 16.9 | 15.2 | 0.77 |
| Valley | Trough | 48 | 5.7 | 682.3 | 61.9 | 91. 7 | 82.9 | 14.21 |
| | **Total** | **845** | **100** | **1,103** | **100** | **110.6** | **100** | **1.3** |

Close to 90% of the glaciers in the Koshi basin were CI type, but DC type glaciers contributed close to 20% (216.7 km²) of the glacier area. The mean slopes of the CI and DC glaciers were 28° and 14°, respectively. The Dudh Koshi and Tamor sub-basins contained the greatest number of DC glaciers, whereas the Indrawati sub-basin contained no valley or other DC type glaciers (Table 3.1). Valley glaciers contributed more than 50% of the total glacierized area in the Dudh Koshi and Tamor sub-basins.

The area-elevation distribution of the glaciers in the Koshi basin based on a 500 m bin is summarized in Table 3.6 and shown graphically for the individual sub-basins using a 100 m bin in Figure 3.24; the detailed values are provided in Annex 2 (Table A2.9).

Figure 3.24: **The 100 m bin area-elevation distribution of glaciers in the Koshi sub-basins (2010)**



Almost 70% of the glaciated area lay between 5,000 and 6,000 masl, with the highest value for a 100 m bin between 5,400 and 5,500 masl (96.6 km$^2$). The Tamor sub-basin had the highest band of glaciated area (8,400–8,500 masl) and the Sun Koshi sub-basin the lowest (4,000–4,100 masl).

## Discussion

The results provide a comprehensive description of the status of Nepal's glaciers in 2010. The Landsat images used were from a narrow time frame, 2009 to 2011, and the consistent approach used means that this dataset now provides a reliable baseline for comparison and identification of changes over time.

Some interesting points were noted from the comparison of the status in the individual basins and sub-basins as follows.

The number of glaciers in the Karnali basin was high compared to the number in the Koshi and Gandaki basins, but the area and ice reserves were lower. This is because there are fewer valley glaciers than in the other basins; valley glaciers generally contribute a much larger area and ice reserves. Similarly, within the Koshi basin, the number and area of glaciers in the Dudh Koshi sub-basin was around three-quarters of those in the Marsyangdi sub-basin, but they had similar levels of ice reserves. Again this is mainly due to the existence of large glaciers in the Dudh Koshi, which contributed higher ice reserves per unit area.

The largest glacier identified in the 2001 ICIMOD inventory was Ktr_gr 193 in the Tamor sub-basin. This glacier has reduced in size and fragmented into two glaciers, and is no longer the largest in Nepal. The present inventory identified the Ngojumba glacier in the Dudh Koshi sub-basin as the largest individual glacier in 2010. However, the area of this glacier was also lower than measured in the 2001 inventory (78.7 km$^2$ compared to 92.4 km$^2$).

# 4 Decadal Glacier Change from 1980 to 2010 in the Nepal Himalayas

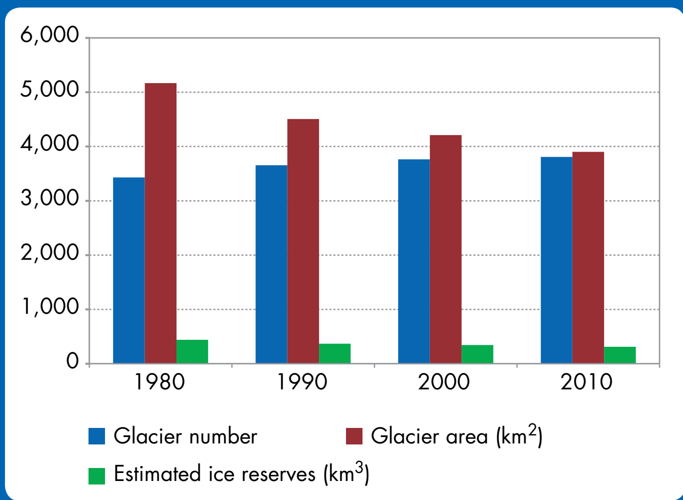
## Decadal Glacier Change in Nepal

There is considerable evidence that glaciers have been retreating over the past decades in the Nepal Himalayas (Kadota et al. 1997; Fujita et al. 2001; Bolch et al. 2008; Bajracharya et al. 2010, 2011). In order to assess and analyse the changes more accurately, a repeat glacier inventory was prepared for the individual basins and Nepal as a whole for ~1980 (1976–1979), 1990, 2000, and 2010. (These designations are approximations used to emphasize the decadal nature of the change, and based on images from a narrow range of years around the given date as explained in Chapter 2).

### Number, area, and estimated ice reserves

The glacier number, area, and estimated ice reserves in the individual sub-basins are given in Table 4.1. A summary for the whole of Nepal in the four different time periods is given in Table 4.2, and shown graphically in Figure 4.1. The number of glaciers increased by 11% (378) over the 30-year period with the greatest increase between ~1980 and 1990. The glacier area decreased by 24% (1,266 km²) and the estimated ice reserves by 29% (129 km³), again with the greatest change between ~1980 and 1990. The overall glacier area decreased from 3.6% of the total land area of Nepal to 2.6%. Although the rate of loss of area was the same between 1990 and 2000 and 2000 and 2010, the rate of loss of ice reserves increased over this period.

Figure 4.1: **Glacier number, area, and estimated ice reserves in Nepal in ~1980, 1990, 2000, and 2010**




### Glacier area classes, aspect, slope, and morphological type

The status and change in glacier area classes, aspect, slope and morphological type in the glaciers in Nepal for the whole period ~1980 to 2010 are summarized in Table 4.3. Details for the individual years are provided in Annex 2 (Tables A2.10–A2.13).

The changes in the number and area of glaciers within the different size classes are shown in Table 4.3; details for the individual years are provided in Annex 2 (Table A2.10). Briefly, the number of glaciers in the smallest class 1a increased in all decades; in the next smallest class 1b they increased in the first two decades but decreased between 2000 and 2010. In all larger classes, the number of glaciers decreased in all decades.

Glaciers facing in all directions can be found in Nepal, but the majority have a southerly aspect. The changes in the aspect of glaciers are shown in Table 4.3; details for the individual years are provided in Annex 2 (Table A2.11). Briefly, the number of glaciers increased noticeably for all aspects, apart from southeast where numbers decreased markedly, and south, where the increase was very small. In contrast, the glacial area decreased for all aspects except north and northwest, which showed small increases, with the greatest losses for the south aspect.

Table 4.1: **Status and change of glaciers in the individual basins and sub-basins in ~1980, 1990, 2000 and 2010**

| | | Glacier number | | | | Glacier area (km²) | | | | Estimated ice reserves (km³) | | | | Minimum elevation (masl) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Basin | Sub-basin | ~1980 | 1990 | 2000 | 2010 | ~1980 | 1990 | 2000 | 2010 | ~1980 | 1990 | 2000 | 2010 | ~1980 | 1990 | 2000 | 2010 |
| Mahakali | Mahakali | 130 | 140 | 151 | 164 | 158.5 | 134.6 | 120.3 | 112.5 | 10.91 | 8.84 | 7.81 | 6.97 | 3,627 | 3,657 | 3,684 | 3,695 |
| Karnali | West Seti | 236 | 248 | 259 | 270 | 210.7 | 191.1 | 162.8 | 146 | 11.85 | 10.36 | 8.5 | 7.28 | 3,903 | 4,032 | 4,112 | 4,132 |
| | Kawari | 44 | 49 | 49 | 48 | 42.3 | 37.2 | 33.5 | 29.2 | 2.33 | 1.92 | 1.72 | 1.45 | 3,572 | 3,572 | 3,599 | 3,631 |
| | Humla | 450 | 468 | 474 | 474 | 457.4 | 408.2 | 374.9 | 337.9 | 28.06 | 24.35 | 21.92 | 19.48 | 4,025 | 4,130 | 4,249 | 4,271 |
| | Mugu | 200 | 206 | 206 | 205 | 164.2 | 142.9 | 130.2 | 119.2 | 8.59 | 7.21 | 6.44 | 5.84 | 4,301 | 4,350 | 4,473 | 4,507 |
| | Tila | 50 | 53 | 56 | 61 | 36.5 | 33.1 | 29.3 | 26.8 | 1.89 | 1.7 | 1.45 | 1.31 | 4,061 | 4,088 | 4,098 | 4,124 |
| | Bheri | 391 | 392 | 400 | 401 | 474.2 | 417.6 | 382.4 | 363.8 | 33.07 | 28.9 | 26.35 | 24.66 | 4,067 | 4,071 | 4,090 | 4,133 |
| | Sub-Total | 1,371 | 1,416 | 1,444 | 1,459 | 1,385.4 | 1,230.1 | 1,113.1 | 1,022.8 | 85.79 | 74.45 | 66.38 | 60.04 | 3,572 | 3,572 | 3,599 | 3,631 |
| Gandaki | Kali Gandaki | 442 | 480 | 500 | 504 | 677.3 | 587.3 | 558.5 | 527.4 | 55.32 | 44.97 | 41.71 | 38.9 | 3,665 | 3,793 | 3,819 | 3,846 |
| | Seti | 37 | 42 | 47 | 45 | 88.6 | 79.8 | 75.5 | 71.6 | 9.76 | 8.72 | 8.42 | 8.09 | 3,701 | 3,701 | 3,754 | 3,894 |
| | Marsyangdi | 347 | 378 | 385 | 384 | 632.8 | 557.8 | 535.9 | 509 | 53.76 | 44.68 | 42.73 | 39.97 | 3,589 | 3,653 | 3,639 | 3,651 |
| | Budhi Gandaki | 224 | 234 | 241 | 242 | 447 | 384.6 | 370.8 | 348.8 | 39.05 | 31.72 | 30.47 | 28.53 | 3,159 | 3,273 | 3,274 | 3,282 |
| | Trishuli | 143 | 160 | 168 | 165 | 279.8 | 237.9 | 224.3 | 207.6 | 27.68 | 23 | 21.53 | 19.26 | 3,517 | 3,600 | 3,640 | 3,650 |
| | Sub-Total | 1,193 | 1,294 | 1,341 | 1,340 | 2,125.5 | 1,847.4 | 1,764.9 | 1,664.4 | 185.57 | 153.09 | 144.85 | 134.75 | 3,159 | 3,273 | 3,274 | 3,282 |
| Koshi | Indrawati | 33 | 37 | 37 | 37 | 23.9 | 20.1 | 18.4 | 16.4 | 1.17 | 0.92 | 0.82 | 0.73 | 4,535 | 4,574 | 4,757 | 4,843 |
| | Sun Koshi | 30 | 34 | 35 | 39 | 72.6 | 62.4 | 59.7 | 52.6 | 6.57 | 5.37 | 4.98 | 4.16 | 3,873 | 3,962 | 3,925 | 4,047 |
| | Tama Koshi | 77 | 87 | 86 | 85 | 120.3 | 101.7 | 94.2 | 84.4 | 11.58 | 9.56 | 8.84 | 7.89 | 4,268 | 4,316 | 4,342 | 4,363 |
| | Likhu | 25 | 26 | 27 | 27 | 32.7 | 27.2 | 25.2 | 23 | 2.25 | 1.76 | 1.58 | 1.42 | 4,109 | 4,117 | 4,300 | 4,357 |
| | Dudh Koshi | 258 | 276 | 282 | 287 | 534.4 | 455.9 | 426.7 | 391.2 | 55.65 | 46.37 | 43.2 | 39.2 | 4,336 | 4,367 | 4,367 | 4,367 |
| | Arun | 84 | 99 | 104 | 108 | 208.2 | 177.8 | 166 | 149.2 | 22 | 18.07 | 16.75 | 14.98 | 4,020 | 4,079 | 4,129 | 4,200 |
| | Tamor | 229 | 247 | 258 | 262 | 506.9 | 449 | 422.5 | 385.9 | 59.87 | 51.16 | 47.75 | 42.26 | 4,081 | 4,116 | 4,144 | 4,161 |
| | Sub-Total | 736 | 806 | 829 | 845 | 1,498.9 | 1,294.2 | 1,212.6 | 1,102.6 | 159.09 | 133.21 | 123.92 | 110.64 | 3,873 | 3,962 | 3,925 | 4,047 |
| Nepal | **Total** | **3430** | **3,656** | **3,765** | **3,808** | **5,168.30** | **4,506.3** | **4,210.9** | **3,902.4** | **441.36** | **369.59** | **342.97** | **312.4** | **3,159** | **3,273** | **3,274** | **3,282** |

Table 4.2: **Status and change in glaciers in Nepal in ~1980, 1990, 2000, and 2010**

| Glacier | Decade (year) | | | | Decadal change | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ~1980 | 1990 | 2000 | 2010 | ~1980–1990 | | 1990–2000 | | 2000–2010 | | ~1980–2010 | |
| Number | 3,430 | 3,656 | 3,765 | 3,808 | +226 | +7% | +109 | +3% | +43 | +1% | +378 | +11% |
| Area (km²) | 5,168 | 4,506 | 4,211 | 3,902 | -662 | -13% | -295 | -7% | -308 | -7% | -1266 | -24% |
| Estimated ice reserves (km³) | 441 | 370 | 343 | 312 | -72 | -16% | -27 | -7% | -31 | -9% | -129 | -29% |

Table 4.3: **Glacier number and area change ~1980–2010**

| | | Glacier number | | Glacier area (km²) | |
|---|---|---|---|---|---|
| | | 2010 | Change ~1980–2010 | 2010 | Change ~1980–2010 |
| **Area class (km²)** | | | | | |
| Class 1a. ≤ 0.10 | | 781 | 602 | 50.3 | 37.2 |
| Class 1b. 0.11–0.50 | | 1,739 | 216 | 431.4 | 10.1 |
| Class 2. 0.51–1.00 | | 556 | -167 | 394.2 | -117.3 |
| Class 3. 1.01–5.00 | | 606 | -225 | 1,234.1 | -453 |
| Class 4. 5.01–10.00 | | 64 | -32 | 444.3 | -218.7 |
| Class 5. ≥ 10.01 | | 62 | -16 | 1,348.1 | -524.1 |
| | **Total** | **3,808** | **378** | **3,902.4** | **-1,265.9** |
| **Aspect** | | | | | |
| North | | 14 | 9 | 1.7 | 0.9 |
| Northeast | | 255 | 84 | 89.1 | -8 |
| East | | 590 | 73 | 466.6 | -69.9 |
| Southeast | | 634 | -54 | 754.6 | -387 |
| South | | 717 | 9 | 1,078.7 | -485.2 |
| Southwest | | 773 | 90 | 991.3 | -198.4 |
| West | | 561 | 68 | 412.6 | -133.1 |
| Northwest | | 264 | 99 | 107.8 | 14.8 |
| | **Total** | **3,808** | **378** | **3,902.4** | **-1,265.9** |
| **Mean slope (degree)** | | | | | |
| 0–10 | | 7 | 5 | 18.6 | 3.5 |
| 10–20 | | 625 | 243 | 1,031.2 | 372.4 |
| 20–30 | | 1,455 | -9 | 2,056.2 | -1090.5 |
| 30–40 | | 1,162 | 20 | 618.4 | -480.7 |
| 40–50 | | 464 | 75 | 152.1 | -72.3 |
| 50–60 | | 89 | 38 | 24.9 | 0.8 |
| >60 | | 6 | 6 | 1 | 1 |
| | **Total** | **3,808** | **378** | **3,902.4** | **-1,265.9** |
| **Glacier type** | | | | | |
| Mountain | Miscellaneous | 18 | 1 | 8.2 | -1.8 |
| | Ice Apron | 943 | 137 | 245.5 | -75.3 |
| | Cirque | 24 | -7 | 4.9 | -8.4 |
| | Niche | 315 | 8 | 39.6 | -70.6 |
| | Basin | 2,396 | 237 | 2,163.4 | -709.3 |
| Valley trough | | 112 | 2 | 1,440.8 | -400.5 |
| | **Total** | **3,808** | **378** | **3,902.4** | **-1,265.9** |

The majority of Nepal's glaciers have mean slopes of 10–50°, and most commonly 20–30°. Only a very few have slopes below 10° or above 60°. The changes in the number and area of glaciers of different slope over the three decades are shown in Table 4.3; the details for the individual years are provided in Annex 2 (Table A2.12). Briefly, between ~1980 and 2010, the overall glacier number increased in glaciers of all slopes except 20–30°, where an initial increase was followed by a decrease in the third decade. The glacier number also decreased in glaciers with slopes of 30–40° in the third decade, but by less than the initial increase. The greatest increase was in glaciers with slopes of 10–20°. In contrast, the glacier area decreased in glaciers with slopes from 20–50° and increased slightly in the remainder, with the greatest decrease in glaciers with slopes of 20–30°; the loss was highest in the first decade.

The changes in the number and area of glaciers of different type over the three decades are shown in Table 4.3; the details for the individual years are provided in Annex 2 (Table A2.13). Briefly, between ~1980 and 2010, the number of glaciers in all types increased, apart from cirque glaciers which showed a small decrease (from 31 to 24), with the greatest change in the first decade. Mountain basin type glaciers showed the greatest increase in number (237, from 2,159 to 2,396), and ice apron type the greatest proportionate increase (17%, from 806 to 943). All types of glacier showed a reduction in area in all decades, with the greatest loss in mountain basin type glaciers (709 km$^2$, from 2,872 to 2,163 km$^2$). The large valley type glaciers comprised both simple and compound basins. Two of these glaciers fragmented, one in ~1980–1990 and another in 1990–2000. The glacier area loss was also greatest in valley basin glaciers, a total of 400 km$^2$ (1,841 to 1,441 km$^2$).

## Glacier area-elevation distribution

In 2010, glaciers were observed at elevations from 3,282 to 8,401 masl. The area-elevation distribution of Nepal's glaciers based on a 500 m bin is summarized in Table 4.4, and shown graphically for the individual sub-basins using a 100 m bin in Figure 4.2. Approximately 80% of the glacier area was found in the elevation range 5,000 to 6,500 masl in all decades with the greater part (65%) between 5,000 and 6,000 masl (Table 4.4). The glacier area decreased in all bands in all decades, with the greatest loss in area between 5,000 and 6,000 masl (823 km$^2$ between ~1980 and 2010; 24% of the total in the band and 65% of the total loss). Proportionately, the highest loss – one-third of the original area – was observed in the 4,500–5,000 masl band.

The glacier hypsography for the four decades shows the decrease in glacier area. The minimum elevation of a glacier terminus rose from 3,159 to 3,282 masl (Figure 4.2, Table 4.1). After 1990, there were no significant changes in total glacier area at elevations above 5,800 masl (Figure 4.2)

Table 4.4: **Area elevation distribution of glaciers in Nepal in ~1980, 1990, 2000, and 2010**

| Elevation zone (masl) | Glacier area | | | | Glacier area change | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ~1980 | 1990 | 2000 | 2010 | ~1980–1990 | | 1990–2000 | | 2000–2010 | | ~1980–2010 | |
| | | | | | km$^2$ | % | km$^2$ | % | km$^2$ | % | km$^2$ | % |
| 3,000–3,500 | 2.4 | 1.9 | 2 | 1.9 | -0.5 | -20.8 | 0.1 | 5.3 | -0.1 | -5 | -0.5 | -20.8 |
| 3,500–4,000 | 26.5 | 22.9 | 21.8 | 20.2 | -3.7 | -13.6 | -1 | -4.8 | -1.6 | -7.3 | -6.3 | -23.8 |
| 4,000–4,500 | 128 | 113.5 | 106.1 | 97.7 | -14.5 | -11.3 | -7.4 | -6.5 | -8.5 | -7.9 | -30.3 | -23.7 |
| 4,500–5,000 | 548.5 | 479.1 | 412.2 | 364.1 | -69.4 | -12.7 | -66.9 | -14 | -48.1 | -11.7 | -184.4 | -33.6 |
| 5,000–5,500 | 1,702.9 | 1,494.3 | 1,368.2 | 1,252.4 | -208.6 | -12.2 | -126.1 | -8.4 | -115.8 | -8.5 | -450.5 | -26.5 |
| 5,500–6,000 | 1,697.2 | 1,477.6 | 1,405.2 | 1,324.8 | -219.6 | -12.9 | -72.4 | -4.9 | -80.4 | -5.7 | -372.4 | -21.9 |
| 6,000–6,500 | 733.2 | 626.8 | 610.8 | 574.8 | -106.4 | -14.5 | -16 | -2.6 | -36 | -5.9 | -158.4 | -21.6 |
| 6,500–7,000 | 230.9 | 202.9 | 201.1 | 189.3 | -2 | -12.1 | -1.8 | -0.9 | -11.8 | -5.9 | -41.6 | -18 |
| 7,000–7,500 | 78.6 | 69 | 67.5 | 62.8 | -9.6 | -12.2 | -1.5 | -2.2 | -4.7 | -7 | -15.8 | -20.1 |
| 7,500–8,000 | 18.4 | 15 | 14.7 | 13.3 | -3.4 | -18.5 | -0.3 | -2 | -1.4 | -9.5 | -5.1 | -27.7 |
| 8,000–8,500 | 1.5 | 0.8 | 0.9 | 0.7 | -0.7 | -46.7 | 0.1 | 12.5 | -0.2 | -22.2 | -0.8 | -53.3 |
| **Total** | **5,168.3** | **4,506.3** | **4,210.9** | **3,902.4** | **-662.0** | **-12.8** | **-295.5** | **-6.6** | **-308.5** | **-7.3** | **-1265.9** | **-24.5** |

Figure 4.2: **The 100 m bin area-elevation distribution of glaciers in Nepal in ~1980, 1990, 2000, and 2010**

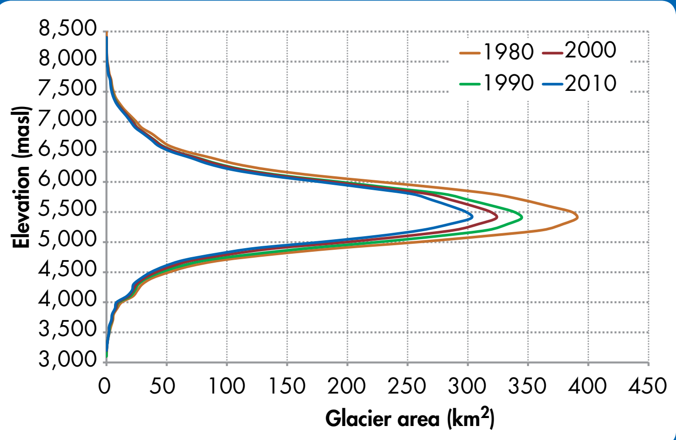
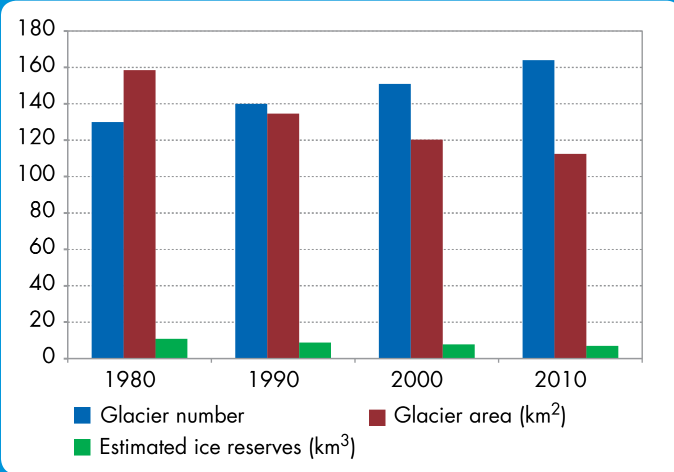



Figure 4.3: **Glacier number, area, and estimated ice reserves in the Mahakali basin in 1980, 1990, 2000, and 2010**




# Decadal Glacier Changes in Individual River Basins

## The Mahakali basin

### Number, area, and estimated ice reserves

The glacier number, area, and estimated ice reserves in the Mahakali basin in the four different time periods are summarized in Table 4.5 and shown graphically in Figure 4.3. The number of glaciers increased by 26% (34) over the 30-year period, with the greatest increase between 2000 and 2010. The glacier area decreased by 29% (46 $km^2$) and the estimated ice reserves by 36% (4 $km^3$), with the greatest change between ~1980 and 1990.

### Glacier area classes

The changes in the number and area of glaciers within the different size classes in the Mahakali basin are given in Annex 2 (Table A2.14). Briefly, the number of glaciers in the smallest class 1a increased in all decades; in the next smallest class 1b they increased overall, but an increase in the first two decades was followed by a decrease between 2000 and 2010. In all larger classes, the number of glaciers remained constant or decreased in all decades, except for class 2, which also showed a small increase between 2000 and 2010, but a greater decrease in the preceding two decades. There were three large class 5 glaciers ($\geq$10 $km^2$) in ~1980, but there was only one by 2010. The total area of class 1a glaciers increased from 1.2 to 2.5 $km^2$, whereas the area of all larger classes decreased overall, with losses in area of 70%, 40%, 1%, 18%, and 8% for classes 5, 4, 3, 2 and 1b glaciers, respectively.

Table 4.5: **Status and change in glaciers in the Mahakali basin in ~ 1980, 1990, 2000, and 2010**

| Glacier | Decade (year) | | | | Decadal glacier change | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ~1980 | 1990 | 2000 | 2010 | ~1980–1990 | | 1990–2000 | | 2000–2010 | | ~1980–2010 | |
| Number | 130 | 140 | 151 | 164 | 10 | 8% | 11 | 8% | 13 | 9% | 34 | 26% |
| Area ($km^2$) | 158 | 135 | 120 | 113 | -24 | -15% | -14 | -11% | -8 | -6% | -46 | -29% |
| Estimated ice reserves ($km^3$) | 11 | 9 | 8 | 7 | -2 | -19% | -1 | -12% | -1 | -11% | -4 | -36% |

## Glacier aspect

The Mahakali basin has an elongated north-south orientation, and the majority of glaciers have a west facing aspect. Details of the number and area of glaciers with different aspects are given in Annex 2 (Table A2.15). Briefly, the number of glaciers increased for all aspects, except north, east, and south, which showed very small reductions. In contrast, the glacial area decreased for all aspects except northwest, which showed a marked increase, with the greatest losses for the west aspect.

## Glacier slope

The majority of glaciers in the Mahakali basin had mean slopes between 20° and 50°, and most commonly between 30° and 40°, with the greatest area for slopes of 20–30°. There were no glaciers with slopes of less than 10° or more than 60°. Details of the changes in the number and area of glaciers of different slope over the three decades are provided in Annex 2 (Table A2.16). Briefly, between 1980 and 2010, the overall glacier number remained constant or increased for all ranges of slope, although a few showed losses in individual decades which were offset by increases in other decades. The greatest increase in number was for glaciers with slopes of 40–50°. In contrast, the glacier area decreased for glaciers with slopes from 20–50°, and increased slightly in the remaining slope ranges, with the greatest decrease for glaciers with slopes of 30–40°.

## Glacier types

The Mahakali basin contained glaciers of all types except 'miscellaneous'. Details of the changes in the number and area of glaciers of different type over the three decades are provided in Annex 2 (Table A2.17). Briefly, between 1980 and 2010, the number of glaciers of all types increased, except for cirque and niche glaciers, which showed a small decrease, and valley trough type glaciers, which showed no change. Mountain basin type glaciers showed the greatest increase (from 65 to 88). All types of glacier showed a reduction in area in all decades, with the greatest loss in valley basin type glaciers (23 km$^2$, from 79 to 56 km$^2$).

## Glacier area-elevation distribution

The area-elevation distribution of the glaciers in the Mahakali basin in the different decades based on a 500 m bin is summarized in Table 4.6, and shown graphically using a 100 m bin in Figure 4.4. Glaciated areas were found from 3,695 to 6,850 masl, with more than 90% of the total in the elevation range from 4,000 to 6,000 masl in all decades, the greater part (68%) between 4,500 and 5,500 masl (Table 4.6). Essentially, the glacier area decreased in all bands in all decades, with the greatest loss in area between 5,000 and 5,500 masl (35 km$^2$ between 1980 and 2010; 29% of the total in the band and 35% of the total in the basin).

Table 4.6: **Area elevation distribution of glaciers in the Mahakali basin in 1980, 1990, 2000, and 2010**

| Elevation zone (masl) | Glacier area | | | | Glacier area change | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ~1980 | 1990 | 2000 | 2010 | ~1980–1990 | | 1990–2000 | | 2000–2010 | | ~1980–2010 | |
| | km$^2$ | | | | km$^2$ | % | km$^2$ | % | km$^2$ | % | km$^2$ | % |
| 3,000–3,500 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3,500–4,000 | 2.3 | 2 | 1.9 | 1.6 | -0.3 | -13 | -0.1 | -5 | -0.3 | -15.8 | -0.7 | -30.4 |
| 4,000–4,500 | 18.9 | 17.9 | 17.1 | 15.2 | -1.0 | -5.3 | -0.9 | -4.5 | -1.8 | -11.1 | -3.7 | -19.6 |
| 4,500–5,000 | 42.1 | 36.7 | 30 | 27 | -5.4 | -12.8 | -6.7 | -18.3 | -3 | -10 | -15.1 | -35.9 |
| 5,000–5,500 | 56.9 | 47.2 | 42.9 | 40.6 | -9.7 | -17 | -4.3 | -9.1 | -2.3 | -5.4 | -16.3 | -28.6 |
| 5,500–6,000 | 29.1 | 22.9 | 20.9 | 20.7 | -6.2 | -21.3 | -2 | -8.7 | -0.2 | -1 | -8.4 | -28.9 |
| 6,000–6,500 | 7.8 | 6.6 | 6.3 | 6.1 | -1.2 | -15.4 | -0.3 | -4.5 | -0.2 | -3.2 | -1.7 | -21.8 |
| 6,500–7,000 | 1.5 | 1.3 | 1.2 | 1.3 | -0.2 | -13.3 | -0.2 | -7.7 | +0.1 | 8.3 | -0.2 | -13.3 |
| 7,000–7,500 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7,500–8,000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Total** | **158.5** | **134.6** | **120.3** | **112.5** | **23.9** | **-15.1** | **14.3** | **-10.6** | **7.8** | **-6.5** | **45.9** | **-29** |

## The Karnali basin

### Number, area, and estimated ice reserves

The glacier number, area, and estimated ice reserves in the Karnali basin in the four different time periods are summarized in Table 4.7 and shown graphically in Figure 4.5. The number of glaciers increased by 6% (88) over the 30-year period, with the greatest increase between 1990 and 2000. The glacier area decreased by 26% (363 km²) and the estimated ice reserves by 30% (26 km³), with the greatest change between 1980 and 1990 and least between 2000 and 2010.

### Glacier area classes

Details of the changes in the number and area of glaciers within the different size classes are provided in Annex 2 (Table A2.18). Briefly, the number of glaciers in the smallest class 1a increased in all decades, with the greatest increase between 1990 and 2000, while the number in class 1b only increased between 1980 and 1990, decreasing thereafter but by less than the initial increase. In all larger classes, the number of glaciers decreased (or remained constant) in all decades. The number of class 5 glaciers was reduced by two (from 12 to 10). The total area of class 1a glaciers increased in all decades (from 6.5 to 22.0 km²), whereas the area of all larger classes decreased overall, with losses in area of 7%, 20%, 33%, 40% and 23% for classes 1a, 2, 3, 4, and 5, respectively.

Figure 4.4: **The 100 m bin area-elevation distribution of glaciers in the Mahakali basin in 1980, 1990, 2000, and 2010**

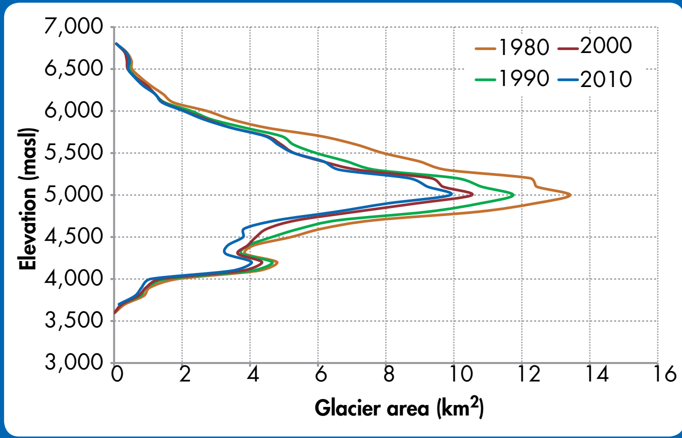
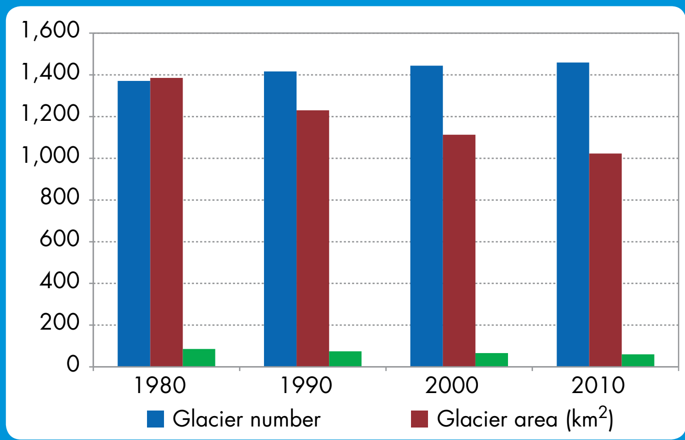



Figure 4.5: **Glacier number, area, and estimated ice reserves in the Karnali basin in 1980, 1990, 2000, and 2010**




### Glacier aspect

Details of the changes in the number and area of glaciers with different aspects are given in Annex 2 (Table A2.19). Briefly, the number of glaciers increased for all aspects, except southeast, which showed a reduction in 1980–1990 and 1990–2000, and south, which showed a reduction in all decades. In contrast, the glacier area decreased for all aspects except north and northwest, which showed a slight increase, with the greatest losses for the southeast and south aspects.

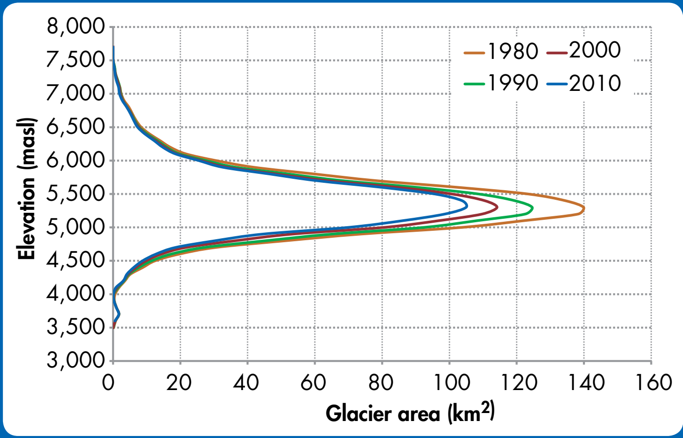
### Glacier slope

The majority of glaciers in the Karnali basin had mean slopes between 20° and 40°, with the greatest number and area for slopes of 20–30°. Details of the changes in the number and area of glaciers of different slope over the

Table 4.7: **Status and change in glaciers in the Karnali basin in 1980, 1990, 2000, and 2010**

| Glacier | Decade (year) | | | | Decadal glacier change | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ~1980 | 1990 | 2000 | 2010 | ~1980–1990 | | 1990–2000 | | 2000–2010 | | ~1980–2010 | |
| Number | 1,371 | 1,416 | 1,444 | 1,459 | +45 | +3% | +28 | +2% | +15 | +1% | +88 | +6% |
| Area (km²) | 1,385 | 1,230 | 1,113 | 1,023 | -155 | -11% | -117 | -10% | -90 | -8% | -363 | -26% |
| Estimated ice reserves (km³) | 86 | 74 | 66 | 60 | -11 | -13% | -8 | -11% | -6 | -10% | -26 | -30% |

Figure 4.6: **The 100 m bin area-elevation distribution of glaciers in the Karnali basin in 1980, 1990, 2000, and 2010**




three decades are provided in Annex 2 (Table A2.20). Briefly, between 1980 and 2010, the overall glacier number decreased for glaciers of slope 20–30° (from 629 to 586) and increased for all other ranges of slope (although a few showed losses in individual decades which were offset by increases in other decades). The greatest increase in number was for glaciers with slopes of 10–20°. In contrast, the glacier area decreased for glaciers with slopes from 20–60°, and increased slightly in the remaining slope ranges, with the greatest decrease for glaciers with slopes of 20–30° (from 790 to 485 km²). There were no glaciers with slopes of >60°.

## Glacier types

The Karnali basin contains glaciers of all types. Details of the changes in the number and area of glaciers of different types over the three decades are provided in Annex 2 (Table A2.21). Briefly, between 1980 and 2010, the number of mountain niche and basin type glaciers increased, whereas the number of all other types remained constant, except cirque glaciers which decreased from five to four. Mountain basin type glaciers showed the greatest increase (from 979 to 1,060). All types of glacier showed a reduction in area in all decades (except cirque glaciers which showed a very small increase between 2000 and 2010), with the greatest losses between 1980 and 1990. Mountain basin type glaciers lost the most area over the 30 years (285 km², from 1,084 to 799 km²) followed by valley type glaciers (32 km², from 203 to 171 km²).

## Glacier area-elevation distribution

The area-elevation distribution of the glaciers in the Karnali basin in the different decades based on a 500 m bin is summarized in Table 4.8, and shown graphically using a 100 m bin in Figure 4.6. Glaciated areas were found from 3,631 to 7,541 masl in 2010, with 73% of the total in the elevation range from 5,000 to 6,000 masl in all decades, The glacier area decreased in all bands in all decades, with the greatest loss in area between 5,000 and 5,500 masl (175 km² between 1980 and 2010; 27% of total in band and 48% of total in basin). The reduction in area was most marked between 1980 and 1990.

Table 4.8: **Area elevation distribution of glaciers in the Karnali basin in 1980, 1990, 2000, and 2010**

| Elevation zone | Glacier area | | | | Glacier area change | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ~1980 | 1990 | 2000 | 2010 | ~1980–1990 | | 1990–2000 | | 2000–2010 | | ~1980–2010 | |
| | km² | | | | km² | % | km² | % | km² | % | km² | % |
| 3,000–3,500 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3,500–4,000 | 4.1 | 3.9 | 3.7 | 3.5 | -0.2 | -4.9 | -0.2 | -5.1 | -0.2 | -5.4 | -0.6 | -14.6 |
| 4,000–4,500 | 19.9 | 17.3 | 15.6 | 14.3 | -2.6 | -13.1 | -1.7 | -9.8 | -1.3 | -8.3 | -5.6 | -28.1 |
| 4,500–5,000 | 187.4 | 165.9 | 135.4 | 114.9 | -21.5 | -11.5 | -30.5 | -18.4 | -20.5 | -15.1 | -72.5 | -38.7 |
| 5,000–5,500 | 638.3 | 567.1 | 511.7 | 463.4 | -71.2 | -11.2 | -55.4 | -9.8 | -48.3 | -9.4 | -174.9 | -27.4 |
| 5,500–6,000 | 405.4 | 355.4 | 331.1 | 315.1 | -50 | -12.3 | -24.3 | -6.8 | -16 | -4.8 | -90.3 | -22.3 |
| 6,000–6,500 | 94.1 | 86.4 | 82.8 | 80.5 | -7.7 | -8.2 | -3.6 | -4.2 | -2.3 | -2.8 | -13.6 | -14.5 |
| 6,500–7,000 | 28.9 | 26.9 | 26.2 | 25.4 | -2 | -6.9 | -0.7 | -2.6 | -0.8 | -3.1 | -3.6 | -12.1 |
| 7,000–7,500 | 7 | 6.9 | 6.3 | 5.4 | -0.1 | -1.4 | -0.6 | -8.7 | -0.9 | -14.3 | -1.6 | -22.9 |
| 7,500–8,000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Total** | **1,385.4** | **1,230.1** | **1,113.1** | **1,022.8** | **-155.3** | **-11.2** | **-117.0** | **-9.5** | **-90.3** | **-8.1** | **-362.6** | **-26.2** |

Table 4.9: **Status and change in glaciers in the Gandaki basin in 1980, 1990, 2000, and 2010**

| Glacier | Decade (Year) | | | | Decadal glacier change | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ~1980 | 1990 | 2000 | 2010 | ~1980–1990 | | 1990–2000 | | 2000–2010 | | ~1980–2010 | |
| Number | 1193 | 1294 | 1341 | 1340 | +101 | +8% | +47 | +4% | -1 | -0% | +147 | +12% |
| Area (km²) | 2125 | 1847 | 1765 | 1664 | -278 | -13% | -82 | -4% | -100 | -6% | -461 | -22% |
| Estimated ice reserves (km³) | 186 | 153 | 145 | 135 | -32 | -18% | -8 | -5% | -10 | -7% | -51 | -27% |

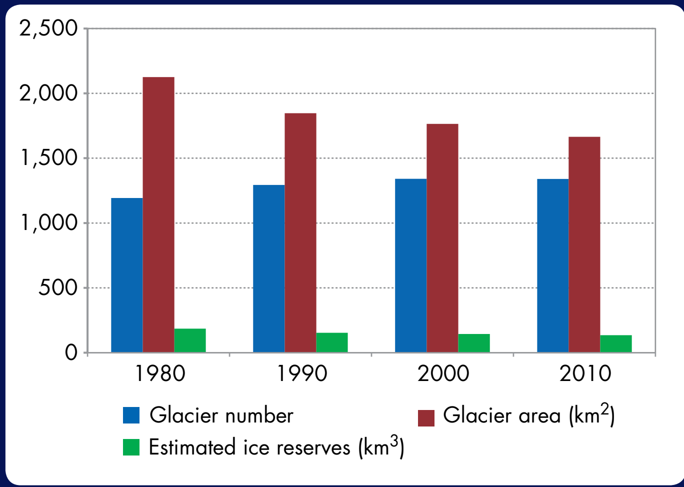
## The Gandaki basin

### Number, area, and estimated ice reserves

The glacier number, area, and estimated ice reserves in the Gandaki basin in the four different time periods are summarized in Table 4.9 and shown graphically in Figure 4.7. The number of glaciers increased by 12% (147) over the 30-year period, with the greatest increase between 2000 and 2010. The glacier area decreased by 22% (461 km²) and the estimated ice reserves by 27% (51 km³), with the greatest change between 1980 and 1990.

Repeat satellite images from the different decades show that the increase in glacier number is associated with the loss of area of mountain glaciers and recession of valley glaciers, and resultant fragmentation. Examples are shown in Figures 4.8 and 4.9.

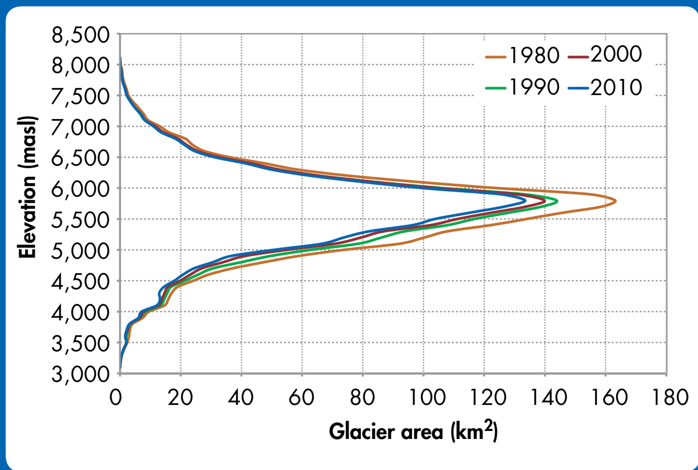
Figure 4.7: **Glacier number, area, and estimated ice reserves in the Gandaki basin in 1980, 1990, 2000, and 2010**




### Glacier area classes

Details of the changes in the number and area of glaciers within the different size classes are provided in Annex 2 (Table A2.22). Briefly, the number of glaciers in the smallest classes 1a and 1b increased in all decades with the greatest increase between 1980 and 1990. In all larger classes, the number of glaciers remained constant or decreased in all decades, except for class 4, which showed a small increase between 1990 and 2000, but a greater decrease in the other two decades. The total area of class 1a and 1b glaciers increased in all decades (from 3.1 to 13.6 km² and 142 to 160 km², respectively) whereas the area of all larger classes decreased overall, with losses in area of 21%, 24%, 27%, and 25% for classes 2, 3, 4, and 5, respectively.

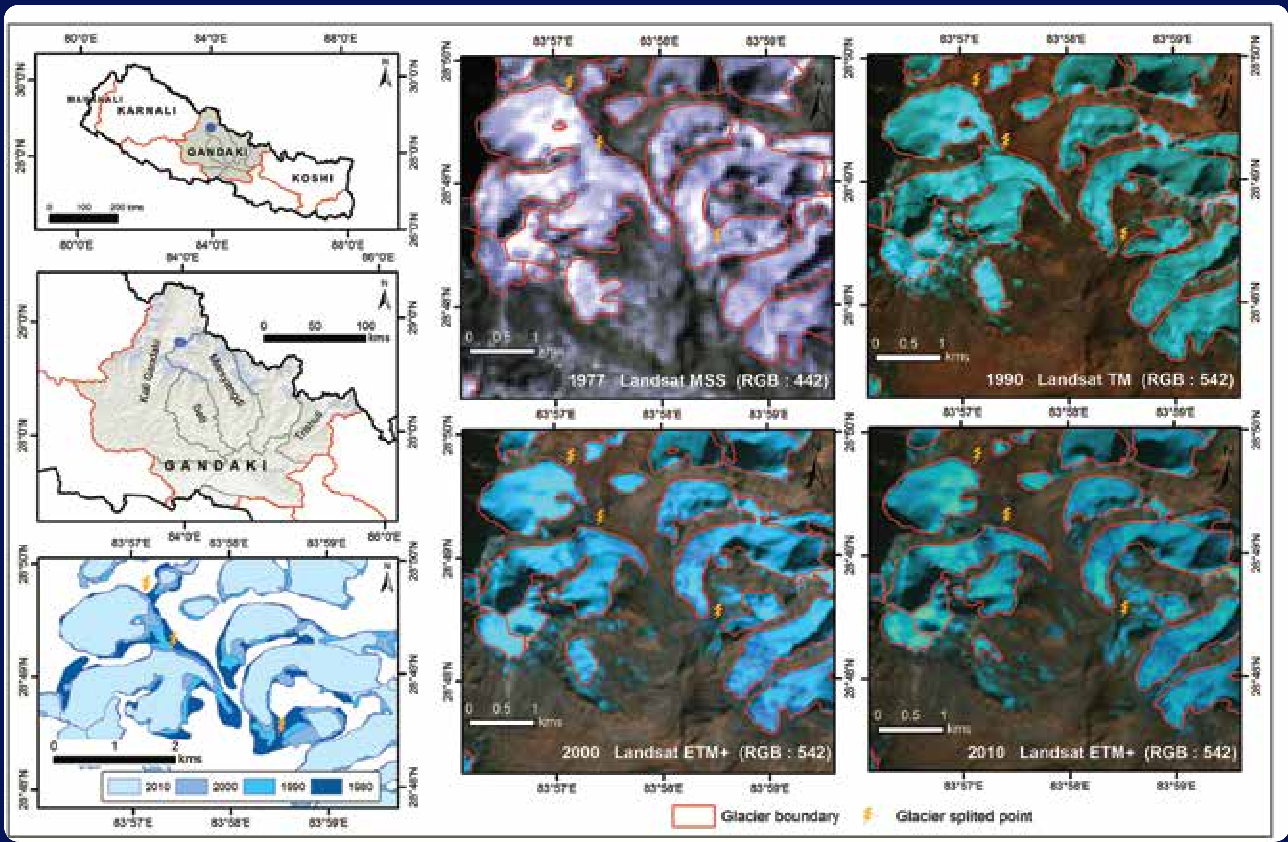
Figure 4.8: **The 100 m bin area-elevation distribution of glaciers in the Gandaki basin in 1980, 1990, 2000, and 2010**




### Glacier aspect

Details of the change in the number and area of glaciers with different aspects are given in Annex 2 (Table A2.23). Briefly, the number of glaciers increased for all aspects, except southeast, which showed a reduction in all decades. In contrast, the glacial area decreased for all aspects except north and northwest, which showed a slight increase, with the greatest losses for the southeast and south aspects. There were no glaciers with a north aspect in the 1980s, but two glaciers changed to a mean north aspect in the 1990s, with an additional four in 2000, followed by a loss of four in 2010.

Figure 4.9: **Loss of glacial area and subsequent fragmentation of mountain glaciers in the Marsyangdi sub-basin of Gandaki basin. Flash symbol shows the position of fragmentation**




## Glacier slope

The majority of glaciers in the Gandaki basin have mean slopes between 20° and 40°, with the greatest number and area for slopes of 20–30°. Details of the changes in the number and area of glaciers of different slope over the three decades are provided in Annex 2 (Table A2.24). Briefly, between 1980 and 2010, the overall glacier number increased for all ranges of slope, although a few showed losses in individual decades which were offset by increases in other decades. The greatest increase in number was for glaciers with slopes of 10–20°. In contrast, the glacier area decreased for glaciers with slopes from 20–60°, and increased slightly in the remaining slope ranges, with the greatest decrease for glaciers with slopes of 30–40°. There were no glaciers with slopes of >60° in 1980, but by 2010 there were six.

## Glacier types

The Gandaki basin contains glaciers of all types. Details of the changes in the number and area of glaciers of different type over the three decades are provided in Annex 2 (Table A2.25). Briefly, between 1980 and 2010, the number of glaciers of all types increased, except for cirque and miscellaneous glaciers, which showed a small decrease, and valley type glaciers, which showed no change. Mountain basin type glaciers showed the greatest increase (from 711 to 797), followed by ice apron type. All types of glacier showed a reduction in area in all decades, with the greatest losses between 1980 and 1990. Mountain basin type glaciers lost the most area over the 30 years (260 $km^2$, from 1,234 to 974 $km^2$) followed by valley trough type glaciers (144 $km^2$, from 675 to 532 $km^2$).

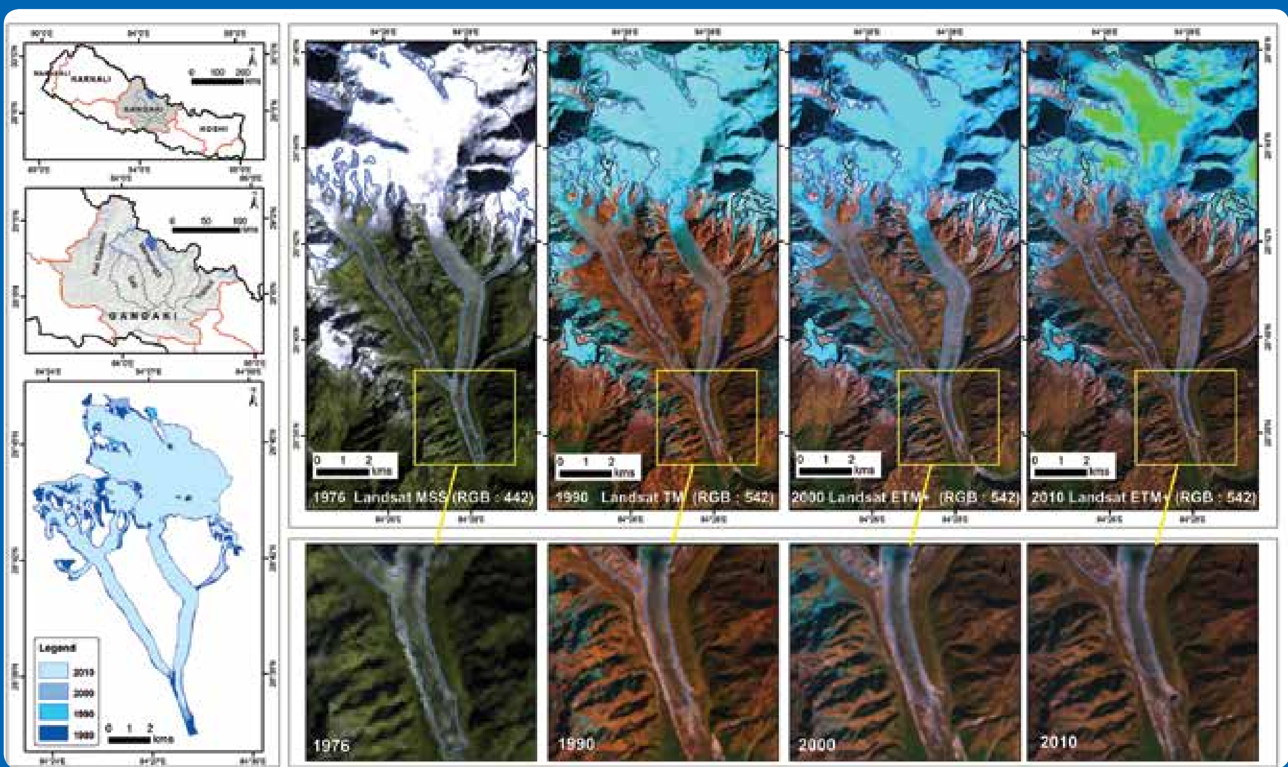
## Glacier area-elevation distribution

The area-elevation distribution of the glaciers in the Gandaki basin in the different decades based on a 500 m bin is summarized in Table 4.9, and shown graphically using a 100 m bin in Figure 4.10. Glaciated areas were found from 3,282 to 8,101 masl in 2010, with close to 76% of the total in the elevation range from 5,000 to 6,500 masl in all decades, the greater part (33%) between 5,500 and 6,000 masl (Table 4.9). Essentially, the glacier area decreased in all bands in all decades (with some minor exceptions between 1990 and 2000 at the highest altitudes), with the greatest loss in area between 5,500 and 6,000 masl (152 km² between 1980 and 2010; 20% of the total in the band and 33% of the total in the basin).The reduction in area was most marked between 1980 and 1990.

Table 4.9: **Area elevation distribution of glaciers in the Gandaki basin in 1980, 1990, 2000, and 2010**

| Elevation zone | Glacier area | | | | Glacier area change | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ~1980 | 1990 | 2000 | 2010 | ~1980–1990 | | 1990–2000 | | 2000–2010 | | ~1980–2010 | |
| | km² | | | | km² | % | km² | % | km² | % | km² | % |
| 3,000–3,500 | 2.4 | 1.9 | 2 | 1.9 | -0.5 | -20.8 | 0 | 5.3 | -0.1 | -5 | -0.5 | -20.8 |
| 3,500–4,000 | 20.1 | 17 | 16.2 | 15.2 | -3.1 | -15.4 | -0.8 | -4.7 | -1 | -6.2 | -4.9 | -24.4 |
| 4,000–4,500 | 76 | 68.6 | 64.6 | 59.7 | -7.4 | -9.7 | -4 | -5.8 | -4.9 | -7.6 | -16.3 | -21.4 |
| 4,500–5,000 | 196.4 | 167.1 | 145 | 130.1 | -29.3 | -14.9 | -22.1 | -13.2 | -14.9 | -10.3 | -66.3 | -33.8 |
| 5,000–5,500 | 496.1 | 429.1 | 394.5 | 369.4 | -67 | -13.5 | -34.6 | -8.1 | -25.1 | -6.4 | -126.7 | -25.5 |
| 5,500–6,000 | 756.4 | 660.5 | 637.8 | 604.4 | -95.9 | -12.7 | -22.7 | -3.4 | -33.4 | -5.2 | -152 | -20.1 |
| 6,000–6,500 | 403.8 | 350.1 | 349.5 | 334.2 | -53.7 | -13.3 | -0.6 | -0.2 | -15.3 | -4.4 | -69.6 | -17.2 |
| 6,500–7,000 | 125.6 | 111.8 | 113.6 | 108.9 | -13.8 | -11 | +1.8 | 1.6 | -4.7 | -4.1 | -16.7 | -13.3 |
| 7,000–7,500 | 40.5 | 34.8 | 35.3 | 34.6 | -5.7 | -14.1 | +0.5 | 1.4 | -0.7 | -2 | -5.9 | -14.6 |
| 7,500–8,000 | 7.9 | 6.2 | 6.3 | 5.8 | -1.7 | -21.5 | +0.1 | 1.6 | -0.5 | -7.9 | -2.1 | -26.6 |
| 8,000–8,500 | 0.2 | 0.1 | 0.1 | 0.1 | -0.1 | -50 | 0 | 0 | 0 | 0 | -0.1 | -50 |
| **Total** | **2,125.5** | **1,847.4** | **1,764.9** | **1,664.4** | **278.1** | **-13.1** | **-82.5** | **-4.5** | **-100. 5** | **-5.7** | **-461.0** | **-21.7** |

Figure 4.10: **Recession and subsequent separation of valley glaciers in the Marsyangdi sub-basin of Gandaki basin**



## The Koshi basin

### Number, area, and estimated ice reserves

The glacier number, area, and estimated ice reserves in the Koshi basin in the four different time periods are summarized in Table 4.10 and shown graphically in Figure 4.11. The number of glaciers increased by 15% (109) over the 30-year period, with the greatest increase between 1980 and 1990. The glacier area decreased by 26% (396 km²) and the estimated ice reserves by 30% (48 km³), with the greatest change between 1980 and 1990.

Repeat satellite images from the different decades show that the increase in glacier number is associated with the loss of area of mountain glaciers and resultant fragmentation. Examples are shown in Figures 4.12 and 4.13.

Table 4.10: **Status and change in glaciers in the Koshi basin in ~1980, 1990, 2000, and 2010**

| Glacier | Decade (year) | | | | Decadal glacier change | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ~1980 | 1990 | 2000 | 2010 | ~1980–1990 | | 1990–2000 | | 2000–2010 | | ~1980–2010 | |
| Number | 736 | 806 | 829 | 845 | +70 | +10% | +23 | +3% | +16 | +2% | +109 | +15% |
| Area (km²) | 1,499 | 1,294 | 1,213 | 1,103 | -205 | -14% | -82 | -6% | -110 | -9% | -396 | -26% |
| Estimated ice reserves (km³) | 159 | 133 | 124 | 111 | -26 | -16% | -9 | -7% | -13 | -11% | -48 | -30% |

Figure 4.11: **Glacier number, area, and estimated ice reserves in the Koshi basin in 1980, 1990, 2000, and 2010**

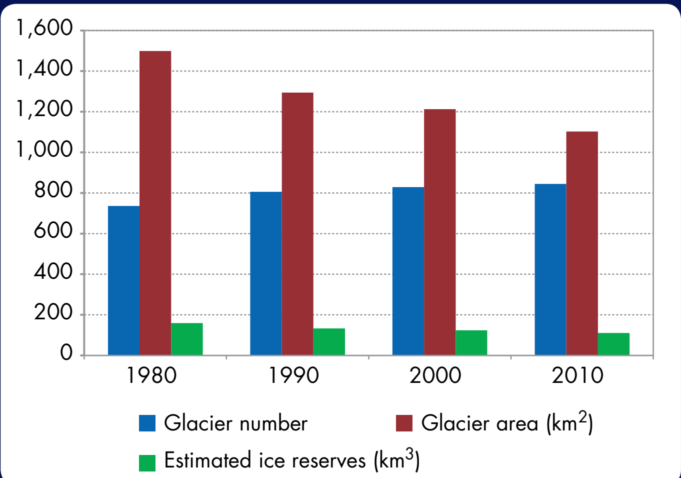
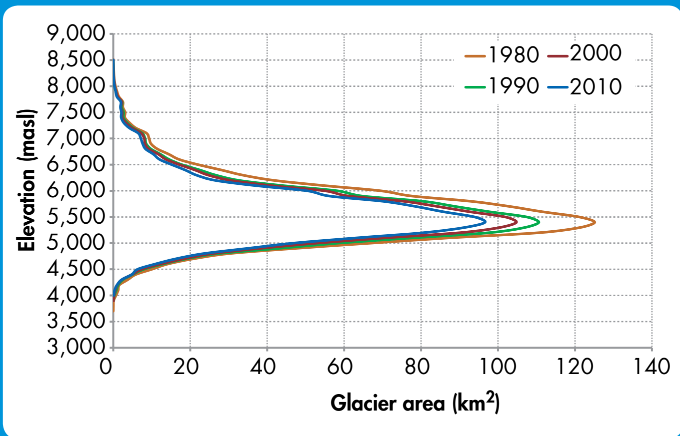


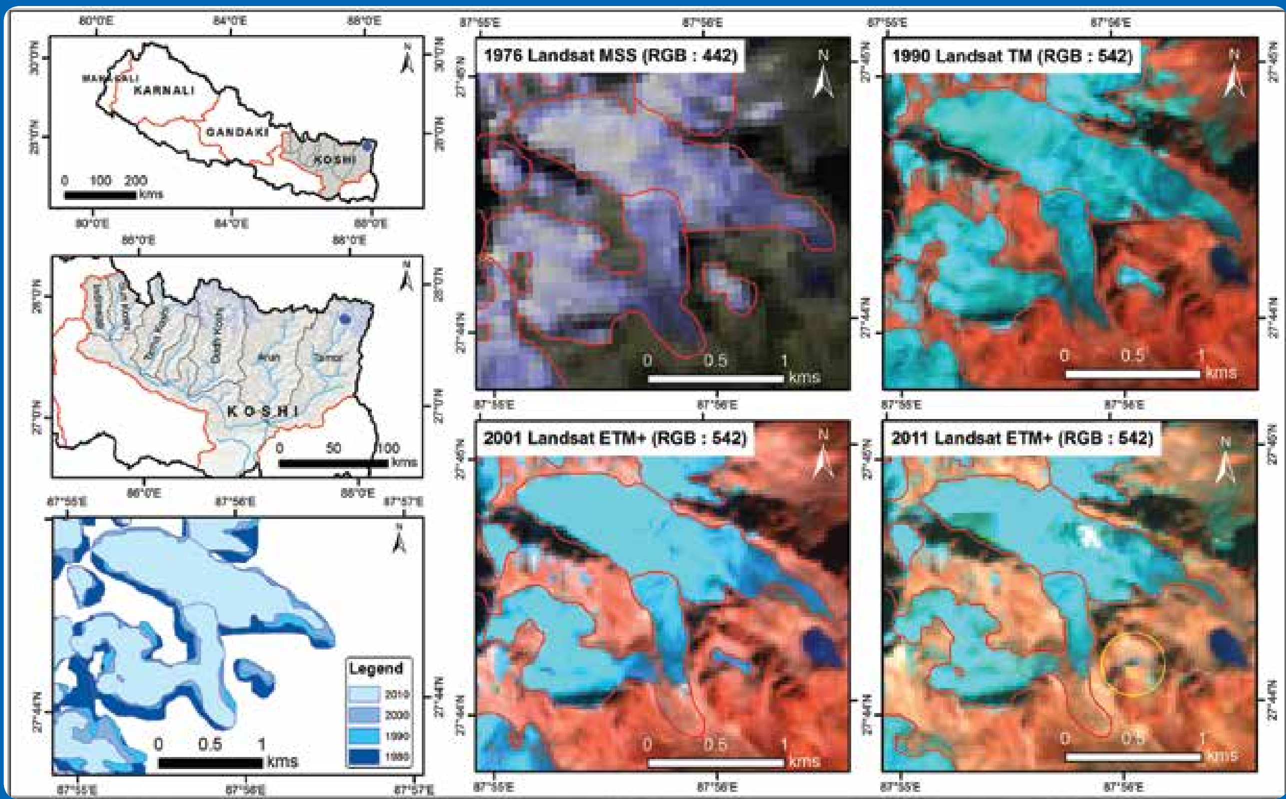

Figure 4.12: **The 100m bin area-elevation distribution of glaciers in the Koshi basin in 1980, 1990, 2000, and 2010**




### Glacier area classes

Details of the changes in the number and area of glaciers within the different size classes are provided in Annex 2 (Table A2.26). Briefly, the number of glaciers in the smallest classes 1a and 1b increased in all decades with the greatest increase between 1980 and 1990. In all larger classes, the number of glaciers decreased in all decades, except for class 4, which showed a very small increase between 1990 and 2000, but a greater decrease in the other two decades. The total area of class 1a glaciers increased in all decades (from 2.4 to 11.2 km²) and of class 1b glaciers in both decades from 1980 to 2000, with a small decrease thereafter. The area of all larger classes decreased overall, with losses in area of 33%, 25%, 30%, and 30% for classes 2, 3, 4, and 5, respectively, and the greatest losses between 1980 and 1990.

Figure 4.13: **Shrinking of glaciers in Tamor sub-basin of Koshi basin. One small mountain glacier shown in the yellow circle has almost disappeared in 2011**




## Glacier aspect

Details of the changes in the number and area of glaciers with different aspects are given in Annex 2 (Table A2.27). Briefly, the number of glaciers increased for all aspects, except southeast, which showed a reduction between 1990 and 2010. In contrast, the glacial area decreased for all aspects except north and northwest, which showed a slight increase, with the greatest losses for the southwest and south aspects.

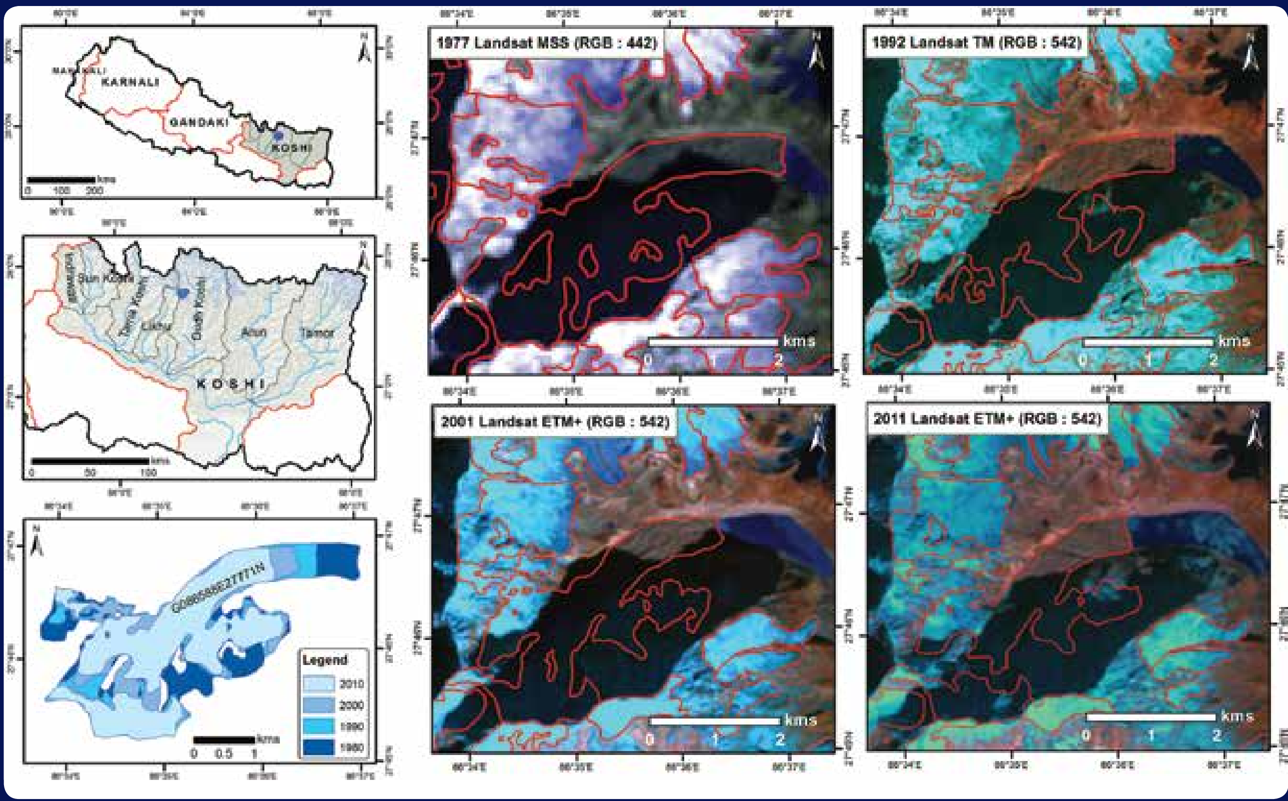
## Glacier slope

The majority of glaciers in the Koshi basin had mean slopes between 20° and 40°, with the greatest number and area for slopes of 20–30°. Details of the changes in the number and area of glaciers of different slope over the three decades are provided in Annex 2 (Table A2.28). Briefly, between 1980 and 2010, the overall glacier number increased for all ranges of slope except 30–40°. The greatest increase in number was for glaciers with slopes of 10–20°. The glacier area decreased for glaciers with slopes from 20–60°, with the greatest decrease for glaciers with slopes of 20–30°. In contrast, the area of glaciers with slopes of 10–20° increased markedly. There were no glaciers with slopes of >60°.

## Glacier types

The Koshi basin contains glaciers of all types. Details of the changes in the number and area of glaciers of different type over the three decades are provided in Annex 2 (Table A2.29). Briefly, between 1980 and 2010, the number of glaciers of all types increased, except for niche glaciers, which decreased by one, and cirque and valley basin type glaciers, which showed no change. Ice apron type glaciers showed the greatest increase (from 183 to 243), followed by mountain basin type. All types of glacier showed a reduction in area in all decades, with the exception of miscellaneous glaciers between 1980 and 1990, with the greatest losses between 1980 and 1990. Mountain basin type glaciers lost the most area over the 30 years (151 km$^2$, from 496 to 345 km$^2$) followed by valley type glaciers (203 km$^2$, from 885 to 682 km$^2$).

Figure 4.14: **Decadal glacier area change of the Lumding glacier and adjacent area in Dudh Koshi sub-basin of Koshi basin**




## Glacier area-elevation distribution

The area-elevation distribution of the glaciers in the Koshi basin in the different decades based on a 500 m bin is summarized in Table 4.11, and shown graphically using a 100 m bin in Figure 4.14. Glaciated areas were found from 4,047 to 8,401 masl in 2010, with more than 80% of the total in the elevation range from 5,000 to 6,500 masl in all decades, the greater part (64%) between 5,000 and 6,000 masl (Table 4.11). Essentially, the glacier area decreased in all bands in all decades (with a minor exception between 1990 and 2000 at the highest altitude), with

Table 4.11: **Area elevation distribution of glaciers in the Koshi basin in 1980, 1990, 2000, and 2010**

| Elevation zone | Glacier area | | | | Glacier area change | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ~1980 | 1990 | 2000 | 2010 | ~1980 – 1990 | | 1990 – 2000 | | 2000 – 2010 | | ~1980 – 2010 | |
| | km² | | | | km² | % | km² | % | km² | % | km² | % |
| 3500– 4000 | 0.1 | 0.1 | 0.1 | 0 | -0.1 | 0 | 0 | 0 | -0.1 | -100 | -0.1 | -100 |
| 4000– 4500 | 13.2 | 9.9 | 8.9 | 8.4 | -3.3 | -25 | -1 | -10.1 | -0.5 | -5.6 | -4.8 | -36.4 |
| 4500– 5000 | 122.5 | 110 | 101.7 | 92 | -12.5 | -10.2 | -8.3 | -7.5 | -9.7 | -9.5 | -30.5 | -24.9 |
| 5000– 5500 | 511.7 | 451.6 | 419.2 | 379 | -60.1 | -11.7 | -32.5 | -7.2 | -40.2 | -9.6 | -132.7 | -25.9 |
| 5500– 6000 | 506.2 | 439.1 | 415.4 | 384.6 | -67.1 | -13.3 | -23.7 | -5.4 | -30.8 | -7.4 | -121.6 | -24 |
| 6000– 6500 | 227.6 | 183.8 | 172.2 | 154 | -43.8 | -19.2 | -11.6 | -6.3 | -18.2 | -10.6 | -73.6 | -32.3 |
| 6500– 7000 | 74.9 | 62.9 | 60.1 | 53.7 | -12 | -16 | -2.8 | -4.5 | -6.4 | -10.6 | -21.2 | -28.3 |
| 7000– 7500 | 31.1 | 27.3 | 25.9 | 22.7 | -3.8 | -12.2 | -1.4 | -5.1 | -3.2 | -12.4 | -8.4 | -27 |
| 7500– 8000 | 10.5 | 8.9 | 8.4 | 7.5 | -1.6 | -15.2 | -0.5 | -5.6 | -0.9 | -10.7 | -3 | -28.6 |
| 8000– 8500 | 1.2 | 0.7 | 0.8 | 0.6 | -0.5 | -41.7 | +0.1 | 14.3 | -0.2 | -25 | -0.6 | -50 |
| **Total** | **1,498.9** | **1,294.2** | **1,212.6** | **1,102.6** | **-204.7** | **-13.7** | **-81.6** | **-6.3** | **-110** | **-9.1** | **396.3** | **-26.4** |

the greatest loss in area between 5,000 and 5,500 masl (133 $km^2$ between 1980 and 2010; 26% of the total in the band and 34% of the total in the basin). The reduction in area was most marked between 1980 and 1990.

## Discussion

The results provide a comprehensive description of the change in status of Nepal's glaciers, both overall and in the individual basins in the period from approximately 1980 to 2010. Although nominally 'decades', it was necessary to use images from other years in order to obtain snow and cloud free views. This may have affected the detailed findings on rate of change, but the trends over the decades are consistent, and the overall change values from 1980 to 2010, prepared using a consistent approach and source, and supported by visual images, can be taken as clear evidence of the changes taking place in Nepal's mountains.

The overall glacier area in Nepal decreased by 24% (1,266 $km^2$) and the estimated ice reserves by 29% (129 $km^3$), while the number of glaciers increased by 11% (378) over the 30-year period. The same pattern was observed in all basins, although with differences reflecting the different elevation, type, and concentration of glaciers in each. The decrease in glacier area accompanied by increase in the number of glaciers is clear evidence of fragmentation as a result of uneven 'shrinking' of individual glaciers. In terms of elevation, the greatest loss of area was in the elevation band 5,000 to 6,000 masl (mainly below 5,800 masl), between 1980 and 1990.

# 5 Case Study: Climate Change Impact on Glaciers in the Langtang and Imja Sub-basins

## Introduction

Glacier recession is one of the key indicators of climate change. Temperature change is considered to be one of the most important factors in glacial retreat, advance, and change in surface area (Raper et al. 2009; Liu et al. 2006; IPCC 2001; Staford et al. 2000), although glacier mass may also be influenced by changes in precipitation, solar radiation, and the presence of surface matter. As the temperature rises, the rate of melting in the lower part of a glacier becomes greater than the rate of accumulation of snow in the upper part. The temperature rise may also lead to a change in precipitation from snowfall to rain, which will also affect the amount of accumulation and rate of melting. As a result of these effects, the glacier will lose mass and may retreat upslope. A recent review estimated the average loss of length of glaciers worldwide to be about 10 m per year (Lemke et al. 2007); with values of 8 to 40 m per year reported in India (Shah et al. 2004; WWF 2005) and 10 to 60 m in the Nepal Himalayas (Yamada et al. 1992; Kadota et al. 2000; Fujita et al. 2001; Bajracharya et al. 2007).

The glaciers in the Nepal Himalayas have shown signs of substantial recession in recent times. To investigate this further, a detailed case study was carried out in the Langtang and Imja valleys of the relationship between average temperature and glacier surface area. The study is described in this chapter. Other factors that affect glacier dynamics such as size, slope, shape, debris cover, and contact with water bodies, as well as energy balance, will be investigated in later studies.

## Study Area

The Langtang valley lies within the Trishuli sub-basin of the Gandaki basin in the central region of Nepal, and the Imja valley lies within the Dudh Koshi sub-basin of the Koshi basin in the eastern region. These valleys were considered particularly suitable for this study because they are heavily glacierized and some long-term climatic data from close by points is available from the Department of Hydrology and Meteorology (DHM) of the Government of Nepal. An analysis of decadal glacier change was carried out in both valleys, with detailed analyses of the Yala, Kimjung, and Lirung Glaciers in Langtang valley and Imja, Lhotse, and East Amadablam glaciers in Imja valley. The basin outlets are near the villages of Kyanjing in the Langtang valley and Dingboche in the Imja valley, which have DHM hydrometeorological stations. The annual, seasonal, and decadal mean temperature was calculated from the daily temperature data provided by DHM. The temperature data was correlated with the individual and total glacier area change in each valley.

## Glacier Change

Glacier area in the different decades was analysed from the outlines in Landsat images from 1976, 1988, 2000, and 2009 for Langtang valley, and 1979, 1992, 2000 and 2010 for Imja valley. The year 1976 was used as the base year for Langtang valley and 1979 for Imja valley for comparison of the decadal variation in glacier area and elevation of the glacier terminus. The results are summarized in Tables 5.1 and 5.2; the glacier outlines are shown in Figures 5.1 and 5.2.

Figure 5.1: **Glaciated area in Langtang valley (inset) and overlay maps of the Lirung, Kimjung, and Yala Glaciers in 1976, 1988, 2000, and 2009**

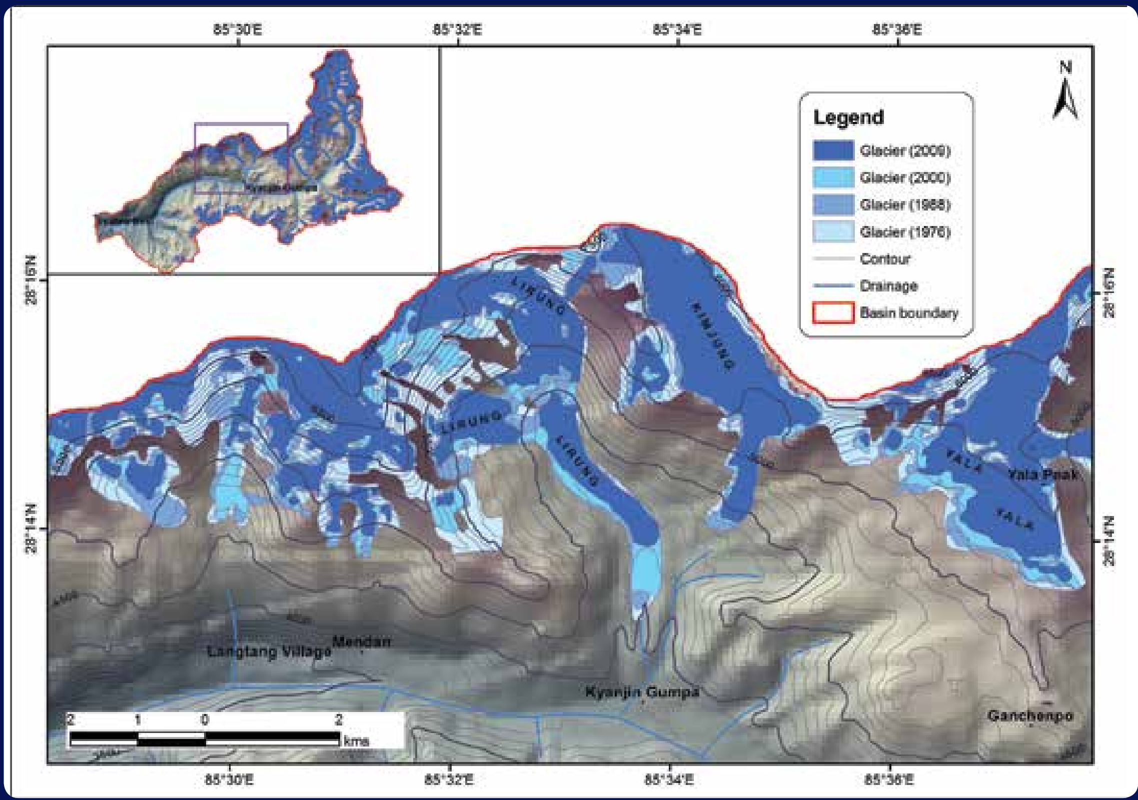



Figure 5.2: **Glaciated area in Imja valley and overlay maps of the Lhotse, Imja and East Amadablam Glaciers in Imja valley in 1979, 1992, 2000, and 2010**

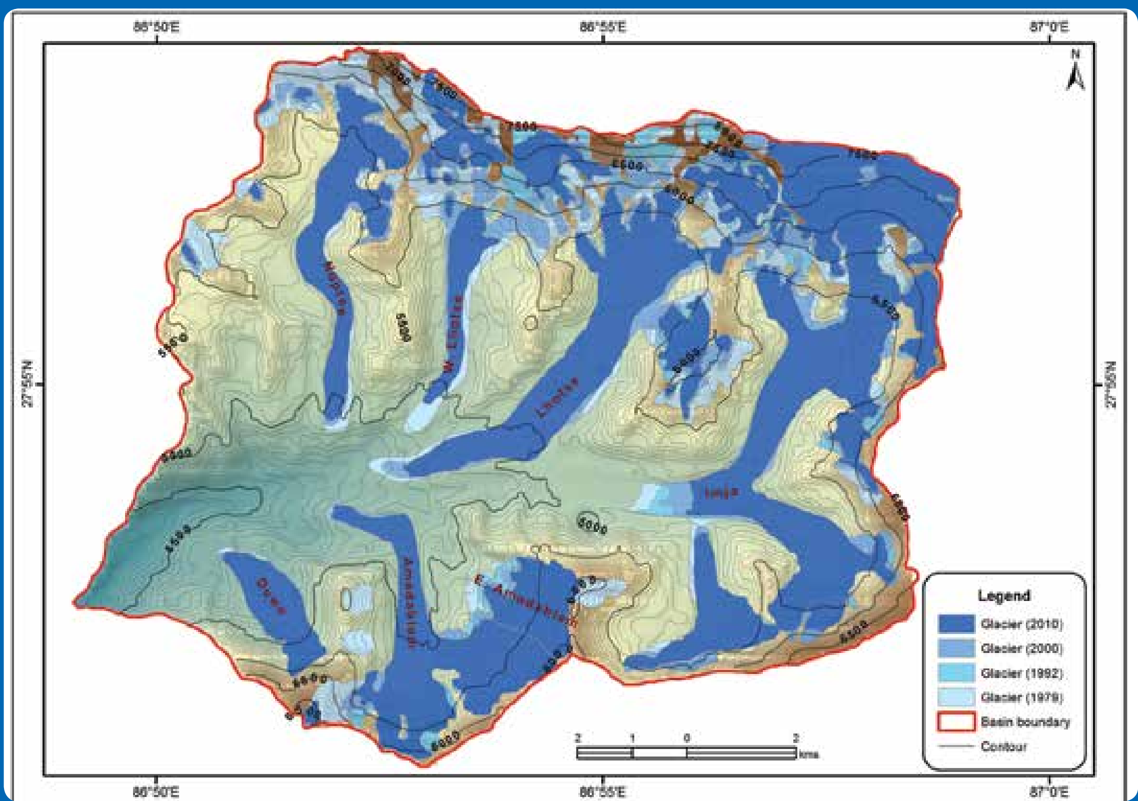


Table 5.1: **Glacier area and elevation from 1976–2009 in Langtang valley**

| Glacier | Year | 1976 | 1988 | 2000 | 2009 |
|---|---|---|---|---|---|
| | No. of years after base year | 0 | 12 | 24 | 33 |
| **All** | Glacier area (km²) | 191.1 | 171.3 | 152.2 | 142.1 |
| | Cumulative area change (km²) | 0 | 19.8 | 38.9 | 49.1 |
| | % area change (from base year 1976) | 0 | 10.4 | 20.4 | 25.7 |
| | % area change (from previous observed year) | 0 | 10.4 | 11.2 | 6.7 |
| | Maximum elevation (masl) | 7,184 | 7,184 | 7,184 | 7,184 |
| | Minimum elevation (masl) | 3,997 | 4,007 | 4,020 | 4,112 |
| | Elevation shift (from base year 1976) (m) | 0 | 10 | 23 | 115 |
| | Elevation shift (from previous observed year) (m) | 0 | 10 | 13 | 92 |
| **Lirung** | Glacier area (km²) | 10 | 7.5 | 7.2 | 5.3 |
| | Cumulative area change (km²) | 0 | 2.5 | 2.8 | 4.7 |
| | % area change (from base year 1976) | 0 | 25.2 | 27.7 | 46.6 |
| | % area change (from previous observed year) | 0 | 25.2 | 3.4 | 26.1 |
| | Maximum elevation (masl) | 7,160 | 7,184 | 7,160 | 7,160 |
| | Minimum elevation (masl) | 3,997 | 4,007 | 4,020 | 4,112 |
| | Elevation shift (from base year 1976) (m) | 0 | 10 | 23 | 115 |
| | Elevation shift (from previous observed year) (m) | 0 | 10 | 13 | 92 |
| **Kimjung** | Glacier area (km²) | 5 | 4.4 | 4.2 | 4.1 |
| | Cumulative area change (km²) | 0 | 0.6 | 0.9 | 1.0 |
| | % area change (from base year 1976) | 0 | 12 | 17.5 | 18.9 |
| | % area change (from previous observed year) | 0 | 12 | 6.3 | 1.6 |
| | Maximum elevation (masl) | 6,633 | 6,504 | 6,337 | 6,433 |
| | Minimum elevation (masl) | 4,313 | 4,313 | 4,399 | 4,426 |
| | Elevation shift (from base year 1976) (m) | 0 | 0 | 86 | 113 |
| | Elevation shift (from previous observed year) (m) | 0 | 0 | 86 | 27 |
| **Yala** | Glacier area (km²) | 5 | 3.5 | 3.1 | 2.4 |
| | Cumulative area change (km²) | 0 | 1.5 | 1.9 | 2.6 |
| | % area change (from base year 1976) | 0 | 29.2 | 38.4 | 51.4 |
| | % area change (from previous observed year) | 0 | 29.2 | 13.1 | 21.1 |
| | Maximum elevation (masl) | 6,452 | 6,522 | 6,522 | 6,522 |
| | Minimum elevation (masl) | 5,079 | 5,067 | 5,111 | 5,171 |
| | Elevation shift (from base year 1976) (m) | 0 | -12 | 32 | 92 |
| | Elevation shift (from previous observed year) (m) | 0 | -12 | 44 | 60 |

Note: Changes in maximum elevation reflect the difficulty of differentiating the glacier boundary at the head from snow in some images.

## Overall area

The glacier outlines shown in Figures 5.1 and 5.2 show clear evidence of a progressive reduction of the glacier area in both valleys over the 30-year period. The cumulative decrease in glacier area is shown in Figure 5.3. The total glacier area decreased from 191 to 142 km² (26%) in Langtang valley and from 63 to 46 km² (27%) in Imja valley – an average rate of loss of 1.49 km²/yr in Langtang valley and 0.57 km²/yr in Imja valley. Overall, the percentage loss was highest between 1988 and 2000 and lowest between 2000 and 2009 in Langtang valley, and highest between 1979 and 1992 and lowest between 1992 and 2000 in Imja valley.

## Individual glacier area

The change in individual glacier area in the two valleys is shown in Figure 5.4.

Table 5.2: **Glacier area and elevation from 1979–2010 in Imja valley**

| Glacier | Year | 1979 | 1992 | 2000 | 2010 |
|---|---|---|---|---|---|
| | No. of years after base year | 0 | 13 | 21 | 31 |
| **All** | Glacier area (km²) | 63.2 | 53.8 | 51.9 | 45.6 |
| | Cumulative area change (km²) | 0 | 9.5 | 11.3 | 17.6 |
| | % area change (from base year 1979) | 0 | 15 | 17.9 | 27.8 |
| | % area change (from previous observed year) | 0 | 15 | 3.4 | 12.1 |
| | Maximum elevation (masl) | 8,427 | 8,329 | 8,329 | 8,057 |
| | Minimum elevation (masl) | 4,675 | 4,689 | 4,689 | 4,728 |
| | Elevation shift (from base year 1979) (m) | 0 | 14 | 14 | 53 |
| | Elevation shift (from previous observed year) (m) | 0 | 14 | 0 | 39 |
| **Imja** | Glacier area (km²) | 21 | 20.1 | 19.4 | 17.6 |
| | Cumulative area change (km²) | 0 | 0.9 | 1.6 | 3.4 |
| | % area change (from base year 1979) | 0 | 4.4 | 7.7 | 16.3 |
| | % area change (from previous observed year) | 0 | 4.4 | 3.4 | 9.3 |
| | Maximum elevation (masl) | 8,329 | 8,329 | 8,329 | 8,057 |
| | Minimum elevation (masl) | 5,002 | 5,002 | 5,013 | 5,019 |
| | Elevation shift (from base year 1979) (m) | 0 | 0 | 11 | 17 |
| | Elevation shift (from previous observed year) (m) | 0 | 0 | 11 | 6 |
| **Lhotse** | Glacier area (km²) | 14.7 | 13.1 | 12.1 | 10.2 |
| | Cumulative area change (km²) | 0 | 1.6 | 2.6 | 4.5 |
| | % area change (from base year 1979) | 0 | 11.2 | 17.6 | 30.5 |
| | % area change (from previous observed year) | 0 | 11.2 | 7.2 | 15.6 |
| | Maximum elevation (masl) | 7,961 | 8,039 | 7,879 | 7,879 |
| | Minimum elevation (masl) | 4,748 | 4,789 | 4,796 | 4,843 |
| | Elevation shift (from base year 1979) (m) | 0 | 41 | 48 | 95 |
| | Elevation shift (from previous observed year) (m) | 0 | 41 | 7 | 47 |
| **East Amadablam** | Glacier area (km²) | 2.4 | 2.2 | 2 | 1.9 |
| | Cumulative area change (km²) | 0 | 0.2 | 0.4 | 0.4 |
| | % area change (from base year 1979) | 0 | 7.8 | 15.3 | 18.8 |
| | % area change (from previous observed year) | 0 | 7.8 | 8.2 | 4.1 |
| | Maximum elevation (masl) | 6,016 | 6,056 | 6,056 | 6,103 |
| | Minimum elevation (masl) | 5,051 | 5,108 | 5,148 | 5,176 |
| | Elevation shift (from base year 1979) (m) | 0 | 57 | 97 | 125 |
| | Elevation shift (from previous observed year) (m) | 0 | 57 | 40 | 28 |

Note: Changes in maximum elevation reflect the difficulty of differentiating the glacier boundary at the head from snow in some images.

## Langtang valley

The Lirung Glacier is a valley glacier with debris cover in the lower reaches, the Yala Glacier is a mountain apron type glacier with clean-ice, and the Kimjung Glacier is a mountain basin type glacier with clean-ice.

In terms of total amount, the Lirung glacier showed the greatest loss and the Kimjung Glacier the least (Figure 5.4a). But the Yala Glacier showed the highest percentage of glacier area loss with 51%, (from 5.0 $km^2$ in 1976 to 2.4 $km^2$ in 2009), followed by the Lirung Glacier with 47% (10.0 $km^2$ to 5.3 $km^2$) and the Kimjung Glacier with 18.9% (5.0 $km^2$ to 4.1 $km^2$) (Table 5.1).

Overall, the percentage loss was highest between 2000 and 2009 for the Lirung Glacier, and 1976 and 1988 for the Kimjung and Yala glaciers.

Figure 5.3: **Total glacier area in different years in the (a) Langtang valley and (b) Imja valley**

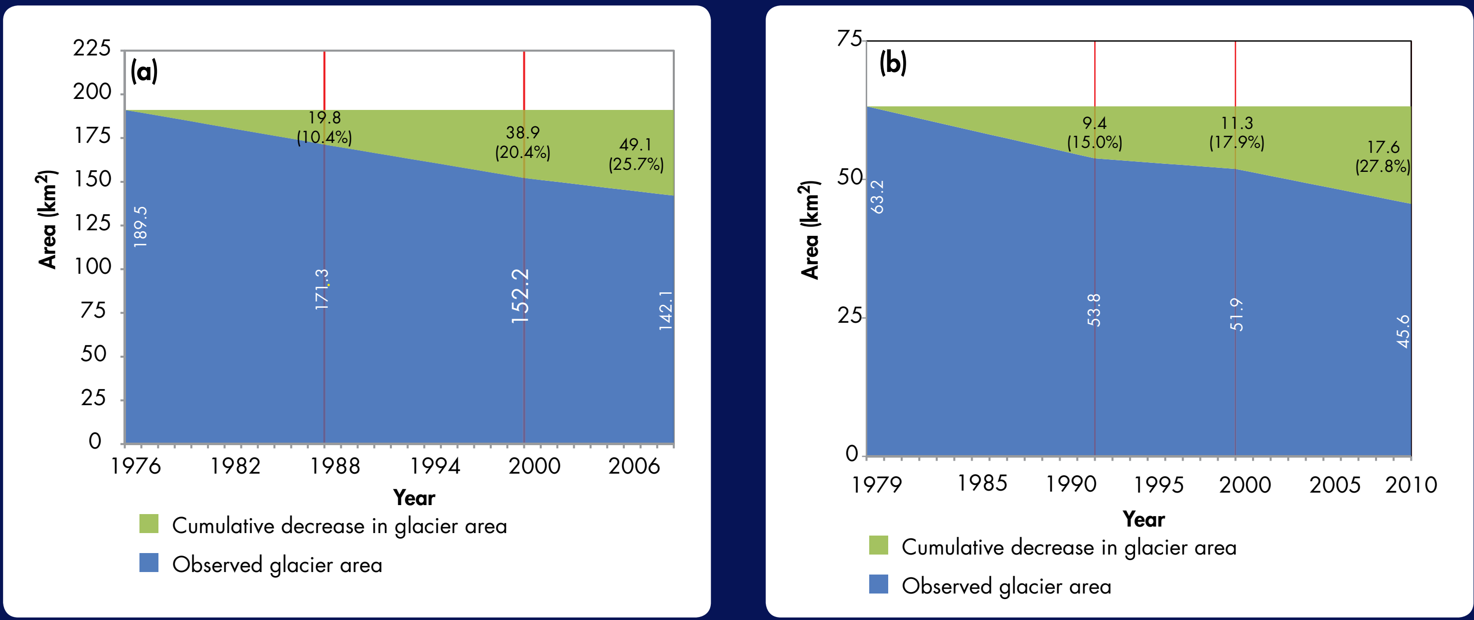
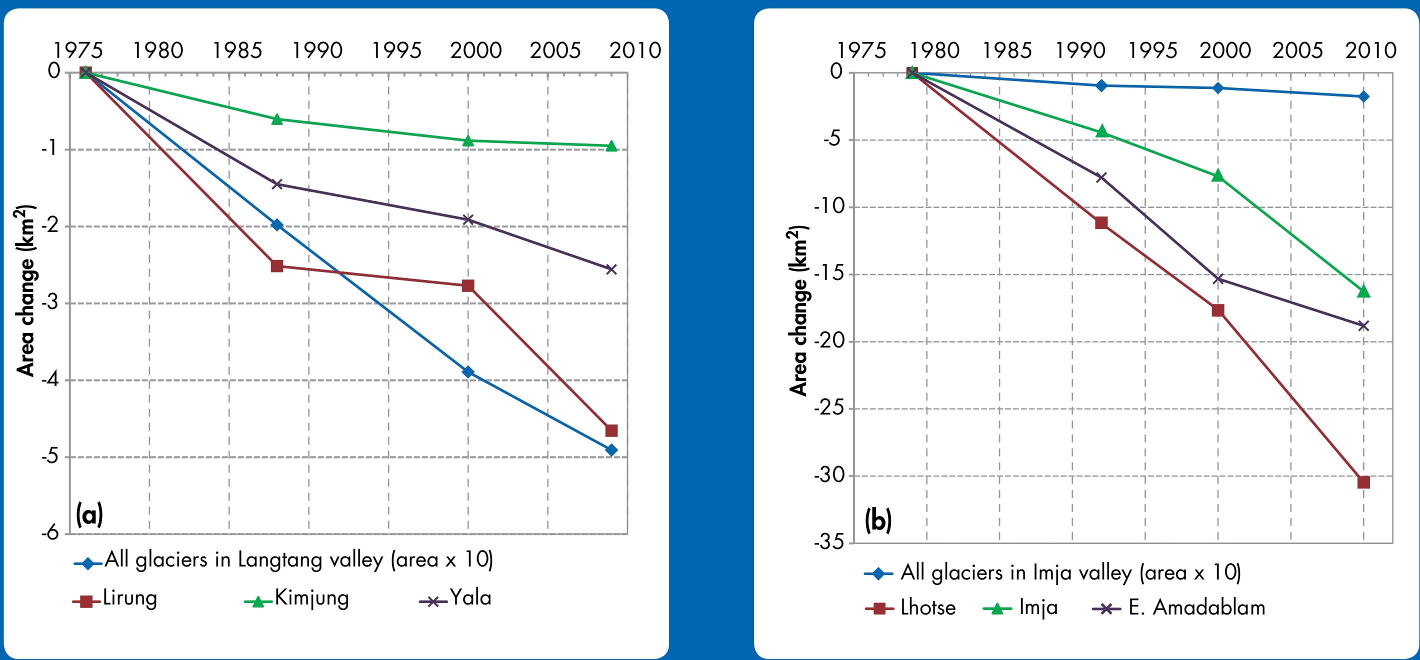



Figure 5.4: **Change in area of the selected glaciers in the (a) Langtang valley and (b) Imja valley**




## Imja valley

The Imja and Lhotse glaciers are valley type glaciers and are debris-covered in the lower parts, whereas the East Amadablam Glacier is a mountain apron type with clean-ice. The Imja Glacier is associated with a moraine-bound lake at its terminus.

In terms of total amount, the Lhotse Glacier showed the greatest loss and the East Amadablam Glacier the least (Figure 5.4b). The Lhotse Glacier also showed the highest percentage of glacier area loss (31%), from 14.7 km² in

1979 to 10.2 km² in 2010, followed by the East Amadablam Glacier with 19% (2.4 km² to 1.9 km²) and the Imja Glacier with 16% (21.0 km² to 17.6 km²) (Table 5.2).

Overall, the percentage loss was highest between 2000 and 2010 for the Imja and Lhotse glaciers, and between 1992 and 2000 for the East Amadablam Glacier. The high percentage of glacier area loss seen in the Lirung and Yala Glaciers was due to the loss from areas with steep slopes in the elevation range 5,000 to 6,500 masl.

### Minimum elevation

The minimum elevation of glaciers in the Langtang valley changed between 1996 and 2009 from 3,997 to 4,112 masl (shift of 115 m); and in the Imja valley between 1979 and 2010, from 4,675 to 4,728 masl (shift of 52 m).

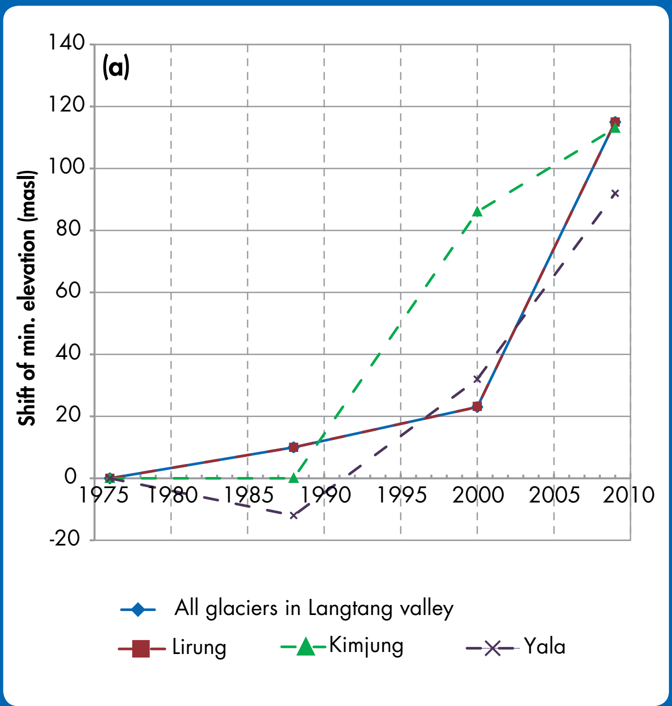
In the Langtang valley, the terminus of the Lirung Glacier, which has the lowest elevation, retreated the most (by 115 m from 3,997 masl in 1976), followed by the Kimjung glacier (by 113 m, from 4,313 masl in 1976), and the Yala glacier (by 92 m from 5,079 masl in 1976) (Table 5.1 and Figure 5.5a).

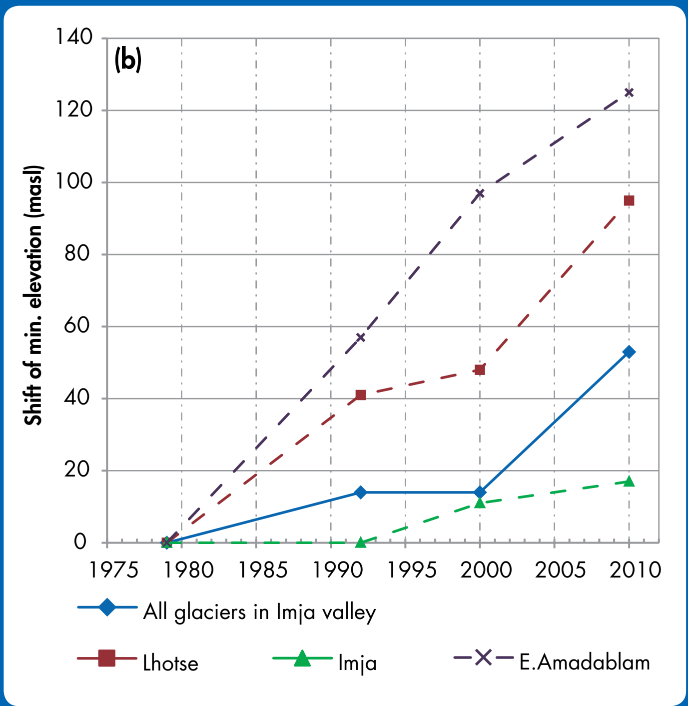
In the Imja valley, the terminus of the East Amadablam Glacier retreated the most (by 125 m from 5,051 masl in 1979), followed by the Lhotse Glacier (by 95 m from 4,748 masl in 1979), and the Imja Glacier (by 17 m, from 5,002 masl in 1979) (Table 5.2 and Figure 5.5b). Overall the shift of elevation was highest for the East Amadablam glacier between 1979 and 1992 followed by Lhotse between 2000 and 2010 and Imja between 1992 and 2000.

## Climate

'Climate' refers to the average weather condition in a region over long periods of time ranging from months to years. The World Meteorological Organization (WMO) has defined a standard averaging period of 30 years for computing the climate at a particular location. In addition to average values, climate statistics include data on extremes and variation. The climate of a location may be affected by the presence of mountains, deserts, vegetation (forests), nearby oceans, and water bodies. "Climate is what you expect and weather is what you get" indicates the difference between the climate and actual day-to-day weather at a place.

Figure 5.5: **Change in minimum elevation of the selected glaciers in the (a) Langtang valley and (b) Imja valley**



The most important climate parameters are temperature and precipitation. The case study analysis looked at yearly and seasonal temperature and precipitation data for 1988 to 2008. Four seasons were defined: winter (December previous year – February), pre-monsoon (March–May), monsoon (June–September), and post-monsoon (October–November).

Monthly temperature data for the period 1988–2008 were obtained from DHM for Kyanjing station in Langtang valley and Dingboche station in Khumbu valley at the confluence with the Imja valley, and monthly rainfall data for the period 1995–2008 for the Kyanjing station. The rainfall data for Khumbu were incomplete and could not be used for analysis. Kyanjing station (3,920 masl) in the Langtang valley and Dingboche station (4,400 masl) in the Khumbu valley are the only stations in Nepal with temperature data for 21 years. Missing values were interpolated and extrapolated using numerical methods, e.g., average and linear trends, data from previous periods, and data patterns. Data gaps were also filled using data from automatic and semi-automatic weather stations in the same area.

## Temperature

### Temperature analysis

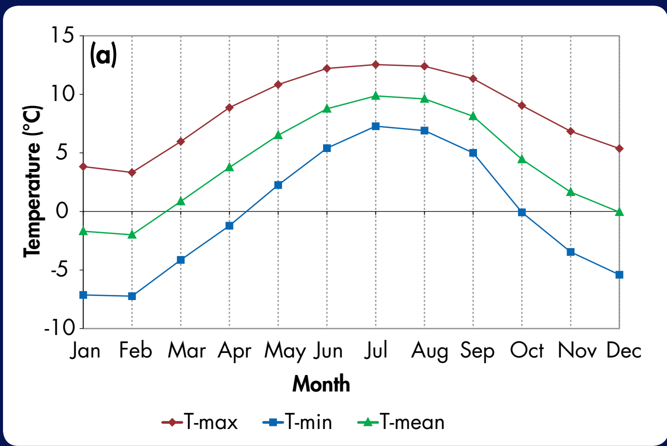
The average monthly temperatures in Langtang and Khumbu over the period 1988–2008 are given in Table 5.3 and shown graphically in Figure 5.6.

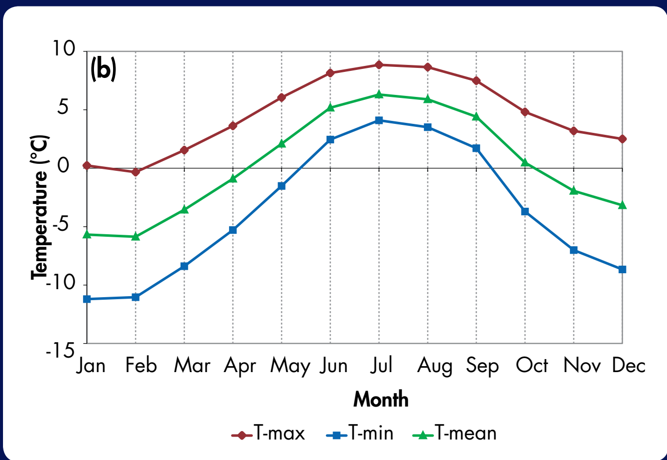
The average monthly temperature distribution pattern is similar in the two areas but between 3.0 and 4.7°C higher in Langtang valley than in Imja valley in different months. The average monthly mean temperature reaches a maximum during July, is lowest in February, and remains below 10°C throughout the year at both stations.

The average monthly maximum temperature is below 13°C in Langtang and 9°C in Khumbu, and the average monthly minimum temperature is above -2.0°C in Langtang and -6.0°C in Khumbu. The average monthly maximum temperature remains above freezing throughout the year in Langtang, but drops below freezing in February in Khumbu, while the average monthly minimum temperature remains below freezing from October to April in Langtang and from October to May in Khumbu, only rising above zero during the four months of the monsoon season.

In terms of seasons, the monsoon is the warmest season; and winter is the coldest season at both the stations, but the average monthly mean temperature is below zero in all seasons except the monsoon in Khumbu (4,355 masl) and it is only below zero in the winter season in Langtang (3,920 masl) (Figure 5.7).

Figure 5.6: **Average monthly temperature in (a) Langtang and (b) Khumbu (1988–2008)**




### Temperature change

The mean annual temperature in Nepal from 1975 to 2005 has been reported to be increasing at a rate of 0.04°C/year (Baidya et al. 2007). The rate varies from place to place and season to season; in general it is higher at higher elevations and lower in the southern plains. The rate of increase in average seasonal and annual mean temperature between 1998 and 2008 in Langtang and Khumbu is shown in Figure 5.8. Overall, the average annual mean temperature increased by 0.12°C/year at the

Table 5.3: **Average monthly maximum, minimum, and mean temperatures in Langtang and Khumbu (1988–2008)**

| Temperature | Winter | | Pre-monsoon | | | Monsoon | | | | Post-monsoon | | Winter |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (°C) | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| **Langtang** | | | | | | | | | | | | |
| Tmax | 3.8 | 3.3 | 6 | 8.9 | 10.8 | 12.2 | 12.5 | 12.4 | 11.3 | 9.0 | 6.8 | 5.4 |
| Tmin | -7.1 | -7.2 | -4.1 | -1.2 | 2.3 | 5.4 | 7.3 | 6.9 | 5 | -0.1 | -3.5 | -5.4 |
| Tmean | -1.7 | -2 | 0.9 | 3.8 | 6.5 | 8.8 | 9.9 | 9.6 | 8.1 | 4.5 | 1.7 | -0.1 |
| **Khumbu** | | | | | | | | | | | | |
| Tmax | 0.2 | -0.3 | 1.5 | 3.6 | 6 | 8.1 | 8.8 | 8.7 | 7.5 | 4.8 | 3.2 | 2.5 |
| Tmin | -11.2 | -11 | -8.4 | -5.3 | -1.5 | 2.4 | 4.1 | 3.5 | 1.7 | -3.7 | -7 | -8.7 |
| Tmean | -5.7 | -5.9 | -3.6 | -0.9 | 2.1 | 5.2 | 6.3 | 5.9 | 4.4 | 0.5 | -1.9 | -3.2 |

Figure 5.7: **Seasonal mean temperature in Langtang and Khumbu (1988–2008)**

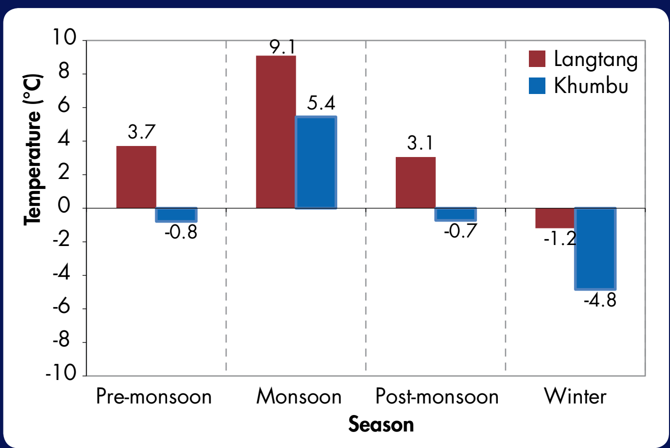
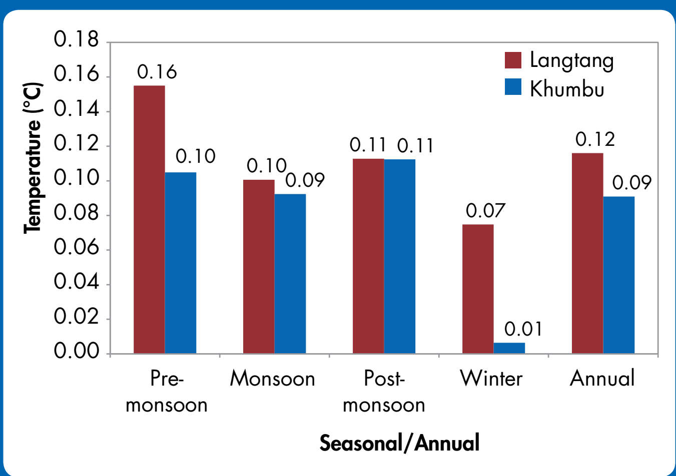



Figure 5.8: **Rate of change in average seasonal and annual mean temperatures between 1998 and 2008 at the stations in Langtang and Khumbu**




Langtang station and 0.09°C/year at the Khumbu station (Figure 5.8), considerably higher than reported for Nepal overall. The increase was observed in all seasons, but was highest in the pre-monsoon season in Langtang and post-monsoon season in Khumbu.

The average mean, minimum, and maximum temperatures in the two valleys in each year are shown in Figures 5.9 and 5.10; and the average annual increase in Table 5.4. In Langtang the maximum and minimum temperatures increased at almost the same rate, whereas in Khumbu the minimum temperature increased slightly faster than the maximum temperature (Table 5.4).

Table 5.4: **Average annual temperature change in Langtang and Khumbu between 1988 and 2008 (°C/yr)**

| Station | Maximum | Minimum | Mean |
|---|---|---|---|
| Langtang | 0.128 | 0.124 | 0.116 |
| Khumbu | 0.093 | 0.139 | 0.091 |

Time series analysis with multiple period regression of mean monthly temperature was also carried out to determine the patterns of change over different periods. The results are shown in Figure 5.11 (Langtang) and Figure 5.12 (Khumbu). In Langtang, there were at least two distinct temperature periods, 1988–2002 and 2003–2008. The regression lines show that mean monthly temperatures rose at an annual rate of 0.024°C between 1988 and 2002, but showed almost no variation between 2003 and 2008. In Khumbu, the regression line indicates a general rising tendency in mean monthly temperature for the period 1988 to 2008 but the rate was not significant, although the annual mean temperature for the same period shows a distinct rise at a rate of 0.09°C/year (Figure 5.10).

Figure 5.9: **Annual average mean, maximum, and minimum temperatures from 1988 to 2008 in Langtang**

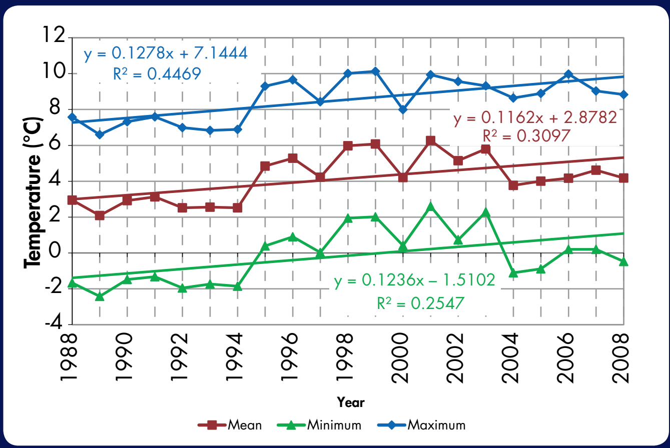



Figure 5.10: **Annual average mean, maximum, and minimum temperatures from 1988 to 2008 in Khumbu**

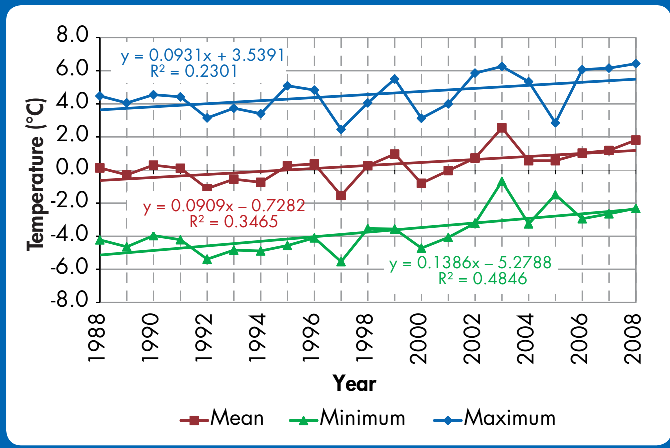



Figure 5.11: **Mean monthly temperature in Langtang, 1988–2008**

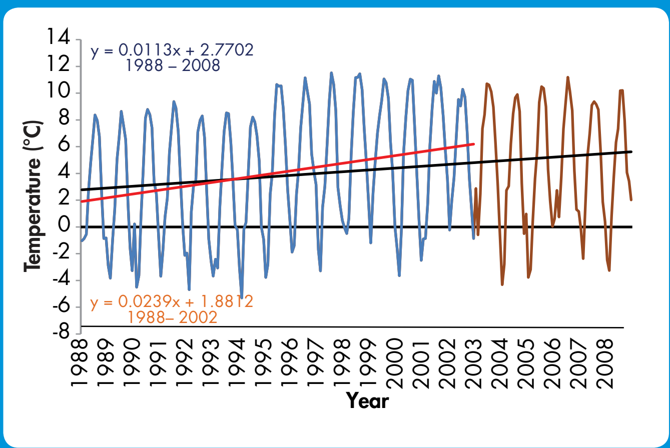
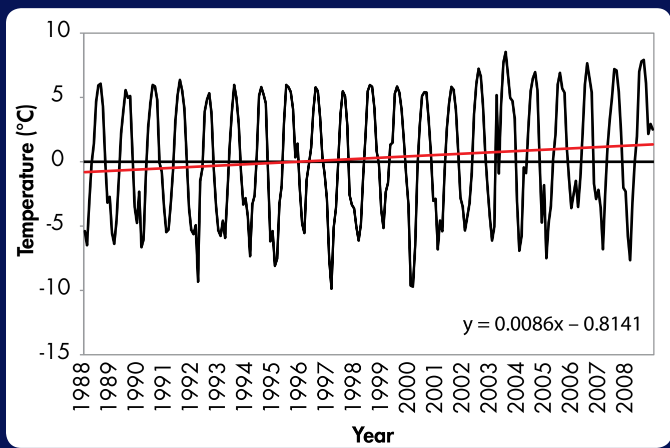



Figure 5.12: **Mean monthly temperature in Khumbu, 1988–2008**




## Decadal temperature change analysis

The differences in temperature change in the two decades 1988–1997 and 1998–2007 are shown in Figure 5.13. Warming was greater between 1998 and 2007 than between 1988 and 1997 in both locations and in all seasons, with the greatest differences observed in the pre-monsoon season and the least in the winter season.

The annual mean temperature in each year and each decade at the two stations is shown in Figure 5.14. The decadal mean temperature increased from 3.3 to 5.0°C in Langtang and from -0.3 to 0.7°C in Khumbu between the decades 1988–1997 and 1998–2007. Statistical analysis was carried out to identify the significance of any differences in the two decadal series at each of the two locations using a paired-sample T test. In Langtang, the difference between the decadal mean temperatures of the series in the two decades was significant at $p=0.014<0.05$, with a 95% confidence interval between 0.44°C and 2.98°C. In Khumbu, the difference was significant at $p=0.036<0.05$, with a 95% confidence interval between 0.08°C and 1.96°C. The total glacier area in the Langtang and Imja valleys in 1998, 2000, and 2009 is also shown for comparison (Tables 5.1, 5.2).

Figure 5.13: **Mean difference in average seasonal temperature between 1988–1997 and 1998–2007 in Langtang and Khumbu**

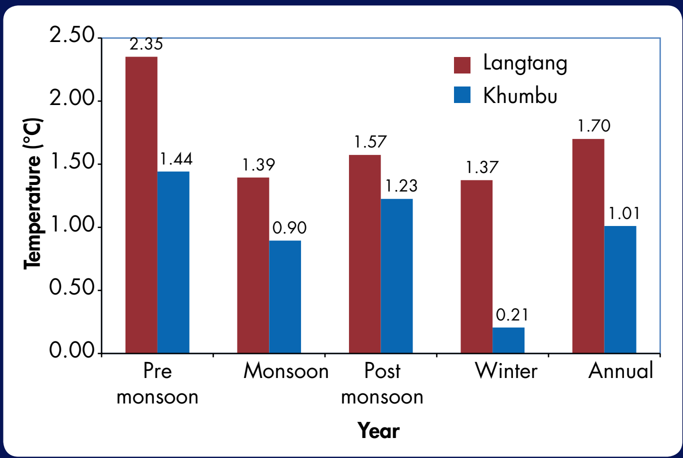
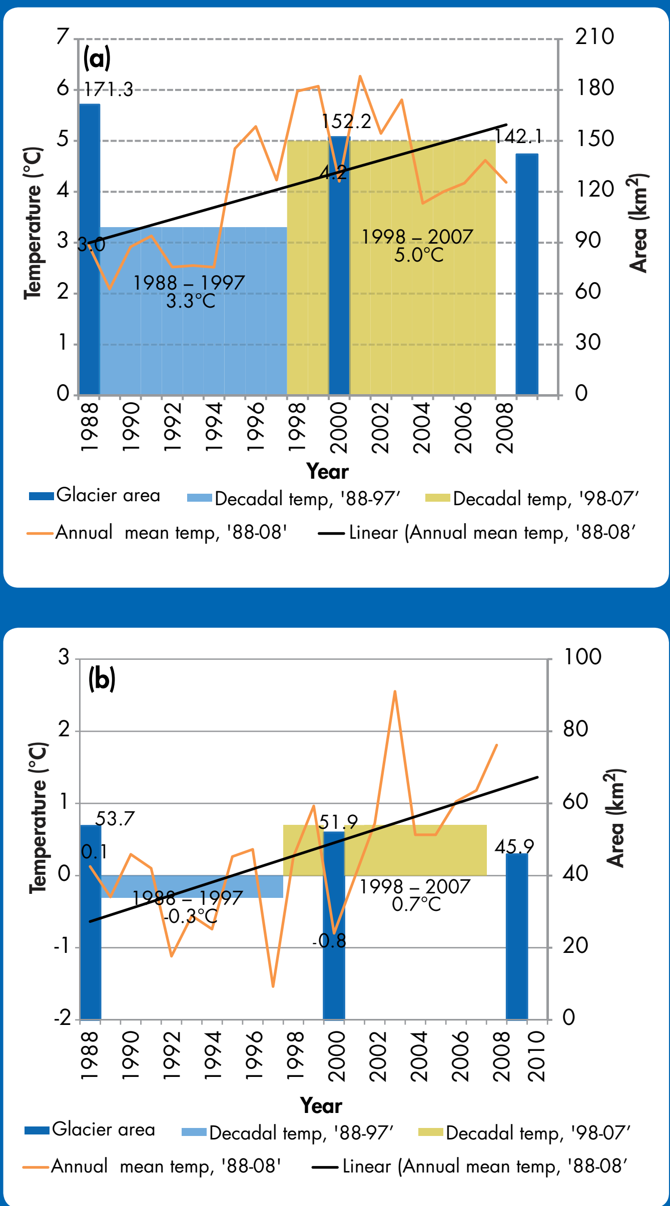



Figure 5.14: **Average decadal and annual mean temperature in (a) Langtang and (b) Khumbu**




## Moving average analysis

A moving average analysis was performed to identify changes in the overall long-term trend. Annual five- and ten-year moving averages of mean, minimum, and maximum temperature were calculated in order to smooth out short-term fluctuations and visualize the long-term temperature trend. The results are shown in Figures 5.15, 5.16, and 5.17. The five-year moving average showed a greater change in annual mean temperature than the ten-year moving average in both regions. Langtang showed a tendency towards a decreasing mean temperature after 2004, whereas Khumbu showed an increasing trend, especially in the ten-year moving average (Figure 5.15). The five- and ten-year moving averages of minimum temperature showed almost the same pattern as those of the mean temperature in both regions, except in Khumbu where there was a noticeable increase in minimum temperature for both the five- and ten-year moving averages after 1997 (Figure 5.16). The changes in maximum temperature were lower than the changes in minimum temperature in both regions (Figure 5.17), with values in the Langtang region relatively stable after 2004, but an increasing tendency in the Khumbu region.

Overall the results indicate that the increasing average temperature in both regions is the result of a continuing rise in both maximum and minimum temperature; the five-year and ten-year moving averages showed the rise in minimum temperature to be significant in both regions.

## Rainfall analysis

In the Nepal Himalayas, rainfall shows large month-to-month, season-to-season, and year-to-year variations. The summer monsoon from June to September is the dominant rain bearing system. More than 80% of annual rainfall occurs in this period, with a general decrease in amount from east to west and south to northwest (Bookhagen and Burbank 2010; Shrestha et al. 2000). In winter, rainfall generally decreases from west to east. During the pre- and post-monsoon seasons, rainfall is usually of convective type and localized. Changes in rainfall were analysed for the Langtang station from 1995 to 2008. (There were gaps in the data for 1988 to 1994, so these years were not included in the analysis.)

The average annual rainfall in Langtang over the period 1995 to 2008 was 805 mm. The percentage average monthly and seasonal contribution to the

Figure 5.15: **Five and ten-year moving average of mean temperature in (a) Langtang and (b) Khumbu**

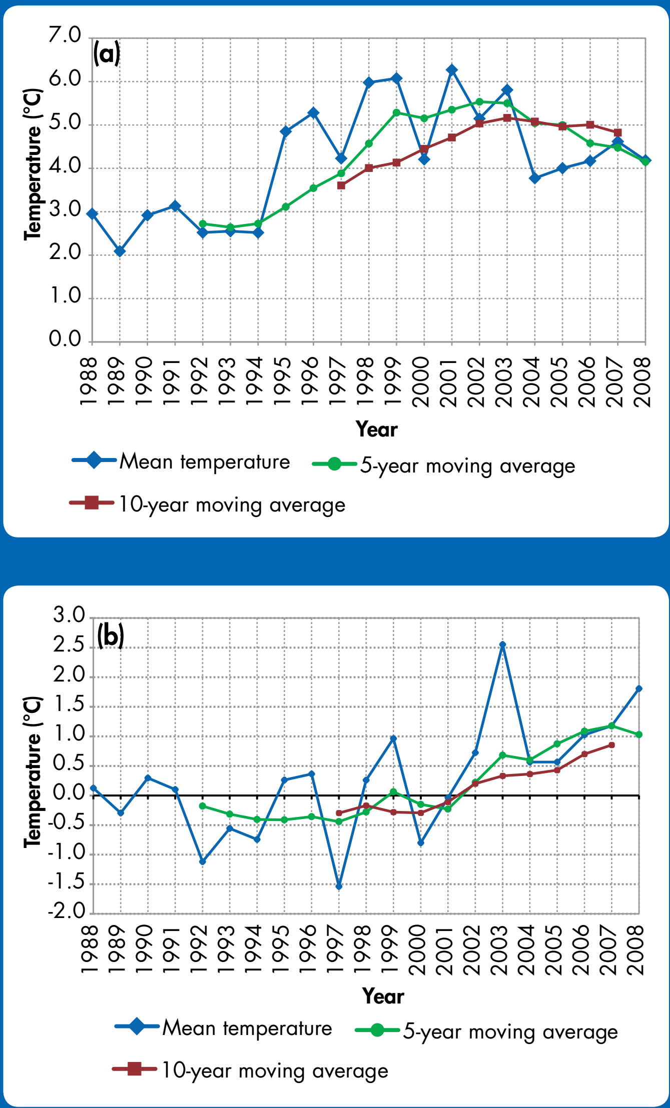



Figure 5.16: **Five- and ten-year moving average of minimum temperature in (a) Langtang and (b) Khumbu**

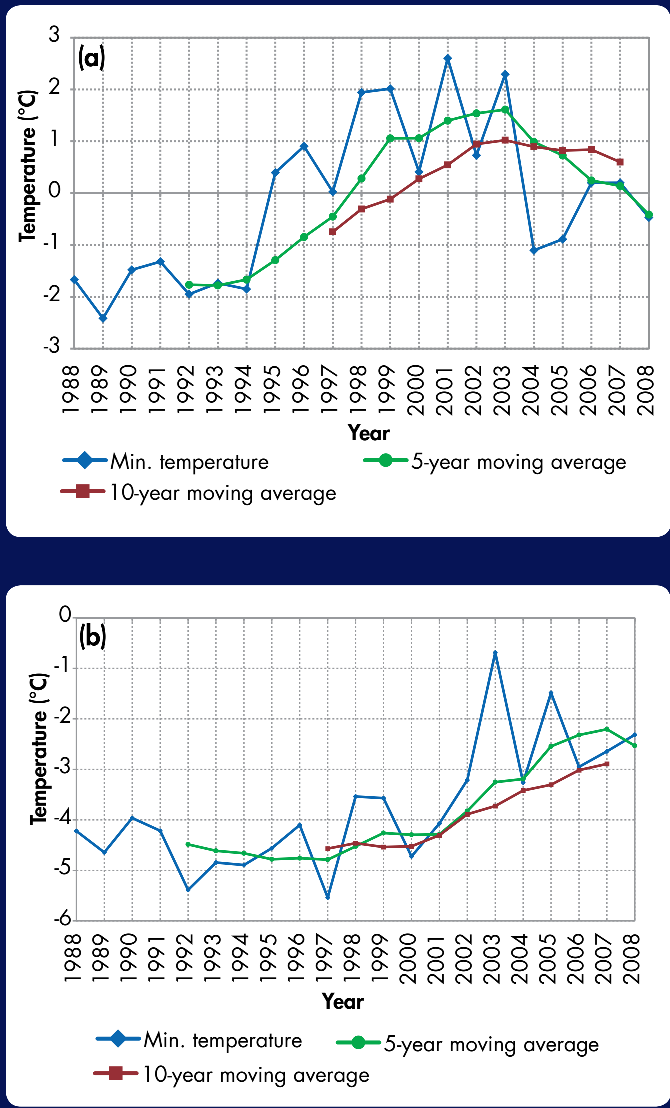



Figure 5.17: **Five- and ten-year moving average of maximum temperature in (a) Langtang and (b) Khumbu**

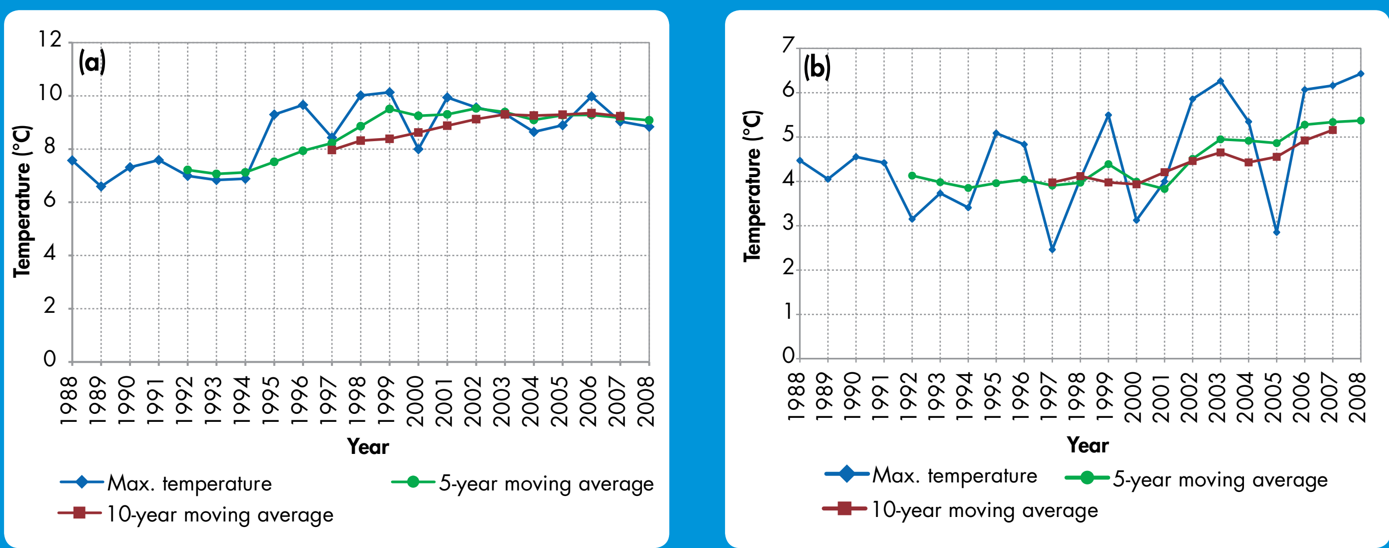


Figure 5.18: **Monthly (a) and seasonal (b) average contribution (%) to total annual rainfall in Langtang (1995–2008)**

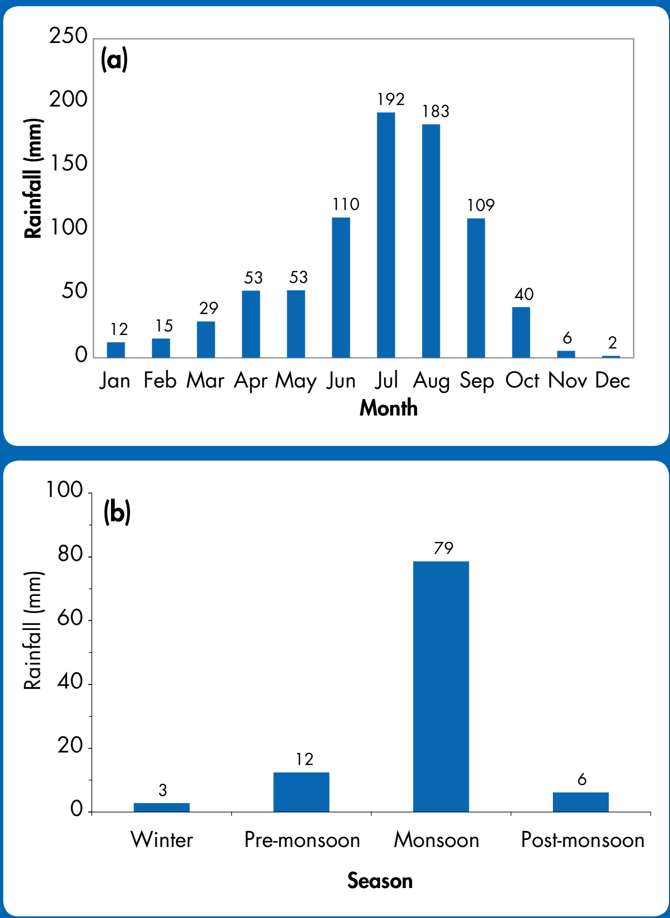
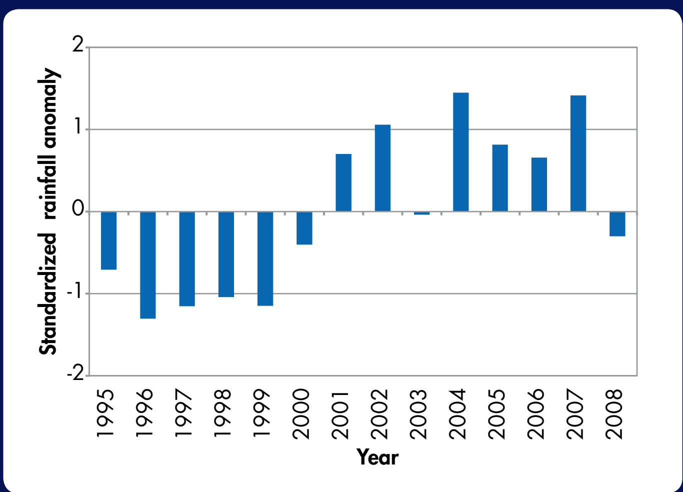



Figure 5.19: **Annual total rainfall anomaly in Langtang**




total is shown in Figure 5.18. July is the wettest month and December the driest. Close to 80% of the total precipitation fell in the monsoon season (June–September), similar to the value of 77% reported by Immerzeel et al. (2012). Winter was the driest season with only 3% of the total rainfall.

The total annual rainfall anomaly provides information about wet and dry years beyond ±1 standard deviations. The annual total rainfall anomaly between 1995 and 2008 in Langtang is shown in Figure 5.19. There were four dry years (1996, 1997, 1998, 1999) and three wet years (2002, 2004, 2007).

Regression analysis of total annual rainfall from 1995 to 2008 in Langtang showed an increasing trend of 31 mm/year (Figure 5.20; Table 5.5). This increase is significantly greater than the trend reported from other stations at lower altitude, e.g., 1.9 mm/year at Kathmandu Airport (Baidya et al. 2008). The overall trend showed an increase in pre-monsoon, monsoon, and post-monsoon seasons but a slight decrease in winter (Table 5.5), which is in agreement with the decreasing rainfall trend observed at other stations during the winter season. The monsoon season showed an increase of 24 mm/year. In other words, the wet season (monsoon) is becoming wetter and the dry season (winter) is becoming drier.

The coefficient of variation (CV) was used to study rainfall variability. The coefficient of variation in the different seasons is shown in Figure 5.21. Post-monsoon rainfall showed the greatest variability and monsoon rainfall the least. The variability of winter rainfall was more than double that in the monsoon season.

Table 5.5: **Trend in seasonal rainfall in Langtang**

| Rainfall trend (mm/year) | Winter | Pre-monsoon | Monsoon | Post-monsoon |
|---|---|---|---|---|
| | -0.4 | 4.97 | 23.69 | 0.98 |

## Discussion

### Limitations

The meteorological equipment installed by DHM in the high-altitude stations is semi-automatic (chart driven recorder) with limited manual supervision in the off-season and operates under climatically harsh conditions. Data errors may occur as a result of various problems, for example, malfunction of the instruments, delay in instrument calibration, and failure to change the recorder chart in a timely

Figure 5.20: **Trend in annual total rainfall in Langtang (1995–2008)**

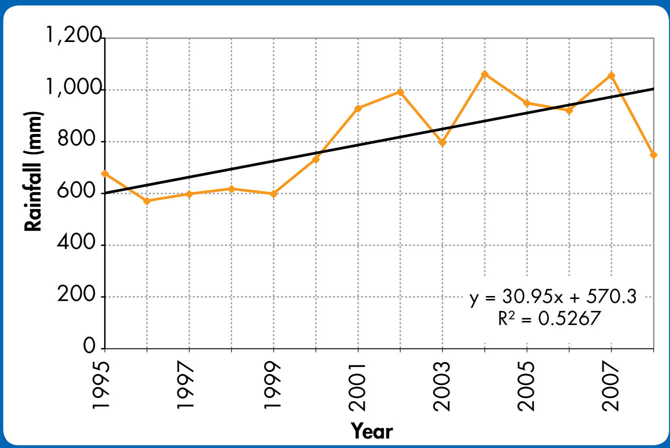
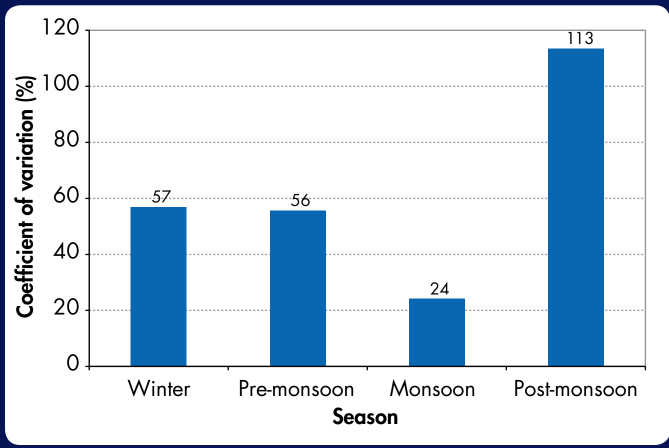



Figure 5.21: **Coefficient of variation (CV) of rainfall in different seasons in Langtang (1995–2008)**




fashion as a result of access difficulties. The data gaps that result can be filled to some extent through interpolation and extrapolation from other stations, but the associated data error still needs to be studied.

The daily mean temperature data used in this study are averages of the daily maximum and minimum temperatures. Such averages tend to be high and affected by extreme values, and statistically, these mean temperatures may not represent the population mean. Long-term hourly temperature data would be needed to ensure that the daily mean represents the population mean, but at present such data are not available.

Simple linear regression is a tool for analysing trends and provides quantitative information for climatological parameters; however, there are a number of limitations to this technique. Generally, there should be a long data period, especially for short data records that do not follow a normal distribution, since outliers can lead to misleading results in short series. Non-parametric tests such as Mann-Kendal, Run, and Mann-Whitney are normally used if the necessary assumptions cannot be made about a dataset, but the statistical power of these tests is generally lower than for parametric tests. The data records in this study covered a period of 21 years. This is sufficient to justify the use of linear regression, but the statistical results could be improved if longer time series were available.

## Changes in glacier area

The total glaciated area showed a loss of just over 25% of the original extent in both valleys in the 30-year study period. However, this change was not homogeneous for all glaciers. The type, size, slope, aspect, elevation, and debris or other cover of a glacier all affect the extent and rate at which it will be affected by changes in climate. The studies of individual glaciers provide an indication of the different response and sensitivity of different glaciers. The six glaciers showed overall area losses ranging from 16 to 51% of the initial area. Overall, the results indicate that low lying small glaciers reduce in size more rapidly than bigger glaciers. Additional ground-based observations also validated that the main area loss for the Imja glacier was at the terminus, and associated with the expansion of the Imja glacial lake. Contact with a glacial lake is another factor that can affect the rate of recession. Such differences need to be studied in more detail in more glaciers to support more precise modelling of future impacts of climate change.

The glaciers also showed a recession in the position of the terminus, by 115 m for the lowest glaciers in Langtang valley, and 53 m for the lowest glaciers in Imja valley. The individual glaciers also showed marked differences in the extent of recession, from 17 m (Imja) to 125 m (East Amadablam). The elevation shift is also affected by a variety of factors including the slope, aspect, initial elevation, type, and cover of the glacier.

## Changes in temperature

Meteorological parameters such as temperature and rainfall play an important role in determining glacier changes. However, direct comparisons of change can only be indicative, in view of the fact that other factors also play a role, and that there is a lag time in the response of glaciers to changes in these parameters that varies, among others, with glacier size. Furthermore, the stations that provided the temperature data in this study lay slightly below the minimum elevation of glaciers in the two valleys, and considerably below the bulk of the glaciated area. Although changes in air temperature are likely to follow a similar pattern within a valley, there may be localized effects, and the extent and rate of change may also be affected by elevation. Nevertheless, it is interesting to compare the overall changes in glacier parameters with the trends in meteorological parameters.

The temperature change was investigated over the 21-year period for which continuous data were available (1988 to 2008). There was a considerable fluctuation in average annual temperatures, but regression analysis showed an overall increase in annual mean temperature in Langtang of 4.2°C, with a rate of change of 0.12°C/year, and in Khumbu of 0.3°C; with a rate of change of 0.09°C/year. The overall increase was higher between 1998 and 2007 than between 1988 and 1997, notwithstanding a small downward fluctuation in Langtang after 2004.

Analysis of five and ten-year moving averages indicated that although both the maximum and minimum temperatures showed a rising tendency, only the increase in minimum temperature was significant. An increase in minimum temperatures could have a more dramatic effect on the surroundings than an overall increase in temperatures (Hughes et al. 2007), partly because it is more likely to raise the temperature above the 0°C threshold, thus extending the melting season.

Differences were also observed among the seasons, with an increase in mean temperature in all seasons, but a greater change in the pre-monsoon season, especially in Langtang, and less change in the winter season, especially in Khumbu. However, longer time series are needed to confirm these findings and seasonal changes need to be investigated further.

The general rise in mean temperature in both Langtang and Imja (Khumbu) paralleled the decrease in glacier area and rise in minimum elevation of glacier terminuses. The temperature rise is considered to be the primary factor responsible for glacier retreat. Future studies will consider other factors that affect glacier dynamics, such as size, slope, shape, debris cover, and contact with water bodies, in more detail.

## Changes in precipitation

Investigation into changes in precipitation were hindered by the lack of a complete rainfall dataset for the Khumbu region, and a limited data set of only 13 years for the Langtang region. Furthermore, measurements were limited to rainfall and did not include snowfall, so that values are only indicative for precipitation. Notwithstanding these limitations, analysis of the limited data series showed clearly the extent of variation in annual rainfall. Although the length of the data set was too short for identifying trends with any certainty, simple regression analysis indicated the possibility of an overall increase in rainfall, with a greater increase during the monsoon and slight decrease in the winter season. The results provide a baseline for future studies. Precipitation plays an important role in glacier dynamics, both in terms of the total amount of precipitation available for accumulation and in changes in the form of precipitation from snow to rain.

# 6 Conclusion

## Glacier Status in 2010 and Trends Over Time

In this study, a semi-automatic method was applied to develop a comprehensive account of the status of glaciers of Nepal in 2010 together with comparable data for approximately 1980, 1990, and 2000 to enable assessment of changes and trends. In an additional case study, glacier outlines for the four decades in the Langtang and Imja sub-basins in central and eastern Nepal were analysed and compared with decadal temperature change. The attribute parameters were all derived from automatic GIS processes, except for the morphological classification and measurement of glacier length. The methodology is an improved version of methods developed by global initiatives like the World Glacier Monitoring Service (WGMS), Global Land Ice Measurement from Space (GLIMS), and GlobGlacier, thus the results can be used as a basis for comparison at an international level. The major findings were as follows:

- In 2010, a total of 3,808 glaciers were identified with a total area of 3,902 km$^2$and estimated ice reserves of 312 km$^3$. The average area of individual glaciers was 1 km$^2$. The Ngojumba glacier in the Dudh Koshi sub-basin was the largest single glacier with an area of 79 km$^2$.
- About 90% of the glacier area lay between 4,500 and 6,500 masl; with 65% between 5,000 and 6,000 masl.
- The contribution of estimated ice reserves is higher for a large glacier than for the same cumulative area from a number of smaller ones. Thus the estimated ice reserves were higher in basins with larger glaciers, and larger glaciers are the most important reserves of freshwater.
- The total glacier area decreased by 24% between 1977 and 2010, and the estimated ice reserves by 29% (129 km$^3$). The number of glaciers increased by 11%, a result of fragmentation following shrinkage. The lowest losses of glacier area (and in some cases gains) were observed from glaciers with a north or northwest aspect (of which there were very few) and slopes of less than 20°. Mountain basin type and valley glaciers also showed a lower proportional loss of area
- The glaciers receded on average by 38 km$^2$ per year.
- The rate of loss of glacial area between ~1980 and 1990 was almost twice that in the subsequent two decades (1990–2000 and 2000–2010). Further study is needed to determine whether this reflects a slowing in the rate of change or an anomalous situation in the first period.
- The average annual mean temperature in the Langtang and Imja (Khumbu) sub-basins rose at an average rate of 0.12°C/year and 0.09°C/year, respectively, between 1988 and 2008. Moving average analysis showed that the rate of increase in average mean minimum temperature was significant and higher than the increase in average mean maximum temperature.

## Conclusions

The results show clearly that the glacier area in the Nepal Himalayas is decreasing at a rapid rate, and that individual glaciers are shrinking, retreating, and fragmenting. The changes appear to be linked primarily with a marked rise in average temperature associated with global climate change. The extent to which changes in precipitation play a role, including total amount, seasonal distribution, and change from snowfall to rainfall, is not yet known. The changes have a number of implications. The high Himalayan region contains important freshwater reserves in the form of glacier ice, and glacial shrinkage will have an impact on the long-term availability of freshwater from these reserves. Initially, increased melting of glaciers might lead to an increase in glacial runoff and thus river flow lasting some decades, but this will be followed in the long term by a reduction. Furthermore, glacial recession can be associated with the formation and expansion of glacial lakes below the retreating terminus, with the associated risk of a glacial lake outburst flood (GLOF); continued recession may lead to an increase in the number of glacial lakes and in the frequency of GLOF events. Finally, the cryosphere also plays a significant role in regional climate regulation, and change in the glacial area may not only be affected by, but also have a long-term impact on, the regional climate.

In order to mitigate the impacts and plan for adaptation, it is important to have clear information on the present situation and rate of change. However, although the overall trends are clear, there is considerable variation in the susceptibility to change of individual glaciers, related to such factors as type, size, aspect, slope, elevation, proximity to water bodies, and the presence of thick or thin layers of debris and other material. Detailed information on these characteristics and variations in response are needed to support development of more accurate projections of future change under different climate scenarios using glacier modelling. The patterns are complex, but the results did indicate some of the differences.

Small glaciers, low elevation glaciers, and low sloping glaciers – especially clean-ice type – may be more significantly affected by climate change. Small glaciers have a low thermal mass for buffering change, and low slope glaciers are more vulnerable because a small rise in elevation of the thermal equilibrium will affect a large area of the glacier. Not all small glaciers are vulnerable to disappearance, however, because they commonly exist in heavily shadowed cirque basins, and many are close to steep slopes and receive abundant snow avalanches and wind-blown snow in addition to direct snowfall. As small glaciers retreat closer to the steepest basin slopes, these contributions may increase and make the final disappearance a very slow process. Similarly, not all low slope glaciers are equally vulnerable. Debris-covered glaciers, which tend to have lower slopes, can be insulated from warming by the debris cover and respond more slowly to change unless a lake forms at the terminus. Although some of the smaller glaciers present in 1980 had disappeared by 2010, the actual number of small glaciers increased as a result of shrinkage and fragmentation of previously larger glaciers. The glacier area and estimated ice reserves contributed by small glaciers are comparatively small, but as these glaciers tend to be more sensitive to climate change they may play a more important role proportionately in the loss of ice reserves.

The separate information for clean-ice and debris-covered glaciers will serve as an important parameter in climate change models. Clean-ice glaciers respond to climate warming on a shorter timescale than debris-covered glaciers, as a result of the thermal insulation provided by the debris in debris-covered glaciers. As climate warming and net ablation proceed, the remaining glacier area is likely to have an increased proportion of debris-covered area. Net ablation also causes transition of some relatively clean-ice areas into debris-covered ice as debris accumulates. Furthermore, as glaciers thin, lateral moraines can destabilize and collpase onto them, adding more debris to the surface. This means that an increase in the percentage of debris-covered glaciers in an area is likely to be an indicator of climate change. The debris-covered and clean-ice area was only differentiated in the images for 2010. In the future, additional analysis will show whether the proportion of debris-covered area is in fact increasing.

Better and longer series of temperature and precipitation data at higher altitudes are needed in order to analyse the causes of the changes in glacier extent in more detail. Long-term hourly measurements of temperature at higher elevations are needed to enable correlation with glacier change, together with measurements of rain and snowfall. The greatest amount of precipitation in the Nepal Himalayas falls during the monsoon and pre-monsoon seasons. At higher elevations this precipitation is in the form of snow and contributes to glacial accumulation. Changes in both total precipitation and seasonal distribution may affect the snow available to glaciers for accumulation. The increase in temperature may also result in precipitation falling as rain at higher altitudes than previously. This will affect the glaciers in two ways: less snow will be available to add to the ice mass, and the rain will increase the melting rate of the existing ice. Long-term series are needed as rainfall patterns show considerable variation in individual years.

## Recommendations

The lack of data on Nepal's glaciers is hindering efforts to project future scenarios and develop plans for mitigation and adaption. To some extent this can be addressed using satellite imagery, but selected ground truthing and good quality mass balance measurements are needed from a range of different glaciers to facilitate data interpretation. The following are recommended for assessments using satellite imagery.

- Small and medium-sized glaciers should be mapped and monitored regularly using high-resolution satellite images.
- A repeat inventory of glaciers of Nepal is recommended at intervals of five years to capture the ongoing change.
- Names of important glaciers should be mentioned in published data in addition to the GLIMS ID code to aid understanding by non-specialists concerned with local impacts.

- On-the-job training in glacier mapping and monitoring using satellite images should be provided as a matter of urgency to the technical staff in Nepalese partner institutes so as to improve the capacity for mapping and monitoring of glaciers, and thus enable regular monitoring of 'hot spot' areas with rapidly retreating glaciers.

The daily mean temperature data used in this study are averages of the maximum and minimum temperatures and tend to be high and affected by extreme values. Statistically, these mean temperatures may not represent the population mean. Long-term hourly temperature data are needed to ensure that the daily mean represents the population mean, but at present such data are not available.

- The hydrometeorological stations should be upgraded with automated data logging systems.
- A representative network of high-altitude hydrometeorological stations should be established.
- The existing high-altitude stations should be made fully functional to ensure the availability of good quality of data.

## Future Outlook

The use of advanced remote sensing and GIS tools and techniques enables rapid delivery of glacier data which enable assessment of glacier status over a wide area, as well as detailed analysis of individual changes. The present study will contribute to an understanding of the status and changes of glaciers in the Nepal Himalayas over the past 33 years; the data will be available for download for further analysis on ICIMOD's website (http://apps.geoportal:icimod.org/nepalglaciers). The data and analysis will also serve as a baseline for future studies. Repetition of the inventory and analysis at regular intervals will enable the changes to be quantified and projections developed as a basis for planning.

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# Annexes

## Annex 1: **Landsat images used in the inventory**

Table A1.1: **Landsat satellite images used in the glacier inventories**

| Sub-basins | Path-row | Images | Date | Remarks |
|---|---|---|---|---|
| **2010 Inventory** | | | | |
| Arun/Tamor | 139–041 | l72139041_04120111225 | 12/25/2011 | For correction |
| | 139–041 | l72139041_04120100120 | 1/20/2010 | Used |
| Arun/Dudh/Tama/Likhu | 140–041 | l72140041_04120091108 | 11/8/2009 | Used |
| Tama/Sun/Indrawati/Trishuli/Budhi Gandaki | 141–040 | l72141040_04020101220 | 12/20/2010 | Used |
| | 141–040 | l72141040_04020101001 | 10/1/2010 | For correction |
| | 141–040 | l72141040_04020111207 | 12/7/2011 | For correction |
| | 141–040 | l72141040_04020101204 | 12/4/2010 | For correction |
| | 141–040 | l72141040_04020111207 | 12/7/2011 | Used |
| Budhi/Marsyangdi/Seti/Kali/Bheri | 142–040 | l72142040_04020101211 | 12/11/2010 | Used |
| Bheri/Tila/Mugu | 143–040 | l72143040_04020101218 | 12/18/2010 | Used |
| | 143–040 | L5143040_04020090206 | 2/6/2009 | For correction |
| | 143–040 | L72143040_04020081212 | 12/12/2008 | For correction |
| Mugu/Humla | 143–039 | l72143039_03920111018 | 10/18/2011 | Used |
| | 143–039 | l72143039_03920101202 | 12/2/2010 | For correction |
| | 143–039 | l72143039_03920111221 | 12/21/2011 | For correction |
| Humla/W.Seti/Kawari/Mahakali | 144–039 | l5144039_03920101115 | 11/15/2010 | Used |
| | 144–039 | l72144039_03920111212 | 12/12/2011 | Used |
| | 144–039 | l72144039_03920101209 | 12/9/2010 | For correction |
| | 144–039 | l72144039_03920101225 | 12/25/2010 | For correction |
| **2000 Inventory** | | | | |
| Tamor/Arun | 139–041 | l72139041_04120001226 | 12/26/2000 | Mapping |
| | 139–040 | l72139040_04020001108 | 11/8/2000 | Correction |
| | 139–040 | l71139040_04020001007 | 10/7/2000 | Correction |
| Arun/Dudh/Likhu/Tama | 140–041 | l72140041_04120011220 | 12/20/2001 | Mapping |
| | 140–041 | l72140041_04120001030 | 10/30/2000 | Correction |
| Sun/Indrawati/Trishuli/Budhi | 141–040 | p141r040_7t20001122 | 11/22/2000 | Mapping |
| Budhi/Marsyangdi/Seti/Kali Gandaki/Bheri | 142–040 | l72142040_04020001215 | 12/15/2000 | Mapping |
| | 142–040 | p142r040_7x19991213 | 12/13/1999 | Correction |
| Kali Gandaki/Bheri/Mugu/Tila/Humla | 143–040 | L72143040_04020011209 | 12/9/2001 | Mapping |
| Mugu/Humla | 143–039 | l72143039_03920001003 | 10/3/2000 | Mapping |
| | 143–039 | l72143039_03919991204 | 12/4/1999 | Correction |
| | 143–040 | p143r040_7t20011225 | 1/25/2001 | Correction |
| Humla/Kawari/West Seti/Mahakali | 144–039 | LE71440392001286SGS00 | 10/13/2001 | Mapping |
| | 144–039 | LT51440391998286XXX02 | 10/13/1998 | Correction |
| | 144–039 | LE71440391999265SGS01 | 9/22/1999 | Correction |
| | 144–039 | LE71440392000268SGS00 | 9/24/2000 | Correction |
| | 144–039 | p144r039_7k20011013 | 1/13/2001 | Correction |
| | 144–039 | l72144039_03919991109 | 11/9/1999 | Correction |

| | | | | |
|---|---|---|---|---|
| **1990 Inventory** | | | | |
| Tamor/Arun | 139–041 | l4139041_04119900113 | 1/13/1990 | Mapping |
| | 139–041 | l4139041_04119891110 | 11/10/1989 | Correction |
| Arun/Dudh/Likhu/Tama | 140–041 | l4140041_04119920922 | 9/22/1992 | Mapping |
| | 140–041 | l4140041_04119900528 | 5/28/1990 | Correction |
| | 140–041 | l4140041_04119900325 | 3/25/1990 | Correction |
| Arun/Dudh/Likhu/Tama | 140–041 | p140r41_5t19921117 | 11/17/1992 | Mapping |
| Sun/Indrawati/Trishuli/Budhi Gandaki | 141–040 | l4141040_04019911130 | 11/30/1991 | Mapping |
| Sun/Indrawati/Trishuli/Budhi Gandaki | 141–040 | p141r40_5t19881012 | 10/12/1988 | Mapping |
| Budhi/Marsyangdi Seti/Kali/Bheri | 142–040 | p142r40_5t19901110 | 11/10/1990 | Mapping |
| Budhi/Marsyangdi/Seti/Kali/Bheri | 142–040 | l4142040_04019890304 | 3/4/1989 | Mapping |
| Bheri/Mugu/Humla/Tila | 143–040 | p143r40_5t19901117 | 11/17/1990 | Mapping |
| Mugu/Humla | 143–039 | p143r39_5t19921021 | 10/21/1992 | Mapping |
| Humla/Kawari/West Seti /Mahakali | 144–039 | p144r39_5t19901023 | 10/23/1990 | Mapping |
| **1980 Inventory** | | | | |
| Tamor/Arun/Dudh | 150–041 | p150r41_2m19761219 | 12/19/1976 | Mapping |
| Dudh/Likhu/Tama/Sun/Indrawati/Trishuli | 151–041 | m2151041_04119770107 | 1/7/1977 | Mapping |
| | 151–041 | m2151041_04119761027 | 10/27/1976 | Mapping |
| Trishuli/Budhi Gandaki/Marsyangdi/Seti | 151–040 | p151r040_2dm19770107 | 1/7/1977 | Mapping |
| | 152–040 | p152r40_2m19761203 | 12/3/1976 | Mapping |
| Trishuli /Budhi Gandaki/Marsyangdi/Seti | 152–040 | LM21520401977044XXX03 | 2/13/1977 | Mapping |
| | 152–040 | LM21520401976302XXX01 | 10/28/1976 | Mapping |
| Kali Gandaki/Bheri/Mugu/Tila/Humla | 153–040 | m2153040_04019770322 | 3/22/1977 | Mapping |
| | 153–040 | m2153040_04019761029 | 10/29/1976 | Mapping |
| | 153–040 | m2153040_04019761204 | 12/4/1976 | Mapping |
| | 153–040 | m2153040_04019770109 | 1/9/1977 | Mapping |
| | 153–040 | m2153040_04019770214 | 2/14/1977 | Mapping |
| | 153–040 | p153r40_3m19790707 | 7/7/1979 | Mapping |
| Bheri/Mugu/Tila | 154–040 | m2154040_04019761030 | 10/30/1976 | Mapping |
| Mugu/Tila | 154–040 | p154r40_3m19790109 | 1/9/1979 | Mapping |
| Mugu/Tila | 154–040 | m2154040_04019761205 | 12/5/1976 | Mapping |
| Mugu/Humla | 154–039 | m2154039_03919761117 | 11/17/1976 | Mapping |
| | 154–039 | m2154039_03919761012 | 10/12/1976 | Mapping |
| | 154–039 | p154r39_2m19770323 | 3/23/1977 | Mapping |
| Humla/Kawari/West Seti/Mahakali | 155–039 | p155r39_2m19761206 | 12/6/1976 | Mapping |
| | 155–039 | LM21550391976305XXX00 | 10/31/1976 | Mapping |

# Annex 2: **Detailed Tables**

Detailed characteristics of the sub-basins in the individual basins in 2010

Table A2.1: **Glacier area classes in the Karnali sub-basins (2010)**

| Basin | Class | Area | Glacier number | | Glacier area | | Estimated ice reserves | | Mean area per glacier |
|---|---|---|---|---|---|---|---|---|---|
| | | km² | Number | % | km² | % | km³ | % | km² |
| **Bheri** | 1a | ≤ 0.10 | 87 | 21.70 | 5.7 | 1.56 | 0.1 | 0.29 | 0.07 |
| | 1b | 0.11–0.50 | 164 | 40.90 | 40.4 | 11.09 | 1 | 4.07 | 0.25 |
| | 2 | 0.51–1.00 | 73 | 18.20 | 51.9 | 14.27 | 1.9 | 7.80 | 0.71 |
| | 3 | 1.01–5.00 | 67 | 16.71 | 141.5 | 38.90 | 8.3 | 33.52 | 2.11 |
| | 4 | 5.01–10.00 | 5 | 1.25 | 34.2 | 9.39 | 2.9 | 11.57 | 6.83 |
| | 5 | ≥ 10.01 | 5 | 1.25 | 90.2 | 24.79 | 10.5 | 42.75 | 18.04 |
| | | **Total** | **401** | **100** | **363.85** | **100** | **24.66** | **100** | **0.91** |
| **Tila** | 1a | ≤ 0.10 | 22 | 36.07 | 1.4 | 5.21 | 0 | 1.33 | 0.06 |
| | 1b | 0.11–0.50 | 26 | 42.62 | 6 | 22.46 | 0.1 | 11.20 | 0.23 |
| | 2 | 0.51–1.00 | 8 | 13.11 | 6.4 | 23.88 | 0.2 | 18.83 | 0.80 |
| | 3 | 1.01–5.00 | 4 | 6.56 | 5.6 | 20.93 | 0.3 | 20.58 | 1.40 |
| | 4 | 5.01–10.00 | 1 | 1.64 | 7.4 | 27.53 | 0.6 | 48.05 | 7.37 |
| | 5 | ≥ 10.01 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | **Total** | **61** | **100** | **26.77** | **100.00** | **1.31** | **100** | **0.44** |
| **Mugu** | 1a | ≤ 0.10 | 53 | 25.85 | 3.4 | 2.85 | 0 | 0.72 | 0.06 |
| | 1b | 0.11–0.50 | 88 | 42.93 | 21.8 | 18.32 | 0.5 | 9.33 | 0.25 |
| | 2 | 0.51–1.00 | 35 | 17.07 | 24.2 | 20.27 | 0.9 | 15.16 | 0.69 |
| | 3 | 1.01–5.00 | 27 | 13.17 | 56.3 | 47.26 | 3.2 | 55.60 | 2.09 |
| | 4 | 5.01–10.00 | 2 | 0.98 | 13.5 | 11.30 | 1.1 | 19.18 | 6.73 |
| | 5 | ≥ 10.01 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | **Total** | **205** | **100** | **119.18** | **100** | **5.84** | **100** | **0.58** |
| **Humla** | 1a | ≤ 0.10 | 115 | 24.26 | 7.6 | 2.25 | 0.1 | 0.49 | 0.07 |
| | 1b | 0.11–0.50 | 209 | 44.09 | 49.3 | 14.58 | 1.2 | 6.18 | 0.24 |
| | 2 | 0.51–1.00 | 65 | 13.71 | 44.9 | 13.29 | 1.6 | 8.46 | 0.69 |
| | 3 | 1.01–5.00 | 73 | 15.40 | 138.1 | 40.88 | 7.7 | 39.29 | 1.89 |
| | 4 | 5.01–10.00 | 8 | 1.69 | 51.2 | 15.16 | 4.2 | 21.49 | 6.40 |
| | 5 | ≥ 10.01 | 4 | 0.84 | 46.8 | 13.84 | 4.7 | 24.09 | 11.69 |
| | | **Total** | **474** | **100** | **337.87** | **100** | **19.48** | **100** | **0.71** |
| **Kawari** | 1a | ≤ 0.10 | 11 | 22.92 | 0.7 | 2.48 | 0.0 | 0.62 | 0.07 |
| | 1b | 0.11–0.50 | 19 | 39.58 | 5.2 | 17.91 | 0.1 | 9.49 | 0.27 |
| | 2 | 0.51–1.00 | 13 | 27.08 | 9.5 | 32.54 | 0.4 | 24.58 | 0.73 |
| | 3 | 1.01–5.00 | 4 | 8.33 | 6.7 | 23.07 | 0.4 | 24.75 | 1.68 |
| | 4 | 5.01–10.00 | 1 | 2.08 | 7 | 24.00 | 0.6 | 40.57 | 7.00 |
| | 5 | ≥ 10.01 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | **Total** | **48** | **100** | **29.16** | **100** | **1.45** | **100** | **0.61** |
| **West Seti** | 1a | ≤ 0.10 | 53 | 19.63 | 3.2 | 2.19 | 0 | 0.54 | 0.06 |
| | 1b | 0.11–0.50 | 146 | 54.07 | 36 | 24.66 | 0.9 | 12.46 | 0.25 |
| | 2 | 0.51–1.00 | 40 | 14.81 | 29.2 | 20.02 | 1.1 | 15.04 | 0.73 |
| | 3 | 1.01–5.00 | 28 | 10.37 | 52.1 | 35.65 | 2.9 | 39.58 | 1.86 |
| | 4 | 5.01–10.00 | 2 | 0.74 | 12.6 | 8.63 | 1 | 14.07 | 6.30 |
| | 5 | ≥ 10.01 | 1 | 0.37 | 12.9 | 8.84 | 1.3 | 18.31 | 12.91 |
| | | **Total** | **270** | **100** | **146.01** | **100** | **7.28** | **100** | **0.54** |

Table A2.2: **Morphological classification of glaciers in the Karnali sub-basins (2010)**

| Basin | Glacier type | | Glacier number | | Glacier area | | Estimated ice reserves | | Mean area per glacier |
|---|---|---|---|---|---|---|---|---|---|
| | | | Number | % | $km^2$ | % | $km^3$ | % | $km^2$ |
| Bheri | Mountain | Miscellaneous | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | Ice Apron | 71 | 17.7 | 12.9 | 3.5 | 0.34 | 1.4 | 0.18 |
| | | Cirque | 1 | 0.2 | 0.1 | 0 | 0 | 0 | 0.12 |
| | | Niche | 36 | 9 | 3.9 | 1.1 | 0.07 | 0.3 | 0.11 |
| | | Basin | 287 | 71.6 | 269.6 | 74.1 | 15.67 | 63.5 | 0.94 |
| | Valley | Trough | 6 | 1.5 | 77.4 | 21.3 | 8.58 | 34.8 | 12.89 |
| | | **Total** | **401** | **100** | **363.8** | **100** | **24.66** | **100** | **0.91** |
| Tila | Mountain | Miscellaneous | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | Ice Apron | 14 | 23 | 1.3 | 4.7 | 0.02 | 1.6 | 0.09 |
| | | Cirque | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | Niche | 4 | 6.6 | 0.2 | 0.9 | 0 | 0.2 | 0.06 |
| | | Basin | 42 | 68.9 | 17.9 | 66.9 | 0.66 | 50.1 | 0.43 |
| | Valley | Trough | 1 | 1.6 | 7.4 | 27.5 | 0.63 | 48.0 | 7.37 |
| | | **Total** | **61** | **100** | **26.8** | **100** | **1.31** | **100** | **0.44** |
| Mugu | Mountain | Miscellaneous | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | Ice Apron | 39 | 19 | 6.9 | 5.8 | 0.18 | 3.1 | 0.18 |
| | | Cirque | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | Niche | 15 | 7.3 | 1.6 | 1.3 | 0.03 | 0.5 | 0.11 |
| | | Basin | 150 | 73.2 | 106.7 | 89.5 | 5.36 | 91.7 | 0.71 |
| | Valley | Trough | 1 | 0.5 | 4 | 3.3 | 0.27 | 4.7 | 3.98 |
| | | **Total** | **205** | **100** | **119.2** | **100** | **5.84** | **100** | **0.58** |
| Humla | Mountain | Miscellaneous | 2 | 0.4 | 0.6 | 0.2 | 0.02 | 0.1 | 0.28 |
| | | Ice Apron | 55 | 11.6 | 9.2 | 2.7 | 0.23 | 1.2 | 0.17 |
| | | Cirque | 1 | 0.2 | 0 | 0.0 | 0 | 0 | 0.04 |
| | | Niche | 55 | 11.6 | 5.2 | 1.5 | 0.09 | 0.4 | 0.09 |
| | | Basin | 357 | 75.3 | 283.6 | 83.9 | 15.31 | 78.6 | 0.79 |
| | Valley | Trough | 4 | 0.8 | 39.3 | 11.6 | 3.85 | 19.8 | 9.82 |
| | | **Total** | **474** | **100** | **337.9** | **100** | **19.48** | **100** | **0.71** |
| Kawari | Mountain | Miscellaneous | 0 | 0 | 0 | 0 | 0 | 0 | 0. |
| | | Ice Apron | 3 | 6.3 | 0.3 | 1.1 | 0.01 | 0.3 | 0.10 |
| | | Cirque | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | Niche | 6 | 12.5 | 0.5 | 1.6 | 0.01 | 0.5 | 0.08 |
| | | Basin | 38 | 79.2 | 21.4 | 73.3 | 0.85 | 58.6 | 0.56 |
| | Valley | Trough | 1 | 2.1 | 7 | 24 | 0.59 | 40.6 | 7 |
| | | **Total** | **48** | **100** | **29.2** | **100** | **1.45** | **100** | **0.61** |
| West Seti | Mountain | Miscellaneous | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | Ice Apron | 43 | 15.9 | 6.9 | 4.7 | 0.17 | 2.3 | 0.16 |
| | | Cirque | 2 | 0.7 | 0.1 | 0.1 | 0 | 0 | 0.06 |
| | | Niche | 33 | 12.2 | 3.2 | 2.2 | 0.05 | 0.7 | 0.10 |
| | | Basin | 186 | 68.9 | 99.8 | 68.3 | 3.97 | 54.5 | 0.54 |
| | Valley | Trough | 6 | 2.2 | 36.1 | 24.7 | 3.10 | 42.5 | 6.02 |
| | | **Total** | **270** | **100** | **146** | **100** | **7.28** | **100** | **0.54** |

Table A2.3: **Area-elevation distribution of glaciers in the Karnali sub-basins (2010)**

| Elevation range (masl) | Area (km²) | | | | | | |
|---|---|---|---|---|---|---|---|
| | West Seti | Kawari | Humla | Mugu | Tila | Bheri | Total |
| 3,600–3,700 | | 0.568 | | | | | 0.566 |
| 3,700–3,800 | | 1.703 | | | | | 1.697 |
| 3,800–3,900 | | 0.967 | | | | | 0.964 |
| 3,900–4,000 | | 0.248 | | | | | 0.247 |
| 4,000–4,100 | | 0.123 | | | | | 0.122 |
| 4,100–4,200 | 0.26 | 0.14 | | | 0.089 | 0.364 | 0.852 |
| 4,200–4,300 | 1.061 | 0.165 | 0.02 | | 0.395 | 1.425 | 3.064 |
| 4,300–4,400 | 1.229 | 0.289 | 0.524 | | 0.843 | 1.24 | 4.12 |
| 4,400–4,500 | 2.263 | 0.286 | 1.382 | | 0.912 | 1.306 | 6.136 |
| 4,500–4,600 | 3.83 | 0.33 | 2.549 | 0.474 | 0.306 | 1.311 | 8.775 |
| 4,600–4,700 | 4.808 | 0.426 | 4.481 | 0.914 | 0.347 | 1.787 | 12.731 |
| 4,700–4,800 | 5.81 | 0.517 | 7.163 | 1.559 | 0.590 | 2.994 | 18.60 |
| 4,800–4,900 | 7.892 | 0.692 | 13.215 | 3.875 | 0.675 | 3.993 | 30.29 |
| 4,900–5,000 | 11.132 | 1.855 | 21.087 | 4.232 | 1.422 | 4.872 | 44.528 |
| 5,000–5,100 | 17.399 | 3.156 | 28.724 | 6.794 | 2.333 | 11.654 | 69.959 |
| 5,100–5,200 | 18.468 | 4.381 | 34.569 | 8.606 | 3.335 | 16.78 | 86.043 |
| 5,200–5,300 | 15.254 | 4.882 | 38.99 | 12.628 | 3.379 | 23.562 | 98.636 |
| 5,300–5,400 | 13.402 | 4.46 | 42.243 | 12.256 | 2.941 | 29.67 | 104.954 |
| 5,400–5,500 | 11.552 | 1.771 | 39.894 | 13.938 | 2.083 | 34.505 | 103.761 |
| 5,500–5,600 | 6.36 | 0.962 | 36.685 | 12.627 | 1.652 | 37.309 | 95.667 |
| 5,600–5,700 | 4.522 | 0.417 | 25.88 | 9.035 | 1.555 | 38.296 | 79.801 |
| 5,700–5,800 | 3.665 | 0.264 | 17.032 | 8.052 | 1.211 | 30.169 | 60.464 |
| 5,800–5,900 | 3.013 | 0.113 | 10.227 | 8.278 | 0.987 | 23.853 | 46.521 |
| 5,900–6,000 | 2.687 | 0.03 | 4.708 | 6.141 | 0.658 | 18.397 | 32.656 |
| 6,000–6,100 | 2.514 | 0.03 | 2.85 | 4.948 | 0.529 | 14.621 | 25.516 |
| 6,100–6,200 | 2.269 | 0.033 | 1.531 | 2.566 | 0.393 | 11.739 | 18.552 |
| 6,200–6,300 | 1.71 | 0.046 | 1.16 | 1.18 | 0.119 | 10.545 | 14.784 |
| 6,300–6,400 | 1.475 | 0.044 | 1.148 | 0.476 | 0.007 | 9.007 | 12.179 |
| 6,400–6,500 | 1.322 | 0.057 | 0.67 | 0.17 | | 7.186 | 9.423 |
| 6,500–6,600 | 0.836 | 0.065 | 0.433 | 0.105 | | 5.838 | 7.293 |
| 6,600–6,700 | 0.536 | 0.06 | 0.304 | 0.134 | | 5.113 | 6.162 |
| 6,700–6,800 | 0.267 | 0.06 | 0.181 | 0.106 | | 4.563 | 5.192 |
| 6,800–6,900 | 0.278 | 0.005 | 0.097 | 0.022 | | 3.643 | 4.057 |
| 6,900–7,000 | 0.1 | | 0.019 | | | 2.61 | 2.739 |
| 7,000–7,100 | | | | | | 1.905 | 1.912 |
| 7,100–7,200 | | | | | | 1.616 | 1.622 |
| 7,200–7,300 | | | | | | 0.982 | 0.985 |
| 7,300–7,400 | | | | | | 0.586 | 0.588 |
| 7,400–7,500 | | | | | | 0.335 | 0.336 |
| | **145.914** | **29.146** | **337.766** | **119.116** | **26.761** | **363.777** | **1022.495** |

Table A2.4: **Glacier area classes in the Gandaki sub-basins (2010)**

| Basin | Class | Area | Glacier number | | Glacier area | | Estimated ice reserves | | Mean area per glacier |
|---|---|---|---|---|---|---|---|---|---|
| | | km² | Number | % | km² | % | km³ | % | km² |
| Trishuli | 1a | ≤ 0.10 | 28 | 16.97 | 1.9 | 0.92 | 0 | 0.13 | 0.07 |
| | 1b | 0.11–0.50 | 83 | 50.3 | 21.7 | 10.46 | 0.6 | 2.9 | 0.26 |
| | 2 | 0.51–1.00 | 20 | 12.12 | 13.7 | 6.62 | 0.5 | 2.61 | 0.69 |
| | 3 | 1.01–5.00 | 28 | 16.97 | 56.6 | 27.27 | 3.2 | 16.71 | 2.02 |
| | 4 | 5.01–10.00 | 2 | 1.21 | 13.4 | 6.48 | 1.1 | 5.81 | 6.72 |
| | 5 | ≥ 10.01 | 4 | 2.42 | 100.2 | 48.26 | 13.8 | 71.83 | 25.04 |
| | | **Total** | **165** | **100** | **207.56** | **100** | **19.26** | **100** | **1.26** |
| Budhi Gandaki | 1a | ≤ 0.10 | 29 | 11.98 | 2 | 0.59 | 0 | 0.09 | 0.07 |
| | 1b | 0.11–0.50 | 108 | 44.63 | 27.2 | 7.80 | 0.7 | 2.4 | 0.25 |
| | 2 | 0.51–1.00 | 44 | 18.18 | 32 | 9.17 | 1.2 | 4.2 | 0.73 |
| | 3 | 1.01–5.00 | 46 | 19.01 | 94 | 26.94 | 5.3 | 18.72 | 2.04 |
| | 4 | 5.01–10.00 | 7 | 2.89 | 51.2 | 14.66 | 4.4 | 15.42 | 7.31 |
| | 5 | ≥ 10.01 | 8 | 3.31 | 142.4 | 40.84 | 16.9 | 59.17 | 17.81 |
| | | **Total** | **242** | **100.00** | **348.81** | **100.00** | **28.53** | **100.00** | **1.44** |
| Marsyangdi | 1a | ≤ 0.10 | 58 | 15.1 | 4.1 | 0.81 | 0.1 | 0.13 | 0.07 |
| | 1b | 0.11–0.50 | 172 | 44.79 | 43.9 | 8.63 | 1.1 | 2.78 | 0.26 |
| | 2 | 0.51–1.00 | 51 | 13.28 | 36.7 | 7.20 | 1.4 | 3.42 | 0.72 |
| | 3 | 1.01–5.00 | 83 | 21.61 | 166.5 | 32.71 | 9.5 | 23.70 | 2.01 |
| | 4 | 5.01–10.00 | 8 | 2.08 | 58.6 | 11.51 | 5 | 12.58 | 7.33 |
| | 5 | ≥ 10.01 | 12 | 3.13 | 199.2 | 39.13 | 22.9 | 57.38 | 16.6 |
| | | **Total** | **384** | **100** | **508.97** | **100** | **39.97** | **100** | **1.33** |
| Seti | 1a | ≤ 0.10 | 10 | 22.22 | 0.7 | 0.98 | 0 | 0.11 | 0.07 |
| | 1b | 0.11–0.50 | 20 | 44.44 | 4.7 | 6.52 | 0.1 | 1.38 | 0.23 |
| | 2 | 0.51–1.00 | 6 | 13.33 | 4.3 | 5.99 | 0.2 | 1.97 | 0.72 |
| | 3 | 1.01–5.00 | 8 | 17.78 | 18.3 | 25.60 | 1.1 | 13.54 | 2.29 |
| | 4 | 5.01–10.00 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 5 | ≥ 10.01 | 1 | 2.22 | 43.6 | 60.91 | 6.7 | 83 | 43.63 |
| | | **Total** | **45** | **100** | **71.63** | **100** | **8.09** | **100** | **1.59** |
| Kali Gandaki | 1a | ≤ 0.10 | 74 | 14.68 | 4.8 | 0.91 | 0.1 | 0.16 | 0.06 |
| | 1b | 0.11–0.50 | 246 | 48.81 | 62.1 | 11.76 | 1.6 | 4.02 | 0.25 |
| | 2 | 0.51–1.00 | 74 | 14.68 | 52.3 | 9.92 | 1.9 | 4.97 | 0.71 |
| | 3 | 1.01–5.00 | 93 | 18.45 | 187 | 35.46 | 10.6 | 27.28 | 2.01 |
| | 4 | 5.01–10.00 | 10 | 1.98 | 67.7 | 12.84 | 5.7 | 14.61 | 6.77 |
| | 5 | ≥ 10.01 | 7 | 1.39 | 153.5 | 29.11 | 19 | 48.96 | 21.93 |
| | | **Total** | **504** | **100** | **527.45** | **100** | **38.90** | **100** | **1.05** |

Table A2.5: **Morphological classification of glaciers in the Gandaki sub-basins (2010)**

| Basin | Glacier type | | Glacier number | | Glacier area | | Estimated ice reserves | | Mean area per glacier |
|---|---|---|---|---|---|---|---|---|---|
| | | | Number | % | km² | % | km³ | % | km² |
| Trishuli | Mountain | Miscellaneous | 1 | 0.6 | 0.5 | 0.2 | 0.02 | 0.1 | 0.48 |
| | | Ice Apron | 61 | 37 | 20.5 | 9.9 | 0.73 | 3.8 | 0.34 |
| | | Cirque | 3 | 1.8 | 0.8 | 0.4 | 0.02 | 0.1 | 0.26 |
| | | Niche | 7 | 4.2 | 1.9 | 0.9 | 0.08 | 0.4 | 0.28 |
| | | Basin | 86 | 52.1 | 71.6 | 34.5 | 3.63 | 18.8 | 0.83 |
| | Valley | Trough | 7 | 4.2 | 112.2 | 54.1 | 14.78 | 76.7 | 16.03 |
| | | **Total** | **165** | **100** | **207.6** | **100** | **19.26** | **100** | **1.26** |
| Budhi Gandaki | Mountain | Miscellaneous | 1 | 0.4 | 0.5 | 0.1 | 0.02 | 0.1 | 0.5 |
| | | Ice Apron | 74 | 30.6 | 35.4 | 10.2 | 1.60 | 5.6 | 0.48 |
| | | Cirque | 2 | 0.8 | 0.4 | 0.1 | 0.01 | 0 | 0.18 |
| | | Niche | 26 | 10.7 | 5 | 1.4 | 0.13 | 0.5 | 0.19 |
| | | Basin | 127 | 52.5 | 161.3 | 46.2 | 10.20 | 35.7 | 1.27 |
| | Valley | Trough | 12 | 5 | 146.3 | 41.9 | 16.58 | 58.1 | 12.19 |
| | | **Total** | **242** | **100** | **348.8** | **100** | **28.53** | **100** | **1.44** |
| Marsyangdi | Mountain | Miscellaneous | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | Ice Apron | 108 | 28.1 | 38.5 | 7.6 | 1.65 | 4.1 | 0.36 |
| | | Cirque | 2 | 0.5 | 0.5 | 0.1 | 0.01 | 0 | 0.23 |
| | | Niche | 26 | 6.8 | 5 | 1 | 0.14 | 0.3 | 0.19 |
| | | Basin | 238 | 62.0 | 307.5 | 60.4 | 19.89 | 49.8 | 1.29 |
| | Valley | Trough | 10 | 2.6 | 157.5 | 30.9 | 18.28 | 45.7 | 15.75 |
| | | **Total** | **384** | **100** | **509** | **100** | **39.97** | **100** | **1.33** |
| Seti | Mountain | Miscellaneous | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | Ice Apron | 16 | 35.6 | 5.5 | 7.7 | 0.19 | 2.4 | 0.34 |
| | | Cirque | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | Niche | 7 | 15.6 | 0.8 | 1.1 | 0.01 | 0.2 | 0.12 |
| | | Basin | 22 | 48.9 | 65.3 | 91.2 | 7.88 | 97.4 | 2.97 |
| | Valley | Trough | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | **Total** | **45** | **100** | **71.6** | **100** | **8.09** | **100** | **1.59** |
| Kali Gandaki | Mountain | Miscellaneous | 1 | 0.2 | 1.2 | 0.2 | 0.05 | 0.1 | 1.2 |
| | | Ice Apron | 158 | 31.3 | 40.9 | 7.8 | 1.30 | 3.3 | 0.26 |
| | | Cirque | 1 | 0.2 | 0.2 | 0.0 | 0.00 | 0.0 | 0.18 |
| | | Niche | 15 | 3 | 1.5 | 0.3 | 0.03 | 0.1 | 0.1 |
| | | Basin | 324 | 64.3 | 367.9 | 69.8 | 22.99 | 59.1 | 1.14 |
| | Valley | Trough | 5 | 1 | 115.7 | 21.9 | 14.54 | 37.4 | 23.13 |
| | | **Total** | **504** | **100** | **527.4** | **100** | **38.90** | **100** | **1.05** |

Table A2.6: **Area-elevation distribution of glaciers in the Gandaki sub-basins (2010)**

| Elevation range (masl) | Area ($km^2$) | | | | | |
|---|---|---|---|---|---|---|
| | Kali Gandaki | Marsyangdi | Seti | Budhi Gandaki | Trishuli | Total |
| 3,200–3,300 | 0 | 0 | 0 | 0.11 | 0 | 0.11 |
| 3,300–3,400 | 0 | 0 | 0 | 0.59 | 0 | 0.59 |
| 3,400–3,500 | 0 | 0 | 0 | 1.24 | 0 | 1.24 |
| 3,500–3,600 | 0 | 0 | 0 | 2.13 | 0 | 2.13 |
| 3,600–3,700 | 0 | 0.08 | 0 | 1.57 | 0.06 | 1.7 |
| 3,700–3,800 | 0 | 0.19 | 0 | 1.72 | 0.25 | 2.17 |
| 3,800–3,900 | 0.04 | 0.51 | 0 | 2.49 | 0.07 | 3.12 |
| 3,900–4,000 | 0.36 | 0.97 | 0.01 | 4.58 | 0.14 | 6.07 |
| 4,000–4,100 | 1.29 | 1.55 | 0.05 | 4.09 | 0.13 | 7.11 |
| 4,100–4,200 | 2.13 | 4.21 | 0.24 | 5.13 | 0.36 | 12.08 |
| 4,200–4,300 | 2.02 | 5.04 | 0.18 | 5.56 | 0.35 | 13.16 |
| 4,300–4,400 | 1.43 | 4.66 | 0.24 | 5.43 | 1.16 | 12.93 |
| 4,400–4,500 | 2.24 | 4.66 | 0.31 | 5.15 | 2.07 | 14.43 |
| 4,500–4,600 | 2.5 | 5.85 | 0.5 | 5.62 | 3.40 | 17.88 |
| 4,600–4,700 | 2.91 | 5.34 | 1.26 | 6.14 | 5.13 | 20.8 |
| 4,700–4,800 | 3.44 | 4.96 | 1.39 | 8.96 | 5.59 | 24.36 |
| 4,800–4,900 | 4.31 | 5.85 | 1.35 | 11.86 | 7.19 | 30.6 |
| 4,900–5,000 | 5.22 | 8.15 | 1.89 | 13.74 | 7.42 | 36.46 |
| 5,000–5,100 | 8.6 | 14.52 | 2.28 | 15.8 | 9.44 | 50.68 |
| 5,100–5,200 | 13.92 | 18.82 | 2.18 | 17.86 | 13.78 | 66.6 |
| 5,200–5,300 | 15.80 | 19.44 | 2.11 | 20.01 | 16.32 | 73.72 |
| 5,300–5,400 | 17.32 | 23.39 | 2.17 | 21.55 | 17.59 | 82.04 |
| 5,400–5,500 | 21.47 | 29.15 | 2.04 | 24.69 | 18.97 | 96.35 |
| 5,500–5,600 | 26.19 | 35.86 | 2.29 | 23.33 | 16.06 | 103.75 |
| 5,600–5,700 | 36.29 | 41.49 | 2.15 | 20.07 | 15.06 | 115.04 |
| 5,700–5,800 | 52.57 | 40.91 | 2.33 | 16.6 | 14.25 | 126.6 |
| 5,800–5,900 | 63.48 | 39.77 | 3.29 | 15.6 | 11.43 | 133.48 |
| 5,900–6,000 | 64.37 | 35.91 | 2.99 | 13.64 | 8.69 | 125.49 |
| 6,000–6,100 | 45.2 | 32.09 | 3.36 | 12.66 | 6.71 | 99.97 |
| 6,100–6,200 | 31.36 | 26.87 | 3.45 | 11.96 | 6.41 | 80.02 |
| 6,200–6,300 | 22.3 | 20.2 | 4 | 11.18 | 5.15 | 62.83 |
| 6,300–6,400 | 15.8 | 16.36 | 4.34 | 9.67 | 3.79 | 49.96 |
| 6,400–6,500 | 12.29 | 13.53 | 6 | 6.23 | 3.32 | 41.4 |
| 6,500–6,600 | 9.29 | 10.8 | 4.59 | 3.95 | 2.56 | 31.19 |
| 6,600–6,700 | 7.93 | 8.29 | 3.17 | 3.35 | 1.82 | 24.56 |
| 6,700–6,800 | 6.7 | 7.05 | 2.95 | 3.29 | 1.26 | 21.26 |
| 6,800–6,900 | 6.02 | 6.05 | 2.53 | 2.8 | 0.82 | 18.23 |
| 6,900–7,000 | 5.16 | 4.7 | 1.51 | 1.9 | 0.38 | 13.63 |
| 7,000–7,100 | 4.52 | 3.36 | 1.31 | 1.53 | 0.32 | 11.04 |
| 7,100–7,200 | 2.88 | 2.88 | 1.04 | 1.28 | 0.12 | 8.19 |
| 7,200–7,300 | 2.22 | 2.69 | 1.06 | 0.88 | 0 | 6.86 |
| 7,300–7,400 | 2.09 | 1.38 | 0.79 | 0.74 | 0 | 4.99 |
| 7,400–7,500 | 1.68 | 0.81 | 0.24 | 0.79 | 0 | 3.51 |
| 7,500–7,600 | 1.24 | 0.43 | 0.02 | 0.56 | 0 | 2.24 |
| 7,600–7,700 | 1.07 | 0.20 | 0 | 0.38 | 0 | 1.64 |
| 7,700–7,800 | 0.84 | 0.06 | 0 | 0.14 | 0 | 1.04 |
| 7,800–7,900 | 0.45 | 0 | 0 | 0.08 | 0 | 0.53 |
| 7,900–8,000 | 0.29 | 0 | 0 | 0.04 | 0 | 0.33 |
| 8,000–8,100 | 0.09 | 0 | 0 | 0 | 0 | 0.09 |
| 8,100–8,200 | 0.01 | 0 | 0 | 0 | 0 | 0.01 |
| **Total** | **527.32** | **509.01** | **71.63** | **348.67** | **207.58** | **1664.22** |

Table A2.7: **Glacier area classification in the Koshi sub-basins (2010)**

| Basin | Class | Area | Glacier number | | Glacier area | | Estimated ice reserves | | Mean area per glacier |
|---|---|---|---|---|---|---|---|---|---|
| | | (km²) | Number | % | km² | % | km³ | % | km² |
| **Tamor** | 1a | ≤ 0.10 | 60 | 22.9 | 3.8 | 0.98 | 0 | 0.11 | 0.06 |
| | 1b | 0.11–0.50 | 116 | 44.27 | 28.2 | 7.31 | 0.7 | 1.67 | 0.24 |
| | 2 | 0.51–1.00 | 34 | 12.98 | 22.8 | 5.91 | 0.8 | 1.95 | 0.67 |
| | 3 | 1.01–5.00 | 40 | 15.27 | 82.3 | 21.32 | 4.7 | 11.20 | 2.06 |
| | 4 | 5.01–10.00 | 5 | 1.91 | 36.8 | 9.54 | 3.2 | 7.51 | 7.36 |
| | 5 | ≥ 10.01 | 7 | 2.67 | 212 | 54.94 | 32.8 | 77.56 | 30.29 |
| | | **Total** | **262** | **100** | **385.93** | **100** | **42.26** | **100** | **1.47** |
| **Arun** | 1a | ≤ 0.10 | 21 | 19.44 | 1.3 | 0.84 | 0.0 | 0.10 | 0.06 |
| | 1b | 0.11–0.50 | 53 | 49.07 | 13.3 | 8.89 | 0.3 | 2.21 | 0.25 |
| | 2 | 0.51–1.00 | 14 | 12.96 | 10.4 | 6.98 | 0.4 | 2.61 | 0.74 |
| | 3 | 1.01–5.00 | 17 | 15.74 | 36.9 | 24.75 | 2.2 | 14.38 | 2.17 |
| | 4 | 5.01–10.00 | 0 | 0 | 0 | 0 | 0 | 0 | x |
| | 5 | ≥ 10.01 | 3 | 2.78 | 87.3 | 58.55 | 12.1 | 80.69 | 29.11 |
| | | **Total** | **108** | **100** | **149.19** | **100** | **15.00** | **100** | **1.38** |
| **Dudh Koshi** | 1a | ≤ 0.10 | 53 | 18.47 | 3.5 | 0.89 | 0 | 0.11 | 0.07 |
| | 1b | 0.11–0.50 | 139 | 48.43 | 36.6 | 9.37 | 0.9 | 2.41 | 0.27 |
| | 2 | 0.51–1.00 | 37 | 12.89 | 26.9 | 6.88 | 1 | 2.57 | 0.73 |
| | 3 | 1.01–5.00 | 46 | 16.03 | 102.3 | 26.14 | 6 | 15.43 | 2.22 |
| | 4 | 5.01–10.00 | 7 | 2.44 | 48.3 | 12.35 | 4.1 | 10.36 | 6.9 |
| | 5 | ≥ 10.01 | 5 | 1.74 | 173.5 | 44.34 | 27.1 | 69.11 | 34.69 |
| | | **Total** | **287** | **100** | **391.15** | **100** | **39.20** | **100** | **1.36** |
| **Likhu** | 1a | ≤ 0.10 | 6 | 22.22 | 0.3 | 1.49 | 0 | 0.29 | 0.06 |
| | 1b | 0.11–0.50 | 13 | 48.15 | 3.5 | 15.41 | 0.1 | 6.32 | 0.27 |
| | 2 | 0.51–1.00 | 2 | 7.41 | 1.4 | 6.27 | 0.1 | 3.75 | 0.72 |
| | 3 | 1.01–5.00 | 5 | 18.52 | 8.8 | 38.18 | 0.5 | 32.64 | 1.75 |
| | 4 | 5.01–10.00 | 1 | 3.70 | 8.9 | 38.65 | 0.8 | 57.01 | 8.87 |
| | 5 | ≥ 10.01 | 0 | 0 | 0.0 | 0 | 0 | 0 | x |
| | | **Total** | **27** | **100** | **22.95** | **100** | **1.42** | **100** | **0.85** |
| **Tama Koshi** | 1a | ≤ 0.10 | 21 | 24.71 | 1.2 | 1.45 | 0 | 0.19 | 0.06 |
| | 1b | 0.11–0.50 | 40 | 47.06 | 9.7 | 11.44 | 0.2 | 3.03 | 0.24 |
| | 2 | 0.51–1.00 | 14 | 16.47 | 10 | 11.82 | 0.4 | 4.69 | 0.71 |
| | 3 | 1.01–5.00 | 8 | 9.41 | 13.3 | 15.79 | 0.7 | 8.8 | 1.67 |
| | 4 | 5.01–10.00 | 0 | 0 | 0 | 0 | 0 | 0 | x |
| | 5 | ≥ 10.01 | 2 | 2.35 | 50.2 | 59.49 | 6.6 | 83.3 | 25.11 |
| | | **Total** | **85** | **100** | **84.42** | **100** | **7.89** | **100** | **0.99** |
| **Sun Koshi** | 1a | ≤ 0.10 | 8 | 20.51 | 0.5 | 0.92 | 0 | 0.14 | 0.06 |
| | 1b | 0.11–0.50 | 17 | 43.59 | 3.2 | 6.08 | 0.1 | 1.67 | 0.19 |
| | 2 | 0.51–1.00 | 4 | 10.26 | 2.5 | 4.84 | 0.1 | 2.16 | 0.64 |
| | 3 | 1.01–5.00 | 7 | 17.95 | 13.4 | 25.46 | 0.7 | 17.64 | 1.91 |
| | 4 | 5.01–10.00 | 1 | 2.56 | 7.9 | 15.02 | 0.7 | 16.62 | 7.89 |
| | 5 | ≥ 10.01 | 2 | 5.13 | 25.1 | 47.68 | 2.6 | 61.77 | 12.53 |
| | | **Total** | **39** | **100** | **52.57** | **100** | **4.16** | **100** | **1.35** |
| **Indrawati** | 1a | ≤ 0.10 | 12 | 32.43 | 0.6 | 3.6 | 0 | 0.86 | 0.05 |
| | 1b | 0.11–0.50 | 16 | 43.24 | 4.1 | 25 | 0.1 | 14.19 | 0.26 |
| | 2 | 0.51–1.00 | 5 | 13.51 | 3.4 | 20.87 | 0.1 | 17.17 | 0.68 |
| | 3 | 1.01–5.00 | 4 | 10.81 | 8.3 | 50.54 | 0.5 | 67.78 | 2.07 |
| | 4 | 5.01–10.00 | 0 | 0 | 0 | 0 | 0 | 0 | x |
| | 5 | ≥ 10.01 | 0 | 0 | 0 | 0 | 0 | 0 | x |
| | | **Total** | **37** | **100** | **16.41** | **100** | **0.73** | **100** | **0.44** |

Table A2.8: **Morphological classification of glaciers in the Koshi sub-basins (2010)**

| Basin | Glacier type | | Glacier number | | Glacier area | | Estimated ice reserves | | Mean area per glacier |
|---|---|---|---|---|---|---|---|---|---|
| | | | Number | % | $km^2$ | % | $km^3$ | % | $km^2$ |
| **Tamor** | Mountain | Miscellaneous | 12 | 4.6 | 5.1 | 1.3 | 0.19 | 0.5 | 0.43 |
| | | Ice Apron | 83 | 31.7 | 15.5 | 4.0 | 0.41 | 1.0 | 0.19 |
| | | Cirque | 5 | 1.9 | 0.8 | 0.2 | 0.02 | 0.0 | 0.16 |
| | | Niche | 17 | 6.5 | 2.6 | 0.7 | 0.07 | 0.2 | 0.15 |
| | | Basin | 128 | 48.9 | 100.0 | 25.9 | 4.87 | 11.5 | 0.78 |
| | Valley | Trough | 17 | 6.5 | 261.9 | 67.9 | 36.70 | 86.8 | 15.40 |
| | **Total** | **262** | **100** | **386** | **100** | **42.26** | **100** | | **1.47** |
| **Arun** | Mountain | Ice Apron | 31 | 28.7 | 8.9 | 6.0 | 0.29 | 1.9 | 0.29 |
| | | Niche | 5 | 4.6 | 0.4 | 0.2 | 0.01 | 0.0 | 0.07 |
| | | Basin | 69 | 63.9 | 52.6 | 35.3 | 2.58 | 17.2 | 0.76 |
| | Valley | Trough | 3 | 2.8 | 87.3 | 58.5 | 12.11 | 80.8 | 29.11 |
| | **Total** | **108** | **100** | **149.2** | **100** | **14.98** | **100** | | **1.38** |
| **Dudh Koshi** | Mountain | Miscellaneous | 1 | 0.3 | 0.3 | 0.1 | 0.01 | 0.0 | 0.31 |
| | | Ice Apron | 84 | 29.3 | 23.1 | 5.9 | 0.74 | 1.9 | 0.28 |
| | | Cirque | 1 | 0.3 | 0.2 | 0.0 | 0.00 | 0.0 | 0.17 |
| | | Niche | 38 | 13.2 | 5.6 | 1.4 | 0.13 | 0.3 | 0.15 |
| | | Basin | 143 | 49.8 | 121.6 | 31.1 | 6.11 | 15.6 | 0.85 |
| | Valley | Trough | 20 | 7.0 | 240.4 | 61.4 | 32.21 | 82.2 | 12.02 |
| | **Total** | **287** | **100** | **391.2** | **100** | **39.20** | **100** | | **1.36** |
| **Likhu** | Mountain | Ice Apron | 6 | 22.2 | 0.8 | 3.4 | 0.02 | 1.1 | 0.13 |
| | | Cirque | 1 | 3.7 | 0.3 | 1.2 | 0.01 | 0.5 | 0.28 |
| | | Niche | 1 | 3.7 | 0.0 | 0.2 | 0.00 | 0.0 | 0.04 |
| | | Basin | 16 | 59.3 | 12.3 | 53.7 | 0.57 | 40.1 | 0.77 |
| | Valley | Trough | 3 | 11.1 | 9.5 | 41.5 | 0.83 | 58.3 | 3.18 |
| | **Total** | **27** | **100** | **23.0** | **100** | **1.42** | **100** | | **0.85** |
| **Tama Koshi** | Mountain | Ice Apron | 20 | 23.5 | 4.5 | 5.3 | 0.13 | 1.7 | 0.22 |
| | | Cirque | 1 | 1.2 | 0.1 | 0.1 | 0.00 | 0.0 | 0.11 |
| | | Niche | 14 | 16.5 | 1.3 | 1.5 | 0.02 | 0.3 | 0.09 |
| | | Basin | 48 | 56.5 | 28.3 | 33.6 | 1.16 | 14.7 | 0.59 |
| | Valley | Trough | 2 | 2.4 | 50.2 | 59.5 | 6.57 | 83.3 | 25.11 |
| | **Total** | **85** | **100** | **84.4** | **100** | **7.89** | **100** | | **0.99** |
| **Sun Koshi** | Mountain | Ice Apron | 11 | 28.2 | 1.7 | 3.2 | 0.03 | 0.8 | 0.15 |
| | | Cirque | 1 | 2.6 | 0.1 | 0.1 | 0.00 | 0.0 | 0.06 |
| | | Niche | 2 | 5.1 | 0.2 | 0.4 | 0.00 | 0.1 | 0.12 |
| | | Basin | 22 | 56.4 | 17.6 | 33.5 | 0.86 | 20.7 | 0.80 |
| | Valley | Trough | 3 | 7.7 | 33.0 | 62.7 | 3.26 | 78.4 | 10.99 |
| | **Total** | **39** | **100** | **52.6** | **100** | **4.16** | **100** | | **1.35** |
| **Indrawati** | Mountain | Ice Apron | 7 | 18.9 | 0.7 | 4.0 | 0.01 | 1.6 | 0.09 |
| | | Cirque | 1 | 2.7 | 0.1 | 0.4 | 0.00 | 0.1 | 0.06 |
| | | Niche | 3 | 8.1 | 0.2 | 1.5 | 0.00 | 0.5 | 0.08 |
| | | Basin | 26 | 70.3 | 15.5 | 94.2 | 0.71 | 97.8 | 0.59 |
| | **Total** | **37** | **100** | **16.4** | **100** | **0.73** | **100** | | **0.44** |

Table A2.9: **Area-elevation distribution of glaciers in the Koshi sub-basins (2010)**

| Elevation ranges (masl) | Area (km²) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Indrawati | Sun | Tama | Likhu | Dudh | Arun | Tamor | Total |
| 4,000–4,100 | | 0.118 | | | | | | 0.117 |
| 4,100–4,200 | | 0.267 | | | | 0.008 | 0.072 | 0.346 |
| 4,200–4,300 | | 0.511 | | | | 0.164 | 0.302 | 0.976 |
| 4,300–4,400 | | 0.487 | 0.062 | 0.042 | 0.047 | 0.507 | 1.031 | 2.178 |
| 4,400–4,500 | | 0.332 | 0.14 | 0.356 | 0.418 | 0.608 | 2.951 | 4.815 |
| 4,500–4,600 | | 0.881 | 0.097 | 0.514 | 1.288 | 0.854 | 2.689 | 6.328 |
| 4,600–4,700 | | 1.232 | 1.014 | 0.316 | 1.451 | 2.063 | 4.829 | 10.911 |
| 4,700–4,800 | | 1.418 | 2.090 | 0.402 | 4.738 | 2.523 | 5.121 | 16.288 |
| 4,800–4,900 | 0.054 | 2.628 | 2.548 | 0.694 | 8.28 | 1.779 | 7.54 | 23.514 |
| 4,900–5,000 | 0.268 | 3.581 | 2.36 | 0.605 | 14.568 | 3.410 | 10.219 | 35.002 |
| 5,000–5,100 | 1.475 | 4.43 | 3.971 | 1.01 | 22.089 | 5.388 | 8.587 | 46.879 |
| 5,100–5,200 | 2.473 | 5.167 | 4.907 | 1.719 | 26.646 | 7.304 | 15.163 | 63.299 |
| 5,200–5,300 | 3.386 | 6.074 | 6.413 | 2.915 | 33.793 | 8.847 | 19.454 | 80.772 |
| 5,300–5,400 | 3.47 | 6.403 | 7.891 | 3.874 | 35.471 | 9.456 | 24.958 | 91.419 |
| 5,400–5,500 | 2.684 | 5.683 | 10.245 | 3.12 | 35.618 | 8.821 | 30.541 | 96.64 |
| 5,500–5,600 | 1.509 | 3.86 | 10.245 | 2.059 | 36.726 | 7.149 | 32.386 | 93.909 |
| 5,600–5,700 | 0.71 | 2.361 | 8.186 | 1.057 | 31.9 | 6.28 | 35.201 | 85.733 |
| 5,700–5,800 | 0.309 | 1.394 | 6.719 | 0.882 | 23.018 | 7.295 | 38.972 | 78.68 |
| 5,800–5,900 | 0.053 | 1.002 | 6.242 | 0.765 | 18.059 | 9.168 | 34.755 | 70.132 |
| 5,900–6,000 | 0.008 | 0.776 | 4.431 | 0.465 | 13.581 | 12.45 | 24.391 | 56.159 |
| 6,000–6,100 | | 0.699 | 3.356 | 0.404 | 11.464 | 15.339 | 19.095 | 50.4 |
| 6,100–6,200 | | 0.64 | 1.466 | 0.57 | 9.868 | 11.999 | 12.359 | 36.928 |
| 6,200–6,300 | | 0.529 | 0.684 | 0.368 | 7.938 | 8.011 | 8.921 | 26.472 |
| 6,300–6,400 | | 0.547 | 0.537 | 0.358 | 7.791 | 6.281 | 6.081 | 21.604 |
| 6,400–6,500 | | 0.654 | 0.415 | 0.282 | 7.718 | 3.53 | 6.012 | 18.623 |
| 6,500–6,600 | | 0.477 | 0.264 | 0.119 | 6.907 | 2.419 | 5.015 | 15.212 |
| 6,600–6,700 | | 0.185 | 0.124 | 0.049 | 5.176 | 2.023 | 4.468 | 12.039 |
| 6,700–6,800 | | 0.149 | | | 4.738 | 1.314 | 4.223 | 10.438 |
| 6,800–6,900 | | 0.074 | | | 3.922 | 1.113 | 3.267 | 8.385 |
| 6,900–7,000 | | 0.008 | | | 3.538 | 1.068 | 3.017 | 7.64 |
| 7,000–7,100 | | | | | 3.229 | 0.789 | 3.143 | 7.171 |
| 7,100–7,200 | | | | | 2.942 | 0.653 | 2.912 | 6.518 |
| 7,200–7,300 | | | | | 1.784 | 0.349 | 2.059 | 4.2 |
| 7,300–7,400 | | | | | 1.444 | 0.125 | 1.177 | 2.75 |
| 7,400–7,500 | | | | | 1.220 | 0.054 | 0.795 | 2.071 |
| 7,500–7,600 | | | | | 1.131 | 0.023 | 0.958 | 2.115 |
| 7,600–7,700 | | | | | 0.855 | 0.008 | 0.989 | 1.856 |
| 7,700–7,800 | | | | | 0.584 | 0.008 | 1.375 | 1.973 |
| 7,800–7,900 | | | | | 0.442 | 0.005 | 0.491 | 0.94 |
| 7,900–8,000 | | | | | 0.421 | | 0.233 | 0.654 |
| 8,000–8,100 | | | | | 0.247 | | 0.066 | 0.313 |
| 8,100–8,200 | | | | | 0.123 | | 0.042 | 0.164 |
| 8,200–8,300 | | | | | 0.008 | | 0.043 | 0.051 |
| 8,300–8,400 | | | | | | | 0.015 | 0.015 |
| 8,400–8,500 | | | | | | | 0.012 | 0.012 |
| **Total** | **16.400** | **52.565** | **84.409** | **22.949** | **391.181** | **149.184** | **385.931** | **1,102.643** |

Table A2.10: **Change in glacier area classes in Nepal**

| Class | Area ($km^2$) | Glacier number | | | | Glacier number change | | | | Glacier area ($km^2$) | | | | Glacier area change ($km^2$) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1980 | 1990 | 2000 | 2010 | 80-90 | 90-00 | 00-10 | 80-10 | 1980 | 1990 | 2000 | 2010 | 80-90 | 90-00 | 00-10 | 80-10 |
| 1a | ≤ 0.10 | 179 | 439 | 618 | 781 | 260 | 179 | 163 | 602 | 13.1 | 30.5 | 41.2 | 50.3 | 17.4 | 10.7 | 9.1 | 37.2 |
| 1b | 0.11–0.50 | 1,523 | 1,687 | 1,743 | 1,739 | 164 | 56 | -4 | 216 | 421.4 | 431.8 | 434.9 | 431.4 | 10.4 | 3.1 | -3.5 | 10.1 |
| 2 | 0.51–1.00 | 723 | 674 | 608 | 556 | -49 | -66 | -52 | -167 | 511.5 | 475.2 | 425 | 394.2 | -36.3 | -50.3 | -30.8 | -117.3 |
| 3 | 1.01–5.00 | 831 | 705 | 652 | 606 | -126 | -53 | -46 | -225 | 1687 | 1,436.4 | 1,305.8 | 1234.1 | -250.7 | -130.5 | -71.8 | -453 |
| 4 | 5.01–10.00 | 96 | 81 | 80 | 64 | -15 | -1 | -16 | -32 | 663.1 | 564.3 | 557.3 | 444.3 | -98.8 | -7 | -112.9 | -218.7 |
| 5 | ≥ 10.01 | 78 | 70 | 64 | 62 | -8 | -6 | -2 | -16 | 1,872.3 | 1,568.2 | 1446.7 | 1348.1 | -304.1 | -121.5 | -98.6 | -524.1 |
| | **Total** | **3,430** | **3,656** | **3,765** | **3,808** | **226** | **109** | **43** | **378** | **5,168.3** | **4,506.3** | **4,210.9** | **3,902.4** | **-662.0** | **-295.5** | **-308.5** | **-1,265.9** |

Table A2.11: **Change in glaciers of different aspect in Nepal**

| Aspect | Glacier number | | | | Glacier number change | | | | Glacier area ($km^2$) | | | | Glacier area change ($km^2$) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1980 | 1990 | 2000 | 2010 | 80-90 | 90-00 | 00-10 | 80-10 | 1980 | 1990 | 2000 | 2010 | 80-90 | 90-00 | 00-10 | 80-10 |
| North | 5 | 11 | 17 | 14 | 6 | 6 | -3 | 9 | 0.8 | 1.9 | 2.6 | 1.7 | 1.2 | 0.7 | -0.9 | 0.9 |
| Northeast | 171 | 216 | 249 | 255 | 45 | 33 | 6 | 84 | 97.1 | 89.4 | 93.5 | 89.1 | -7.7 | 4.2 | -4.4 | -8 |
| East | 517 | 543 | 577 | 590 | 26 | 34 | 13 | 73 | 536.5 | 435.4 | 475.8 | 466.6 | -101.1 | 40.4 | -9.2 | -69.9 |
| Southeast | 688 | 685 | 631 | 634 | -3 | -54 | 3 | -54 | 1,141.6 | 944 | 796.2 | 754.6 | -197.6 | -147.8 | -41.6 | -387 |
| South | 708 | 716 | 720 | 717 | 8 | 4 | -3 | 9 | 1,563.9 | 1,322.8 | 1,214.4 | 1,078.7 | -241.1 | -108.4 | -135.7 | -485.2 |
| Southwest | 683 | 754 | 790 | 773 | 71 | 36 | -17 | 90 | 1,189.7 | 1,168 | 1,090.5 | 991.3 | -21.7 | -77.6 | -99.1 | -198.4 |
| West | 493 | 524 | 545 | 561 | 31 | 21 | 16 | 68 | 545.7 | 448.2 | 432.7 | 412.6 | -97.5 | -15.4 | -20.1 | -133.1 |
| Northwest | 165 | 207 | 236 | 264 | 42 | 29 | 28 | 99 | 93 | 96.7 | 105.2 | 107.8 | 3.7 | 8.5 | 2.6 | 14.8 |
| **Total** | **3,430** | **3,656** | **3,765** | **3,808** | **226** | **109** | **43** | **378** | **5,168.3** | **4,506.3** | **4,210.9** | **3,902.4** | **-662.0** | **-295.5** | **-308.5** | **-1,265.9** |

Table A2.12: **Change in glaciers of different slope in Nepal**

| Mean slope (degree) | Glacier number | | | | Glacier number change | | | | Glacier area ($km^2$) | | | | Glacier area change ($km^2$) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1980 | 1990 | 2000 | 2010 | 80-90 | 90-00 | 00-10 | 80-10 | 1980 | 1990 | 2000 | 2010 | 80-90 | 90-00 | 00-10 | 80-10 |
| 0–10 | 2 | 5 | 3 | 7 | 3 | -2 | 4 | 5 | 15.2 | 15.6 | 15.4 | 18.6 | 0.4 | -0.2 | 3.2 | 3.5 |
| 10–20 | 382 | 486 | 550 | 625 | 104 | 64 | 75 | 243 | 658.8 | 874.7 | 1012.8 | 1031.2 | 215.9 | 138.1 | 18.4 | 372.4 |
| 20–30 | 1,464 | 1,508 | 1,521 | 1,455 | 44 | 13 | -66 | -9 | 3,146.7 | 2,691.3 | 2,321.8 | 2,056.2 | -455.3 | -369.5 | -265.7 | -1090.5 |
| 30–40 | 1,142 | 1,147 | 1,171 | 1,162 | 5 | 24 | -9 | 20 | 1,099.2 | 725.1 | 667.2 | 618.4 | -374.1 | -57.9 | -48.8 | -480.7 |
| 40–50 | 389 | 437 | 443 | 464 | 48 | 6 | 21 | 75 | 224.4 | 175.8 | 168.4 | 152.1 | -48.6 | -7.4 | -16.3 | -72.3 |
| 50–60 | 51 | 72 | 75 | 89 | 21 | 3 | 14 | 38 | 24.1 | 23.6 | 25.0 | 24.9 | -0.5 | 1.4 | -0.2 | 0.8 |
| >60 | 0 | 1 | 2 | 6 | 1 | 1 | 4 | 6 | 0 | 0.2 | 0.3 | 1 | 0.2 | 0 | 0.7 | 1 |
| **Total** | **3,430** | **3,656** | **3,765** | **3,808** | **-226** | **-109** | **-43** | **-378** | **5,168** | **4,506** | **4,211** | **3,902** | **-662.0** | **-295.5** | **-308.5** | **-1265.9** |

Table A2.13: **Change in glaciers of different morphological type in Nepal**

| Glacier type | | Glacier number | | | | Glacier number change | | | | Glacier area ($km^2$) | | | | Glacier area change ($km^2$) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1980 | 1990 | 2000 | 2010 | 80-90 | 90-00 | 00-10 | 80-10 | 1980 | 1990 | 2000 | 2010 | 80-90 | 90-00 | 00-10 | 80-10 |
| Mountain | Miscellaneous | 17 | 18 | 19 | 18 | 1 | 1 | -1 | 1 | 10.0 | 9.3 | 9.1 | 8.2 | -0.6 | -0.3 | -0.9 | -1.8 |
| | Ice Apron | 806 | 902 | 934 | 943 | 96 | 32 | 9 | 137 | 320.8 | 274.9 | 260.9 | 245.5 | -45.9 | -14 | -15.4 | -75.3 |
| | Cirque | 31 | 31 | 26 | 24 | 0 | -5 | -2 | -7 | 13.3 | 9.6 | 6.4 | 4.9 | -3.7 | -3.2 | -1.5 | -8.4 |
| | Niche | 307 | 322 | 328 | 315 | 15 | 6 | -13 | 8 | 110.2 | 66.9 | 49.6 | 39.6 | -43.3 | -17.3 | -10 | -70.6 |
| | Basin | 2159 | 2272 | 2346 | 2396 | 113 | 74 | 50 | 237 | 2872.7 | 2535.1 | 2349.4 | 2163.4 | -337.6 | -185.7 | -186.0 | -709.3 |
| Valley | Trough | 110 | 111 | 112 | 112 | 1 | 1 | 0 | 2 | 1841.3 | 1610.4 | 1535.5 | 1440.8 | -230.8 | -74.9 | -94.7 | -400.5 |
| | **Total** | **3430** | **3656** | **3765** | **3808** | **226** | **109** | **43** | **378** | **5168.3** | **4506.3** | **4210.9** | **3902.4** | **-662** | **-295.5** | **-308.5** | **-1265.9** |

Table A2.14: **Change in glacier number and area in the Mahakali basin**

| Class | Area ($km^2$) | Glacier number | | | | Glacier number change | | | | Glacier area ($km^2$) | | | | Glacier area change ($km^2$) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1980 | 1990 | 2000 | 2010 | 80-90 | 90-00 | 00-10 | 80-10 | 1980 | 1990 | 2000 | 2010 | 80-90 | 90-00 | 00-10 | 80-10 |
| 1a | ≤ 0.10 | 16 | 34 | 44 | 60 | 18 | 10 | 16 | 44 | 1.1 | 2.3 | 2.6 | 3.6 | 1.2 | 0.3 | 1.0 | 2.5 |
| 1b | 0.11–0.50 | 59 | 59 | 67 | 64 | 0 | 8 | -3 | 5 | 15.4 | 15.2 | 14.8 | 14.1 | -0.3 | -0.4 | -0.6 | -1.3 |
| 2 | 0.51–1.00 | 20 | 19 | 15 | 17 | -1 | -4 | 2 | -3 | 14.1 | 14 | 10.9 | 11.6 | 0 | -3.1 | 0.7 | -2.5 |
| 3 | 1.01–5.00 | 25 | 20 | 18 | 18 | -5 | -2 | 0 | -7 | 46.5 | 41.8 | 39.1 | 46.2 | -4.7 | -2.7 | 7.1 | -0.3 |
| 4 | 5.01–10.00 | 7 | 6 | 6 | 4 | -1 | 0 | -2 | -3 | 43.9 | 39.5 | 41.4 | 25.9 | -4.5 | 1.9 | -15.5 | -18 |
| 5 | ≥ 10.01 | 3 | 2 | 1 | 1 | -1 | -1 | 0 | -2 | 37.5 | 21.9 | 11.6 | 11.1 | -15.6 | -10.3 | -0.4 | -26.4 |
| | **Total** | **130** | **140** | **151** | **164** | **10** | **11** | **13** | **34** | **158.5** | **134.6** | **120.3** | **112.5** | **-23.9** | **-14.3** | **-7.8** | **-45.9** |

Table A2.15: **Change in glaciers of different aspect in the Mahakali basin**

| Aspect | Glacier number | | | | Glacier number change | | | | Glacier area ($km^2$) | | | | Glacier area change ($km^2$) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1980 | 1990 | 2000 | 2010 | 80-90 | 90-00 | 00-10 | 80-10 | 1980 | 1990 | 2000 | 2010 | 80-90 | 90-00 | 00-10 | 80-10 |
| North | 2 | 2 | 1 | 1 | 0 | -1 | 0 | -1 | 0.3 | 0.3 | 0.2 | 0.2 | 0 | -0.1 | 0 | -0.1 |
| Northeast | 5 | 9 | 10 | 9 | 4 | 1 | -1 | 4 | 2.1 | 2 | 2.2 | 1.9 | -0.1 | 0.1 | -0.3 | -0.3 |
| East | 17 | 17 | 18 | 15 | 0 | 1 | -3 | -2 | 10.9 | 9.3 | 7.9 | 6.3 | -1.6 | -1.4 | -1.6 | -4.7 |
| Southeast | 16 | 17 | 19 | 23 | 1 | 2 | 4 | 7 | 15.3 | 9.6 | 7.1 | 9.6 | -5.6 | -2.5 | 2.5 | -5.7 |
| South | 28 | 24 | 24 | 24 | -4 | 0 | 0 | -4 | 42.2 | 37.7 | 34.1 | 29.9 | -4.5 | -3.5 | -4.2 | -12.3 |
| Southwest | 28 | 34 | 38 | 40 | 6 | 4 | 2 | 12 | 29.7 | 35.9 | 23.2 | 20.8 | 6.1 | -12.6 | -2.5 | -9 |
| West | 30 | 30 | 31 | 37 | 0 | 1 | 6 | 7 | 54.5 | 37.1 | 41.2 | 35.3 | -17.4 | 4.1 | -5.9 | -19.3 |
| Northwest | 4 | 7 | 10 | 15 | 3 | 3 | 5 | 11 | 3.5 | 2.7 | 4.3 | 8.7 | -0.8 | 1.6 | 4.4 | 5.2 |
| **Total** | **130** | **140** | **151** | **164** | **10** | **11** | **13** | **34** | **158.5** | **134.6** | **120.3** | **112.5** | **-23.9** | **-14.3** | **-7.8** | **-45.9** |

Table A2.16: **Change in glaciers of different slope in the Mahakali basin**

| Mean slope (degree) | Glacier number | | | | Glacier number change | | | | Glacier area ($km^2$) | | | | Glacier area change ($km^2$) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1980 | 1990 | 2000 | 2010 | 80-90 | 90-00 | 00-10 | 80-10 | 1980 | 1990 | 2000 | 2010 | 80-90 | 90-00 | 00-10 | 80-10 |
| 0–10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10–20 | 3 | 4 | 4 | 10 | 1 | 0 | 6 | 7 | 1.6 | 1.4 | 1.2 | 8.1 | -0.2 | -0.2 | 6.9 | 6.5 |
| 20–30 | 37 | 43 | 46 | 44 | 6 | 3 | -2 | 7 | 90.2 | 82.3 | 75.2 | 70.1 | -7.9 | -7.1 | -5.1 | -20.1 |
| 30–40 | 52 | 56 | 62 | 56 | 4 | 6 | -6 | 4 | 52.9 | 42.4 | 36.9 | 25.2 | -10.5 | -5.5 | -11.7 | -27.7 |
| 40–50 | 33 | 31 | 30 | 43 | -2 | -1 | 13 | 10 | 13.1 | 7.7 | 5.9 | 7.8 | -5.3 | -1.9 | 1.9 | -5.2 |
| 50–60 | 5 | 6 | 9 | 11 | 1 | 3 | 2 | 6 | 0.7 | 0.7 | 1.1 | 1.4 | 0 | 0.4 | 0.3 | 0.6 |
| >60 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Total** | **130** | **140** | **151** | **164** | **10** | **11** | **13** | **34** | **158.5** | **134.6** | **120.3** | **112.5** | **-23.9** | **-14.3** | **-7.8** | **-45.9** |

Table A2.17: **Change in glaciers of different morphological type in the Mahakali basin**

| Glacier type | | Glacier number | | | | Glacier number change | | | | Glacier area ($km^2$) | | | | Glacier area change ($km^2$) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1980 | 1990 | 2000 | 2010 | 80-90 | 90-00 | 00-10 | 80-10 | 1980 | 1990 | 2000 | 2010 | 80-90 | 90-00 | 00-10 | 80-10 |
| Mountain | Miscellaneous | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Ice Apron | 44 | 47 | 53 | 58 | 3 | 6 | 5 | 14 | 17 | 10.5 | 9.4 | 9.7 | -6.5 | -1 | 0.2 | -7.3 |
| | Cirque | 3 | 3 | 2 | 2 | 0 | -1 | 0 | -1 | 2.2 | 1.8 | 1.5 | 1.4 | -0.4 | -0.2 | -0.2 | -0.9 |
| | Niche | 7 | 6 | 5 | 5 | -1 | -1 | 0 | -2 | 1.4 | 0.8 | 0.4 | 0.4 | -0.6 | -0.4 | 0 | -1 |
| | Basin | 65 | 73 | 80 | 88 | 8 | 7 | 8 | 23 | 59.3 | 54.3 | 45.6 | 45.4 | -5 | -8.6 | -0.3 | -13.9 |
| Valley | Trough | 11 | 11 | 11 | 11 | 0 | 0 | 0 | 0 | 78.6 | 67.3 | 63.3 | 55.8 | -11.3 | -4 | -7.5 | -22.9 |
| | **Total** | **130** | **140** | **151** | **164** | **10** | **11** | **13** | **34** | **158.5** | **134.6** | **120.3** | **112.5** | **-23.9** | **-14.3** | **-7.8** | **-45.9** |

Table A2.18: **Change in glacier area classes in the Karnali basin**

| Class | Area ($km^2$) | Glaicer number | | | | Glacier number change | | | | Glacier area ($km^2$) | | | | Glacier area change ($km^2$) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1980 | 1990 | 2000 | 2010 | 80-90 | 90-00 | 00-10 | 80-10 | 1980 | 1990 | 2000 | 2010 | 80-90 | 90-00 | 00-10 | 80-10 |
| 1a | ≤ 0.10 | 91 | 168 | 261 | 341 | 77 | 93 | 80 | 250 | 6.5 | 11.6 | 17.8 | 22 | 5.2 | 6.1 | 4.2 | 15.5 |
| 1b | 0.11–0.50 | 644 | 685 | 672 | 652 | 41 | -13 | -20 | 8 | 171.5 | 172.5 | 162.7 | 158.7 | 1 | -9.8 | -4 | -12.8 |
| 2 | 0.51–1.00 | 294 | 269 | 243 | 234 | -25 | -26 | -9 | -60 | 207.1 | 192 | 169.2 | 166.1 | -15.1 | -22.8 | -3.1 | -41 |
| 3 | 1.01–5.00 | 300 | 256 | 234 | 203 | -44 | -22 | -31 | -97 | 594.3 | 495.2 | 444.3 | 400.4 | -99.1 | -50.9 | -43.9 | -193.9 |
| 4 | 5.01–10.00 | 30 | 27 | 23 | 19 | -3 | -4 | -4 | -11 | 210.6 | 182.4 | 152 | 125.8 | -28.2 | -30.4 | -26.1 | -84.8 |
| 5 | ≥ 10.01 | 12 | 11 | 11 | 10 | -1 | 0 | -1 | -2 | 195.4 | 176.3 | 167.1 | 149.9 | -19.1 | -9.2 | -17.2 | -45.5 |
| | **Total** | **1,371** | **1,416** | **1,444** | **1,459** | **45** | **28** | **15** | **88** | **1,385.4** | **1,230.1** | **1,113.1** | **1,022.8** | **-155.3** | **-117.0** | **-90.3** | **-362.6** |

Table A2.19: **Change in glaciers of different aspect in the Karnali basin**

| Aspect | Glacier number | | | | Glacier number change | | | | Glacier area ($km^2$) | | | | Glacier area change ($km^2$) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1980 | 1990 | 2000 | 2010 | 80-90 | 90-00 | 00-10 | 80-10 | 1980 | 1990 | 2000 | 2010 | 80-90 | 90-00 | 00-10 | 80-10 |
| North | 2 | 5 | 7 | 8 | 3 | 2 | 1 | 6 | 0.2 | 0.6 | 0.7 | 0.6 | 0.5 | 0.1 | -0.1 | 0.5 |
| Northeast | 76 | 96 | 111 | 114 | 20 | 15 | 3 | 38 | 34.2 | 32.6 | 32.6 | 31.9 | -1.6 | 0 | -0.7 | -2.3 |
| East | 217 | 223 | 239 | 243 | 6 | 16 | 4 | 26 | 174.4 | 153.4 | 150.6 | 139.1 | -21 | -2.9 | -11.4 | -35.3 |
| Southeast | 261 | 256 | 226 | 236 | -5 | -30 | 10 | -25 | 277.9 | 227 | 185 | 189 | -50.9 | -42 | 4 | -88.9 |
| South | 241 | 240 | 239 | 223 | -1 | -1 | -16 | -18 | 348.1 | 305.7 | 253.2 | 213.7 | -42.4 | -52.5 | -39.5 | -134.4 |
| Southwest | 262 | 274 | 275 | 272 | 12 | 1 | -3 | 10 | 325.2 | 311.4 | 300.9 | 269.3 | -13.8 | -10.5 | -31.6 | -55.9 |
| West | 230 | 222 | 241 | 244 | -8 | 19 | 3 | 14 | 188.5 | 157.7 | 148.1 | 140.2 | -30.9 | -9.6 | -7.8 | -48.3 |
| Northwest | 82 | 100 | 106 | 119 | 18 | 6 | 13 | 37 | 36.9 | 41.7 | 42.1 | 39 | 4.8 | 0.4 | -3.1 | 2 |
| **Total** | **1,371** | **1,416** | **1,444** | **1,459** | **45** | **28** | **15** | **88** | **1,385.4** | **1,230.1** | **1,113.1** | **1,022.8** | **-155.3** | **-117.0** | **-90.3** | **-362.6** |

Table A2.20: **Change in glaciers of different slope in the Karnali basin**

| Mean slope (degree) | Glacier number | | | | Glacier number change | | | | Glacier area ($km^2$) | | | | Glacier area change ($km^2$) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1980 | 1990 | 2000 | 2010 | 80-90 | 90-00 | 00-10 | 80-10 | 1980 | 1990 | 2000 | 2010 | 80-90 | 90-00 | 00-10 | 80-10 |
| 0–10 | 0 | 1 | 0 | 4 | 1 | -1 | 4 | 4 | 0 | 0.2 | 0 | 3.4 | 0.2 | -0.2 | 3.4 | 3.4 |
| 10–20 | 195 | 236 | 263 | 279 | 41 | 27 | 16 | 84 | 299.8 | 330 | 328.8 | 314.9 | 30.2 | -1.2 | -13.9 | 15.1 |
| 20–30 | 629 | 616 | 611 | 586 | -13 | -5 | -25 | -43 | 790.1 | 650.1 | 562.3 | 485.4 | -140.0 | -87.8 | -76.9 | -304.7 |
| 30–40 | 433 | 425 | 435 | 445 | -8 | 10 | 10 | 12 | 251.9 | 205.8 | 182.5 | 180.6 | -46.1 | -23.3 | -1.9 | -71.3 |
| 40–50 | 108 | 131 | 129 | 136 | 23 | -2 | 7 | 28 | 42.2 | 43.2 | 38.3 | 36.9 | 1 | -4.9 | -1.4 | -5.3 |
| 50–60 | 6 | 7 | 6 | 9 | 1 | -1 | 3 | 3 | 1.4 | 0.9 | 1.2 | 1.7 | -0.5 | 0.2 | 0.6 | 0.3 |
| >60 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Total** | **1,371** | **1,416** | **1,444** | **1,459** | **45** | **28** | **15** | **88** | **1,385** | **1,230** | **1,113** | **1,023** | **-155.3** | **-117.0** | **-90.3** | **-362.6** |

Table A2.21: **Change in glaciers of different morphological type in the Karnali basin**

| Glacier type | | Glacier number | | | | Glacier number change | | | | Glacier area ($km^2$) | | | | Glacier area change ($km^2$) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1980 | 1990 | 2000 | 2010 | 80-90 | 90-00 | 00-10 | 80-10 | 1980 | 1990 | 2000 | 2010 | 80-90 | 90-00 | 00-10 | 80-10 |
| Mountain | Miscellaneous | 2 | 2 | 2 | 2 | 0 | 0 | 0 | 0 | 1 | 0.7 | 0.6 | 0.6 | -0.2 | -0.1 | -0.1 | -0.4 |
| | Ice Apron | 225 | 226 | 228 | 225 | 1 | 2 | -3 | 0 | 57.9 | 45.8 | 40.5 | 37.5 | -12 | -5.3 | -3.1 | -20.4 |
| | Cirque | 5 | 5 | 3 | 4 | 0 | -2 | 1 | -1 | 1.4 | 1.1 | 0.2 | 0.3 | -0.4 | -0.9 | 0.1 | -1.2 |
| | Niche | 141 | 145 | 148 | 149 | 4 | 3 | 1 | 8 | 39.1 | 27.7 | 18.6 | 14.6 | -11.4 | -9.1 | -4 | -24.5 |
| | Basin | 979 | 1019 | 1044 | 1060 | 40 | 25 | 16 | 81 | 1083.5 | 963.2 | 873.8 | 798.9 | -120.3 | -89.4 | -74.9 | -284.6 |
| Valley | Trough | 19 | 19 | 19 | 19 | 0 | 0 | 0 | 0 | 202.5 | 191.6 | 179.3 | 171.1 | -11 | -12.2 | -8.3 | -31.5 |
| | **Total** | **1,371** | **1,416** | **1,444** | **1,459** | **45** | **28** | **15** | **88** | **1,385.4** | **1,230.1** | **1,113.1** | **1,022.8** | **-155.3** | **-117.0** | **-90.3** | **-362.6** |

Table A2.22: **Change in glacier number and area in the Gandaki basin**

| Class | Area (km²) | Glacier number | | | | Glacier number change | | | | Glacier area (km²) | | | | Glacier area change (km²) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1980 | 1990 | 2000 | 2010 | 80-90 | 90-00 | 00-10 | 80-10 | 1980 | 1990 | 2000 | 2010 | 80-90 | 90-00 | 00-10 | 80-10 |
| 1a | ≤ 0.10 | 42 | 141 | 173 | 199 | 99 | 32 | 26 | 157 | 3.1 | 9.7 | 11.6 | 13.6 | 6.6 | 1.8 | 2 | 10.4 |
| 1b | 0.11–0.50 | 495 | 567 | 618 | 629 | 72 | 51 | 11 | 134 | 142.1 | 145.7 | 156.6 | 159.5 | 3.6 | 11 | 2.9 | 17.4 |
| 2 | 0.51–1.00 | 246 | 226 | 217 | 195 | -20 | -9 | -22 | -51 | 175.1 | 157.1 | 153.3 | 139 | -17.9 | -3.8 | -14.3 | -36.1 |
| 3 | 1.01–5.00 | 338 | 295 | 267 | 258 | -43 | -28 | -9 | -80 | 691.4 | 598.5 | 535 | 522.5 | -92.9 | -63.6 | -12.5 | -168.9 |
| 4 | 5.01–10.00 | 36 | 32 | 34 | 27 | -4 | 2 | -7 | -9 | 262.9 | 234.4 | 240.1 | 190.9 | -28.6 | 5.7 | -49.2 | -72 |
| 5 | ≥ 10.01 | 36 | 33 | 32 | 32 | -3 | -1 | 0 | -4 | 850.9 | 702 | 668.4 | 639 | -148.9 | -33.6 | -29.4 | -211.9 |
| | **Total** | **1,193** | **1,294** | **1,341** | **1,340** | **101** | **47** | **-1** | **147** | **2,125.5** | **1,847.4** | **1,764.9** | **1,664.4** | **-278.1** | **-82.5** | **-100.5** | **-461.0** |

Table A2.23: **Change in glaciers of different aspect in the Gandaki basin**

| Aspect | Glacier number | | | | Glacier number change | | | | Glacier area (km²) | | | | Glacier area change (km²) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1980 | 1990 | 2000 | 2010 | 80-90 | 90-00 | 00-10 | 80-10 | 1980 | 1990 | 2000 | 2010 | 80-90 | 90-00 | 00-10 | 80-10 |
| North | 0 | 2 | 6 | 2 | 2 | 4 | -4 | 2 | 0 | 0.3 | 0.9 | 0.5 | 0.3 | 0.6 | -0.4 | 0.5 |
| Northeast | 64 | 74 | 87 | 89 | 10 | 13 | 2 | 25 | 42.2 | 32.2 | 40.5 | 37 | -10 | 8.4 | -3.6 | -5.2 |
| East | 173 | 190 | 190 | 193 | 17 | 0 | 3 | 20 | 254.2 | 198.9 | 241.7 | 253.6 | -55.4 | 42.8 | 11.9 | -0.7 |
| Southeast | 252 | 248 | 232 | 225 | -4 | -16 | -7 | -27 | 635.7 | 533.6 | 450.6 | 415.4 | -102.1 | -83 | -35.3 | -220.4 |
| South | 271 | 280 | 289 | 293 | 9 | 9 | 4 | 22 | 543.1 | 435.7 | 413.6 | 367 | -107.5 | -22.1 | -46.6 | -176.1 |
| Southwest | 229 | 260 | 275 | 275 | 31 | 15 | 0 | 46 | 406.5 | 436.3 | 407.6 | 374.9 | 29.7 | -28.7 | -32.7 | -31.6 |
| West | 138 | 160 | 170 | 170 | 22 | 10 | 0 | 32 | 199.1 | 165 | 159.7 | 168 | -34.1 | -5.3 | 8.4 | -31.1 |
| Northwest | 66 | 80 | 92 | 93 | 14 | 12 | 1 | 27 | 44.6 | 45.5 | 50.4 | 48.2 | 1 | 4.8 | -2.2 | 3.6 |
| **Total** | **1,193** | **1,294** | **1,341** | **1,340** | **101** | **47** | **-1** | **147** | **2,125.5** | **1,847.4** | **1,764.9** | **1,664.4** | **-278.1** | **-82.5** | **-100.5** | **-461.0** |

Table A2.24 : **Change in glaciers of different slope in the Gandaki basin**

| Mean slope (degree) | Glacier number | | | | Glacier number change | | | | Glacier area ($km^2$) | | | | Glacier area change ($km^2$) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1980 | 1990 | 2000 | 2010 | 80-90 | 90-00 | 00-10 | 80-10 | 1980 | 1990 | 2000 | 2010 | 80-90 | 90-00 | 00-10 | 80-10 |
| 0–10 | 2 | 4 | 3 | 3 | 2 | -1 | 0 | 1 | 15.2 | 15.4 | 15.4 | 15.2 | 0.3 | 0 | -0.2 | 0.1 |
| 10–20 | 110 | 142 | 160 | 166 | 32 | 18 | 6 | 56 | 245.8 | 284.3 | 276.9 | 287.7 | 38.5 | -7.5 | 10.8 | 41.9 |
| 20–30 | 481 | 516 | 514 | 505 | 35 | -2 | -9 | 24 | 1156.7 | 1092.7 | 1026.9 | 934.7 | -64 | -65.9 | -92.1 | -222 |
| 30–40 | 394 | 398 | 414 | 409 | 4 | 16 | -5 | 15 | 561.1 | 340 | 327.4 | 322 | -221.2 | -12.6 | -5.4 | -239.1 |
| 40–50 | 170 | 182 | 197 | 196 | 12 | 15 | -1 | 26 | 127.1 | 96.3 | 98.8 | 84.9 | -30.8 | 2.5 | -14.0 | -42.3 |
| 50–60 | 36 | 51 | 51 | 55 | 15 | 0 | 4 | 19 | 19.5 | 18.4 | 19.3 | 18.9 | -1.1 | 0.9 | -0.4 | -0.6 |
| >60 | 0 | 1 | 2 | 6 | 1 | 1 | 4 | 6 | 0 | 0.2 | 0.3 | 1 | 0.2 | 0 | 0.7 | 1 |
| **Total** | **1,193** | **1,294** | **1,341** | **1,340** | **101** | **47** | **-1** | **147** | **2,125** | **1,847** | **1,765** | **1,664** | **-278.1** | **-82.5** | **-100.5** | **-461.0** |

Table A2.25: **Change in glaciers of different morphological type in the Gandaki basin**

| Glacier type | | Glacier number | | | | Glacier number change | | | | Glacier area ($km^2$) | | | | Glacier area change ($km^2$) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1980 | 1990 | 2000 | 2010 | 80-90 | 90-00 | 00-10 | 80-10 | 1980 | 1990 | 2000 | 2010 | 80-90 | 90-00 | 00-10 | 80-10 |
| Mountain | Miscellaneous | 5 | 3 | 4 | 3 | -2 | 1 | -1 | -2 | 4.1 | 2.5 | 2.5 | 2.2 | -1.6 | 0.0 | -0.3 | -1.9 |
| | Ice Apron | 354 | 407 | 420 | 417 | 53 | 13 | -3 | 63 | 171.0 | 152.4 | 147.1 | 140.9 | -18.7 | -5.2 | -6.2 | -30.2 |
| | Cirque | 13 | 12 | 11 | 8 | -1 | -1 | -3 | -5 | 5.5 | 3.7 | 2.6 | 1.8 | -1.8 | -1.1 | -0.8 | -3.8 |
| | Niche | 78 | 86 | 90 | 81 | 8 | 4 | -9 | 3 | 36.1 | 18.8 | 16.5 | 14.3 | -17.3 | -2.4 | -2.2 | -21.8 |
| | Basin | 711 | 753 | 782 | 797 | 42 | 29 | 15 | 86 | 1233.6 | 1096.4 | 1041.6 | 973.7 | -137.1 | -54.9 | -67.9 | -259.9 |
| Valley | Trough | 32 | 33 | 34 | 34 | 1 | 1 | 0 | 2 | 675.1 | 573.6 | 554.7 | 531.7 | -101.5 | -18.9 | -23.0 | -143.5 |
| | **Total** | **1,193** | **1,294** | **1,341** | **1,340** | **101** | **47** | **-1** | **147** | **2,125.5** | **1,847.4** | **1,764.9** | **1664.4** | **-278.1** | **-82.5** | **-100.5** | **-461.0** |

Table A2.26: **Change in glacier area classes in the Koshi basin**

| Class | Area (km²) | Glacier number | | | | Glacier number change | | | | Glacier area (km²) | | | | Glacier area change (km²) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1980 | 1990 | 2000 | 2010 | 80-90 | 90-00 | 00-10 | 80-10 | 1980 | 1990 | 2000 | 2010 | 80-90 | 90-00 | 00-10 | 80-10 |
| 1a | ≤ 0.10 | 30 | 96 | 140 | 181 | 66 | 44 | 41 | 151 | 2.4 | 6.9 | 9.3 | 11.2 | 4.4 | 2.4 | 1.9 | 8.7 |
| 1b | 0.11–0.50 | 325 | 376 | 386 | 394 | 51 | 10 | 8 | 69 | 92.3 | 98.4 | 100.7 | 99.1 | 6.1 | 2.3 | -1.7 | 6.7 |
| 2 | 0.51–1.00 | 163 | 160 | 133 | 110 | -3 | -27 | -23 | -53 | 115.3 | 112.1 | 91.6 | 77.5 | -3.2 | -20.5 | -14 | -37.8 |
| 3 | 1.01–5.00 | 168 | 134 | 133 | 127 | -34 | -1 | -6 | -41 | 354.9 | 300.8 | 287.5 | 265 | -54.1 | -13.4 | -22.5 | -89.9 |
| 4 | 5.01–10.00 | 23 | 16 | 17 | 14 | -7 | 1 | -3 | -9 | 145.5 | 108 | 123.8 | 101.7 | -37.5 | 15.8 | -22.1 | -43.8 |
| 5 | ≥ 10.01 | 27 | 24 | 20 | 19 | -3 | -4 | -1 | -8 | 788.5 | 668 | 599.7 | 548.1 | -120.4 | -68.4 | -51.5 | -240.3 |
| | **Total** | **736** | **806** | **829** | **845** | **70** | **23** | **16** | **109** | **1,498.9** | **1,294.2** | **1,212.6** | **1,102.6** | **-204.7** | **-81.6** | **-110.0** | **-396.3** |

Table A2.27: **Change in glaciers of different aspect in the Koshi basin**

| Aspect | Glacier number | | | | Glacier number change | | | | Glacier area (km²) | | | | Glacier area change (km²) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1980 | 1990 | 2000 | 2010 | 80-90 | 90-00 | 00-10 | 80-10 | 1980 | 1990 | 2000 | 2010 | 80-90 | 90-00 | 00-10 | 80-10 |
| North | 1 | 2 | 3 | 3 | 1 | 1 | 0 | 2 | 0.3 | 0.7 | 0.8 | 0.4 | 0.3 | 0.2 | -0.4 | 0.1 |
| Northeast | 26 | 37 | 41 | 43 | 11 | 4 | 2 | 17 | 18.7 | 22.6 | 18.2 | 18.4 | 3.9 | -4.4 | 0.3 | -0.2 |
| East | 110 | 113 | 130 | 139 | 3 | 17 | 9 | 29 | 96.9 | 73.8 | 75.6 | 67.7 | -23.1 | 1.8 | -8 | -29.3 |
| Southeast | 159 | 164 | 154 | 150 | 5 | -10 | -4 | -9 | 212.8 | 173.8 | 153.5 | 140.7 | -39 | -20.3 | -12.8 | -72.1 |
| South | 168 | 172 | 168 | 177 | 4 | -4 | 9 | 9 | 630.4 | 543.7 | 513.5 | 468 | -86.7 | -30.2 | -45.5 | -162.4 |
| Southwest | 164 | 186 | 202 | 186 | 22 | 16 | -16 | 22 | 428.3 | 384.5 | 358.8 | 326.4 | -43.8 | -25.8 | -32.4 | -101.9 |
| West | 95 | 112 | 103 | 110 | 17 | -9 | 7 | 15 | 103.5 | 88.4 | 83.8 | 69.1 | -15.1 | -4.6 | -14.7 | -34.4 |
| Northwest | 13 | 20 | 28 | 37 | 7 | 8 | 9 | 24 | 8.1 | 6.8 | 8.4 | 11.9 | -1.3 | 1.7 | 3.5 | 3.9 |
| **Total** | **736** | **806** | **829** | **845** | **70** | **23** | **16** | **109** | **1,498.9** | **1,294.2** | **1,212.6** | **1,102.6** | **-204.7** | **-81.6** | **-110.0** | **-396.3** |

Table A2.28 : **Change in glaciers of different slope in the Koshi basin**

| Mean slope (degree) | Glacier number | | | | Glacier number change | | | | Glacier area (km$^2$) | | | | Glacier area change (km$^2$) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1980 | 1990 | 2000 | 2010 | 80-90 | 90-00 | 00-10 | 80-10 | 1980 | 1990 | 2000 | 2010 | 80-90 | 90-00 | 00-10 | 80-10 |
| 0–10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10–20 | 74 | 104 | 123 | 170 | 30 | 19 | 47 | 96 | 111.6 | 259 | 405.9 | 420.6 | 147.4 | 147 | 14.7 | 309 |
| 20–30 | 317 | 333 | 350 | 320 | 16 | 17 | -30 | 3 | 1,109.6 | 866.2 | 657.5 | 566 | -243.4 | -208.7 | -91.5 | -543.7 |
| 30–40 | 263 | 268 | 260 | 252 | 5 | -8 | -8 | -11 | 233.2 | 136.9 | 120.4 | 90.6 | -96.3 | -16.6 | -29.7 | -142.6 |
| 40–50 | 78 | 93 | 87 | 89 | 15 | -6 | 2 | 11 | 42.1 | 28.6 | 25.4 | 22.6 | -13.5 | -3.2 | -2.8 | -19.5 |
| 50–60 | 4 | 8 | 9 | 14 | 4 | 1 | 5 | 10 | 2.4 | 3.5 | 3.4 | 2.9 | 1.1 | -0.1 | -0.6 | 0.5 |
| >60 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Total** | **736** | **806** | **829** | **845** | **70** | **23** | **16** | **109** | **1,499** | **1,294** | **1,213** | **1,103** | **-204.7** | **-81.6** | **-110.0** | **-396.3** |

Table A2.29: **Change in glaciers of different morphological type in the Koshi basin**

| Glacier type | | Glacier number | | | | Glacier number change | | | | Glacier area (km$^2$) | | | | Glacier area change (km$^2$) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1980 | 1990 | 2000 | 2010 | 80-90 | 90-00 | 00-10 | 80-10 | 1980 | 1990 | 2000 | 2010 | 80-90 | 90-00 | 00-10 | 80-10 |
| Mountain | Miscellaneous | 10 | 13 | 13 | 13 | 3 | 0 | 0 | 3 | 4.9 | 6.2 | 5.9 | 5.4 | 1.3 | -0.2 | -0.5 | 0.5 |
| | Ice Apron | 183 | 222 | 233 | 243 | 39 | 11 | 10 | 60 | 74.9 | 66.2 | 63.8 | 57.5 | -8.7 | -2.5 | -6.3 | -17.5 |
| | Cirque | 10 | 11 | 10 | 10 | 1 | -1 | 0 | 0 | 4.1 | 3 | 2 | 1.5 | -1.1 | -1.0 | -0.6 | -2.6 |
| | Niche | 81 | 85 | 85 | 80 | 4 | 0 | -5 | -1 | 33.6 | 19.6 | 14.2 | 10.4 | -14.1 | -5.4 | -3.7 | -23.2 |
| | Basin | 404 | 427 | 440 | 451 | 23 | 13 | 11 | 47 | 496.4 | 421.2 | 388.5 | 345.5 | -75.1 | -32.8 | -42.9 | -150.8 |
| Valley | Trough | 48 | 48 | 48 | 48 | 0 | 0 | 0 | 0 | 885 | 778 | 738.2 | 682.3 | -107 | -39.8 | -55.9 | -202.7 |
| | **Total** | **736** | **806** | **829** | **845** | **70** | **23** | **16** | **109** | **1,498.9** | **1,294.2** | **1,212.6** | **1,102.6** | **-204.7** | **-81.6** | **-110.0** | **-396.3** |

# Annex 3: **Elevation, aspect and slope of glaciers in the sub-basins (2010)**

Figure A3.1: **Elevation, aspect and slope of glaciers in the Mahakali basin (2010)**

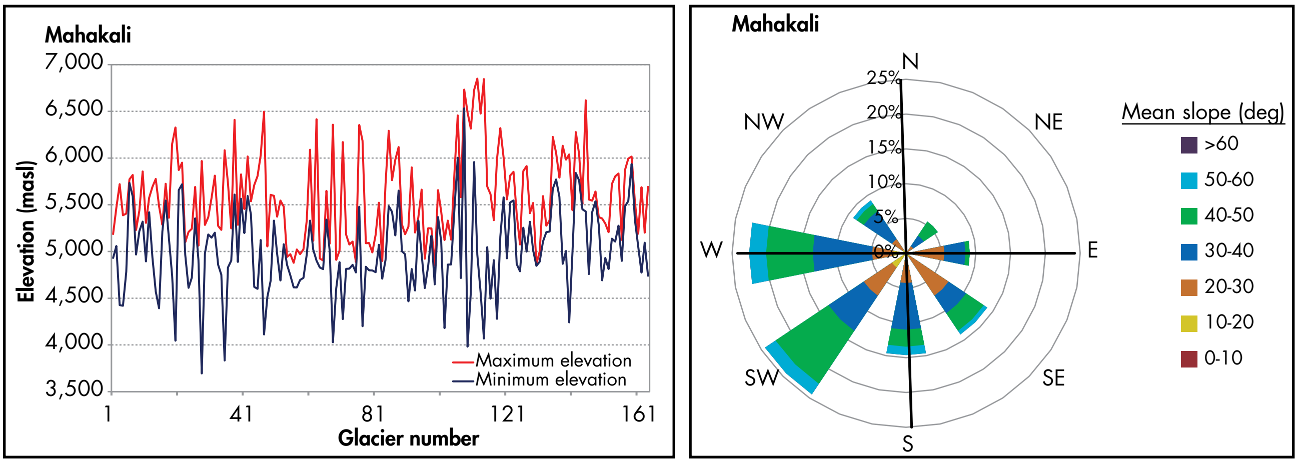



Figure A3.2: **Aspect and slope of glaciers in the Karnali sub-basins (2010)**

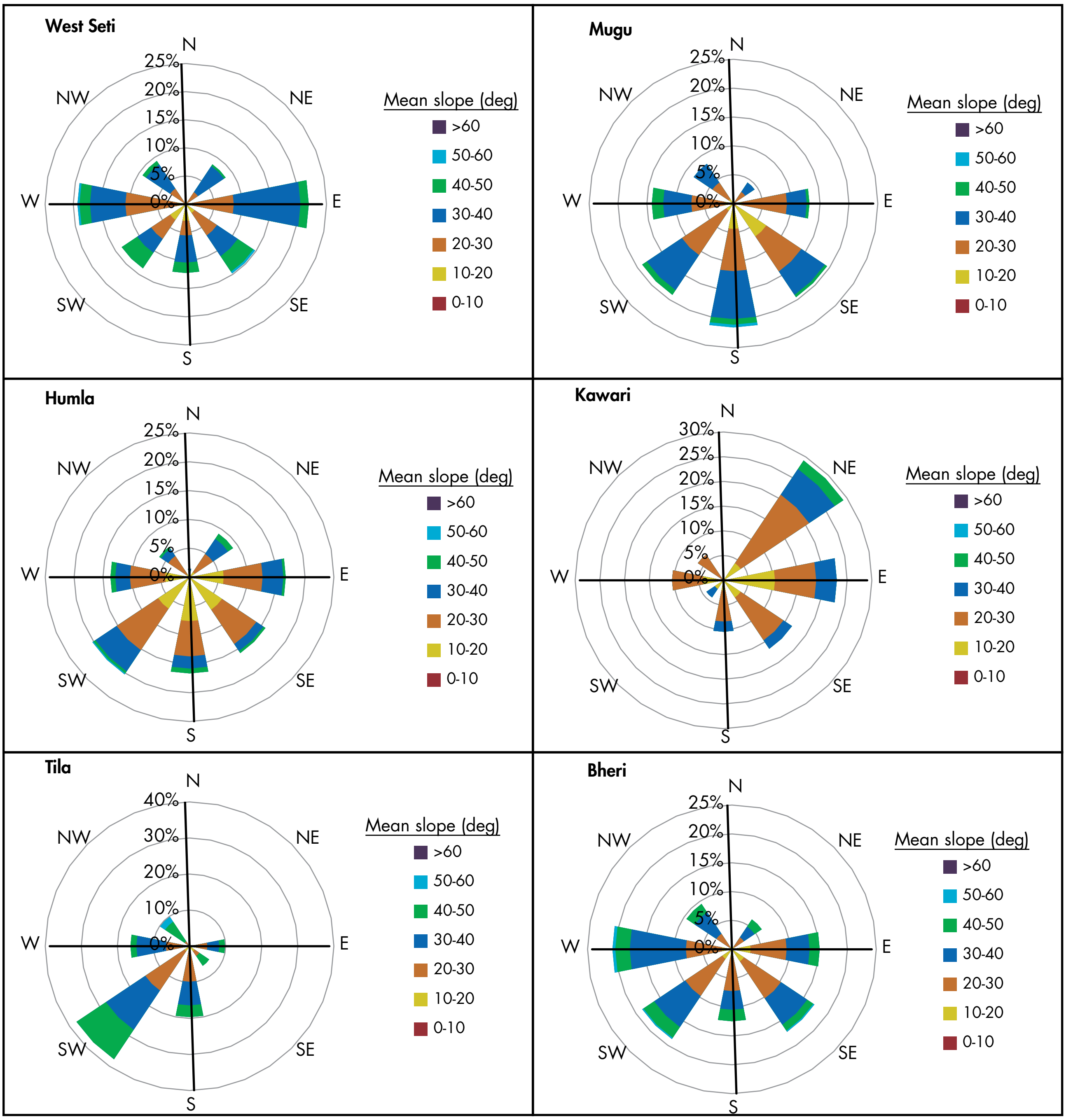


Figure A3.3: **Aspect and slope of glaciers in the Gandaki sub-basins (2010)**

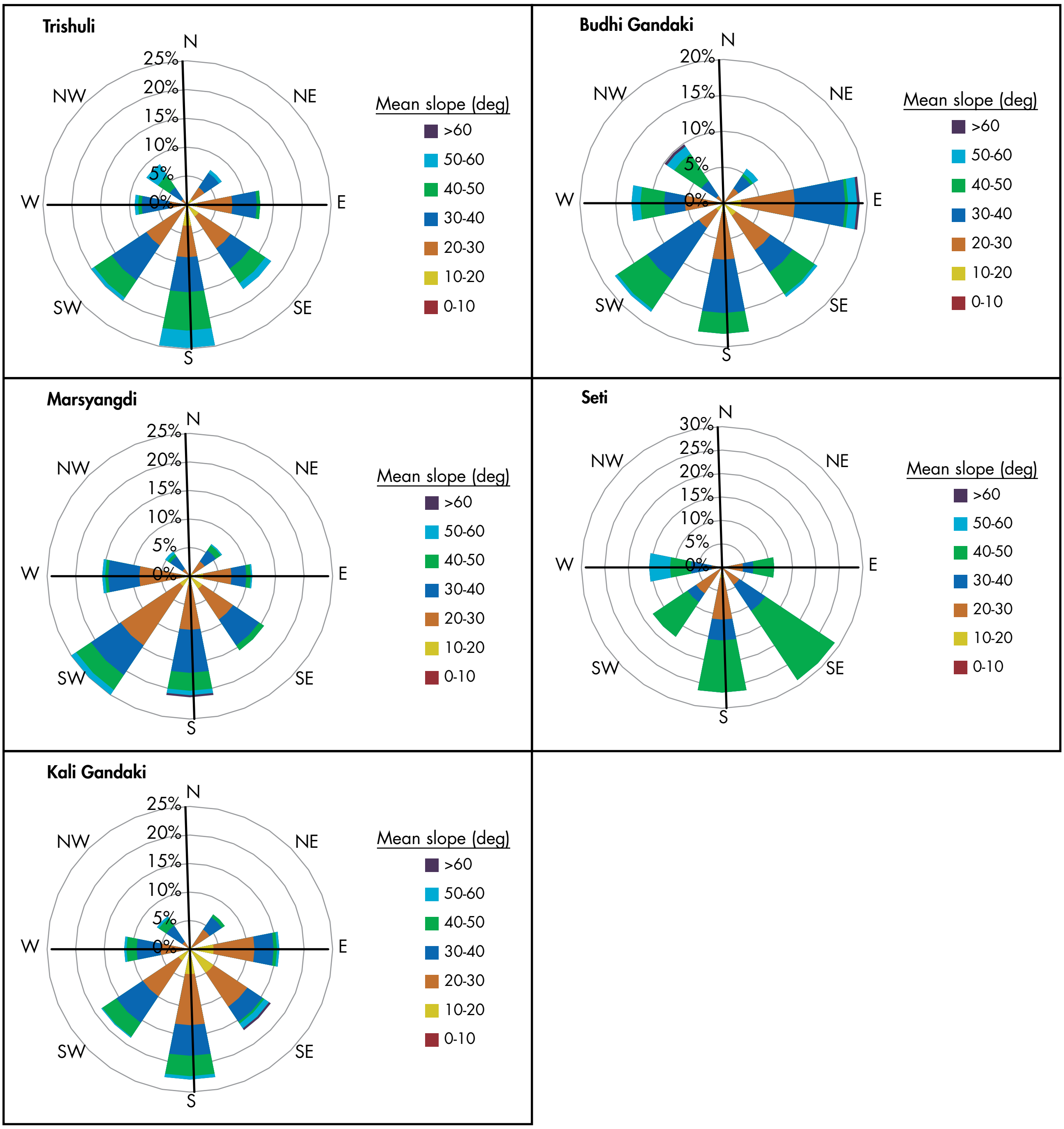
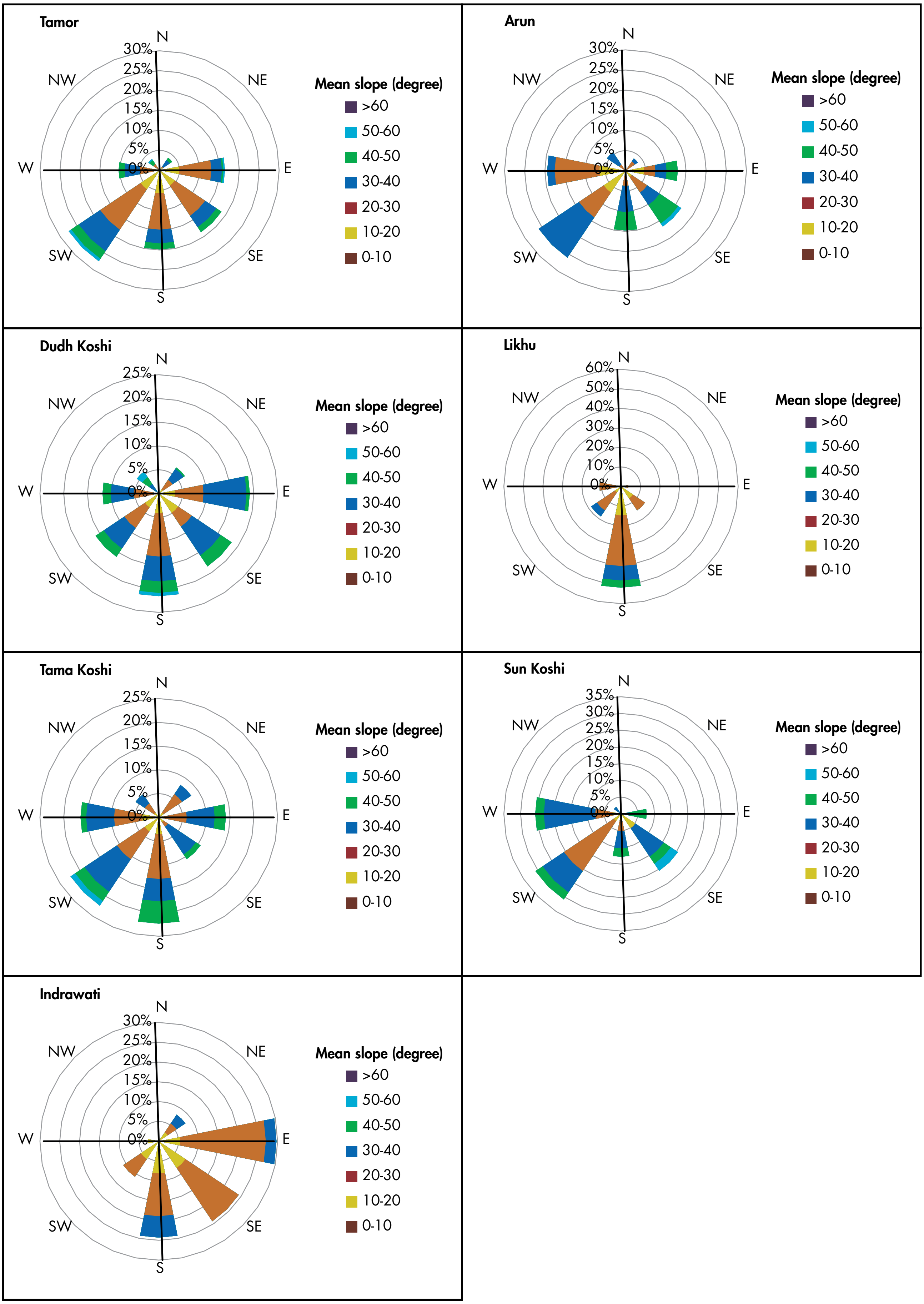


Figure A3.4: **Aspect and slope of glaciers in the Koshi sub-basins (2010)**



# About ICIMOD

The International Centre for Integrated Mountain Development, ICIMOD, is a regional knowledge development and learning centre serving the eight regional member countries of the Hindu Kush Himalayas – Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, and Pakistan – and based in Kathmandu, Nepal. Globalization and climate change have an increasing influence on the stability of fragile mountain ecosystems and the livelihoods of mountain people. ICIMOD aims to assist mountain people to understand these changes, adapt to them, and make the most of new opportunities, while addressing upstream-downstream issues. We support regional transboundary programmes through partnership with regional partner institutions, facilitate the exchange of experience, and serve as a regional knowledge hub. We strengthen networking among regional and global centres of excellence. Overall, we are working to develop an economically and environmentally sound mountain ecosystem to improve the living standards of mountain populations and to sustain vital ecosystem services for the billions of people living downstream – now, and for the future.

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