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The Status of Glaciers in the Hindu Kush-Himalayan Region

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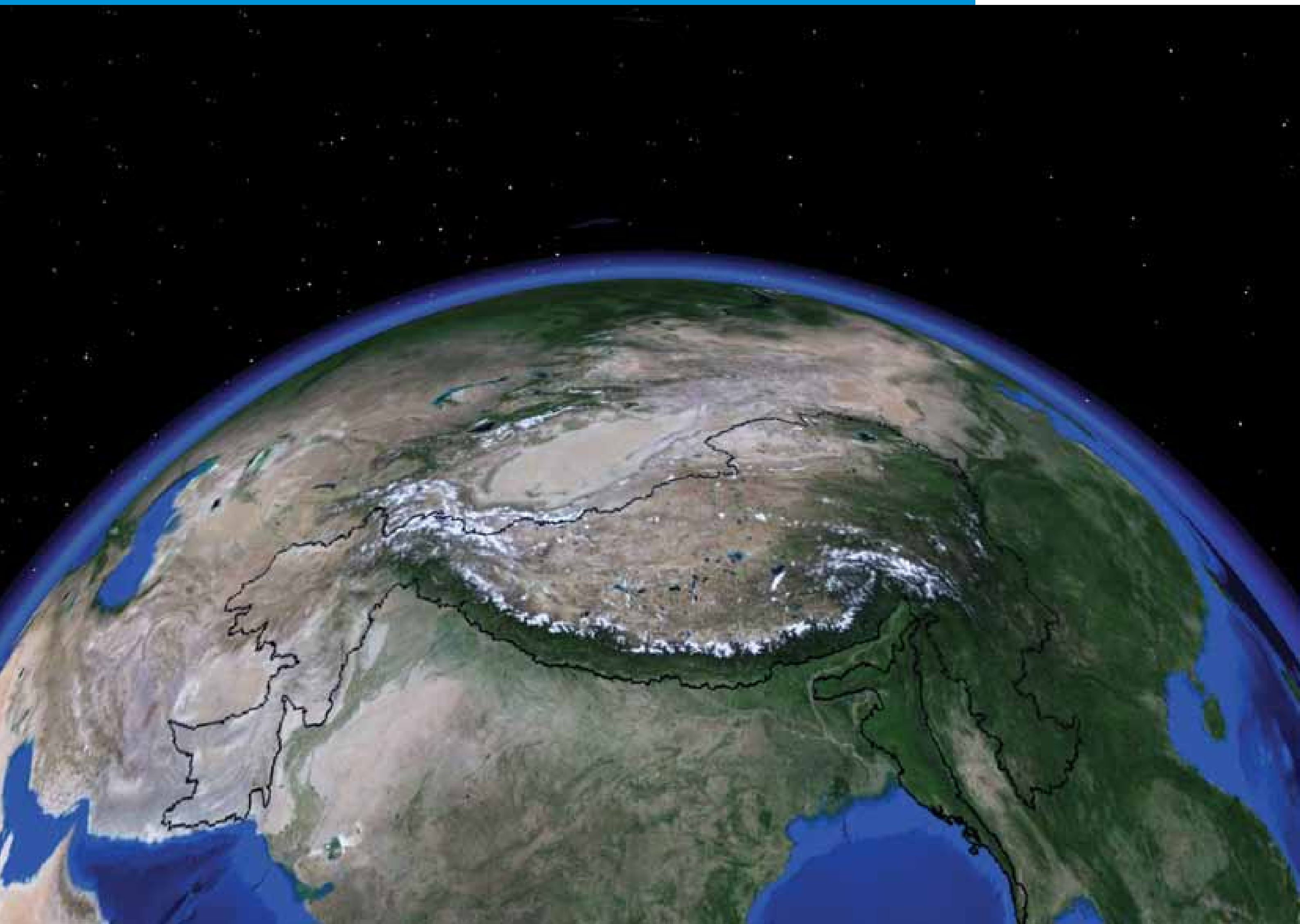

The Status of Glaciers in the Hindu Kush-Himalayan Region

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International Centre for Integrated Mountain Development, Kathmandu, Nepal, November 2011

Published by
International Centre for Integrated Mountain Development
GPO Box 3226, Kathmandu, Nepal

ISBN 978 92 9115 215 5 (printed)
978 92 9115 217 9 (electronic)
LCCN 2011-312013

Printed and bound in Nepal by
Sewa Printing Press, Kathmandu, Nepal

Production team
A Beatrice Murray (Consultant editor)
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Asha Kaji Thaku (Editorial assistant)

Note

This publication is available in electronic form at www.icimod.org/publications

Citation: Bajracharya, SR; Shrestha, B (eds) (2011) *The status of glaciers in the Hindu Kush-Himalayan region*. Kathmandu: ICIMOD

Foreword

I am very pleased to present this report on the state of the glaciers in the Hindu Kush-Himalayan region. The study represents a major advance on ICIMOD's first publication on the state of glaciers in 2001. Close collaboration with specialists from the different countries has enabled the preparation of a comprehensive account of the glacier cover of the entire region using a consistent approach and methodology based on remote sensing information from a limited time period.

The Hindu Kush-Himalayan region encompasses more than 4 million square kilometres of hills and mountains in the eight countries of Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, and Pakistan. The vast expanse of snow and ice gives it the name 'water tower of Asia'. The meltwater from snow and ice feeds ten large river systems: the Amu Darya, Brahmaputra, Ganges, Indus, Irrawaddy, Mekong, Salween, Tarim, Yangtze, and Yellow Rivers. The river basins cover an area of about 9 million square kilometres of which 2.8 million square kilometres lie within the Hindu Kush-Himalayan region. The inventory identifies 54,000 glaciers, clean-ice and debris-covered, with a total area of 60,000 km^2 and estimated 6,000 km^3 of ice reserves, within the ten river basins and large interior basin of HKH region.

The cryosphere of the Hindu Kush-Himalayan region plays a significant role in the regional climatic system, and is also a sensitive indicator of global climate change. Climate change is a major driver affecting the cryospheric environment, threatening the freshwater reserves and posing increased risks from climate-induced hazards to the mountain region and its immediate downstream communities. However, there is a marked lack of consistent, detailed, and long-term information for the region, and in particular for glacier and snow cover. The Intergovernmental Panel on Climate Change (IPCC) fourth assessment report shows that the Hindu Kush-Himalayan region comprises a major data gap in terms of any climatic assessment.

We believe that this study represents a significant step towards bridging the data and information gap on the glaciers of the Hindu Kush-Himalayan region. It is the first report to cover the entire region from a single consistent source. The complete database and analyses will be made available online in a mountain portal at http://geoportal.icimod.org/HKHGlacier, which can be used by all stakeholders, from national and local governments to the public at large. The database provides basic information and knowledge for regional level assessments and monitoring of the glaciated environment to support 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 the mountain ecosystem and the downstream riparian countries in terms of water availability.

We believe that this glacier data has immense importance and will serve the scientific community, decision makers, and other relevant stakeholders. However, we are also aware of the limitations. This inventory is only a first step in obtaining the information needed. Field verification of the data could only be carried out at a few selected sites, and mass balancing remains a task ahead. The estimates on ice volumes are thus imprecise and serve as an indicator only. They will be corrected as more reliable information becomes available from in situ investigations. As a regional knowledge centre, ICIMOD hopes to develop the information base further by fostering regional cooperation and promoting sharing and exchange of data at the international level, thus contributing to reducing the scientific uncertainty in understanding of the impacts of climate change.

ICIMOD is grateful to the Swedish International Development Cooperation Agency (Sida) for its financial support for the cryosphere monitoring project and advice given during implementation. We are especially pleased that the project has enabled us to further strengthen our collaboration and cooperation with national partners in our regional member countries. 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 publication and data portal will be a useful resource for the countries of the region, as well as for scientists worldwide studying the processes, potential impacts, and implications of climate change.

Andreas Schild
Director General
ICIMOD

About This Report

This report provides a comprehensive account of the glacier coverage of the entire Hindu Kush-Himalayan region based on a standardised analysis of satellite images over a limited time frame. A mountain web portal (http://geoportal.icimod.org/HKHGlacier) has been set up to complement the report and provide easy access to the data and analyses. The report and the database serve as a significant step in filling the gap in information on the glaciers of the Hindu Kush-Himalayan region. The data analyses are presented in terms of the major river basins: Amu Darya, Brahmaputra, Ganges, Indus, Irrawaddy, Mekong, Salween, Tarim, Yangtze, and Yellow, and the large Himalayan interior basin. These basins extend across the seven Hindu Kush-Himalayan countries of Afghanistan, Bhutan, China, India, Myanmar, Nepal, and Pakistan. The eighth Hindu Kush-Himalayan country, Bangladesh, has no glacial cover. A consistent remote sensing methodology was used to delineate the clean-ice and debris cover of glaciers and the glacier attribute parameters which are documented in line with the standards provided by the World Glacier Monitoring Services. The report provides a comprehensive account of glaciers to cover the entire region utilising a uniform methodological approach.

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Contributing Authors

The original data for this report was prepared at ICIMOD in collaboration with national partners and later synthesised and analysed to provide a basin-wise picture. The contributions of the individual authors to the chapters are listed below.

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Acknowledgements

The editors and authors want to express their sincere thanks to Professor Jeffrey S Kargel, University of Arizona, Department of Hydrology and Water Resources, USA; Dr Walter W Immerzeel, Utrecht University, Faculty of Geosciences, The Netherlands, and Dr Anil Kulkarni, Divecha Centre for Climate Change, Centre for Atmospheric and Oceanic Sciences, Indian Institute of Science, India, for their detailed review of the manuscript. Our special thanks go also to Dr Tobias Bolch of the Geographisches Institut, Universität Zurich, Switzerland, and Professor Dr Vishnu Dangol of the Department of Geology, Tri-Chandra Campus, Tribhuvan University, Nepal, for their comments and suggestions for improving the manuscript.

Many people have contributed to the preparation of this report and we would like to thank them all. In particular we would like to thank Mr Sangay (Tiger) and Mr Sherub (Bird) from Ugyen Wangchuk Institute for Conservation and Environment (UWICE), Bhutan, for their assistance during the initial stages of glacier mapping of the Bhutan Himalayas; Mr Kabir Uddin, Mr Deo Raj Gurung, and Mr Hammad Gilani from ICIMOD for their assistance and support in the development of the semi-automatic methodology for mapping of glaciers; and Mr Pradeep Dangol from ICIMOD for his untiring support in the preparation of graphics and developing a standard format for the Figures and Tables.

The inventory was prepared under the project 'Too Much, Too Little Water – Adaptation Strategies to Climate-Induced Water Stress and Hazards in the Greater Himalayan Region', funded by the Swedish International Development Cooperation Agency (Sida). This financial support from Sweden is gratefully acknowledged. We wish to express our sincere gratitude to Mr Pradeep Mool, coordinator of the Cryosphere Group; Dr Mats Eriksson, former coordinator of the 'Too Much, Too Little Water' project, and Professor Hua Ouyang, Programme Manager, for their indispensable support for this undertaking.

We particularly wish to express our great appreciation and thanks to our colleague Mr Rajan Man Bajracharya for his support in structuring the glacier database for the geoportal, and to extend our thanks to Mr Birendra Bajracharya from ICIMOD and Mr Wu Lizong from CAREERI, CAS, for their support, strength, help, and co-operation in the completion of this assignment.

Last but not least we thank the staff and consultants of the Publications Unit for their dedicated support in preparing the manuscript for publication

Acronyms and Abbreviations

ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
CI	clean-ice
DC	debris-covered
DEM	digital elevation model
ETM	Enhanced Thematic Mapper
GIS	geographic information system
GLIMS	Global Land Ice Measurements from Space
HKH	Hindu Kush-Himalayas
ID	Identity
Landsat	Land Resources Satellite
LWM	land and water mask
masl	metres above sea level
NDSI	Normalized Difference Snow Index
NDVI	Normalized Difference Vegetative Index
SLC	Scan Line Corrector
SKLCS	State Key Laboratory of Cryospheric Sciences
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 Secretariat
UNESCO	United Nations Educational, Scientific and Cultural Organization
UTM	Universal Transverse Mercator
WGI	World Glacier Inventory
WGMS	World Glacier Monitoring Service
WGS	World Geodetic System

Part 1

Methodology

1 Introduction

The Hindu Kush-Himalayan (HKH) region extends from 15.95° to 39.31° N latitude and 60.85° to 105.04° E longitude, encompassing an area of mountains more than 4,192,000 km^2 in the eight countries of Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, and Pakistan. The region is one of the most dynamic, fragile, and complex mountain systems in the world as a result of tectonic activity and the rich diversity of climates, hydrology, and ecology. The high Himalayan region is the freshwater tower of South Asia; it has the highest concentration of snow and glaciers outside the polar regions giving it the name Third Pole (Dyhrenfurth 1955). Meltwater from the snow and glaciers feeds the ten largest river systems in Asia, which together support some 1.3 billion people in their downstream basin areas. These mountain ranges not only present a beautiful landscape, they play an important role in global atmospheric circulation, the hydrological cycle, and water resources availability, and provide a wide range of ecosystem services.

Mountain areas are particularly vulnerable to climate change, and the HKH region is no exception. A number of noticeable impacts related to climate change have already been documented. For example, the temperature has increased in the Nepalese Himalayas 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, 2001b). The glaciers in much of the region show 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) (Ives 1986; Kattelmann 2003; Mool et al. 2001a, 2001b; Richardson and Reynolds 2000; Quincey et al. 2007; Yamada 1998; Zimmermann et al. 1986; Bolch et al. 2008). A number of GLOFs have already been reported in this region (Bajracharya et al. 2007; Mool 1995; Mool et al. 2001a, 2001b; Reynolds 1998; Yamada 2000, 1998; Yamada and Sharma 1993).If the present trends persist, the store of glacier ice will gradually be reduced, which will impact on the availability of water resources (Barnett et al. 2005; IPCC 2007).

Climate and glacier changes cannot be generalised 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 (Bajracharya et al. 2007). At the same time, increasing ice mass balances and growing glaciers have been reported in the Karakoram mountains in the western part of the region (Hewitt 2005, 2010; Scherler et al. 2011) illustrating the complexity of the situation. It is likely that there are large variations in glacier response to a complex pattern of climatic changes within the Himalayas.

Notwithstanding the importance of the HKH region, 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. This publication presents the results of a recent study designed to provide a comprehensive account of the number and status of glaciers across the whole region.

Existing Regional Inventories

There are an estimated 160,000 glaciers worldwide (Paul et al. 2009) covering nearly 15 million square kilometres (including the polar ice sheets), or about 10% of the land area, and containing 2.15% of all freshwater. About 3% of the glacier cover is found in the mountains of Asia, Europe, and America. The Hindu Kush-Himalayan region (HKH) has the largest concentration of snow and glaciers outside the polar regions (Kulkarni 1991, 1994).

The Geological Survey of India (GSI) and Cold and Arid Region Environmental and Engineering Research Institute (CAREERI) of the Chinese Academy of Sciences (CAS) have both carried out glacier studies in the HKH region.

The Geological Survey of India has carried out hydrological studies and glacier mass balancing (on a limited scale) of Indian Himalayan glaciers since 1978. It inventoried 5,243 glaciers with a total area of 37,959 km² distributed among the States of Arunachal Pradesh, Himachal Pradesh, Jammu and Kashmir, Sikkim, and Uttarakhand (GSI 1999, Raina and Srivastava 2008). The Indian glacier data were based on Survey of India topographic maps, aerial photographs, and satellite images, with limited field verification. The inventory showed that Jammu and Kashmir has the highest concentration of glaciers in India, and Arunachal Pradesh the lowest.

The first detailed Chinese glacier inventory was published in 2000 in the form of 22 separate documents, based on the World Glacier Inventory guidelines. It described 46,298 glaciers with a total area of 59,406 km², 48% of the total area of glaciers in Asia (Chao-hai et al. 2000). The Cold and Arid Regions Environmental and Engineering Research Institute (CAREERI) is in the process of carrying out a second national inventory.

Between 1999 and 2004, ICIMOD and its partner institutes prepared an inventory of glaciers in selected parts of the HKH region (Figure 1.1). The inventory was based on the 1:50,000 scale topographic maps published by the Survey of India in the 1970s or Landsat satellite images from 2000 for areas for which no topographic maps

Figure 1.1: The Hindu Kush-Himalayan region showing the areas covered by ICIMOD's inventory of glaciers and glacial lakes study from 1999-2004

were available. This study identified more than 15,000 glaciers with a total area of some 33,000 km^2 in Bhutan (1,317 km^2), Nepal (5,324 km^2 in the high Himalayas), Pakistan (15,041 km^2 in the Hindu Kush, Himalaya, and Karakoram mountains), and selected river basins of India and China. (Bajracharya and Mool 2007; Ives et al. 2010).

Armstrong (2011) recently prepared a report for USAID, later published by ICIMOD, summarising the literature on glaciers, and especially glacier melt and retreat, in the Himalayan, Hindu Kush, Karakoram, Pamir, and Tien Shan mountain ranges (Armstrong 2011).

The Present Study

The study presented here was designed to develop comprehensive baseline information on the glaciers of the entire HKH region organised by major basins and sub-basins. The glacier inventory was prepared from satellite images taken within a short period to maintain uniformity of the observational database, and for areas in all countries except China was prepared at ICIMOD. The inventory data for basin areas in China were received through collaboration with CAREERI.

In addition to the immediate research objectives, the long-term objective is to support global climate change research by facilitating access to well-documented glacier data. The project also aimed to build the regional capacity of partner institutes engaged in glacier mapping and to undertake the glacier inventory using tools and methods developed at the local and national level. The glacier database will be provided online to facilitate access to information by policy and decision makers, scientists, and the public at large in the region and beyond. The database provides a basis for assessing the rates of change of glaciers, which is important for understanding climate change, water resource planning, and mitigation of glacial lake outburst flood (GLOF) hazards.

The methodology used and basin-wise results are presented in the following chapters. The detailed data are available in the online database.

2 The Glacier Inventory Approach

Global Level Glacier Inventory Initiatives

There are three major global initiatives related to glacier inventory, all interlinked but with different emphases and approaches.

World Glacier Monitoring Service (WGMS)

A worldwide collection of information about ongoing glacier changes was initiated in 1894 with the foundation of the International Glacier Commission at the 6th International Geological Congress in Zurich, Switzerland. The United Nations Educational, Scientific and Cultural Organization (UNESCO) introduced a classification scheme for perennial snow and glacier masses in 1970 as a contribution to the International Hydrological Decade. The aim was to provide a useful database of glacial observations in a standardised digital form. The system was designed to characterise the morphology of glaciers rapidly and precisely. The major advantage of this system was that it allowed the assignment of several parameters of the glaciers. A series of six key parameters that describe various glacial characteristics facilitated the subsequent compilation. By applying a matrix-type classification based on specific glaciological characteristics, it was possible to provide a defined number of values for each parameter. This system offers a multitude of possibilities for description of individual glaciers.

In 1986 the World Glacier Monitoring Service (WGMS) started to maintain and continue the collection of information on ongoing glacier changes following the combining of the former International Commission on Snow and Ice (ICSI) services of PSFG (Permanent Service on Fluctuations of Glaciers) and TTS/WGI (Temporal Technical Secretariat/World Glacier Inventory). WGMS adopted the UNESCO classification scheme in a revised form and has proven its general applicability to over 67,000 glaciers worldwide. Today, WGMS (www.geo.uzh.ch/wgms) collects standardised observations on changes with time in mass, volume, area, and length of glaciers (glacier fluctuations) as well as statistical information on the distribution of perennial surface ice in space (glacier inventories). Along with further relevant glacier data, the information is compiled in the World Glacier Inventory which is located at the National Snow and Ice Data Center (NSIDC, http://nsidc.org).

Global Land Ice Measurements from Space (GLIMS)

Field-based mapping of glaciers can be hard and time consuming as glaciers are generally located in remote high areas with rugged topography. Satellite remote sensing has therefore become a key application for glacier mapping. The Global Land Ice Measurements from Space initiative (GLIMS, www.glims.org) was initiated to capitalise on new developments in the field of remote sensing technologies and monitor the world's glaciers primarily using data from optical satellite sensors, such as the Advanced Spaceborne Thermal Emission and reflection Radiometer (ASTER) and Landsat 7 ETM+ (Kargel et al. 2005, 2010). GLIMS has a formalised partnership with WGMS and GLIMS data are also archived at the National Snow and Ice Data Center (NSIDC, http://nsidc.org).

Because of the enormous variety of glacier types and sizes, it is often not easy to map them unambiguously. Likewise, it is difficult to map all glaciers using a single methodology, and for practical reasons, such as availability of cloud free imagery, various alternatives or supplementary datasets are used. GLIMS researchers have developed a set of technological approaches to support the mapping of glaciers, glacier flow velocities, debris loads, glacier lake development, and elevation changes (Wessels et al. 2002; Bishop et al. 2004; Kargel et al. 2005; Rivera et al. 2005; Raup et al. 2007a, 2007b; Kääb et al. 2003; Paul et al. 2009). GLIMS has also been active in higher-order glacier assessments, such as assessment of glacier-related hazards (Kääb et al. 2003; Huggel et al. 2005;

Kargel et al. 2010). GLIMS has developed guidelines for mapping and documenting glacier data to ensure consistency and homogeneity in the morphological classification, taking account of the many datasets and methodologies available. The illustrated GLIMS Glacier Classification Manual provides practical guidance for analysts (Rau et al. 2005). GLIMS relies most strongly on satellite-based mapping, but most remote sensing glaciology experts also include field-based evidence to validate or supplement the glacier analysis products produced from satellite data.

Over 60 institutions across the globe are involved in GLIMS; ICIMOD serves as the regional coordinator for Bhutan, India, and Nepal.

GlobGlacier

GlobGlacier (http://globglacier.ch) is supported by the European Space Agency (ESA) to complement and strengthen the existing network for global glacier monitoring. The project helps to establish a global picture of glaciers and ice caps, and their role as essential climate variables (ECVs). The major focus of the GlobGlacier initiative is to complete the 1970s World Glacier Inventory (WGI) by producing glacier outlines in regions where data are lacking or non-existent. Moreover, GlobGlacier will integrate satellite data from various sensors to create value added products for a wide range of user communities. Close cooperation of GlobGlacier with major user groups such as WGMS, and related projects such as GLIMS, is designed to ensure that maximum benefit is obtained from the generated products from a global perspective (Paul et al. 2009).

GlobGlacier is developing a set of 'Guidelines for the compilation of glacier inventory data from digital sources', currently under review. The structure of the document closely follows the original guidelines by Müller et al. (1977) for the former WGI developed by the Temporary Technical Secretariat (TTS) at the Swiss Federal Institute of Technology, Zurich. The main idea is to provide a selection of essential topographic glacier parameters and other attributes that can be calculated from glacier outlines and digital elevation models (DEM) using mostly automated methods. These should be provided whenever possible with any submission to the GLIMS database. A further set of parameters is listed as useful but not mandatory.

Regional Level Glacier Inventory Initiatives

A number of institutes and scientists in the HKH region have carried out studies of glaciers using different observational databases and methodologies. However, there is still a need to develop a common approach for the entire region and to support coordination among the countries for regular long-term mapping and monitoring of the glaciated environment. ICIMOD has been working with national partners on mapping of different aspects of the cryosphere to support regional water resources assessment, hazard management applications, and global climate change research.

The methodology used by ICIMOD in the past for mapping and inventory of the glaciers was based on the guidelines for the WGI (Müller et al. 1977). These were based on visual interpretation and manual digitisation of glacier boundaries followed by integration of a non-spatial database. The ICIMOD inventory was systematically carried out for selected drainage basins using topographic maps published from 1963 to 1982, or satellite images from 1999 and 2000 in areas without topographic map coverage. The inventory provided a first overview of the glaciers in the region, but the data were based on a wide temporal range and derived from different sources. The present study was designed to address this problem and deliver a first comprehensive and consistent inventory of the region's glaciers. The study employs a glacier mapping methodology that is able to rapidly deliver glacier data consistent with established international inventory standards.

Automatic delineation of glaciers is only valid for clean-ice glaciers (Paul 2002; Racoviteanu 2009; Bolch et al. 2008). However, 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. Thus the current inventory used a combination of manual and automatic methods. The updated inventory used a single source of satellite imagery from a limited period of time to facilitate more precise spatial and temporal assessment of glacier status and change.

3 Data Collection and Glacier Mapping Methodology

Field-based glacier mapping is a challenging task in the high Hindu Kush-Himalayan region because of the rugged terrain, high altitude, harsh climatic conditions, lack of logistical support, and remoteness. 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. The updated ICIMOD inventory used a combination of automated and manual interpretation of satellite images, complemented by limited field studies. The data collection and mapping methodology is described in the following sections, and the allocation of attributes for the inventory in the following chapter.

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 renamed 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 used by GLIMS, and SPOT and ASTER used by GlobGlacier.

The present inventory used Landsat 5-MSS and Landsat 7-ETM+ images from 2005 ± 3 years, which are freely downloadable. The best images in this period were selected, i.e., those with least snow cover and no clouds. Figure 3.1 shows the image index map for the HKH region.

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 (DEM)

Topographic information such as elevation and slope play a crucial role in 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/median elevation, and equilibrium line altitude (ELA). The study used the SRTM (Shuttle Radar Topography Mission) DEM at a spatial resolution of 90 metres (Figure 3.2).

Figure 3.1: Landsat ETM+ index map for the Hindu Kush-Himalayan region

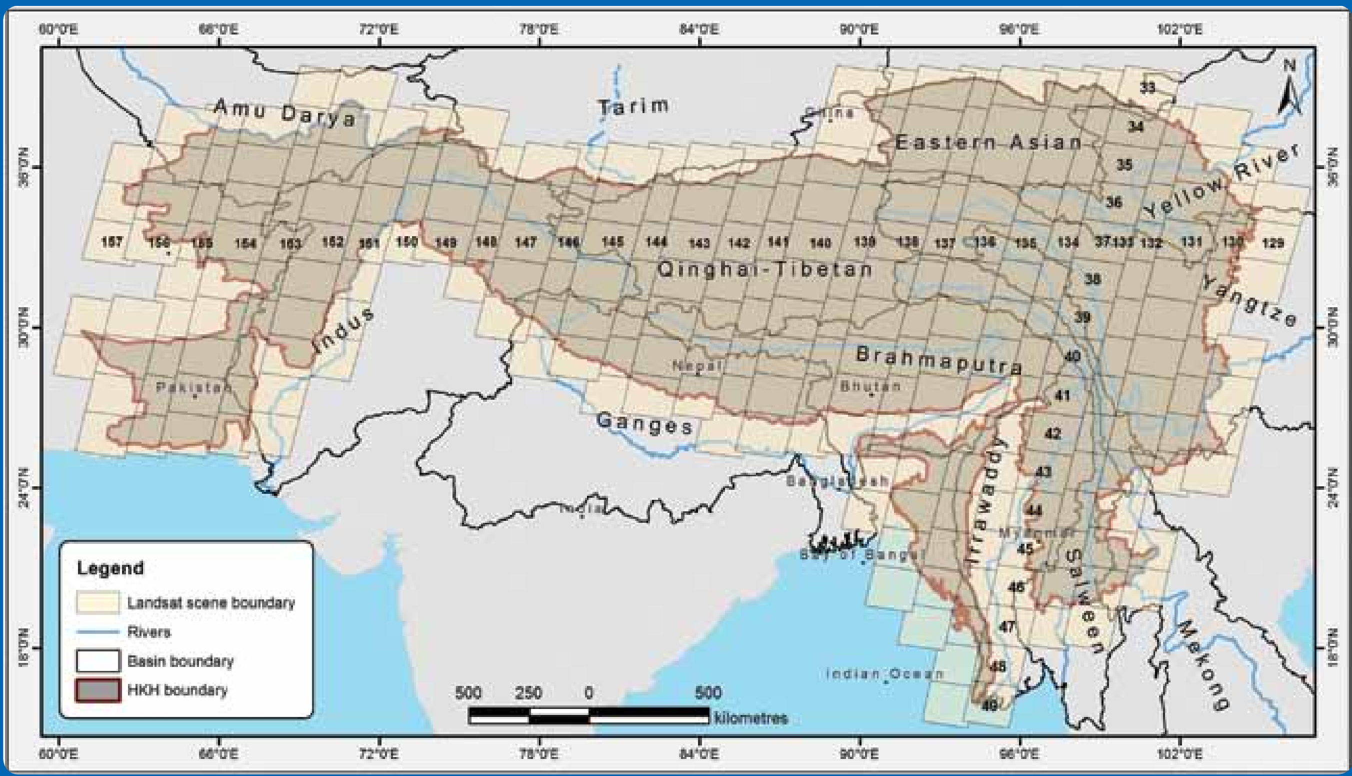
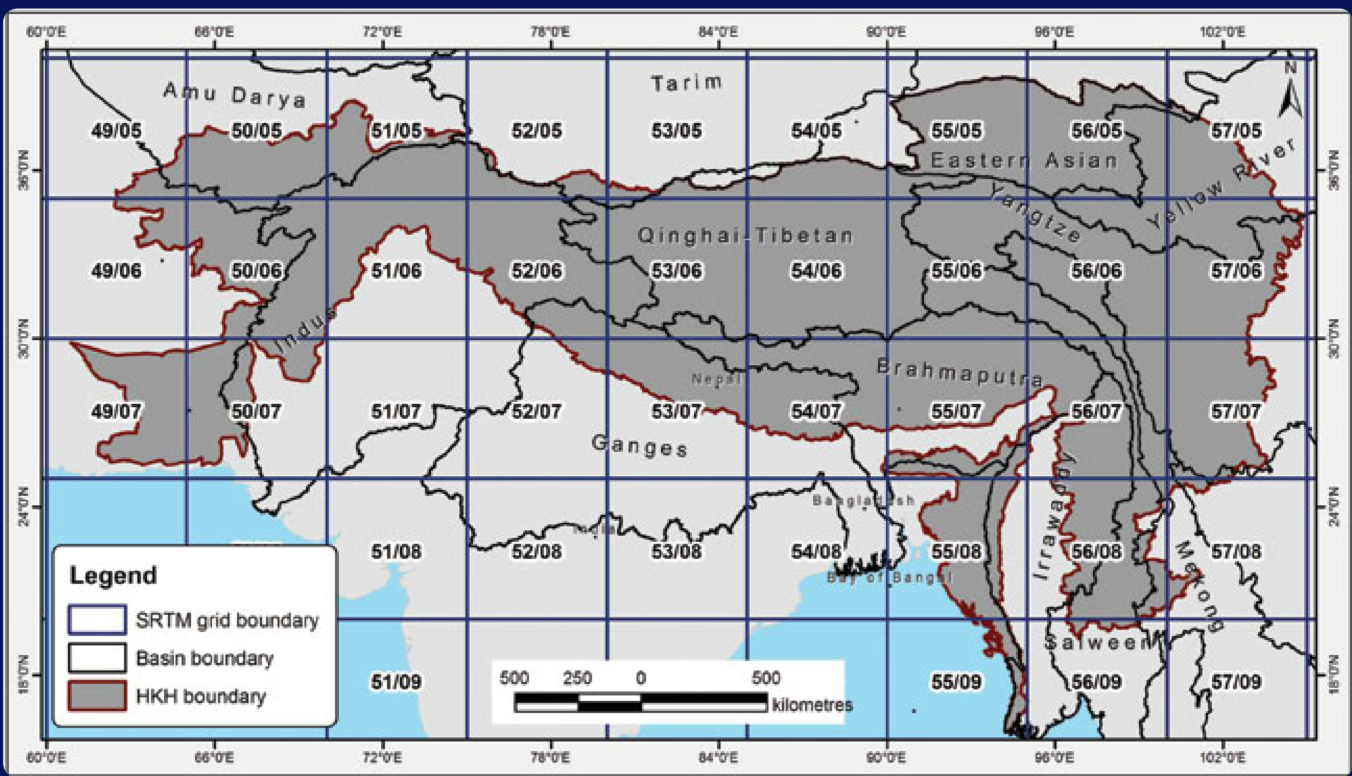


Figure 3.2: SRTM index map for the Hindu Kush-Himalayan region



Glacier Delineation

A semi-automatic methodology was adopted for delineation of glaciers using an object-based image analysis approach. After the SLC-off correction, the image was segmented in Definiens Developer software using multi-resolution segmentation. This is a heuristic optimisation procedure to locally minimise 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 overall multi-stage process of classification is summarised in Figure 3.3.

Delineation of clean-ice glaciers

The identification of CI glaciers relied primarily on the normalised difference snow and ice index (NDSI) with NDSI = ([Mean Band 2]-[Mean Band 5])/([Mean Band 2]+[Mean Band 5]). An appropriate threshold value for NDSI based on the histogram and visual judgment was applied to capture the CI segments. The NDSI threshold values differ slightly from image to image, thus some small polygons of shadow, water bodies, vegetation, bare rock, debris, and other misclassified polygons are also captured. Further refinements were performed using different filters including the normalised difference vegetation index (NDVI) for vegetation, a land and water mask (LWM) for water bodies, and mean hue for shadow. Slope (>60°) and elevation criteria were applied to further refine the data (Figure 3.4). Polygons smaller than a minimum mapping unit of 0.02 km^2 were removed. This process satisfactorily delineates the outline of CI-type glaciers with minimal manual intervention. The glacier outlines were validated using available high resolution images in the Google Earth.

Delineation of debris-covered glaciers

Capturing of DC glaciers is further complicated by illuminating errors due to effects from the surroundings. Following delineation of CI glaciers using NDSI, the DC glaciers were captured from the remaining areas of the image using either NDVI or mean slope, selected by subjective judgment for each satellite image used (Figure 3.5). This classification scheme also captures other features such as vegetation, bedrock, and shadows. These were then removed using filters such as LWM, slope (>25°), and elevation (above 6,000 and below 3,000 masl depending upon the locality). Areas less than 0.02 km^2 were also removed. The delineated glaciers were then checked and refined in high resolution images from Google Earth.

Generalising and smoothing

The delineation of CI and DC glacier polygons using the automated method generates straight edges and angular corners consistent with the pixel resolution of the satellite image. These then need to be smoothed. The glacier polygons were exported into shp file format for further processing and the glacier outlines refined using the G-S-G (generalise – smooth – regeneralise) method for smooth corners (Figure 3.6).

Figure 3.3: Flow diagram of the methodology for mapping clean-ice and debris-covered glaciers using satellite images

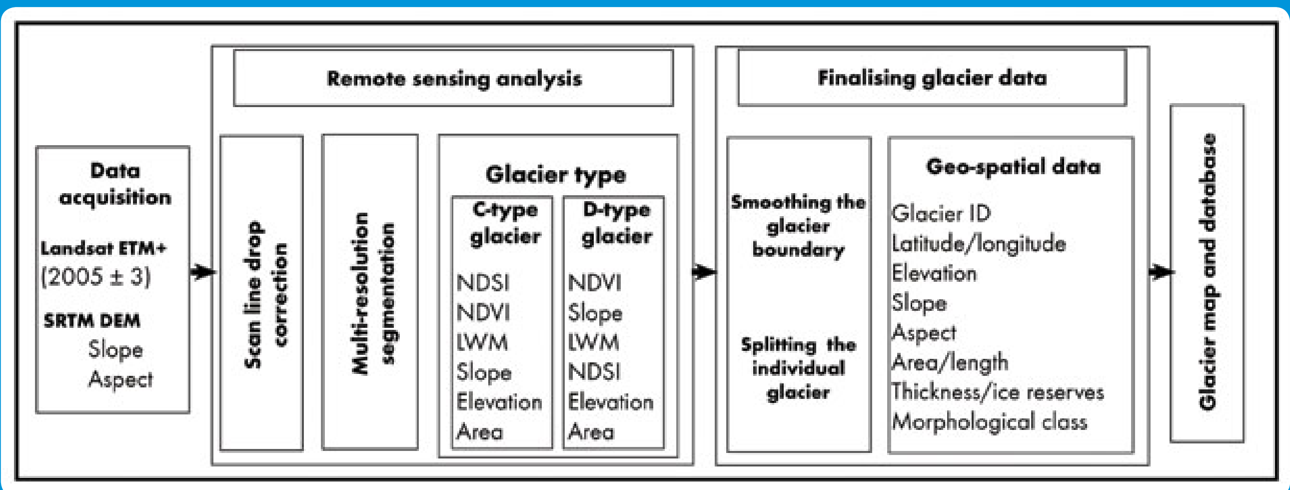


Figure 3.4: Steps used in CI delineation

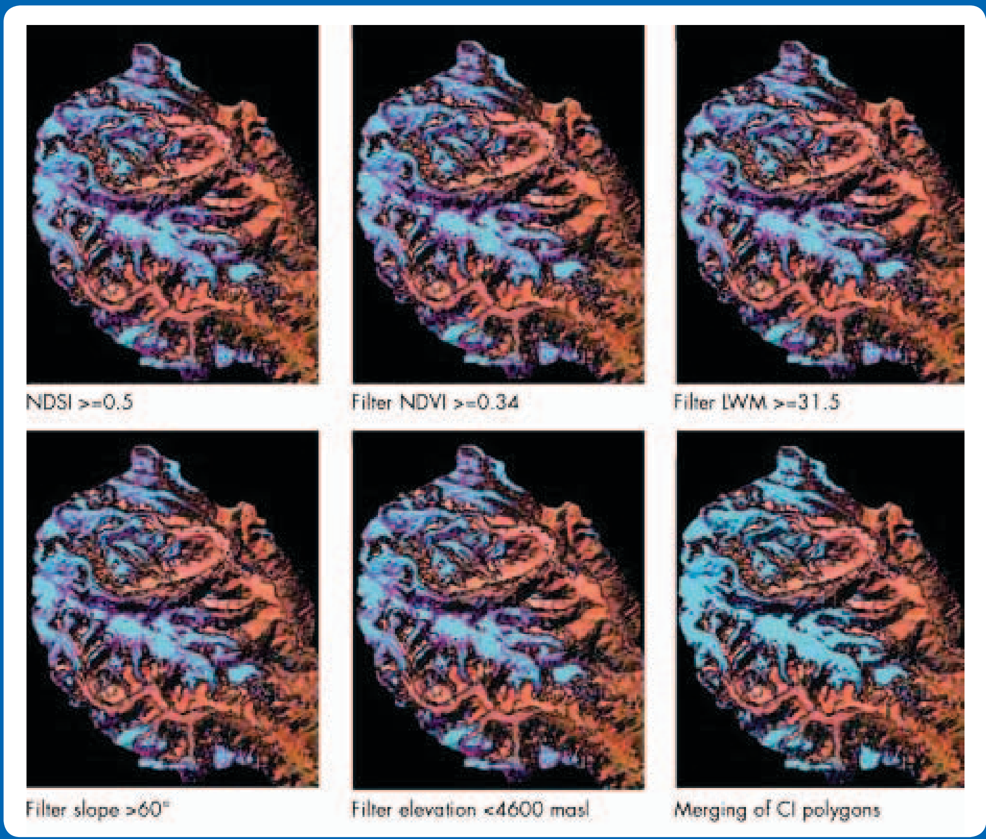
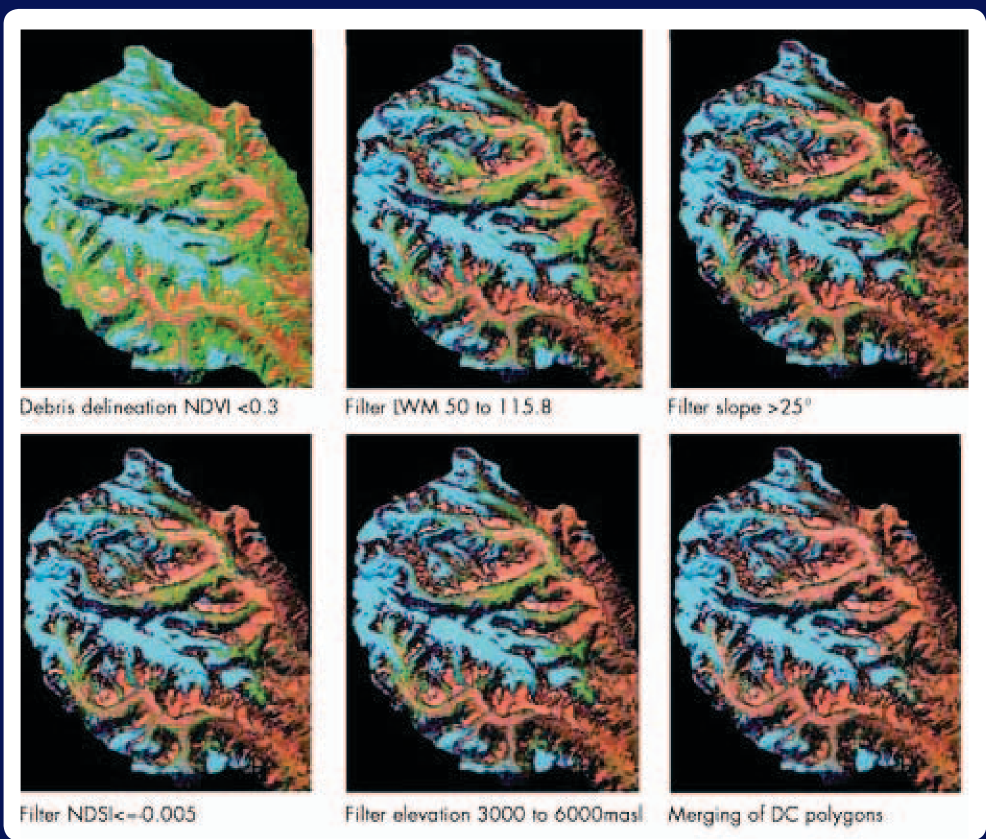


Figure 3.5: Steps used in DC delineation



Glacier inventory

The CI and DC glacier polygons derived from the above processes were then merged into a single polygon layer. A GLIMS ID was assigned at the centre of each glacier polygon. When combined with a DEM, glacier outlines serve to derive glacier parameters such as aspect, slope, and hypsometry. The post-classification data management and parameterisation were carried out in an ArcGIS platform. Additional data sets like topographic maps were used to derive some important attributes which were then inserted into the glacier database.

Glacier Area Analysis

HKH basin boundary

Meltwater from the snow and ice of the HKH region feeds the ten largest river systems in South Asia: the Amu Darya, Brahmaputra, Ganges, Indus, Irrawaddy, Mekong, Salween, Tarim Interior, Yangtze, and Yellow (Figure 3.7). Thus it is important to understand the dynamics of the glacial environment in the river watersheds for assessments of climate change impacts and adaptation measures.

The watershed boundaries of the river basins were delineated using the SRTM DEM and the ArcHydro tool, developed as an add-on to ArcGIS Software. The results were refined manually by backdropping the 30 m resolution Landsat images. The improved results were further verified and refined on high resolution (mostly 1 m) images in Google Earth. The ten major basins were further divided into basins and sub-basins, particularly in the glaciated region. A further area was delineated which lies between the major basins, the Qinghai-Tibetan Interior. Water from this area remains on the plateau and does not drain into the major river systems.

Different reports give different values for the areas of the ten major river basins; this is the result of different projection systems being used as well as some differences in the boundary delineation. The present study used the Universal

Figure 3.6: Successive steps used to delineate glacier boundaries

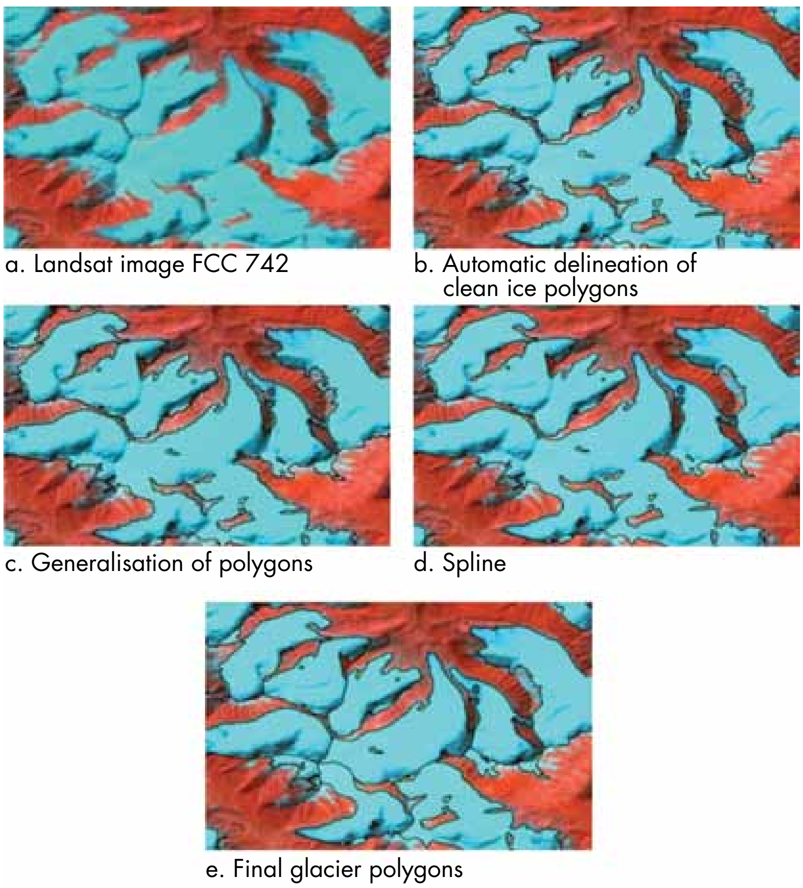
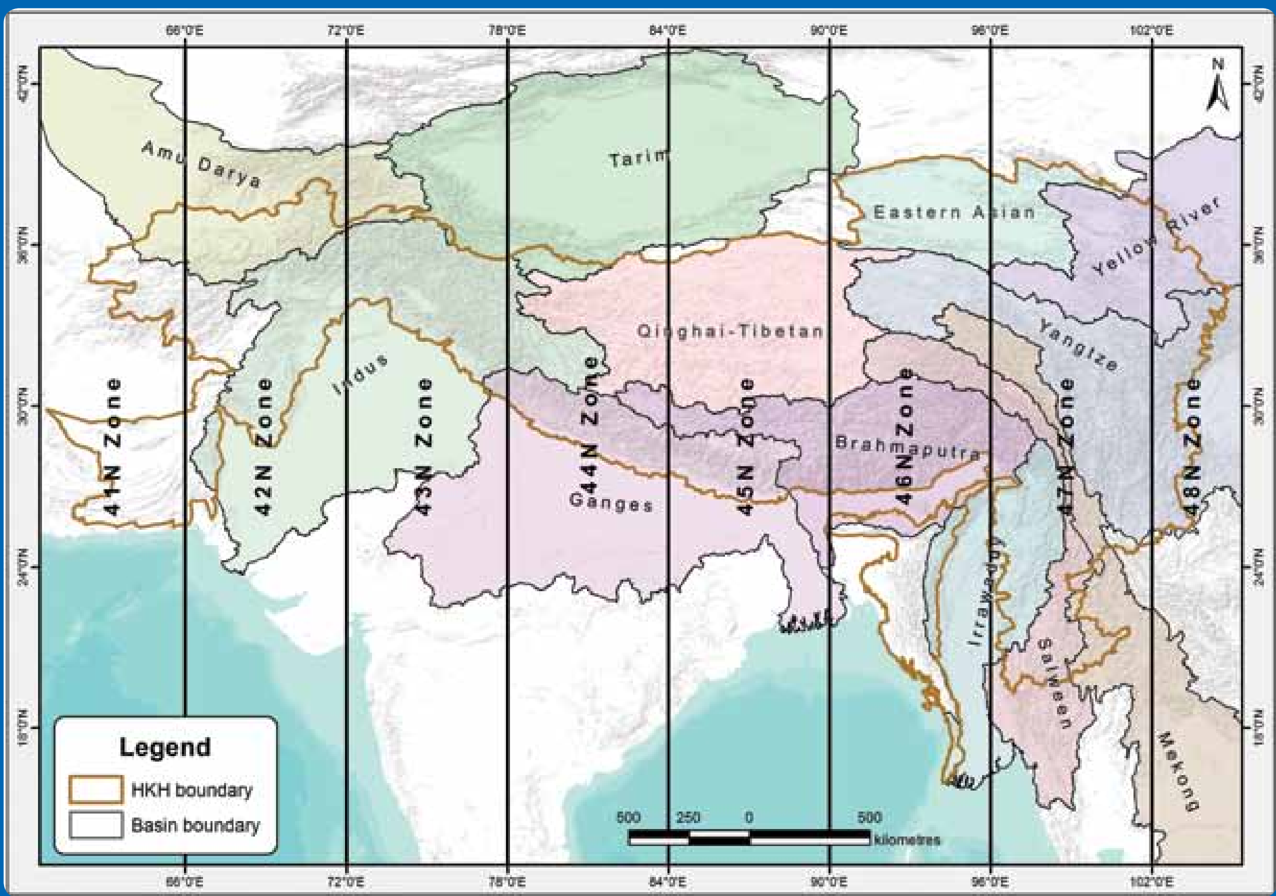


Figure 3.7: The ten major river basins in the Hindu Kush-Himalayas

Figure 3.8: The UTM zones in the basins of the Hindu Kush-Himalayas



Transverse Mercator (UTM) WGS 84 projection system for glacier mapping because the base satellite imagery (Landsat) was provided in this projection system. In the UTM WGS 84 projection system, the HKH region falls into Zone 41N to 48N (Figure 3.8). Using this projection system, the area of the HKH region was calculated to be 4,192,446 km², of which 2,795,898 km² falls within the ten major basins and a further 909,824 km² in the Qinghai-Tibetan Interior (Table 3.1). The remaining 486,725 km² comprises areas of barren, rugged mountains in Pakistan. The glacier area was analysed in each of the basins and sub-basins.

Table 3.1: Total area of major basins and area within HKH region

Major Basins	Area (km²)	Area in HKH (km²)
Amu Darya	645,726	166,686
Indus	1,116,086	555,450
Ganges	1,001,019	244,806
Brahmaputra	528,079	432,480
Irrawaddy	426,501	202,745
Salween	363,778	211,122
Mekong	841,322	138,876
Yangtze	2,065,763	565,102
Yellow	1,073,168	250,540
Tarim Interior	929,003	26,729
Qinghai Tibetan Interior	NA	909,824
Total	**8,990,445**	**3,705,721**

Note: Total HKH area is 4,192,446 km²; 486,725 km² of the area lies outside the ten major basins and the interior basin

Limitations

The part of the glacier database for areas within all countries except China was prepared at ICIMOD using the uniform methodology described above. The inventory for the areas lying in China were analysed by the Cold and Arid Regions Environmental and Engineering Research Institute (CAREERI) under a collaborative arrangement, with the data provided to ICIMOD for the purpose of preparing this regional status report. The details of this part of the inventory will be published separately by CAREERI following the completion of the updated version of the Chinese glacier inventory. Of the 54,000 glaciers identified in the inventory, 45% were in China. The inventory data from China used a different methodology for delineating basins and sub-basins based on the original Technical Temporary Secretariat (TTS) methodology (TTS 1978). The dataset did not distinguish between CI and DC glaciers, included glaciers equal to and larger than 0.01 km². There were also differences in the definition of basin boundaries in the China part between the Chinese data and that prepared at ICIMOD. All of these pose a challenge to uniformity in this status report. In order to resolve the above issues as far as possible, the study reconciled the data from China for the Brahmaputra, Ganges, and Indus river basins, and left the major basins that are entirely in China as they were provided without a sub-basin level differentiation.

4 Glacier Inventory Attributes

Each glacier entity must have a unique identification code. In the earlier ICIMOD inventory, this code was related to the hydrological unit of first and lower order basins. In the present inventory, a GLIMS ID was generated from the coordinates of the glacier in geographic projection (latitude and longitude). The hydrological IDs used in previous inventories were correlated with the present inventory IDs to the extent possible. Eleven attribute parameters were assigned to each glacier: hydrological ID, GLIMS ID, location (latitude/longitude), area, elevation, aspect, average slope, mean glacier thickness, estimated ice reserve, six digit classification (TTS), and morphological classification.

Hydrological ID

The hydrological ID is assigned by numbering the glaciers starting from the outlet of the major stream and proceeding clockwise around the basin through each significant small tributary. The coding system is based on that used in the World Glacier Inventory. For example, Kdugr10_106 stands for Koshi (K), Dudh Koshi (du), glacier (gr), data of 2010 (10), and individual glacier number 106.

GLIMS ID

The GLIMS ID is based on the longitude and latitude location of a centre point in the polygon of the glacier. The GLIMS ID is a 14 digit code including G for Global, E for East and N for North. The latitude and longitude should be in degrees defined to three decimal places (e.g., G086700E28016N).

Location (latitude and longitude)

The location of the glacier was described using the central coordinates (latitude and longitude) of the glacier polygon. The latitude and longitude are stored in degrees defined to three decimal places. The centroid of the glacier polygon was generated automatically, if the central point was in a rocky outcrop (glacier void), the points were shifted manually to the nearest point inside the glacier polygon

Area

The surface area of a glacier is a very sensitive parameter as it is used in a wide range of applications including global scaling up of glacier area. The area and perimeter of CI and DC glacier polygons were derived automatically using the GIS (geographical information system) software. The glacier area was derived in square kilometres to three decimal places using a metric projection (like UTM). The glaciers were only mapped if their area was larger than 0.02 km^2. The glacier areas were divided into five classes: class 1 ≤0.5 km^2; class 2 = 0.51 to 1.00 km^2; class 3 = 1.01 to 5.00 km^2; class 4 = 5.01 to 10.00 km^2 and class 5 ≥10.00 km^2.

The area of valley glaciers is generally large, as they extend from the mountains into the valleys; their ice reserves are proportionately even larger as ice thickness increases with increase in the glacier area.

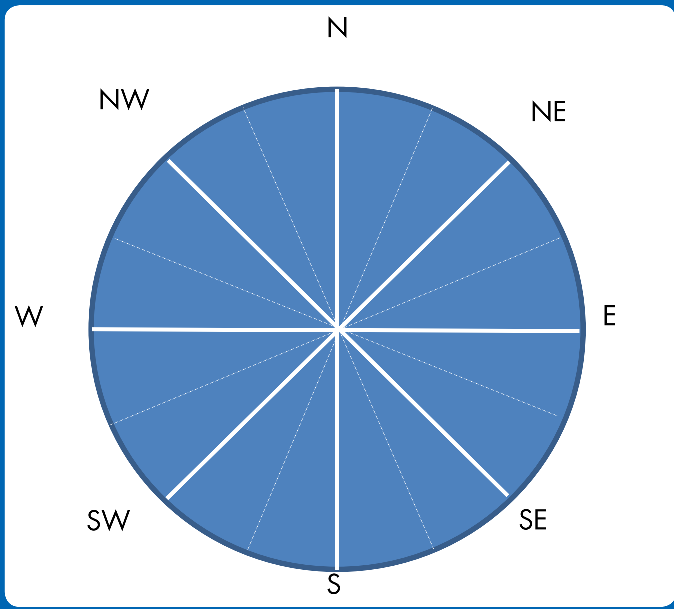
Elevation

The highest and lowest elevations of CI and DC glaciers were derived from the digital elevation model for each glacier. The glacier elevation was divided into highest elevation (the elevation of the glacier crown) derived from the clean-ice, and lowest elevation (elevation at toe of the glacier) derived from the debris-covered ice, or when debris-covered ice was not present then from the clean-ice, and mean elevation (the arithmetic mean value of the highest glacier elevation and the lowest glacier elevation), measured in metres above sea level (masl).

Aspect

Aspect is an important parameter for all kinds of modelling. The mean aspect was derived from a DEM as the average value of all the individual cells covered by the glacier. Aspect is a circular (directional) parameter and mean aspect values must be derived by a decomposition into the respective sine and cosine values (cf. Manley 2008). The calculated value is transformed to the eight cardinal directions (N, NE, E, SE, S, SW, W, and NW) (Figure 4.1). Each cardinal direction has a range of 45 degrees, half to each side, as shown in the figure. Some glaciers are ice caps forming an apron around a peak and thus sloping in all directions; such glaciers were represented as 'open'. The orientations of CI and DC type glaciers in the compound basins can be different.

Figure 4.1: The eight cardinal directions of aspect



Mean slope

The mean slope was derived for each glacier from the DEM; it is independent of glacier length and refers to all individual cells of the DEM within the glacier boundary (cf. Manley 2008). The mean slope is a rough proxy for other parameters like mean thickness (cf. Haeberli and Hoelzle 1995) and also relates to other dynamic measures, such as surface flow speed. The glaciers on steep slopes are generally more unsTable as a result of the higher flow velocity; those with maximum slope correspond to icefalls. It is strongly recommended to include the DEM-derived mean slope value in a basic inventory (Paul et.al. 2009).

The mean slope was calculated for the CI and DC components of each glacier separately wherever both were available. The mean slope was divided into seven classes at intervals of 10°.

Mean glacier thickness

There are no measurements of glacial ice thickness for the southern flank of the Himalayas. Measurements of glacial ice thickness in the northern flank (Tianshan Mountains, China) have shown that the glacial thickness increases with area (LIGG/WECS/NEA 1988; Mool et al. 2001a,b; Shi et al. 2008). The relationship between ice thickness (H) and glacial area (F) was obtained using the empirical formula

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

This scaling formula was used to estimate the mean ice thickness of the glaciers. However, the value is a tentative figure and highly uncertain, since surface slope, annual mass balance, and many other attributes affect ice thickness.

Estimated ice reserves

The ice reserves were estimated from the mean ice thickness multiplied by the glacial area. The value is also highly uncertain as it is derived from the already highly uncertain glacier thickness. Surface slope, annual mass balance, and many other attributes affect the ice thickness and ice reserve values. The ice thickness and ice reserve were included despite the high uncertainty as they are the main component of ice mass and the only information available until such time as actual measurements can be carried out.

Six-digit morphological classification

A morphological matrix-type classification and description was also used in the study in line with the classification proposed by Müller et al. (1977) for the TTS to use in the WGI. Each glacier was coded as a six-digit number, one digit for each of six different morphological characteristics. The scheme is shown in Table 4.1; the individual numbers for each digit (horizontal row numbers) are read on the left-hand side. This scheme is a simple key used in the classification of glaciers all over the world.

The glacier classification used by the World Glacier Monitoring Service was used for the overall morphological classification (WGMS 1989). The glaciers were divided into different types using a combination of Digit 1 'primary classification' and Digit 2 'form' from the six-digit classification. Generally, six types of glacier were observed in the Hindu Kush-Himalayas – valley troughs, and five types of mountain glacier (ice caps, ice apron, cirque, niche, and basin). Ice caps were disaggregated into their components and these were then analysed individually. When the morphology was unclear, the glacier was characterised as a mountain glacier 'miscellaneous' type. The classes are often not unique and different analysts might choose a different type. In regions of rapid glacier change (e.g., with formation of pro-glacial lakes) the classification might also change in just a few years so that updating of the database is a continuous effort.

Mountain glaciers commonly have a hanging profile; the major sources of nourishment are drift snow and direct snowfall. Small mountain glaciers are generally poorly represented in glacier studies but are of considerable importance in the study of climate change impact on water resources. Mountain glaciers, often with a hanging profile, were the most common type identified in the HKH inventory in terms of number. However, the area and estimated ice thickness, and thus estimated ice reserves, were comparatively low.

Valley type glaciers have a regular longitudinal profile from crown to terminus (snout). The profile is concave, with steeper slopes in the upper levels and less steep 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 considered to be a valley glacier. Valley type glaciers are mainly nourished by snow and drift snow in the accumulation zone and snow and ice avalanches in the lower valley. A large accumulation area is normally needed for a glacier to be able to extend far into the valleys. Hence, the average area of valley glaciers is usually higher than that of mountain glaciers and although few in number, they contribute most to glacier area and ice reserves.

Basin glaciers, whether mountain or valley type, can have a clean-ice (CI) or debris-covered (DC) surface. Mountain glaciers tend to be CI type, whereas valley glaciers have a CI component mostly in the accumulation zone and DC component in the ablation zone. CI glaciers generally have steeper slopes than DC glaciers. The CI and DC components were also mapped and the glacier attributes derived separately.

Table 4.1: Classification and description of glaciers

Digit 1	Digit 2	Digit 3	Digit 4	Digit 5	Digit 6
Primary classification	Form	Frontal characteristic	Longitudinal profile	Major source of nourishment	Activity of tongue
Uncertain or miscellaneous	Uncertain or miscellaneous	Normal or miscellaneous	Uncertain or miscellaneous	Uncertain or miscellaneous	Uncertain
Continental ice sheet	Compound basins	Piedmont	Even: regular	Snow and/or drift snow	Marked retreat
Ice field	Compound basin	Expanded foot	Hanging	Avalanche and/or snow	Slight retreat
Ice cap	Simple basin	Lobed	Cascading	Superimposed ice	Stationary
Outlet glacier	Cirque	Calving	Ice fall		Slight advance
Valley glacier	Niche	Confluent	Interrupted		Marked advance
Mountain glacier	Crater				Possible surge
Glacieret and snow field	Ice apron				Known surge
Ice shelf	Group				Oscillating
Rock glacier	Remnant				

Part 2

Status of Glaciers

5 Amu Darya Basin

The Amu Darya river originates in Tajikistan and Kyrgyzstan in two headstreams, the Panj and Vakhsh rivers. The river flows west-northwest into the Aral Sea and is one of the longest rivers in Central Asia: 2,540 km measured from the remotest sources of the Panj river. The catchment area is about 645,726 km^2. The Amu Darya river forms a part of Afghanistan's border with Tajikistan, Uzbekistan, and Turkmenistan, and a part of Uzbekistan's border with Turkmenistan. The part of the Amu Darya river basin within the HKH region lies entirely within Afghanistan, covering an area of about 166,686 km^2, a quarter of the total basin area.

Data

The mapping and inventory of the glaciated areas in the sub-basins of the Amu Darya basin within the territory of Afghanistan was carried out using ETM+ images from 2005 and 2006. The topographic characteristics were derived using the SRTM DEM. The list of images used is shown in Table 5.1.

Mapping and Inventory of Glaciers

The part of the Amu Darya river basin within Afghanistan consists of three major sub-basins: the Wakhan, Kokcha, and Surkhab (Figure 5.1). The glaciers are distributed between 34.58° and 38.35° N latitude and 67.63° and 74.88° E longitude, with the highest concentration between 36.45° and 38.35° N latitude and 70.65° and 74.88° E longitude in the Wakhan sub-basin. The distribution and characteristics of the glaciers in each sub-basin are summarised in Table 5.2.

Number, area, and ice reserves

The Amu Darya basin had 3,277 glaciers (2,047 in the Wakhan sub-basin, 913 in the Kokcha sub-basin, and 317 in the Surkhab sub-basin) with a total area of 2,566 km^2 and estimated ice reserves of 163 km^3 (Table 5.2 and Figure 5.2).

The Wakhan is the third largest sub-basin in Afghanistan but the most glaciated, with 76% of the total glaciated area, the largest number of CI and DC glaciers, the largest ice reserves (82% of the total), the longest glacier, the largest glacier, and the glacier with the greatest elevation difference.

Glacier area classes

The number, area, and estimated ice reserves of glaciers in the different size classes are summarised in Table 5.3 and shown as a percentage of the total in Figure 5.3. The area per glacier in the different sub-basins ranged from 0.35 km^2 to 0.95 km^2, with an average of 0.78 km^2 overall (Table 5.2). The majority of glaciers (67%) were in the smallest class 1 ($\leq$0.5 km^2), and contributed 16% of the glacier area and 6% of the ice reserves. These small

Table 5.1: Landsat images used for the Amu Darya basin

Path-Row	Image	Date	Used for	Sub-basin
150-34	LE71500342005259PFS00	16/09/2005	correction	Wakhan
151-34	LE71510342005234PFS00	22/08/2005	correction	Wakhan
152-33	LE71520332006212ASN00	31/07/2006	analysis	Wakhan
152-34	LE71520342006212ASN00	31/07/2006	analysis	Wakhan, Kokcha, Surkhab
152-35	LE71520352006260PFS01	17/09/2006	analysis	Kokcha

Figure 5.1: Distribution of glaciers in the Amu Darya basin

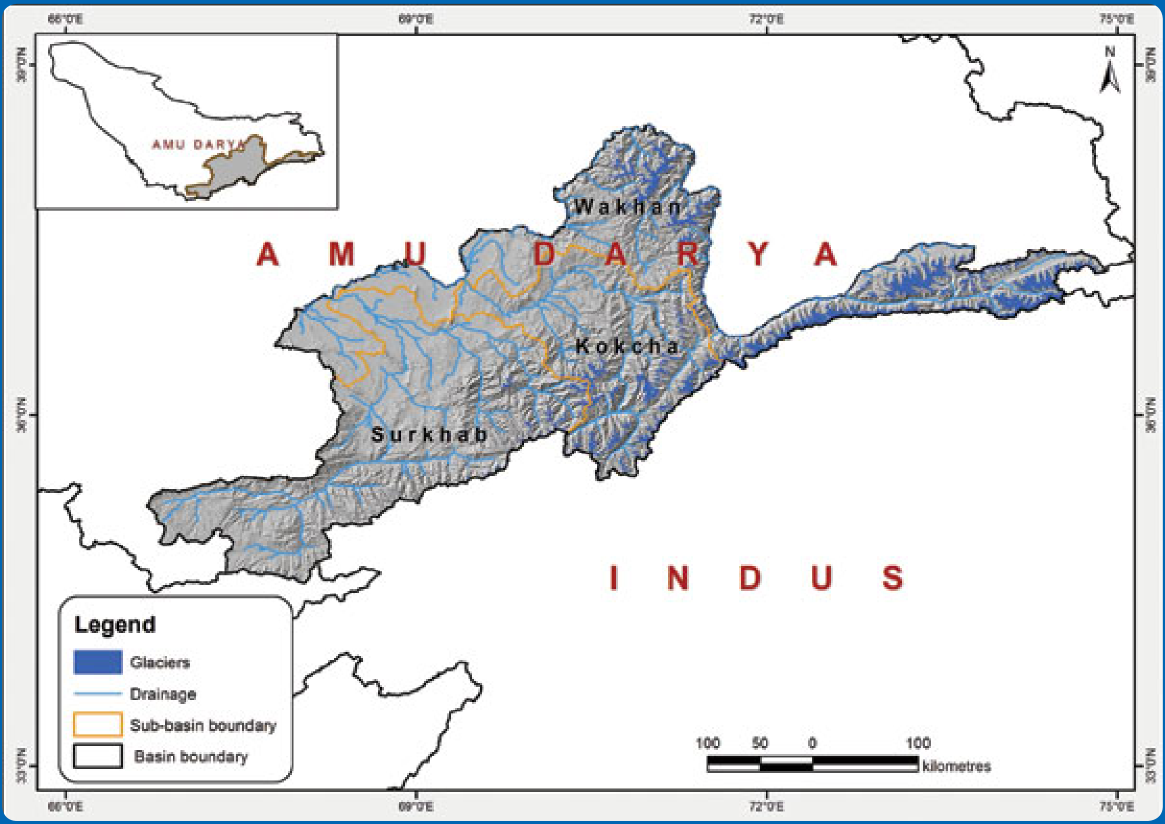


Table 5.2: Glacier characteristics in the sub-basins of the Amu Darya basin within the HKH region

Parameter	Unit	Sub-basin			Amu Darya
		Wakhan	Kokcha	Surkhab	
Basin area	km²	27,173	21,338	37,913	166,686*
Latitude	degrees	36.45-38.35	35.45-37.22	34.56-36.48	34.58-38.35
Longitude	degrees	70.65-74.88	70.11-71.63	67.63-70.49	67.63-74.88
Number of glaciers	unit	2,047	913	317	3,277
CI glacier area	km²	1,878.48	430.11	97.00	2,405.59
DC glacier area	km²	72.57	72.99	15.03	160.59
Total glacier area	km²	1,951.05	503.10	112.03	2,566.18
Largest glacier area	km²	39.72	9.36	9.82	39.72
Total ice reserves	km³	133.56	24.27	4.48	162.61
Highest elevation	masl	7,213	6,790	5639	7,213
Lowest elevation	masl	3,131	3,616	3,621	3,131
CI glacier elevation	masl	3,415-7,213	3,990-6,790	3,888-5,639	3,415-7,213
DC glacier elevation	masl	3,131-5,425	3,616-5,466	3,621-4,998	3,131-5,466
Mean CI glacier slope	degrees	24	26	24	25
Mean DC glacier slope	degrees	10	13	12	11
CI-DC area ratio	unit	25.89	5.89	6.46	14.98
Average glacier area	km²	0.95	0.55	0.35	0.78

*Area including not glaciated sub-basins

Table 5.3: Glacier area classes in the Amu Darya basin within the HKH region

Area class	Area (km²)	Number		Area		Estimated ice reserves		Mean area per glacier
		Total	%	km²	%	km³	%	km²
1	≤ 0.5	2,203	67.2	415.31	16.2	9.807	6.0	0.19
2	0.51-1.00	523	16.0	371.42	14.5	13.764	8.5	0.71
3	1.01-5.00	474	14.5	969.78	37.8	55.612	34.2	2.05
4	5.01-10.00	50	1.5	345.06	13.5	29.092	17.9	6.90
5	≥10.00	27	0.8	464.62	18.1	54.334	33.4	17.21
	Total	**3,277**	**100**	**2,566.18**	**100**	**162.609**	**100**	**0.78**

glaciers are very sensitive to changes in climate. Glaciers in class 3 (1.0 to 5.0 km²) were third highest in number but had the greatest area (38% of the total) and estimated ice reserves (34% of the total). The large glaciers in class 5 (≥10.0 km²) had an average area of 17.21 km² and contributed about 18% of the glacier area and 33% of the ice reserves.

The largest glacier was GLIMS ID G072586E36890N (Awagr10_1022), located in the Wakhan sub-basin (36.89° N latitude and 72.59° E longitude). It had an area of 39.72 km² and estimated ice reserves of 5.93 km³, and extended from 6,293 masl to 3,131 masl, the lowest terminus in Afghanistan. The highest elevation glacier was GLIMS ID G071765E36445N (Awagr10_1198), with a crown at 7,213 masl, glacier area of 17.40 km², and estimated ice reserves of 1.98 km³.

Glacier elevation

The elevation of Afghanistan's land area ranges from 7,485 masl at the peak of Noshak mountain to 258 masl in the Amu Darya river valley. The highest glacier elevation was 7,213 masl and the lowest 3,131 masl, both in the Wakhan sub-basin. The extended elevation range in the Wakhan sub-basin reflects the presence of valley type glaciers. CI glaciers were found from 7,213 to 3,415 masl and DC glaciers from 5,466 to 3,131 masl (Figure 5.4). The lower extension of DC glaciers indicates the presence of basin type glaciers.

Figure 5.2: Glacier number, area, and estimated ice reserves in the sub-basins of the Amu Darya basin

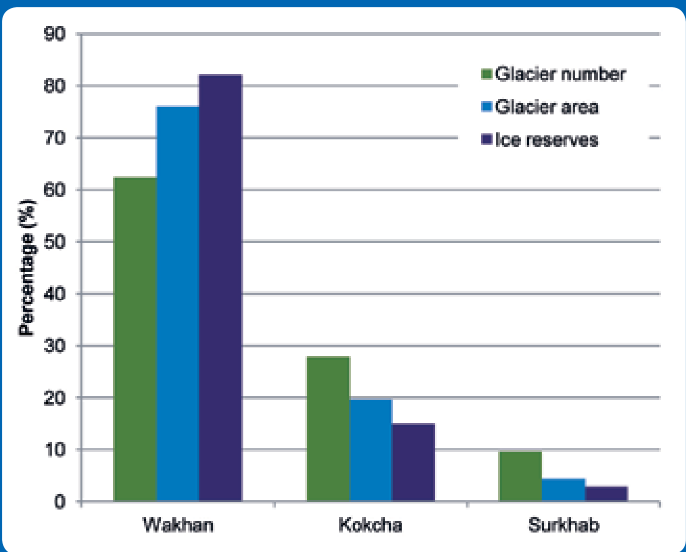
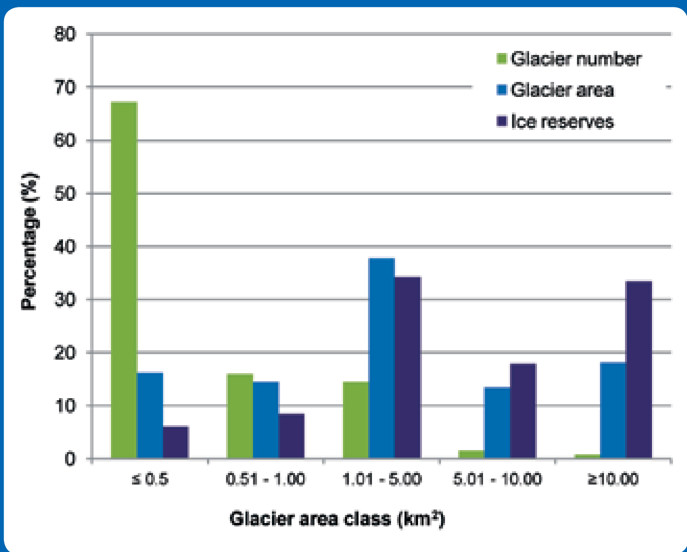


Figure 5.3: Percentage of glacier number, area, and estimated ice reserves in the different glacier size classes in the Amu Darya basin



Glacier aspect

The glaciers in the Amu Darya basin are mostly concentrated in the northeastern part of the country in the Wakhan corridor, which is a NE-SW elongated valley. Many of the other glaciers in Afghanistan are similarly situated in tectonic valleys, and this has a strong influence on glacier aspect.

Figure 5.5 shows the percentage of glaciers with different aspects and mean slope. Close to 21% of the glaciers had an east aspect, about 16% a southeast aspect, around 13 to 14% a northeast, south, southwest, or west aspect, 8% a northwest aspect, and only a very few glaciers (all within the Kokcha and Surkhab sub-basins) a north aspect.

Slope

The mean slope of the glaciers in the basin ranged from 10° to 50°, with slopes of 20° to 30° most common and 40° to 50° least common in all cardinal directions. A negligible number had mean slopes less than 10° or above 50° (Figure 5.5).

The mean slope of the CI glaciers ranged from 24° to 26°, and of DC glaciers from 10° to 13° with slight basin-to-basin variations (Figure 5.6). These ranges are fairly typical for the HKH region.

Morphological glacier type

The morphological classification of glaciers in the Amu Darya basin is summarised in Table 5.4; the comparative distribution by number, area, and estimated ice reserves is shown graphically in Figure 5.7.

Just over 94% of the glaciers were identified as mountain type, the vast majority of them mountain basin type. Mountain glaciers had average areas ranging from 0.08 to 0.55 km², covered 57% of the total glacier area, and contained 38% of the total ice reserves.

The valley glaciers in the Amu Darya basin have both compound basins and simple basins. The ice reserves of the valley glaciers are generally large because ice thickness increases with glacial area. The valley glaciers comprised less than 6% of the total by number, but with an average area of 5.79 km², contributed almost 43% of the total glacier area and 62% of the total ice reserves (Table 5.4, Figure 5.7).

Figure 5.4: Elevation of CI and DC glaciers in the sub-basins of the Amu Darya basin

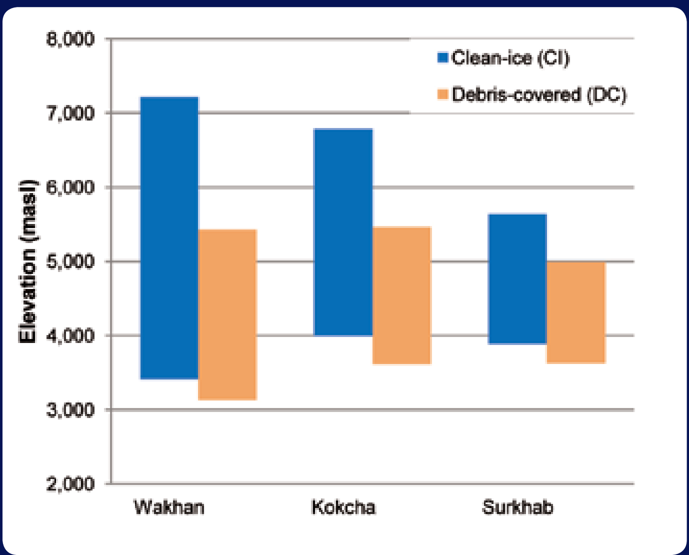


Figure 5.5: Aspect and mean slope of glaciers in the Amu Darya basin

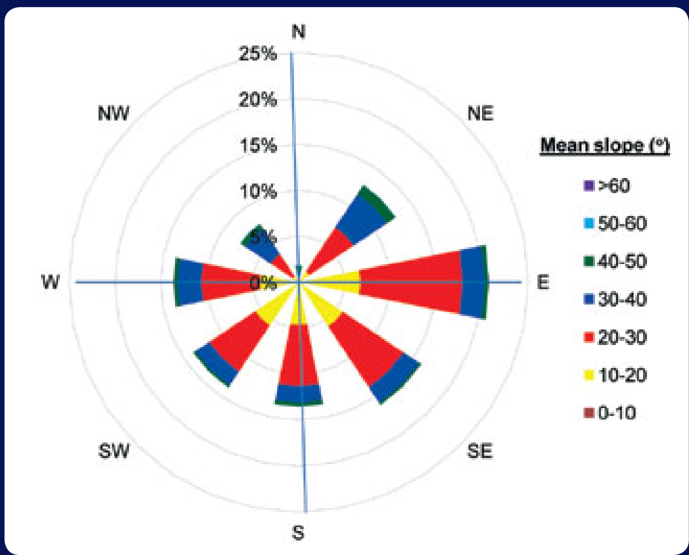


Table 5.4: Morphological classification of glaciers in the Amu Darya basin

Glacier type		Number		Area		Estimated ice reserves		Mean area per glacier
		Total	%	km²	%	km³	%	km²
Mountain	Miscellaneous	0	0.0	0.00	0.0	0.000	0.0	0.00
	Ice apron	500	15.3	67.20	2.6	1.512	0.9	0.13
	Cirque	18	0.6	1.81	0.1	0.033	0.02	0.10
	Niche	48	1.56	3.70	0.1	0.061	0.04	0.08
	Basin	2,521	76.9	1,393.32	54.3	59.741	36.7	0.55
Valley	Trough	190	5.8	1,100.14	42.9	101.262	62.3	5.79
	Total	**3,277**	**100**	**2,566.18**	**100.0**	**162.609**	**100**	**0.78**

Figure 5.6: Mean slope of CI and DC glaciers in the sub-basins of the Amu Darya basin

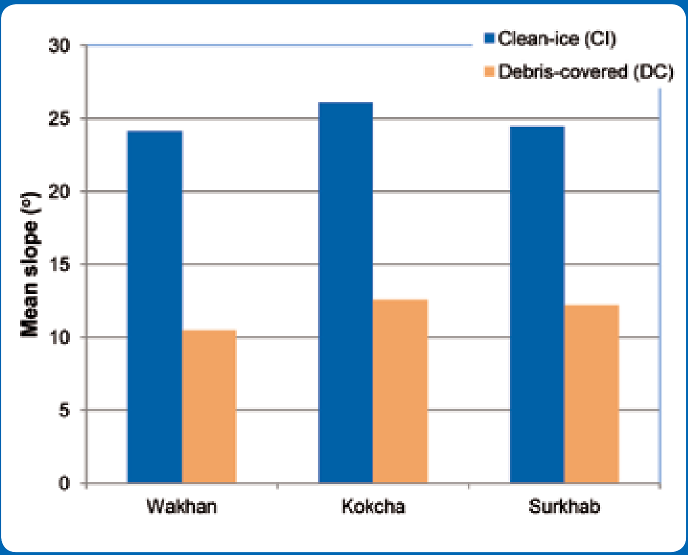


Figure 5.7: Comparative distribution of different glacier types in the Amu Darya basin by number, area, and estimated ice reserves

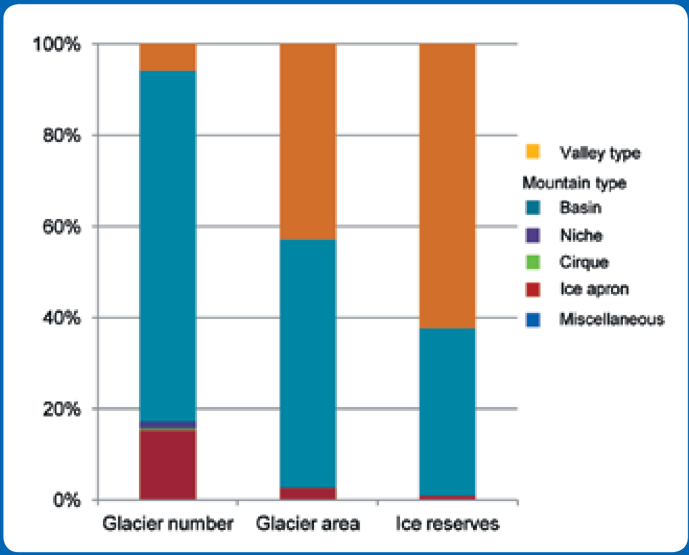


Figure 5.8: Percentage distribution by area of CI and DC glaciers in the sub-basins of the Amu Darya basin

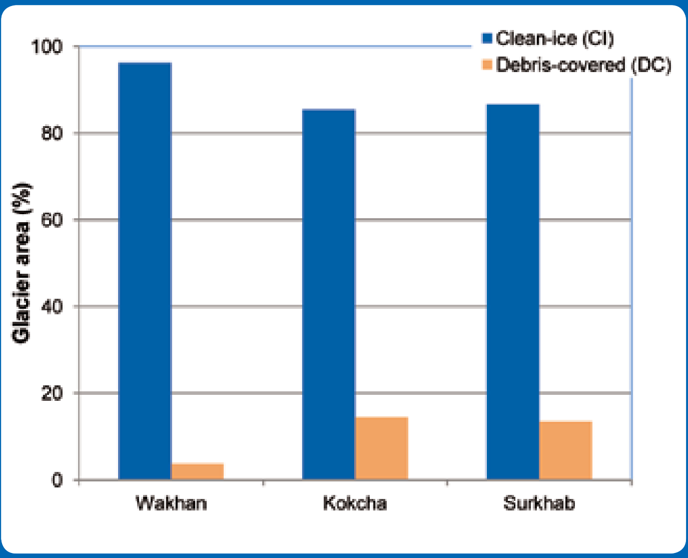
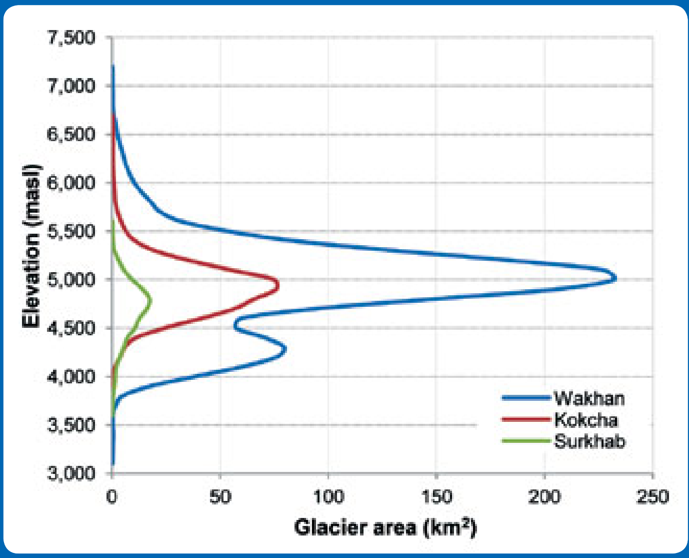


Figure 5.9: Area-altitude distribution of glaciers in the sub-basins of the Amu Darya basin within the HKH region



Clean-ice and debris-covered glaciers

Only 282 (9%) of the 3,277 glaciers in the basin had both CI and DC components. In total, 160 km^2 or 6% of the total glacier area was debris covered. The lowest DC area was found in the Wakhan basin and the highest in the Surkhab basin (Figure 5.8).

Hypsography

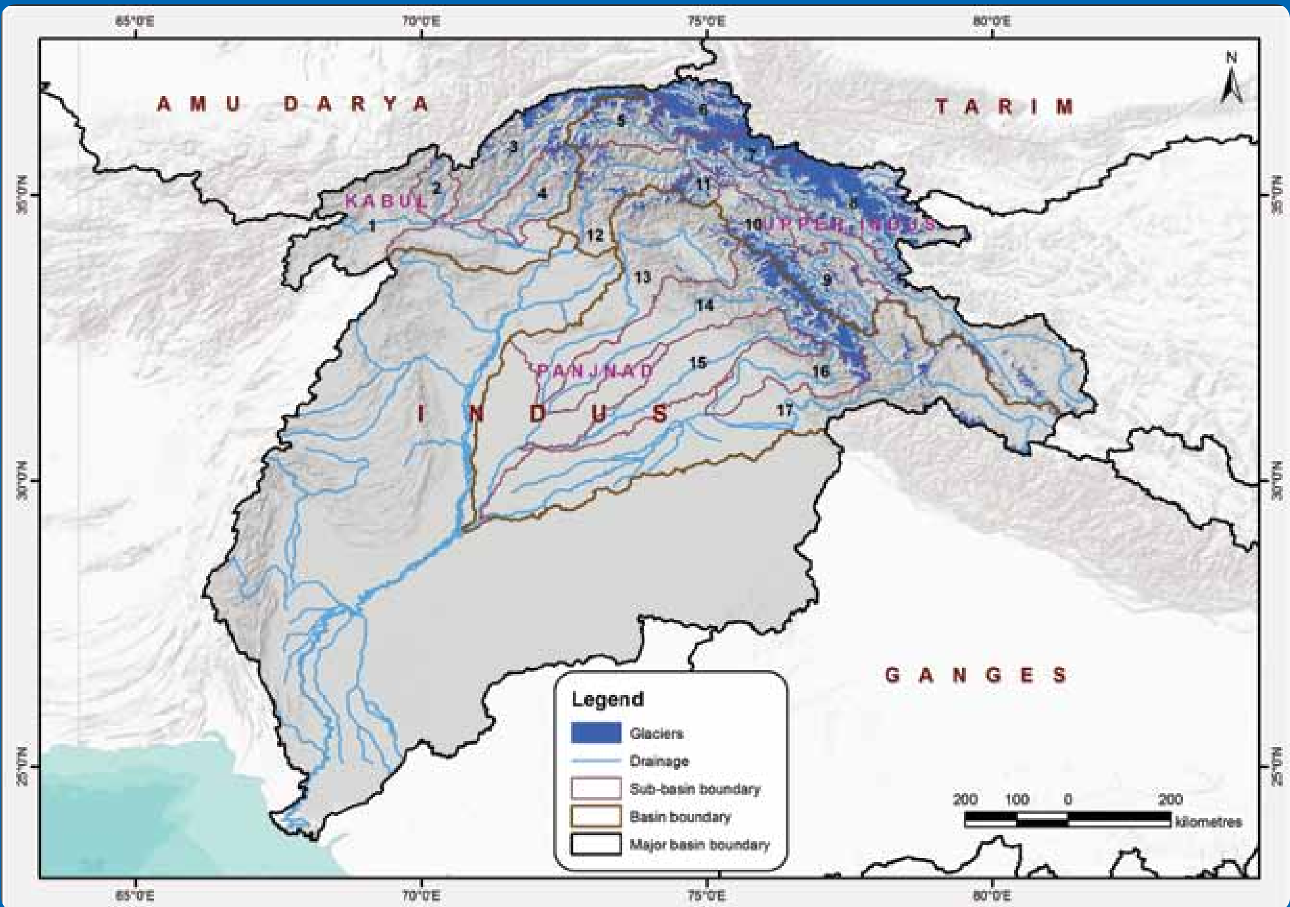
The glacier area-altitude distribution in the three sub-basins is shown in Figure 5.9. The maximum glaciated areas were 232.22 km^2 at 5,000-5,100 masl in the Wakhan sub-basin, 75.81 km^2 at 4,900-5,000 masl in the Kokcha sub-basin, and 17.41 km^2 at 4,800-4,900 masl in the Surkhab sub-basin. The Wakhan sub-basin had the highest elevation band (7,200 masl) followed by the Kokcha sub-basin (6,700 masl). The Wakhan sub-basin showed a distinctive bimodal area-altitude distribution.

6 Indus Basin

The Indus river (the 'Father River') is one of the major rivers flowing through the Indian subcontinent. The river originates from the Tibetan plateau in the vicinity of Lake Mansarovar in the Tibet Autonomous Region of China and flows first to the northwest, turns southwest at Gilgit in Pakistan, and then flows south and southwest through the country (Figure 6.1). The river has a total basin area of 1,116,086 km², of which 555,450 km² lies within the HKH region. The river has an estimated annual flow of around 207 km³, the twenty-first highest in the world.

The Indus river is the main source of water in Pakistan. For the purposes of the present study, the upper reaches of the major Indus river basin were divided into three basins – the Kabul, Upper Indus, and Panjnad (Figure 6.1). The Kabul basin includes the Panjsher-Ghorband, Alingar-Alishing-Nuristan, Kunar, and Swat sub-basins; the Upper Indus basin includes the Gilgit, Hunza, Shigar, Shyok, Zanskar, Shingo, Astor, and Upper Indus sub-basins; and the Panjnad basin includes the Jhelum, Chenab, Ravi, Beas, and Sutlej sub-basins.

Figure 6.1: The Indus river system showing the basins and sub-basins in the upper reaches and distribution of glaciers



Kabul basin	Upper Indus basin*		Panjnad basin*
1. Panjsher-Ghorband	5. Gilgit	9. Zanskar	13. Jhelum
2. Alingar-Alishing-Nuristan	6. Hunza	10. Shingo	14. Chenab
3. Kunar	7. Shigar	11. Astor	15. Ravi
4. Swat	8. Shyok*	12. Upper Indus*	16. Beas
			17. Sutlej*

*drainage catchment partly in China

Data

The mapping and inventory of the glaciated areas in the Indus basin was carried out using ETM+ images from 2004 to 2009 (and some earlier images for correction). The list of images is shown in Table 6.1. The topographic characteristics were derived using the SRTM DEM. The list of images used is shown in Table 6.1

Mapping and Inventory of Glaciers

The glaciers in the Indus basin were distributed between 30.45° and 37.08° N latitude and 69.36° and 81.65° E longitude (Figure 6.1). The distribution and characteristics of the glaciers in each sub-basin are summarised in Table 6.2. The basin had a total of 18,495 glaciers with an area of 21,192 km² and estimated ice reserves of 2,696 km³. The elevation ranged from 8,566 masl to 2,409 masl, the lowest elevation of all the glaciers in the HKH region. This basin also contains the largest glacier in the HKH region: the Siachen glacier, which covers about 926 km².

Table 6.1: Landsat images used for the Indus basin

Path-Row	Image	Date	Used for	Sub-basin
153-36	LE71530362006267PFS00	24/09/2006	analysis	Panjsher-Ghorband
	LE71530362009275SGS00	02/10/2009	correction	
	LE71530362001237SGS00	25/08/2001	correction	
152-35	LE71520352006260PFS01	17/09/2006	analysis	Kunar, Alingar-Alishing-Nuristan
151-35	LE71510352006189ASN00	08/07/2006	analysis	Gilgit, Swat, Kunar
	LE71500352007256PFS01	13/09/2007	analysis	
	LE71510352007192ASN00	25/08/2007	analysis	
151-34	LE71510342005234PFS00	22/08/2005	analysis	Kunar
	LE71510342008259SGS00	15/09/2008	analysis	
150-36	LE71500362005259PFS00	16/09/2005	analysis	Upper Indus, Jhelum
150-35	LE71500362005259PFS00	16/09/2005	analysis	Jhelum, Gilgit, Hunza, Upper Indus, Kunar
150-34	LE71500342005259PFS00	16/09/2005	analysis	Gilgit, Hunza, Kunar
149- 37	L71149037_03720041024	10/24/2004	analysis	Jhelum, Chenab
	LE71490372002324SGS00	11/20/2001	correction	
	LE71490372008277PFS00	10/3/2008	analysis	
	LE71490372009263SGS00	9/20/2009	analysis	
149-36	L71149036_03620071102	11/2/2007	analysis	Shingo, Upper Indus, Chenab, Jhelum, Upper Indus
	LE71490362002276SGS00	10/3/2002	correction	
	LE71490362009263SGS00	9/20/2009	analysis	
149-35	LE71490352006207PFS00	26/07/2006	correction	Gilgit, Hunza, Shigar, Upper Indus
	LE71490352007258PFS00	15/09/2007	analysis	
149-34	LE71490342006207PFS00	26/07/2006	analysis	Shyok
148-37	L71148037_03720051020	10/20/2005	correction	Zanskar, Upper Indus, Chenab
	LE71480372007331SGS00	11/27/2007	analysis	
	LE71480372008206SGS00	7/24/2008	analysis	
	LE71480372008238SGS00	8/25/2008	analysis	
	LE71480372009272SGS00	9/29/2009	analysis	
148-36	L71148036_03620050902	9/2/2005	analysis	Shyok, Zanskar, Shingo, Upper Indus
	LE71480362006280PFS00	10/7/2006	analysis	
	LE71480362007331SGS00	11/27/2007	analysis	
148-35	LE71480352002221SGS00	8/9/2002	correction	Shyok, Upper Indus, Shigar
	LE71480352006312PFS00	11/8/2006	analysis	
	LE71480352009224SGS00	8/12/2009	analysis	

Table 6.1 continued

147-38	LE71470382004252PFS01	9/8/2004	analysis	Sutlej, Ravi, Beas,
	L71147038_03820051029	10/29/2005	correction	
	LE71470382006273PFS00	9/30/2006	analysis	
	LE71470382007324PFS00	11/20/2007	analysis	
	LE71470382008183PFS00	7/1/2008	analysis	
	LE71470382008247ASN00	9/3/2008	analysis	
	LE71470382009297SGS00	10/24/2009	analysis	
147-37	L71147037_03720060930	9/30/2006	analysis	Zanskar, Upper Indus, Chenab
	LE71470372006273PFS00	9/30/2006	analysis	
	LE71470372007228PFS00	8/16/2007	analysis	
147-36	L71147036_03620060930	9/30/2006	analysis	Shyok, Upper Indus
	LE71470362007228PFS00	8/16/2007	analysis	
	LE71470362008215ASN00	8/2/2008	analysis	
	LE71470362009265ASN00	9/22/2009	correction	
147-35	L71147035_03520050826	8/26/2005	analysis	Shyok
	LE71470351999190SGS00	7/9/1999	correction	
	LE71470352009265ASN00	9/22/2009	analysis	
146-38	L71146038_03820060923	9/23/2006	analysis	Sutlej
	LE71460382000282SGS00	1/8/2000	correction	
	LE71460382006282ASN00	10/9/2006	analysis	
	LE71460382008240SGS00	8/27/2008	analysis	
	LE71460382001252SGS00	9/9/2001	correction	
146-37	L71146037_03720060923	9/23/2006	correction	Sutlej
	LE71460372007365ASN00	12/31/2007	analysis	
	LE71460372008240SGS00	8/27/2008	analysis	
	LE71460372008256ASN00	9/12/2008	analysis	
	LE71460372009178ASN00	6/27/2009	analysis	
146-36	L71146036_03620050904	9/4/2005	correction	Shyok
	LE71460362009226ASN00	8/14/2009	analysis	
	LE71460362009274ASN00	10/1/2009	analysis	

Kabul basin

The Kabul river is a major tributary of the Indus. It originates in Pakistan, traverses Afghanistan, and later merges with the Indus at Attock in Pakistan. It has four glaciated sub-basins: the Panjsher-Ghorband, Alingar-Alishing-Nuristan, Kunar, and Swat (Figure 6.2). The glaciers in the Kabul basin lie between 35.20° and 36.91° N latitude and 69.36° and 73.82° E longitude. The distribution and characteristics of the glaciers in each sub-basin are summarised in Table 6.3. The Kunar sub-basin has both the highest number and the largest glaciers.

Number, area, and ice reserves – Altogether 1,601 glaciers were mapped in the Kabul basin (Table 6.2) with a total area of 1,722 km^2 and estimated ice reserves of 183 km^3 (Table 6.3). The Kunar sub-basin had the highest number and largest area of glaciers and the greatest estimated ice reserves (Figure 6.3). It also had the largest individual glacier in the Kabul basin, the compound basin type glacier GLIMS ID G073722E36798N (Kkugr10_322) with an area of 189.47 km^2 extending from 6,077 to 3,715 masl.

Glacier area classes – The number, area and estimated ice reserves of glaciers in the different size classes is summarised in Table 6.4 and shown as a percentage of the total in Figure 6.4. The mean area per glacier was 1.08 km^2.The great majority of the glaciers (1,178) were in the smallest class, with only 28 and 26, respectively, in the largest two classes. The largest class 5 had 1.6% of the glacier number but contributed about 48% of the glacier area, and 74% of the estimated ice reserves.

Table 6.2: Glacier characteristics in the major Indus basin within the HKH region

Parameter	Unit	Basin			Indus
		Kabul	Upper Indus*	Panjnad*	
Basin area	km^2	94,291	173,213	133,552	555,450**
Latitude	degrees	35.20-36.91	31.10-37.08	30.45-35.10	30.45-37.08
Longitude	degrees	69.36-73.82	72.53-81.65	73.42-81.22	69.36-81.65
Number of glaciers	unit	1,601	11,413	5,481	18,495
CI glacier area	km^2	1,561.73	13,459.11	3,610.19	18,631.04
DC glacier area	km^2	159.96	1,399.40	410.22	1,969.58
Total glacier area	km^2	1,721.69	15,061.74	4,409.24	21,192.67
Largest glacier area	km^2	189.47	925.93	109.33	925.93
Total ice reserves	km^3	182.67	2,173.52	339.86	2,696.05
Highest elevation	masl	7,578	8,566	7,103	8,566
Lowest elevation	masl	3,114	2,409	3,001	2,409
CI glacier elevation	masl	3,335-7,578	2,723-8,566	3,001-7,103	2,723-8,566
DC glacier elevation	masl	3,114-5,447	2,409-5,666	3,115-5,913	2,409-5,913
Mean CI glacier slope	degrees	25	25	27	25
Mean DC glacier slope	degrees	9	10	11	10
CI-DE area ratio	unit	9.76	9.62	8.80	9.46
Average glacier area	km^2	1.08	1.32	0.80	1.15

*Extends into China (area in China contains 1,274 glaciers with an area of 592 km^2; CI/DC differentiation refers to the remaining 17,221 glaciers with an area of 20,600 km^2); ** includes area of non-glaciated sub-basins

Figure 6.2: Distribution of glaciers in the Kabul basin

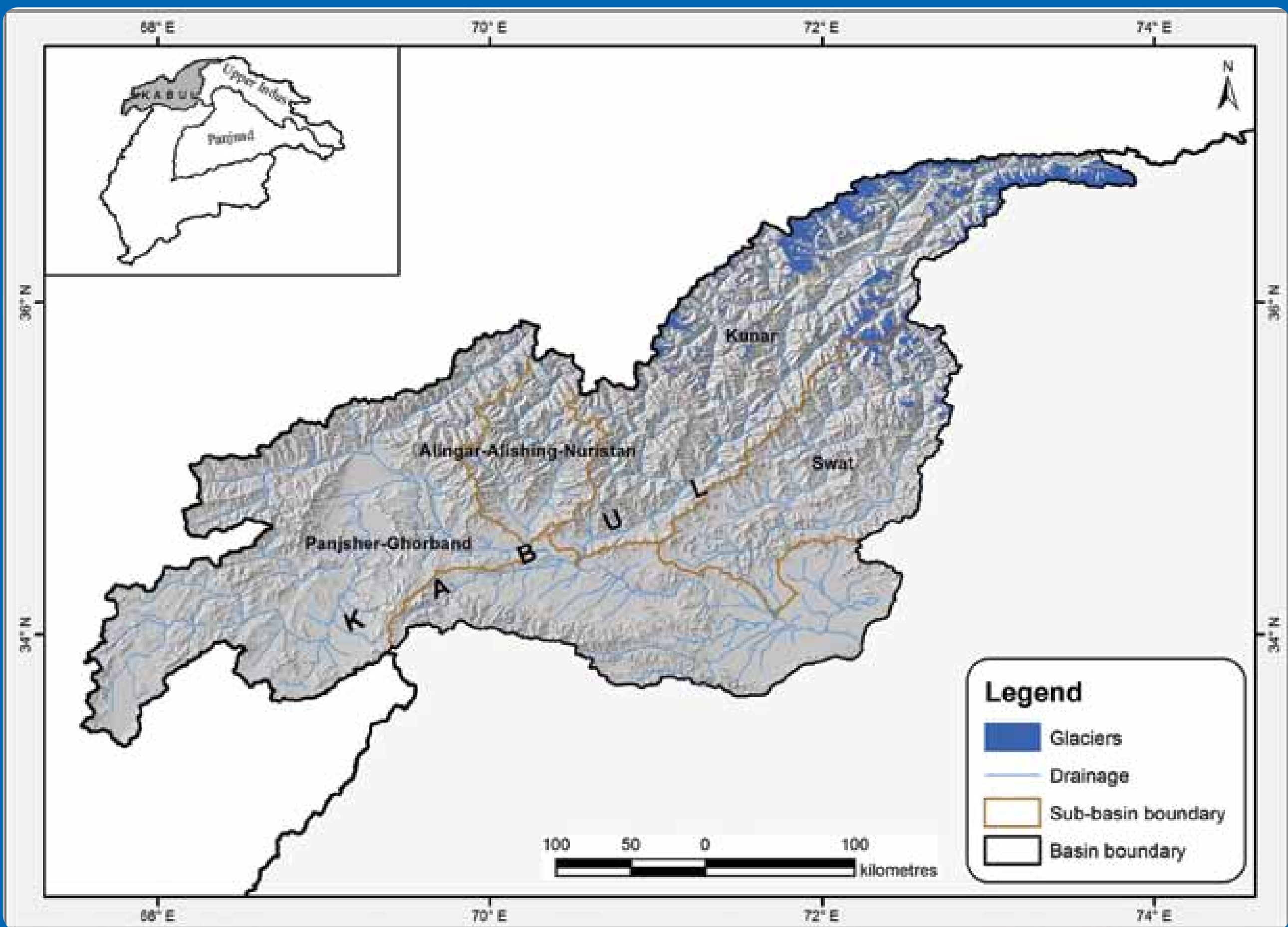


Table 6.3: Glacier characteristics in the Kabul basin within the HKH region

Parameter	Unit	Sub-basin				Kabul
		Panjsher-Ghorband	Alingar-Alishing-Nuristan	Kunar	Swat	
Basin area	km²	29,823	6,217	25,925	14,728	94,291*
Latitude	degrees	35.29-35.86	35.28-35.71	35.44-36.91	35.20-35.88	35.20-36.91
Longitude	degrees	69.36-70.29	69.92-70.54	70.55-73.82	72.05-72.79	69.36-73.82
Number of glaciers	unit	88	37	1,149	327	1,601
CI glacier area	km²	12.11	4.67	1,419.95	125.00	1,561.73
DC glacier area	km²	2.52	1.15	153.93	2.35	159.96
Total glacier area	km²	14.63	5.82	1,573.89	127.35	1,721.69
Largest glacier area	km²	2.50	1.45	189.47	4.87	189.47
Total ice reserves	km³	0.44	0.16	176.77	5.30	182.67
Highest elevation	masl	5,242	5,284	7,578	5,580	7,578
Lowest elevation	masl	3,857	4,162	3,114	3,772	3,114
CI glacier elevation	masl	3,857-5,242	4,162-5,284	3,335-7,578	3,772-5,580	3,335-7,578
DC glacier elevation	masl	4,224-4,788	4,363-4,658	3,114-5,447	3,872-4,408	3,114-5,447
Mean CI glacier slope	degrees	24	27	25	22	25
Mean DC glacier slope	degrees	9	9	11	9	9
CI-DE area ratio	unit	4.81	4.05	9.22	53.19	9.76
Average glacier area	km²	0.17	0.16	1.37	0.39	1.08

* Includes area of non-glaciated sub-basins

Table 6.4: Glacier area classes in the Kabul basin

Area class	Area (km²)	Number		Area		Estimated ice reserves		Mean area per glacier
		Total	%	km²	%	km³	%	km²
1	≤ 0.5	1,178	73.6	204.31	11.9	4.691	2.6	0.17
2	0.51-1.00	183	11.4	126.34	7.3	4.633	2.5	0.69
3	1.01-5.00	186	11.6	376.82	21.9	21.542	11.8	2.03
4	5.01-10.00	28	1.8	195.99	11.4	16.666	9.1	7.00
5	≥10.00	26	1.6	818.23	47.5	135.135	74.0	31.47
	Total	**1,601**	**100**	**1,721.69**	**100**	**182.667**	**100**	**1.08**

Glacier elevation – The highest glacier elevation was 7,578 masl and the lowest 3,114 masl (Figure 6.5 and Table 6.3), both in the Kunar sub-basin. CI glaciers were found from 7,578 to 3,335 masl and DC glaciers from 5,447 to 3,114 masl.

Glacier aspect – Figure 6.6 shows the percentage of glaciers in the Kabul basin with different aspects and mean slope. Almost 20% of the glaciers had an east aspect and a similar number a west aspect; around 15% of the glaciers had a southeast, south, or southwest aspect. Only 7 to 9% of glaciers had a northeast or northwest aspect, and less than 0.5% a north aspect.

Slope – The mean slope of the glaciers in the basin ranged from 10° to 50°, with slopes of 20° to 30° most common and 40° to 50° least common in all cardinal directions (Figure 6.6).

The mean slope of the CI glaciers ranged from 22° to 27° with an average of 25°; and those of the DC glaciers from 9° to 11° with an average of 9° (Figure 6.7 and Table 6.3).

Figure 6.3: Glacier number, area, and estimated ice reserves in the sub-basins of the Kabul basin

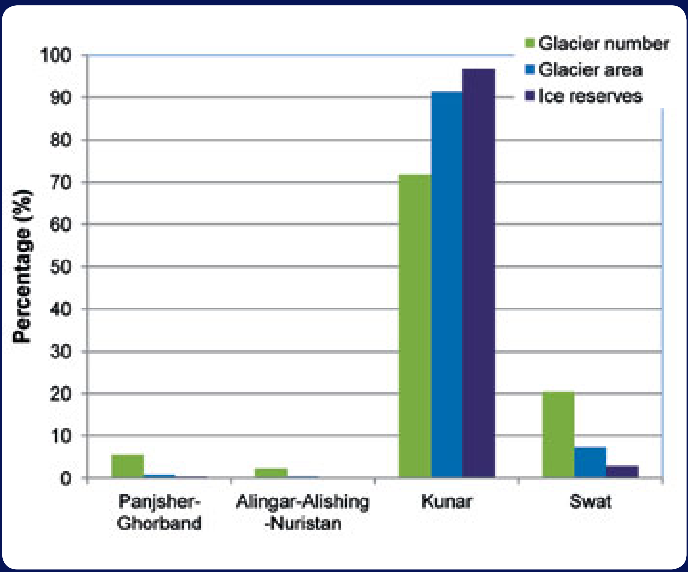


Figure 6.4: Percentage of glacier number, area, and estimated ice reserves in the different glacier size classes in the Kabul basin

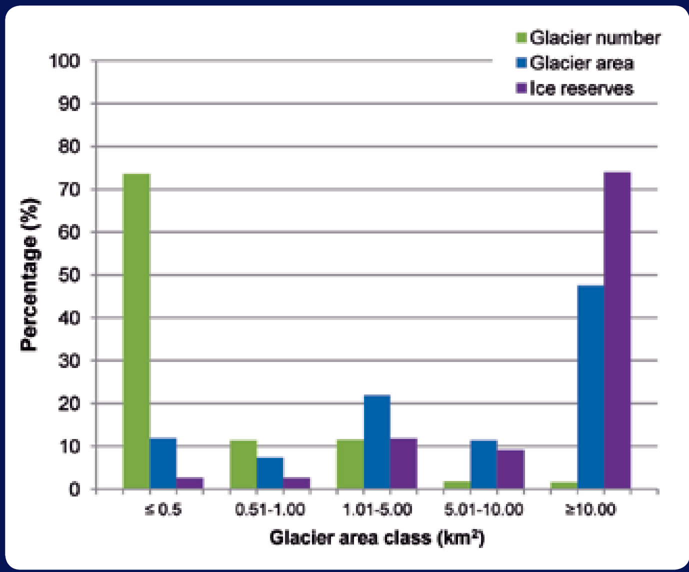


Figure 6.5: Elevation of CI and DC glaciers in the sub-basins of the Kabul basin

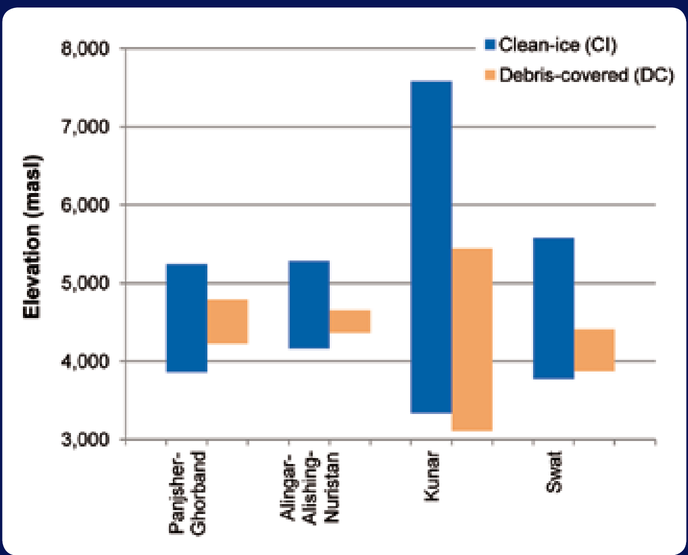
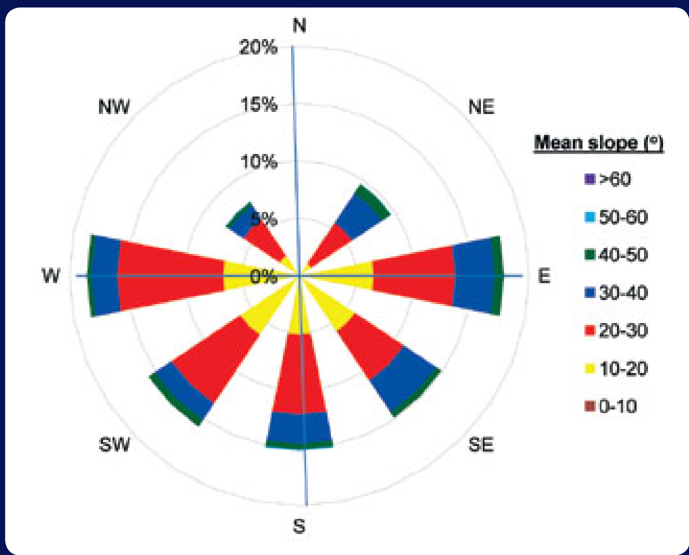


Figure 6.6: Aspect and mean slope of glaciers in the Kabul basin



Morphological glacier type – The morphological classification of glaciers in the Kabul basin is summarised in Table 6.5; the comparative distribution by number, area, and estimated ice reserves is shown graphically in Figure 6.8.

About 90% of the glaciers were identified as mountain type (ice apron, cirque, niche, and basin), the majority of them mountain basin type (61% of the total); 10% of the glaciers were valley type (Figure 6.8, Table 6.5). The mountain basin type glaciers had an average area of 0.44 km^2, covered 25% of the total glacier area, and contained 9% of the total ice reserves. The valley trough type glaciers had an average area of 7.24 km^2; covered 71% of the total glacier area, and contained 89% of the total ice reserves.

Table 6.5: Morphological classification of glaciers in the Kabul basin

Glacier type		Number		Area		Estimated ice reserves		Mean area per glacier
		Total	%	km²	%	km³	%	km²
Mountain	Miscellaneous	0	0.0	0.00	0.0	0.000	0.0	0.00
	Ice apron	288	18.0	62.33	3.6	2.049	1.1	0.22
	Cirque	36	2.3	6.76	0.4	0.171	0.1	0.19
	Niche	135	8.4	7.23	0.4	0.084	0.1	0.05
	Basin	974	60.8	428.86	24.9	17.112	9.4	0.44
Valley	Trough	168	10.5	1,216.51	70.7	163.251	89.4	7.24
	Total	**1,601**	**100**	**1,721.69**	**100**	**182.667**	**100**	**1.08**

Figure 6.7: Mean slope of CI and DC glaciers in the sub-basins of the Kabul basin

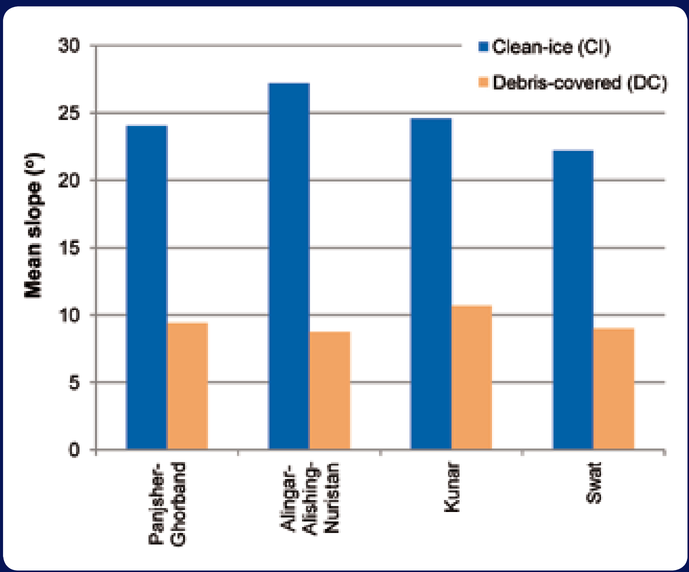


Figure 6.8: Comparative distribution of different glacier types in the Kabul basin by number, area, and estimated ice reserves

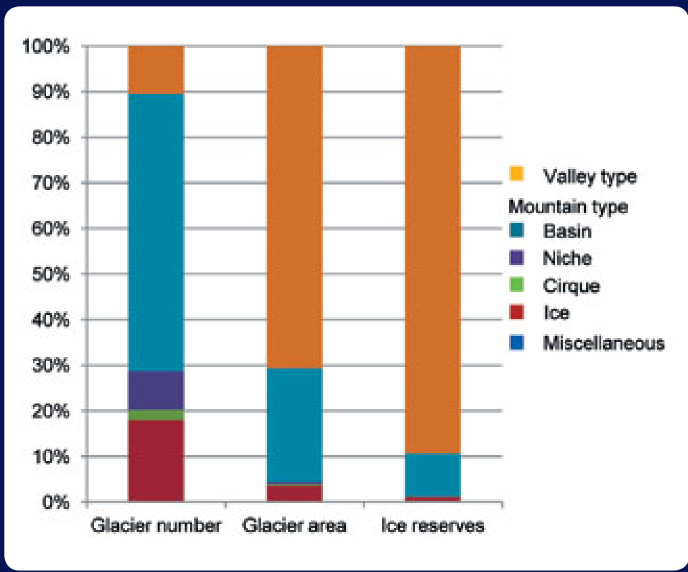


Figure 6.9: Percentage distribution by area of CI and DC glaciers in the sub-basins of the Kabul basin

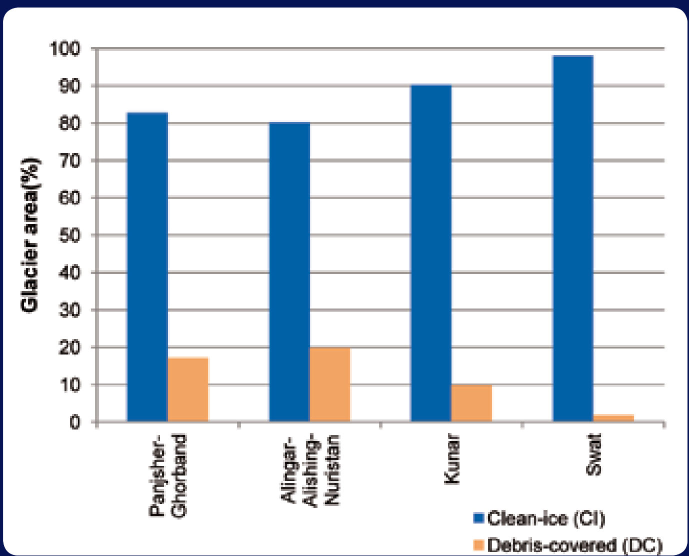
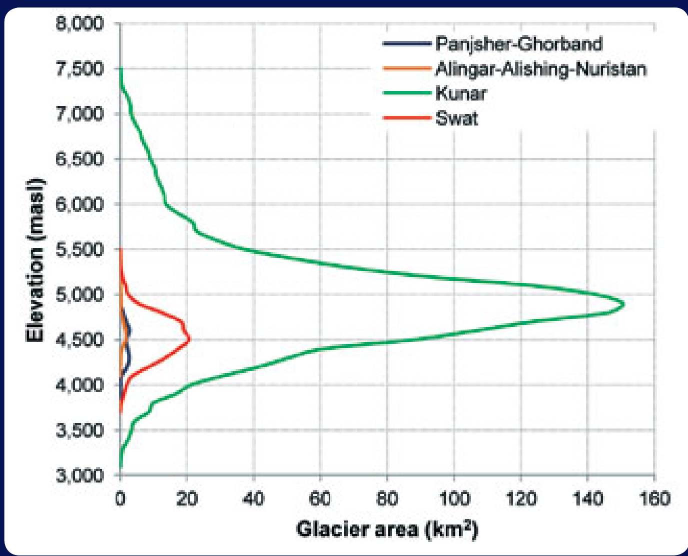


Figure 6.10: Area-altitude distribution of glaciers in the sub-basins of the Kabul basin



Clean-ice and debris-covered glaciers – Figure 6.9 shows the percentage distribution of CI and DC glacier area in the Kabul sub-basins. About 9% of the total glacier area was debris-covered (Table 6.3), with the highest proportion being 20% in the Alingar-Alishing Nuristan sub-basin.

Hypsography – The glacier area-altitude distribution in the four sub-basins is shown in Figure 6.10. The maximum glaciated areas were 150.66 km² at 4,900-5,000 masl in the Kunar sub-basin, 20.59 km² at 4,500-4,600 masl in the Swat sub-basin, 2.73 km² at 4,600-4,700 masl in the Panjsher-Ghorband sub-basin, and 1.70 km² at 4,500-4,600 masl in the Alingar-Alishing Nuristan sub-basin. The Kunar sub-basin had the highest elevation band (7,500 masl) followed by the Swat sub-basin (5,500 masl) (Figure 6.10).

Upper Indus basin

The Upper Indus basin intersects three countries: Pakistan, India, and China. Most of the glaciers are found in two large northwesterly trending ranges each side of the basin (Figure 6.11). The distribution and characteristics of the glaciers in each sub-basin are summarised in Table 6.6. A part of the basin lies in China. Descriptions of the typology, morphological classification, and hypsography of the 704 glaciers with an area of 203 km² in this part of the basin are not yet available and not included in the description here.

Number, area, and ice reserves – The Upper Indus basin had 11,413 glaciers with a total area of 15,061 km² and 2,174 km³ of estimated ice reserves.

The number, area and estimated ice reserves of glaciers in the Upper Indus sub-basins are shown in Figure 6.12. The Shyok sub-basin had the most glaciers and largest ice reserves, and the Astor sub-basin the least. The glacier

Figure 6.11: Distribution of glaciers in the Upper Indus basin

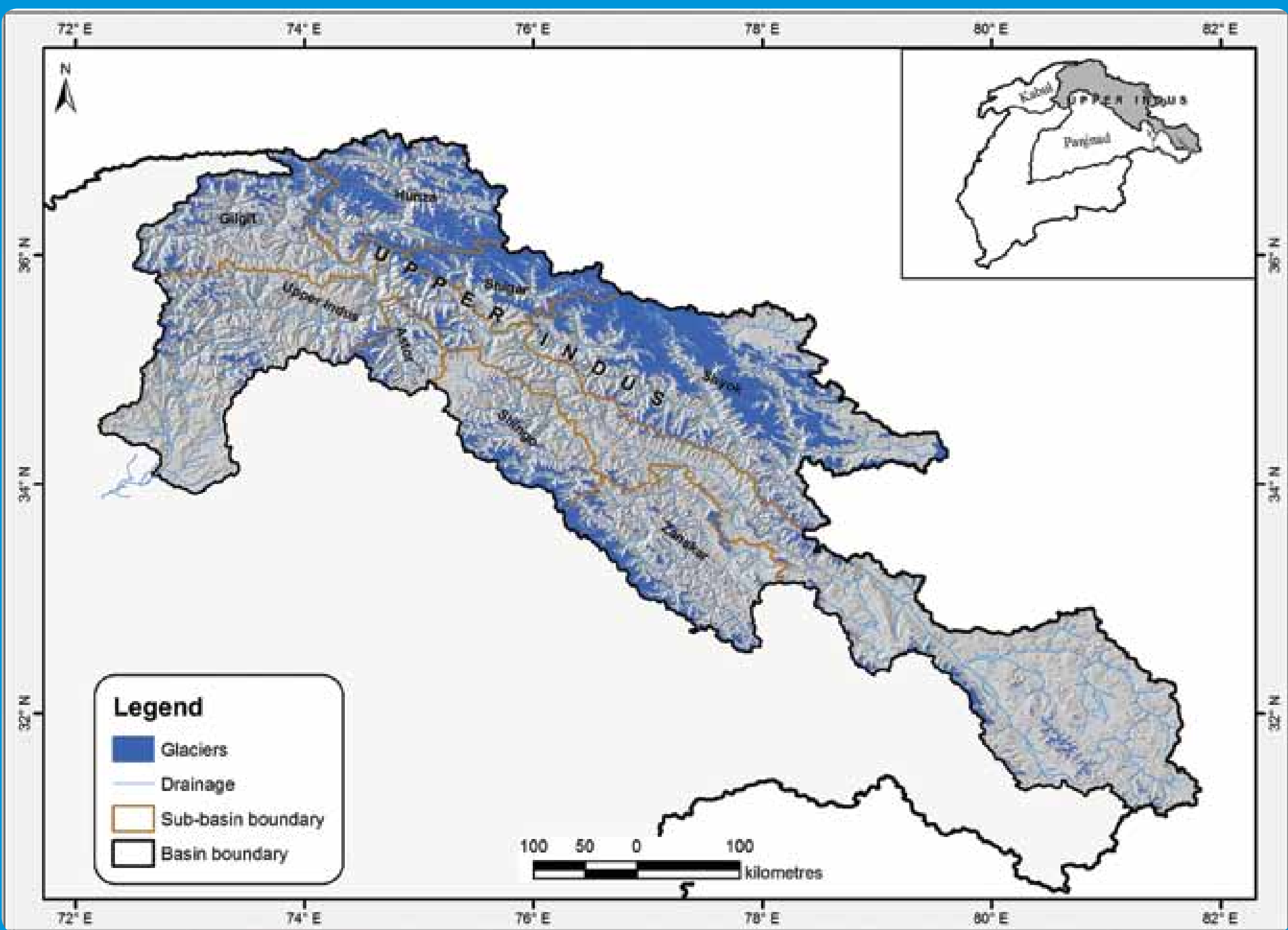


Table 6.6: Glacier characteristics in the sub-basins of the Upper Indus basin within the HKH region

Parameter	Unit	Sub-basin								Upper Indus
		Gilgit	Hunza	Shigar	Shyok*	Zanskar	Shingo	Astor	Upper Indus*	
Basin area	km^2	13,540	13,734	7,046	33,429	15,856	10,502	3,988	75,117	173,213
Latitude	degrees	35.80-36.91	36.05-37.08	35.41-36.07	33.60-35.68	32.54-34.12	33.80-35.17	34.80-35.64	31.10-36.04	31.10-37.08
Longitude	degrees	72.53-74.70	74.04-75.77	74.94-76.69	75.96-79.59	76.26-78.21	75.27-76.67	74.46-75.24	72.71-81.65	72.53-81.65
Number of glaciers	unit	968	1,384	439	3,357	1,197	882	372	2,814	11,413
CI glacier area	km^2	857.33	2,344.04	1,984.83	5,548.78	926.99	588.42	208.71	1,000.01	13,459.11
DC glacier area	km^2	81.00	409.56	389.22	372.03	48.53	24.26	30.88	43.93	1,399.40
Total glacier area	km^2	938.33	2,753.88	2,374.05	5,937.72	975.51	612.68	239.59	1,229.98	15,061.74
Largest glacier area	km^2	61.81	345.72	631.48	925.93	62.56	46.30	30.98	51.94	925.93
Total ice reserves	km^3	71.32	310.61	601.94	981.70	82.13	42.88	16.88	66.06	2,173.52
Highest elevation	masl	7,730	7,749	8,566	7,803	6,368	7,027	8,032	7,820	8,566
Lowest elevation	masl	2,703	2,409	2,774	3,231	3,997	3,656	2,991	2,760	2,409
CI glacier elevation	masl	2,840-7,730	2,723-7,749	3,395-8,566	3,646-7,803	4,133-6,368	3,656-7,027	3,367-8,032	3,149-7,820	2,723-8,566
DC glacier elevation	masl	2,703-4,925	2,409-5,297	2,774-5,481	3,231-5,666	3,997-5,433	3,868-5,023	2,991-5,031	2,760-5,364	2,409-5,666
Mean CI glacier slope	degrees	23	27	29	26	25	22	22	24	25
Mean DC glacier slope	degrees	11	10	12	12	9	9	10	10	10
CI-DC area ratio	unit	10.58	5.72	5.10	14.91	19.10	24.26	6.76	22.76	9.62
Average glacier area	km^2	0.97	1.99	5.41	1.77	0.81	0.69	0.64	0.44	1.32

*Extends into China (area in China contains 704 glaciers with an area of 203 km^2; CI/DC refer to the remaining 10,709 glaciers with an area of 14,858 km^2)
sub-basins

area was much higher in the Shyok, Hunza, and Shigar sub-basins than in the other basins. Although the Shigar sub-basin had the second smallest number of glaciers, it had the third highest glacier area and second highest estimated ice reserves.

The average area of individual glaciers in the Upper Indus basin was 1.3 km² reflecting the large number of small glaciers; in the Shigar sub-basin the average glacier area was 5.4 km².

Glacier area classes – The number, area, and estimated ice reserves of glaciers in the different size classes are summarised in Table 6.7 and shown as a percentage of the total in Figure 6.13. Small Class 1 glaciers (≤0.5 km²) accounted for 71% of the total, but contributed less than 9% of the area and 2% of the estimated ice reserves. Glaciers in class 3 (1.0 to 5.0 km²) were second highest in number, total area, and estimated ice reserves. Class 5 (≥10.0 km²) had the smallest number of glaciers but contributed more than half of the glacier area and 83% of the estimated ice reserves. The average area of class 5 glaciers was 52.2 km² compared to 1.3 km² for the basin as a whole.

Glacier elevation – The highest glacier elevation was 8,566 in the Shigar sub-basin and the lowest 2,409 masl in the Hunza sub-basin (Table 6.6). The Shigar sub-basin had the widest range of glacier elevation and the Zanskar sub-basin the smallest (Figure 6.14). The majority of glaciers were found at elevations of 4,000 to 7,000 masl.

Glacier aspect – Figure 6.15 shows the percentage of glaciers with different aspects and mean slope. Close to 20% of the glaciers had an east aspect, 17% southeast, 15% south, and 14% southwest. Less than 5% of glaciers had a north aspect.

Table 6.7: Glacier area classes in the Upper Indus basin

Area class	Area (km²)	Number		Area		Estimated ice reserves		Mean area per glacier
		Total	%	km²	%	km³	%	km²
1	≤0.5	8,052	70.6	1,430.23	9.5	33.138	1.5	0.18
2	0.51-1.00	1,500	13.1	1,055.54	7.0	38.783	1.8	0.70
3	1.01-5.00	1,513	13.3	3,142.41	20.9	179.305	8.3	2.08
4	5.01-10.00	192	1.7	1,298.22	8.6	106.460	4.9	6.76
5	≥10.00	156	1.4	8,135.06	54.0	1,815.838	83.5	52.15
	Total	**11,413**	**100**	**15,061.46**	**100**	**2,173.524**	**100**	**1.32**

Figure 6.12: The number, area, and estimated ice reserves of glaciers in the sub-basins of the Upper Indus basin

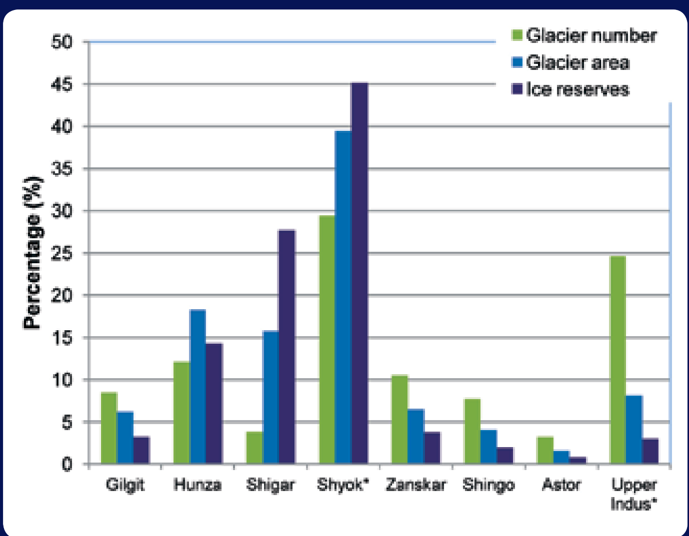
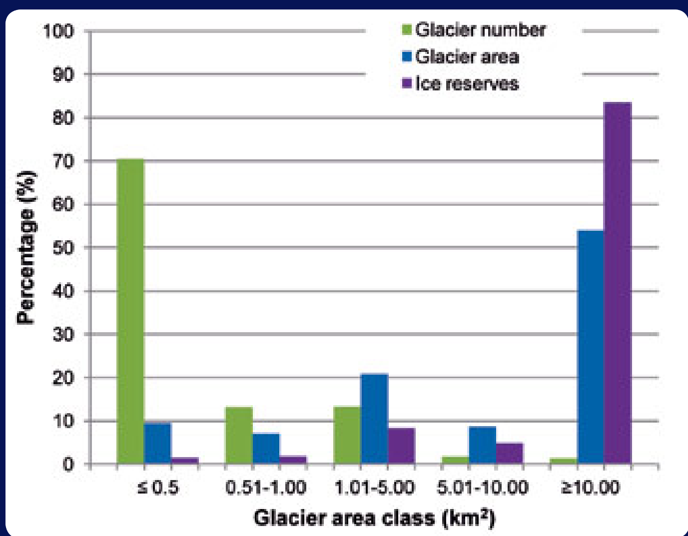


Figure 6.13: Percentage of glacier number, area, and estimated ice reserves in the different glacier size classes in the Upper Indus basin

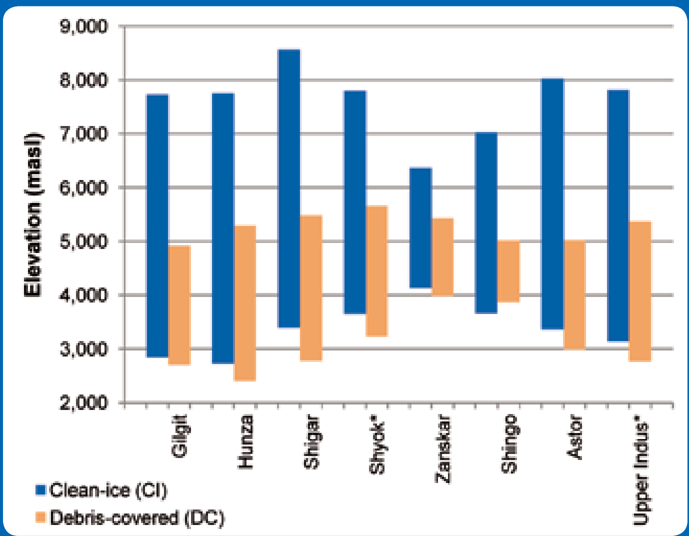


Slope – The mean slope of the glaciers in the basin ranged from less than 10° to 60° (Figure 6.15), with slopes of 10° to 40° most common, except for glaciers with a northern aspect very few of which had slopes of less than 20°; less than 2% of glaciers had slopes of 40° to 60°.

The mean slope of the CI glaciers ranged from 22° to 29° (Figure 6.16), with an average of 25°, higher than in other basins and consistent with a greater dominance of mountain glaciers. The mean slope of the DC glaciers ranged from 9° to 12°, with an average of 10°.

Morphological glacier type – The morphological classification of glaciers in the Upper Indus basin is summarised in Table 6.8; the comparative distribution by number, area, and estimated ice reserves is shown graphically in Figure 6.17. Altogether 10,709 of the 11,413 glaciers were classified morphologically.

Figure 6.14: Elevation of CI and DC glaciers in the sub-basins of Upper Indus basin



Excluding glaciers in China

Figure 6.15: Aspect and mean slope of glaciers in the Upper Indus basin

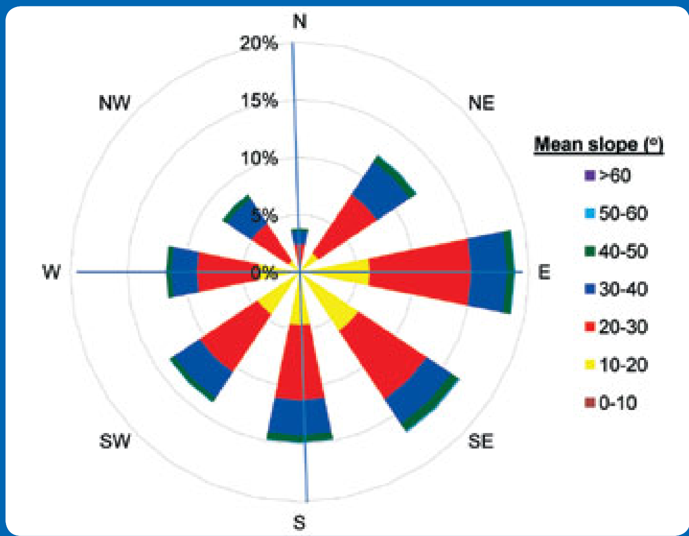
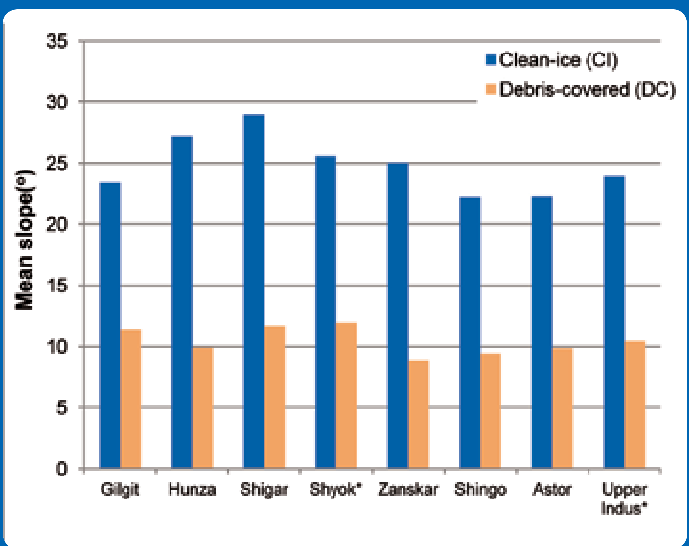
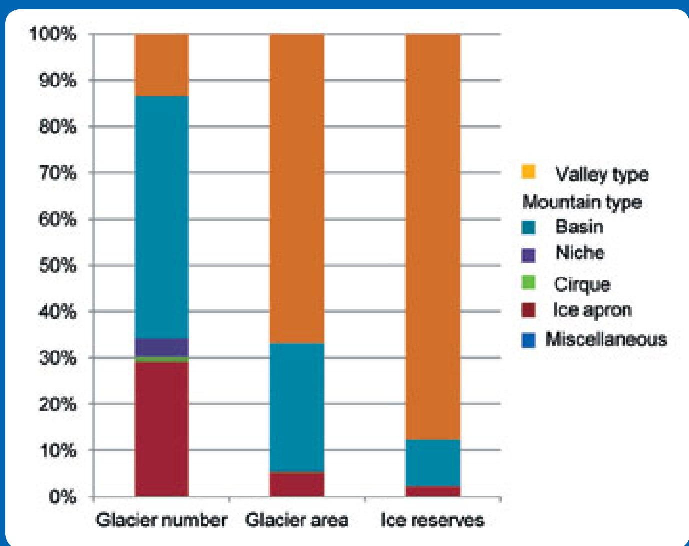


Figure 6.16: Mean slope of CI and DC glaciers in the sub-basins of the Upper Indus basin



Excluding glaciers in China

Figure 6.17: Comparative distribution of different glacier types in the Upper Indus basin by number, area, and estimated ice reserves



Just over 85% of the glaciers were identified as mountain type, of which 52% were mountain basin type and 29% ice apron type. Mountain basin type glaciers covered 27% of the glacier area and contained 10% of the estimated ice reserves (Table 6.8).

The valley glaciers in the region have both compound basins and simple basins Only 13% of the glaciers were valley trough type, but they contributed 67% of the total glacier area and 88% of the ice reserves. Basin type glaciers, valley trough and mountain basin together, covered altogether 94% of the glacier area and contained 98% of the estimated ice reserves. This reflects the maturity of these mountains compared to the relatively young Himalayan range. The average area of the mountain basin type glaciers was 0.73 km^2 and of valley troughs 6.88 km^2.

Clean-ice and debris-covered glaciers – About 13% of the total glacier area was debris-covered, with percentages in the different sub-basins ranging from 2% (Shingo and Upper Indus) to 16% (Shigar) (Figure 6.18).

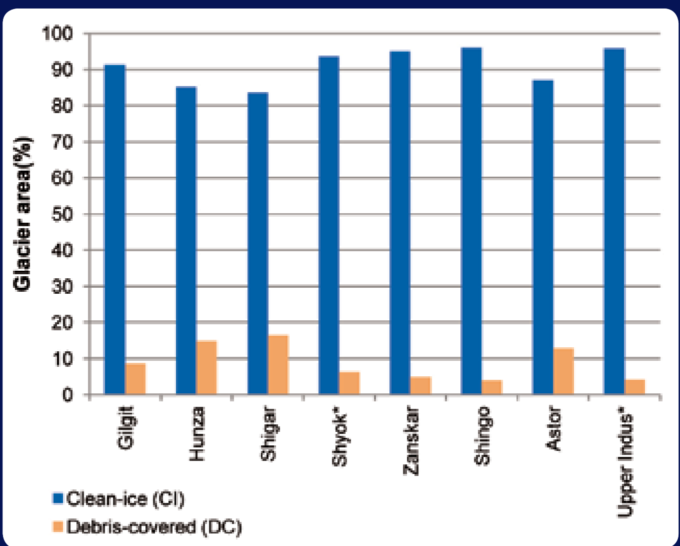
Hypsography – The glacier area-altitude distribution in the sub-basins is shown in Figure 6.19. More than 500 km^2 of the total 1500 km^2 glaciated area lay within the elevation zone from 4,600-6,000 masl. The maximum glaciated areas were 589 km^2 at 5,700-5,800 masl in the Shyok sub-basin; 197 km^2 at 5,100-5,200 masl in the Hunza sub-basin; 170 km^2 at 5,000-5,100 masl in the Shigar sub-basin; 130 km^2 at 5,400-5,500 masl in the Zanskar

Table 6.8: Morphological classification of glaciers in the Upper Indus basin*

Glacier type		Number		Area		Estimated ice reserves		Mean area per glacier
		Total	%	km^2	%	km^3	%	km^2
Mountain	Miscellaneous	17	0.2	7.61	0.1	0.352	0.02	0.45
	Ice apron	3,104	29.0	763.85	5.1	47.295	2.2	0.25
	Cirque	121	1.1	28.56	0.2	0.787	0.04	0.24
	Niche	424	4.0	41.82	0.3	1.095	0.05	0.10
	Basin	5,598	52.3	4,081.34	27.5	216.713	10.0	0.73
Valley	Trough	1,445	13.5	9,935.49	66.9	1,899.280	87.7	6.88
	Total	**10,709**	**100**	**14,858.67**	**100**	**2,165.522**	**100**	**1.39**

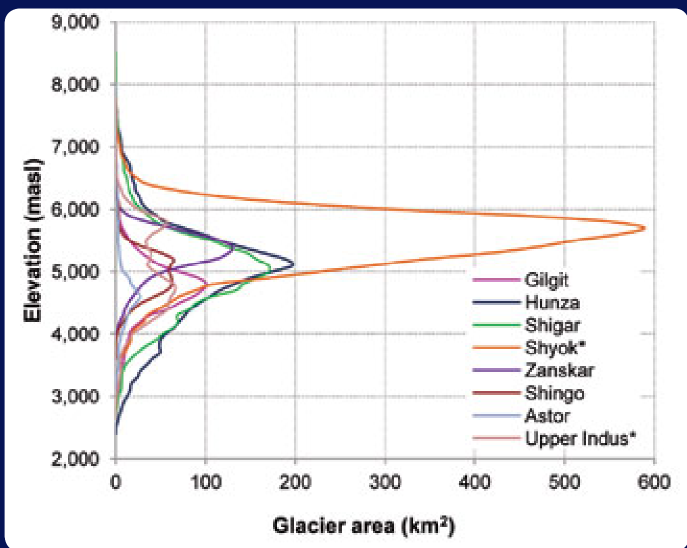
* Excluding glaciers in China

Figure 6.18: Percentage distribution by area of CI and DC glaciers in sub-basins of the Upper Indus basin



Excluding glaciers in China

Figure 6.19: Area-altitude distribution of glaciers in the Upper Indus basin



Excluding glaciers in China

sub-basin; 100 km² at 4,800-4,900 masl in the Gilgit sub-basin; 75 km² at 4,700 to 4,800 masl in the Upper Indus sub-basin; 64 km² at 5,200-5,300 masl in the Shingo sub-basin; and 27 km² at 4,600-4,700 masl in the Astor sub-basin.

Panjnad basin

The main glaciated sub-basins of the Panjnad basin are the Jhelum, Chenab, Ravi, Beas, and Sutlej (Figure 6.20). A part of the Sutlej sub-basin lies within the territory of China. Descriptions of the typology, morphological classification, and hypsography of the 827 glaciers in this part of the basin are not yet available and not included in the description here.

The glaciers in the Panjnad basin are distributed in the northern part of the watershed between latitudes 30.45° and 35.12° N and longitudes 73.42° and 81.22° E (Figure 6.20). High concentrations of glaciers were particularly prominent in the Chenab and Beas sub-basins; the glaciers elsewhere are more scattered.

The distribution and characteristics of the glaciers in each sub-basin are summarised in Table 6.6.

Number, area, and ice reserves – The Panjnad basin had 5,481 glaciers with a total area of 4,409 km² and estimated ice reserves of 340 km³ (Table 6.9).

The number, area, and estimated ice reserves of glaciers in the Panjnad sub-basins are shown in Figure 6.21. The Sutlej and Chenab sub-basins both had more than 2,000 glaciers. The Chenab sub-basin had the greatest glaciated area and estimated ice reserves. It also had the largest individual glacier in the Panjnad basin, the compound basin type valley glacier GLIMS ID G077681E32169N (Pchgr10_941) with an area of 109.33 km² extending from 6,268 masl to 3,904 masl

Figure 6.20: Distribution of glaciers in the Panjnad basin

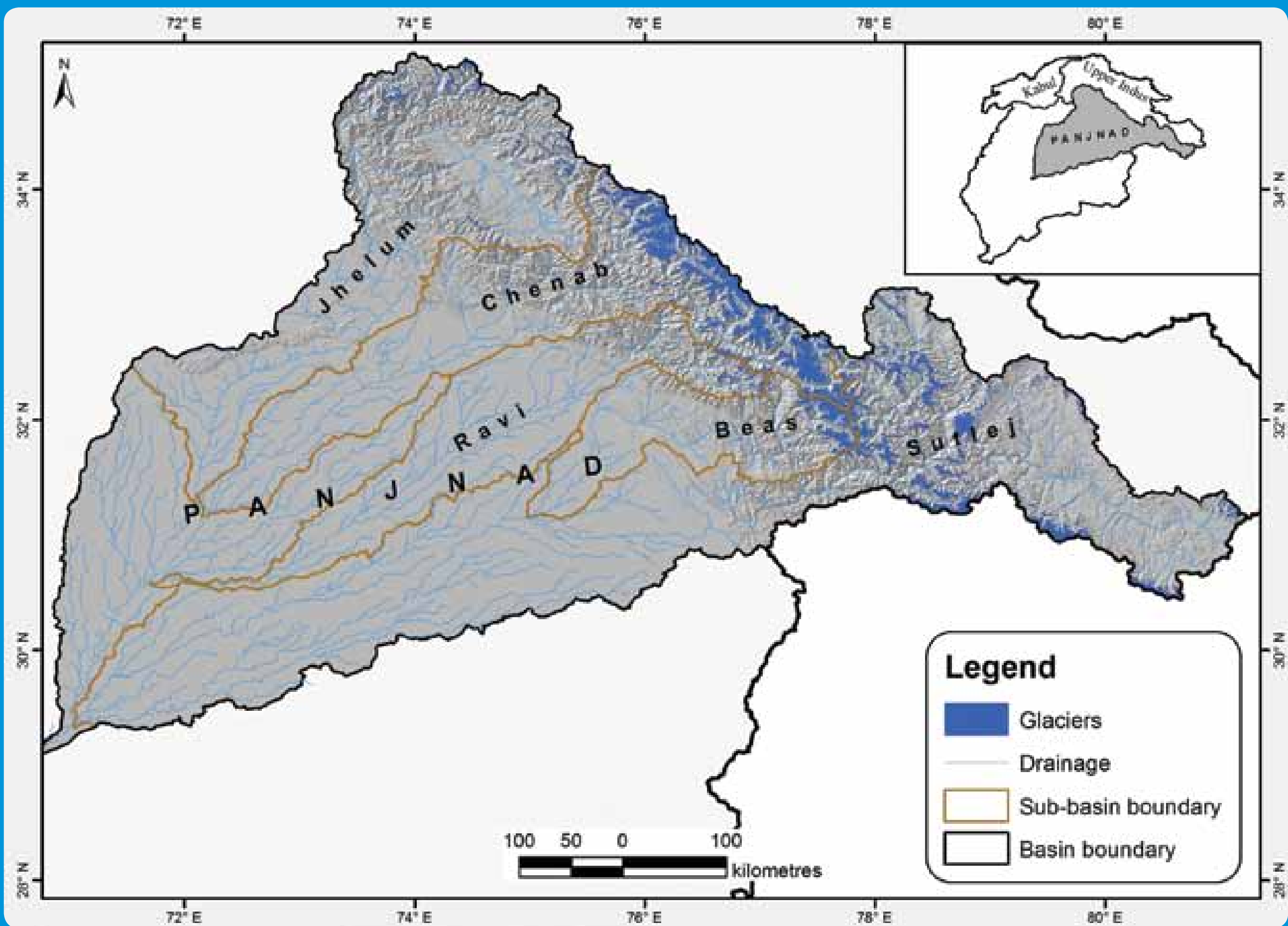


Table 6.9: Glacier characteristics in the Panjnad basin

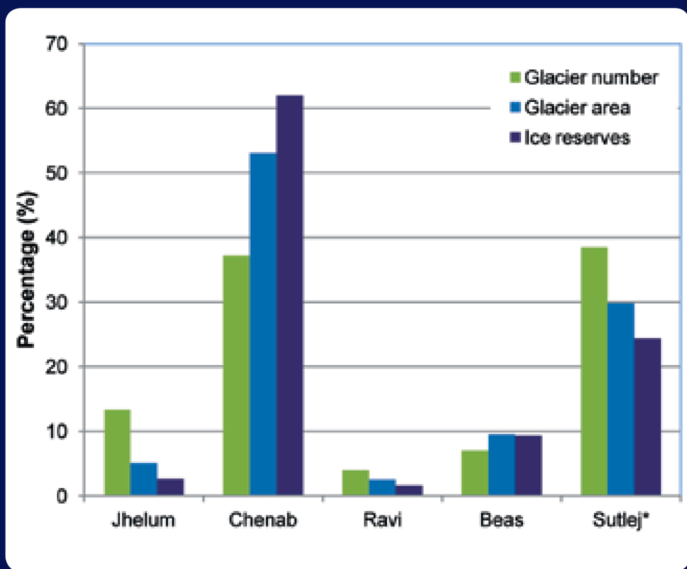
Parameter	Units	Sub-basin					Panjnad basin
		Jhelum	Chenab	Ravi	Beas	Sutlej*	
Basin area in HKH	km²	31,811	29,115	9,276	13,970	49,380	133,552
Latitude	degrees	33.47-35.11	32.12-34.20	32.19-33.01	31.66-32.41	30.45-33.14	30.45-35.11
Longitude	degrees	73.42-75.59	74.79-77.77	76.23-77.06	76.77-77.84	77.61-81.22	73.42-81.22
Number of glaciers	unit	733	2,039	217	384	2,108	5,481
CI glacier area	km²	213.95	2,064.67	96.63	379.78	855.17	3,610.19
DC glacier area	km²	8.82	276.57	16.99	36.82	71.02	410.22
Total glacier area	km²	222.77	2,341.23	113.62	416.60	1,315.01	4,409.24
Largest glacier area	km²	6.82	109.33	9.23	29.04	49.55	109.33
Total ice reserves	km³	8.97	210.70	5.51	31.78	82.89	339.86
Highest elevation	masl	6,285	7,103	5,824	6,196	6,652	7,103
Lowest elevation	masl	3,404	3,001	3,276	3,079	3,606	3,001
CI glacier elevation	masl	3,536-6,285	3,001-7,103	3,511-5,824	3,079-6,196	3,606-6,652	3,001-7,103
DC glacier elevation	masl	3,404-4,368	3,115-5,913	3,276-5,008	3,612-5,274	4,006-5,830	3,115-5,913
Mean CI glacier slope	degrees	30	28	27	25	24	27
Mean DC glacier slope	degrees	12	11	11	10	12	11
CI-DC area ratio	unit	24.26	7.47	5.69	10.31	12.04	8.80
Average glacier area	km²	0.30	1.15	0.52	1.08	0.62	0.80

*extends into China (area in China contains 570 glaciers with an area of 388 km², all in the Sutlej basin; CI/DC differentiation excludes these)

The majority of glaciers were small with an average glacier area of less than 1 km² in the Jhelum, Ravi, and Sutlej sub-basins, and slightly more than 1 km² in the Chenab and Beas sub-basins (Figure 6.21). The overall average glacier area of the Panjnad basin was only 0.80 km².

Glacier area classes – The number, area, and estimated ice reserves of glaciers in the different size classes are summarised in Table 6.10 and shown as a percentage of the total in Figure 6.22. Of the 5,481 glaciers in the basin, 3,995 (73%) were in the smallest size class 1 (≤0.5 km²), together comprising about 15% of the total glacier area and 4% of the estimated ice reserves. Class 3 (1.0 to 5.0 km²) had the second highest number of glaciers and the highest total area (33% of the total). The large glaciers in class 5 (≥10.0 km²) were fewest in number but contributed 30% of the total area and 53% of the ice reserves.

Figure 6.21: Glacier number, area, and estimated ice reserves in the sub-basins of the Panjnad basin



Glacier elevation – Figure 6.23 shows the elevation range of CI and DC glacier components in the sub-basins. The highest glacier elevation was 7,213 masl and the lowest 3,001 masl, both in the Chenab sub-basin. The small mountain glaciers had only small individual elevation ranges, whereas the valley glaciers had a large range from crown to terminus. CI type glaciers were generally found at higher elevations and debris-covered (DC) glacier areas at lower elevations.

Table 6.10: Glacier area classes in the Panjnad basin

Area class	Area (km^2)	Number		Area		Estimated ice reserves		Mean area per glacier
		Total	%	km^2	%	km^3	%	km^2
1	≤ 0.5	3,995	72.9	655.52	14.9	14.708	4.3	0.16
2	0.51-1.00	658	12.0	461.77	10.5	16.764	4.9	0.70
3	1.01-5.00	697	12.7	1,467.73	33.3	84.541	24.9	2.11
4	5.01-10.00	74	1.4	516.25	11.7	43.295	12.7	6.98
5	≥10.00	57	1.04	1,307.97	29.7	180.551	53.1	22.95
	Total	**5,481**	**100**	**4,409.24**	**100**	**339.859**	**100**	**0.80**

Figure 6.22: Percentage of glacier number, area, and estimated ice reserves in the different glacier size classes in the Panjnad basin

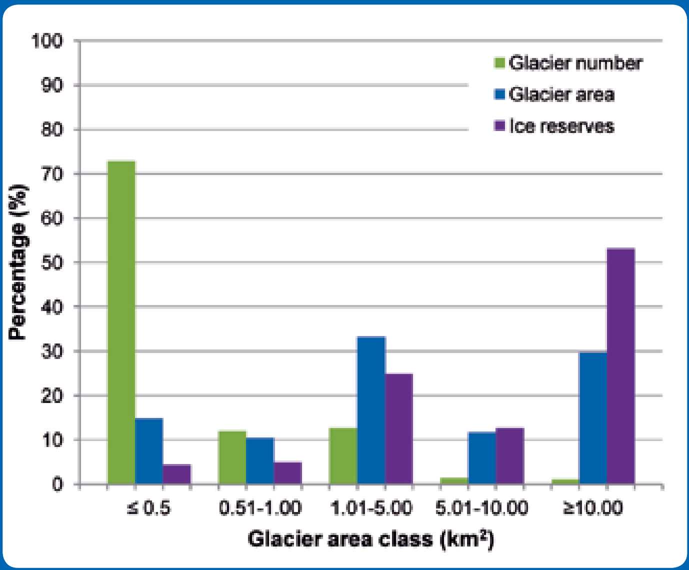
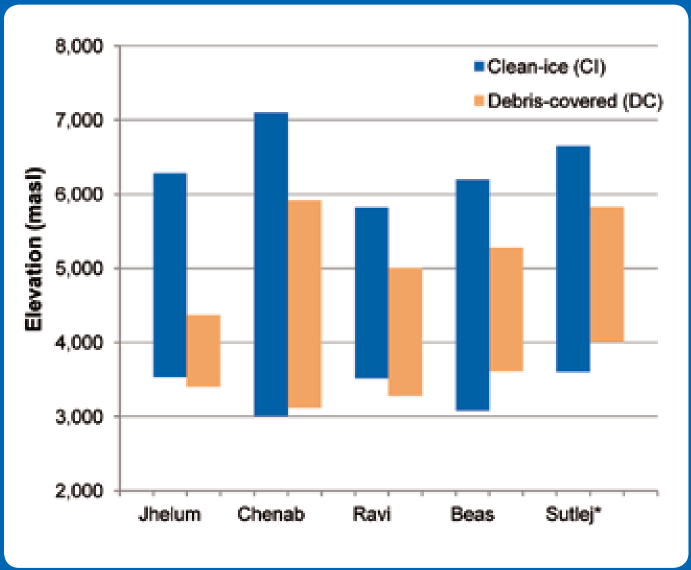


Figure 6.23: Elevation of CI and DC glaciers in the sub-basins of the Panjnad basin



Excluding glaciers in China

Figure 6.24: Aspect and mean slope of glaciers in the Panjnad basin

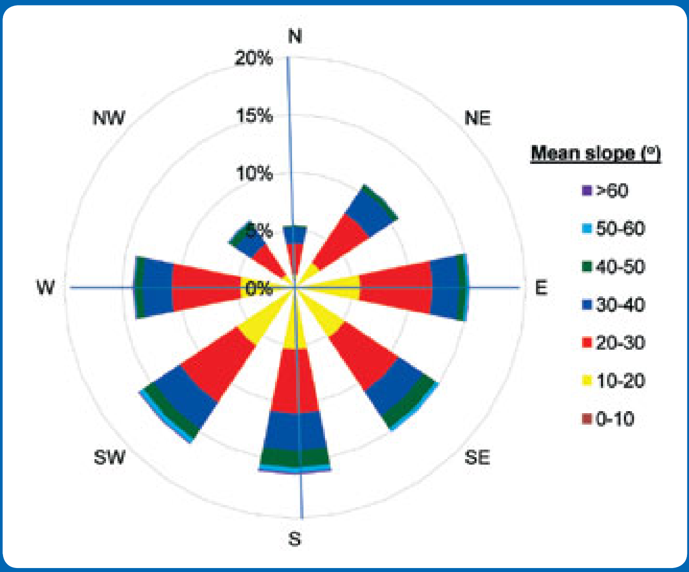
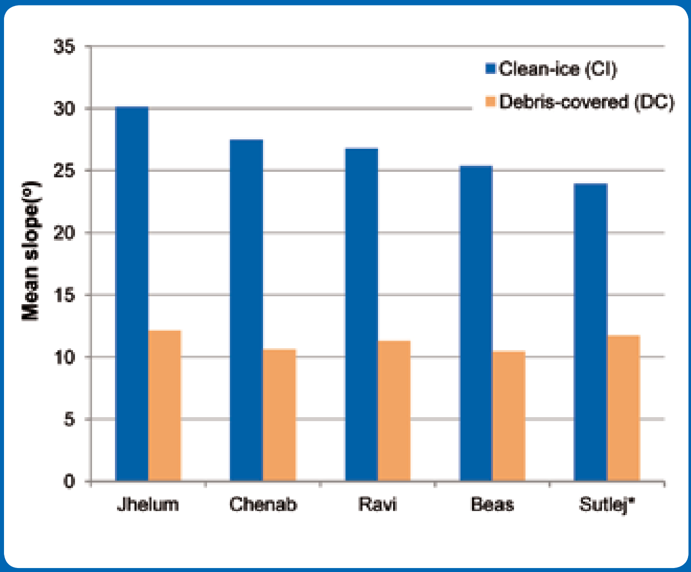


Figure 6.25: Mean slope of CI and DC glaciers in the sub-basins of the Panjnad basin



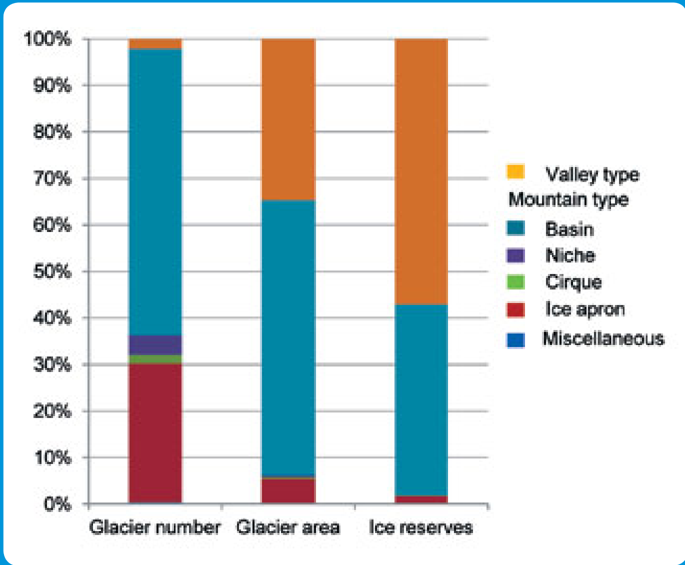
Excluding glaciers in China

Glacier aspect – Figure 6.24 shows the percentage of glaciers with different aspects and mean slope. Similar numbers of glaciers had west (14%), southwest (16%), south (16%), southeast, (15%) and east (15%) aspects, and slightly less a northeast aspect (11%). Only a few had north or northwest aspects.

Slope – The mean slope of the glaciers in the basin ranged from 10° to 60°, with slopes of 20° to 30° most common in all cardinal directions, followed by slopes of 10° to 20° and 30° to 40°. The very few glaciers with slopes greater than 60° had south, southwest, and west aspects (Figure 6.24).

The mean slope of the CI glaciers was 27° and of DC glaciers 11° with small variations in the different sub-basins (Figure 6.25).

Figure 6.26: Comparative distribution of different glacier types in the Panjnad basin by number, area, and estimated ice reserves



Excluding glaciers in China

Morphological glacier type – The morphological classification of glaciers in the Panjnad basin is summarised in Table 6.11; the comparative distribution by number, area, and estimated ice reserves is shown graphically in Figure 6.26. The 827 glaciers in China were not classified morphologically.

Just over 98% of the glaciers were identified as mountain type: 62% mountain basin type, 30% ice apron type, and the remaining 6% various other types. Mountain basin glaciers covered 59% of the total glacier area, and contained 41% of the total ice reserves; ice apron type glaciers contributed relatively little to these.

The area and ice reserves of the valley glaciers are generally large as discussed in previous sections. The valley glaciers in the Panjnad basin have both compound and simple basins. They comprised only 2% of the total by number, but contributed almost 35% of the total glacier area and 57% of the total estimated ice reserves (Table 6.11, Figure 6.26).

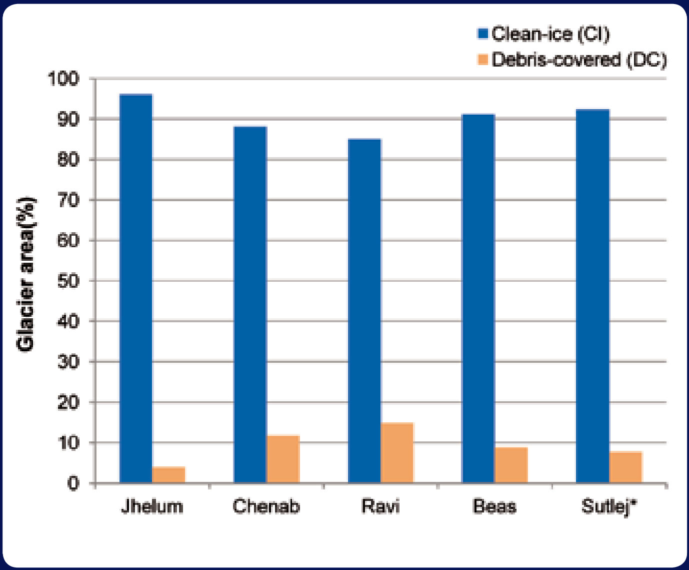
Clean-ice and debris-covered glaciers – Figure 6.27 shows the area distribution of CI and DC glacier components in the sub-basins. A total of 410 km² (10%) of the total analysed glacier area was debris covered (Table 6.9). The Chenab sub-basin had the maximum DC glacier area (276 km²) and the Ravi sub-basin the highest percentage DC area.

Table 6.11: Morphological classification of glaciers in the Panjnad basin*

Glacier type		Number		Area		Estimated ice reserves		Mean area per glacier
		Total	%	km²	%	km³	%	km²
Mountain	Miscellaneous	20	0.4	5.05	0.1	0.168	0.1	0.25
	Ice apron	1,388	29.8	206.05	5.3	5.018	1.7	0.15
	Cirque	84	1.8	13.43	0.3	0.315	0.1	0.16
	Niche	194	4.2	12.69	0.3	0.172	0.1	0.07
	Basin	2,868	61.6	2,309.70	59.3	124.524	41.0	0.81
Valley	Trough	100	2.2	1,349.86	34.6	173.446	57.1	13.50
	Total	**4,654**	**100**	**3,896.79**	**100**	**303.642**	**100**	**0.84**

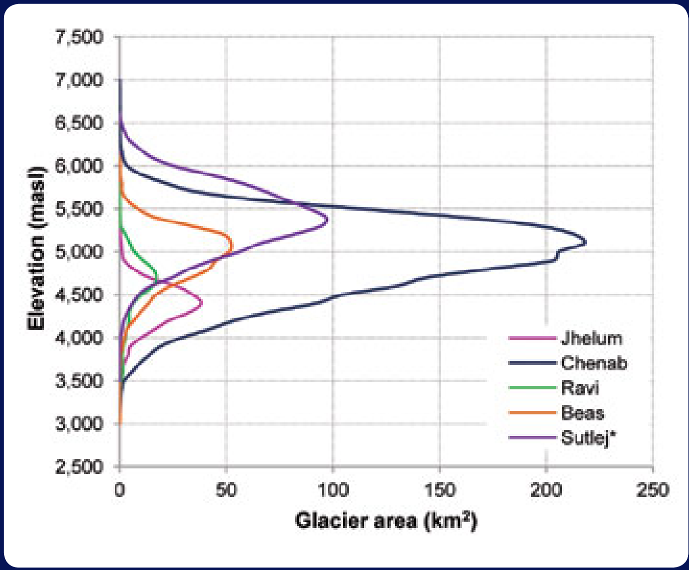
* Excluding glaciers in China

Figure 6.27: Percentage distribution by area of CI and DC glaciers in sub-basins of the Panjnad basin



Excluding glaciers in China

Figure 6.28: Area-altitude distribution of glaciers in the sub-basins of the Panjnad basin



Excluding glaciers in China

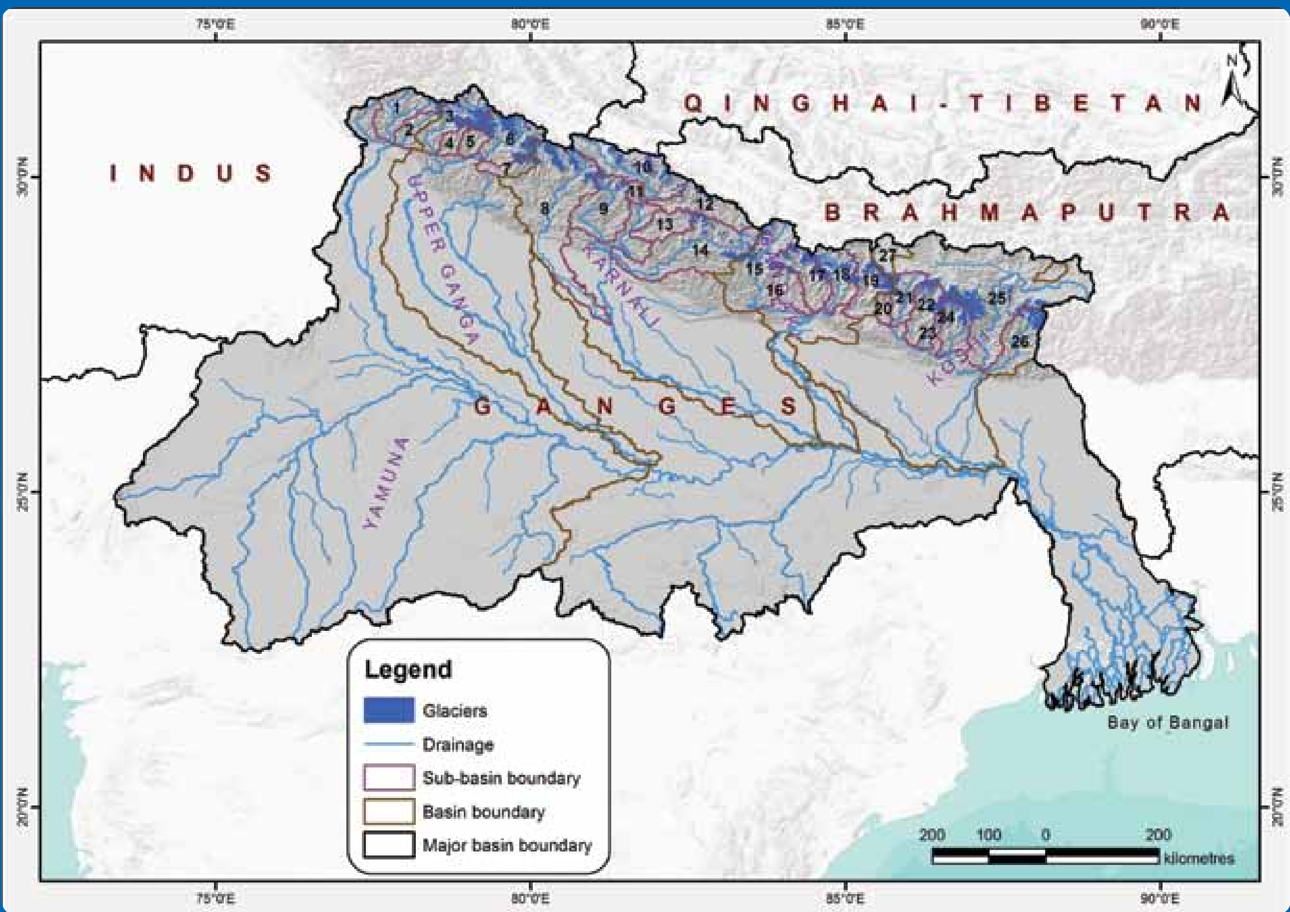
Hypsography – The glacier area-altitude distribution in the sub-basins is shown in Figure 6.28. Overall, there were glaciated areas of more than 100 km^2 at every 100 m level from 4,300 – 5,800 masl. The maximum glaciated area overall was 347 km^2 at an elevation of 5,200-5,300 masl. The maximum glaciated areas in the individual basins were 218 km^2 at 5,100-5,200 masl in the Chenab sub-basin; 97 km^2 at 5,400-5,500 masl for the Sutlej sub-basin; 52 km^2 at 5,100-5,200 masl for the Beas sub-basin; 38 km^2 at 4,400-4,500 masl for the Jhelum sub-basin; and 17 km^2 at 4,700-4,800 masl for the Ravi sub-basin.

7 Ganges (Ganga) Basin

The Ganges (Ganga) river is one of the major rivers of the Indian subcontinent and revered by Hindus who consider it holy. It forms at Devprayag at the confluence of the Bhagirathi and Alaknanda rivers. The Bhagirathi river originates from Gaumukh (3,920 masl), the terminus of the Gangotri Glacier in Uttarakhand, India. The Alaknanda river, also known as the Vishnu Ganga, originates from the terminus of the Satopanth and Bhagirath Kharak glaciers, which rise from the Chaukhamba mountain also in Uttarakhand, India. Many major tributaries feed into the Alaknanda river, including the Mandakani, Pindar, Nandakani, Birahi, Dhauliganga, and Saraswati rivers. Further down, the Ganges is joined by major tributaries from Nepal: the Karnali, Gandaki (Narayani), and Koshi rivers.

The glaciated regions of the major Ganges basin are divided into 5 basins and 26 sub-basins (Figure 7.1). The largest tributaries of the Ganges are the Yamuna, Upper Ganga, Karnali (Ghagara in India) from western Nepal,

Figure 7.1: The basins and sub-basins of the glaciated part of the Ganges river system showing distribution of glaciers



Yamuna
1. Tons
2. Upper Yamuna

Upper Ganga
3. Bhagirathi
4. Bhilanga
5. Mandakini
6. Alaknanda
7. Pindar

Karnali
8. Kali
9. W. Seti
10. Humla
11. Kawari
12. Mugu
13. Tila
14. Bheri

Gandaki*
15. Kali Gandaki*
16. Seti
17. Marsyangdi
18. Budhi Gandaki*
19. Trishuli*

Koshi*
20. Indrawati
21. Sun Koshi*
22. Tama Koshi*
23. Likhu
24. Dudh Koshi
25. Arun*
26. Tamor
27. Pelkhu is an interior basin

*extends into China

Gandaki (Narayani) from central Nepal, and the Koshi from eastern Nepal. All the Nepali tributaries contain a large amount of Himalayan glacier melt. The Padma river (a major distributary of the Ganges) is joined by the Jamuna (or Yamuna) and Meghna rivers (largest and second largest distributaries of the Brahmaputra river). Fanning out into a 350 km wide delta (world's largest), the Ganges empties into the Bay of Bengal.

The Ganges has a total basin area of 1,001,019 km^2, of which 244,806 km^2 lies within the HKH region. The river flows for about 2,510 km, generally southeastward, through a vast plain to the Bay of Bengal. The basin extends from 27.53° to 31.42° N latitude and 77.98° to 88.70° E longitude, with an elevation ranging from sea level to the highest peak in the world (Mt. Everest – 8,850 masl).

Data

The mapping and inventory of the glaciated areas in the sub-basins of the Ganges were carried out using ETM+ images from 2000 to 2008. The topographic characteristics were derived using the SRTM DEM. The list of images used is shown in Table 7.1.

Table 7.1: Landsat images used for the Ganges basin

Path-Row	Image	Date	Used for	Sub-basin
146-39	LE71460392000362SGS00	12/27/2000	correction	Bhilanda, Mandakini, Yamuna, Tons, Bhagirathi
	L71146039_03920051123	11/23/2005	analysis	
	LE71460392005343PFS00	12/9/2005	analysis	
	LE71460392008320SGS00	11/15/2008	analysis	
146-38	L71146038_03820060923	9/23/2006	analysis	Tons, Bhagirathi, Yamuna
	LE71460382000282SGS00	1/8/2000	correction	
	LE71460382006282ASN00	10/9/2006	analysis	
	LE71460382008240SGS00	8/27/2008	analysis	
	LE71460382001252SGS00	9/9/2001	correction	
145-39	LE71450392001293SGS00	10/20/2001	analysis	Pindar, Alaknanda, Dhauliganga, Goriganga, Ramganga, Mandakini
	LE71450392005320SGS00	11/16/2005	analysis	
	LE71450392008313SGS00	11/8/2008	analysis	
144-39	LE71440392008338SGS00	10/13/2001	analysis	Kali
144-39	LE71440391999313SGS00	09/11/1999	correction	Humla, Kawari, Mahakali, West Seti
	LE71440392005345PFS00	11/12/2005	correction	
	LE71440392008338SGS00	03/12/2008	analysis	
143-39	LE71430392002298SGS01	25/10/2002	correction	Mugu
	LE71430392008347SGS00	12/12/2008	analysis	
143-40	LE71430402005290PFS00	17/10/2005	analysis	Tila
	LE71430402008347SGS00	12/12/2008	analysis	
	LE71430402002362SGS00	28/12/2002	correction	
142-40	l5142040_04020060207	07/02/2006	analysis	Bheri, Kali, Seti, Marsyangdi
	l72143040_04020081212	12/12/2008	analysis	
141-40	LT51410402005316BKT00	12/11/2005	analysis	Trishuli
	LT51410402006303BKT00	30/10/2006	analysis	
141-41	LT51410412005316BKT00	12/11/2005	analysis	Sun, Indrawati
	LT51410412006303BKT00	30/10/2006	analysis	
140-41	LE71400412007355SGS01	21/12/2007	analysis	Arun, Dudh, Tama, Likhu
	LT51400412005309BKT00	05/11/2005	correction	
139-41	LE71390412002350SGS00	16/12/2002	correction	Tamor
	LE71390412007348PFS00	14/12/2007	analysis	

Mapping and Inventory of Glaciers

The Ganges basin contains a total of 7,963 glaciers distributed between 27.53° and 31.42° N latitude and 77.98° and 88.70° E longitude (Figure 7.1). It has a total glaciated area of 9,012 km² with estimated ice reserves of about 794 km³. The major glaciated basins from west to east are the Yamuna (Jamuna), Upper Ganga, Karnali (together with the Kali), Gandaki (Narayani), and Koshi. The distribution and characteristics of the glaciers in each main basin are summarised in Table 7.2.

Yamuna basin

The Yamuna river originates from the Yamunotri glacier on the southwestern slopes of the Bandarpunchh peak in the Garhwal Himalaya and forms the western boundary of Himachal Pradesh. It has two glaciated sub-basins – the Tons and the Upper Yamuna. The glaciers are concentrated in the northeast corner of the catchment with the Tons catchment the most glaciated (Figure 7.2). The distribution and characteristics of the glaciers in each sub-basin are summarised in Table 7.3.

Number, area, and ice reserves – The Yamuna basin had 185 glaciers (166 in the Tons sub-basin and 19 in the Upper Yamuna sub-basin) with a total area of 114 km² and estimated ice reserves of close to 9 km³ (Table 7.3). The number, area, and estimated ice reserves of glaciers in the sub-basins are shown in Figure 7.3. The Tons river catchment contains about 110 km² of glaciers but the estimated ice reserves are only 8.42 km³; the glaciers in the Upper Yamuna have only a nominal volume of ice reserves, indicating that most of the glaciers are small.

Glacier area classes – The number, area, and estimated ice reserves of glaciers in the different size classes are summarised in Table 7.4 and shown as a percentage of the total in Figure 7.4. There were 147 glaciers in class 1 (≤0.5 km²), 79% of the total number but with only 15% of the total area and 4% of the ice reserves. The two large glaciers with an area ≥10 km² covered 37% of the total area and contained 60% of the ice reserves.

Figure 7.2: Distribution of glaciers in the Yamuna basin

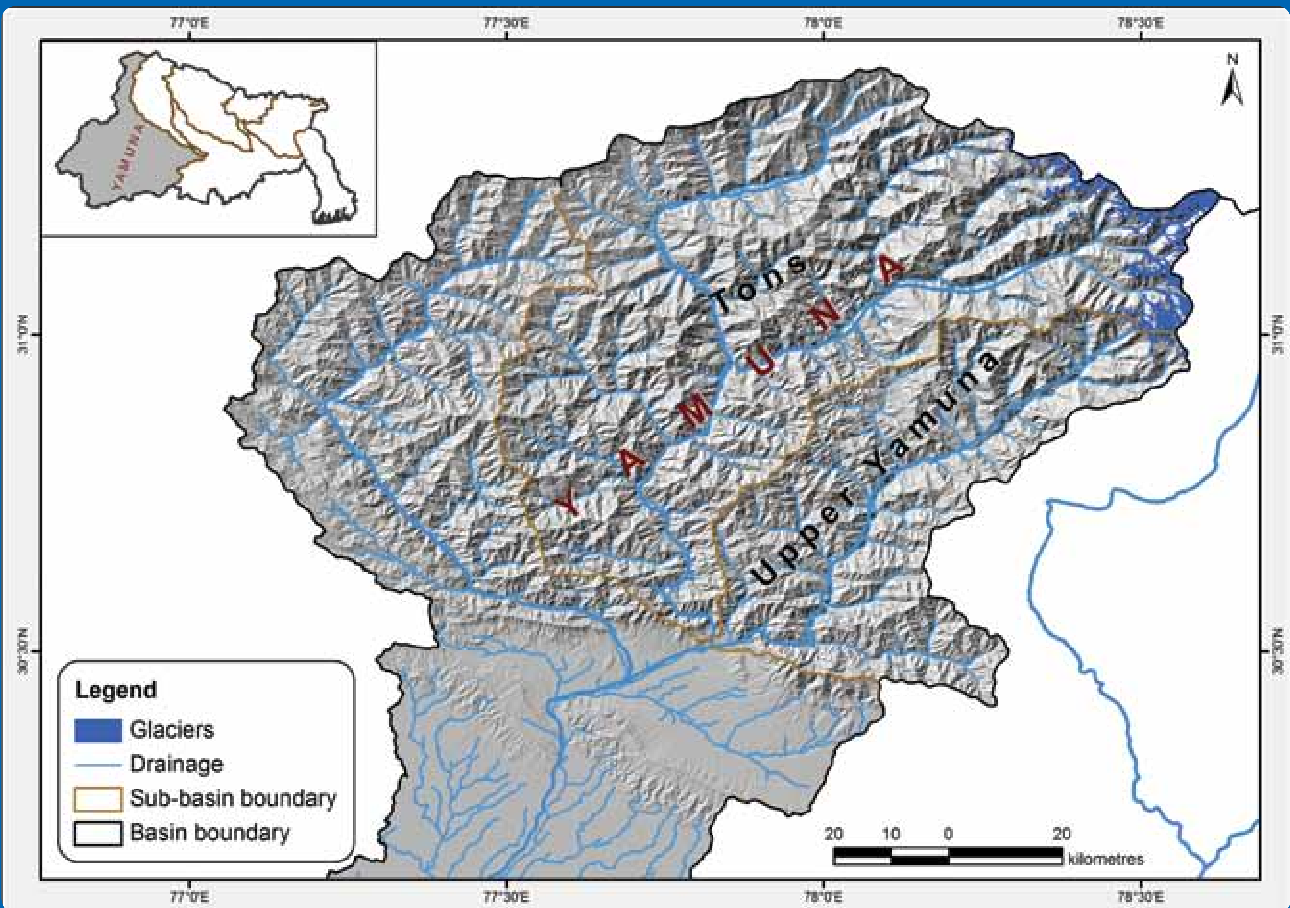


Table 7.2: Glacier characteristics in the Ganges basin within the HKH region

Parameter	Units	Basin						Ganges
		Yamuna	Upper Ganga	Karnali*	Gandaki*	Koshi*	Pelkhu**	
Basin area	km²	11,370	34,504	81,711	36,450	71,047	2,404	244,806***
Latitude	degrees	30.97-31.42	30.19-31.37	28.67-30.58	28.11-29.33	27.53-28.95	28.42-28.74	27.53-31.42
Longitude	degrees	77.98-78.60	78.55-80.23	80.00-83.66	83.25-85.74	85.48-88.70	85.40-85.74	77.98-88.70
Number of glaciers	unit	185	1,536	2,417	1,710	2,073	42	7,963
CI glacier area	km²	98.58	1,372.49	1,489.12	1,701.05	960.42	NA	5,621.68
DC glacier area	km²	15.84	254.59	191.61	128.48	219.42	NA	809.92
Total glacier area	km²	114.42	1,627.08	1,871.98	2,285.18	2,983.61	129.27	9,011.53
Largest glacier area	km²	22.03	176.76	46.34	59.02	80.72	36.26	176.76
Total ice reserves	km³	8.57	162.08	121.56	194.25	294.53	12.55	793.53
Highest elevation	masl	6,287	7,481	7678	8,093	8,806	7,228	8,806
Lowest elevation	masl	3,872	3,762	3,476	3,273	3,719	4,985	3,273
CI glacier elevation	masl	4,153-6,287	3,895-7,481	3,610-7,678	3,734-8,093	3,962-8,806	4,985-7,228	3,610-8,806
DC glacier elevation	masl	3,872-5,036	3,762-5,929	3,476-5,839	3,273-5,754	3,977-6,009	NA	3,273-6,009
Mean CI glacier slope	degrees	26	30	28	31	28	24	28
Mean DC glacier slope	degrees	10	15	11	13	15	NA	13
CI-DC area ratio	unit	6.23	5.39	7.77	13.24	4.38	NA	6.94
Average glacier area	km²	0.62	1.06	0.77	1.34	1.44	3.08	1.13

*Extends into China (area in China contains 1,841 glaciers with an area of 2,579 km²; CI/DC refers to the remaining 6,122 glaciers with an area of 6,431 km²); ** includes area at the watershed head of the Koshi basin; *** includes area of non-glaciated sub-basins

Glacier elevation – The highest glacier elevation was 6,287 masl and the lowest 3,872 masl both in the Tons sub-basin (Table 7.3). DC glaciers in the Tons sub-basin were found from 5,036 to 3,872 masl. The elevation range in the Upper Yamuna sub-basin was much less (5,670 to 4,564 masl) and it had no DC glaciers.

Glacier aspect – Figure 7.5 shows the percentage of glaciers with different aspects and mean slope. The most common aspect was southwest (27%) of followed by west (17%) and south (19%). Only 2% had a northern aspect.

Slope – The mean slope of the glaciers ranged from 10° to 60°, with slopes of 20° to 30° most common in the south, southwest, and west facing glaciers (Figure 7.5).

Table 7.3: Glacier characteristics in the Yamuna basin

Parameter	Units	Sub-basin		Yamuna
		Tons	Upper Yamuna	
Basin area	km²	5,142	2,331	11,370*
Latitude	degrees	31.02-31.42	30.97-31.03	30.97-31.42
Longitude	degrees	77.98-78.60	78.46-78.57	77.98-78.60
Number of glaciers	unit	166	19	185
CI glacier area	km²	93.98	4.60	98.58
DC glacier area	km²	15.84	0	15.84
Total glacier area	km²	109.82	4.60	114.42
Largest glacier area	km²	22.03	1.23	22.03
Total ice reserves	km³	8.42	0.15	8.57
Highest elevation	masl	6,287	5,670	6,287
Lowest elevation	masl	3,872	4,564	3,872
CI glacier elevation	masl	4,153-6,287	4,564-5,670	4,153-6,287
DC glacier elevation	masl	3,872-5,036	0	3,872-5,036
Mean CI glacier slope	degrees	28	23	26
Mean DC glacier slope	degrees	10	0	10
CI-DC area ratio	unit	5.93	0	6.23
Average glacier area	km²	0.66	0.24	0.62

*Area including not glaciated sub-basins

Figure 7.3: Glacier number, area, and estimated ice reserves in the sub-basins of the Yamuna basin

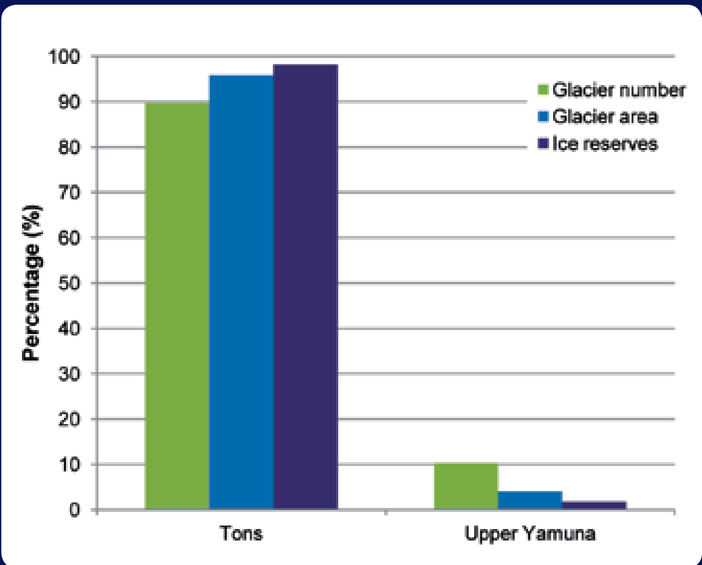


Figure 7.4: Percentage of glacier number, area, and estimated ice reserves in the different glacier size classes in the Yamuna basin

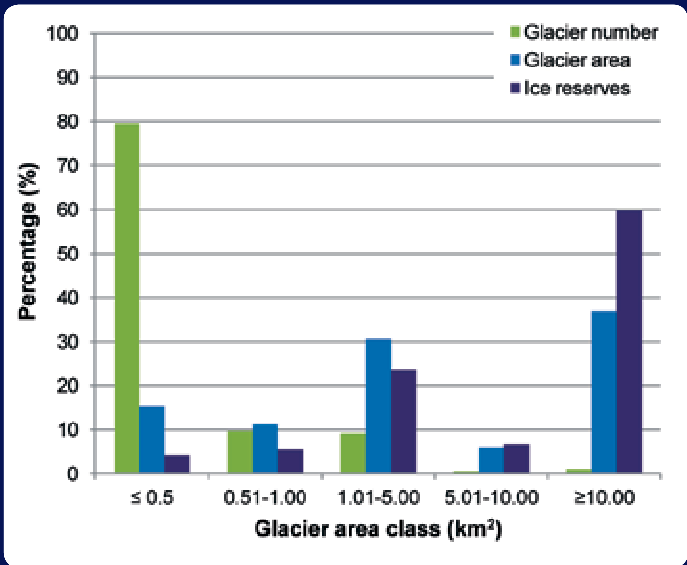


Table 7.4: Glacier area classes in the Yamuna basin

Area class	Area (km²)	Number		Area		Estimated ice reserves		Mean area per glacier
		Total	%	km²	%	km³	%	km²
1	≤ 0.5	147	79.5	17.46	15.3	0.361	4.2	0.12
2	0.51-1.00	18	9.7	12.82	11.2	0.475	5.5	0.71
3	1.01-5.00	17	9.2	35.00	30.6	2.025	23.6	2.06
4	5.01-10.00	1	0.5	6.95	6.1	0.583	6.8	6.95
5	≥10.00	2	1.1	42.19	36.9	5.128	59.8	21.10
	Total	**185**	**100**	**114.42**	**100**	**8.571**	**100**	**0.62**

The mean slope of CI glaciers was 28° in the Tons sub-basin and 23° in the Upper Yamuna sub-basin. The mean slope of DC glaciers was 10°.

Morphological glacier type – The morphological classification of glaciers in the Yamuna basin is summarised in Table 7.5; the comparative distribution by number, area, and ice reserves is shown graphically in Figure 7.6.

Close to 97% of the glaciers were identified as mountain type: 54% mountain basin type, 31% ice apron type, and the remainder a mix of types. The Tons and upper Yamuna sub-basins contained 92 and 8 mountain basin type glaciers, respectively. Mountain type glaciers covered 49% of the glacier area, and contained 27% of the estimated ice reserves (Table 7.5).

The valley glaciers in the region have both compound and simple basins. There were six valley glaciers, all in the Tons sub-basin. Although only 3% of the total number, the valley glaciers covered more than 50% of the glacier area and contained 73% of the ice reserves (Figure 7.6).

Clean-ice and debris-covered glaciers – Overall, 14% of the glaciers in the Yamuna basin were DC type, all within the Tons sub-basin, and covering an area of 16 km². The majority of glaciers in the Upper Yamuna sub-basin were smaller CI type glaciers on the mountain slopes.

Hypsography – The glacier area-altitude distribution in the two sub-basins is shown in Figure 7.7. The glaciers extended from 3,800 to 6,200 masl in the Tons sub-basin and from 4,500 to 5,400 masl in the Upper Yamuna

Figure 7.5: Aspect and mean slope of glaciers in the Yamuna basin

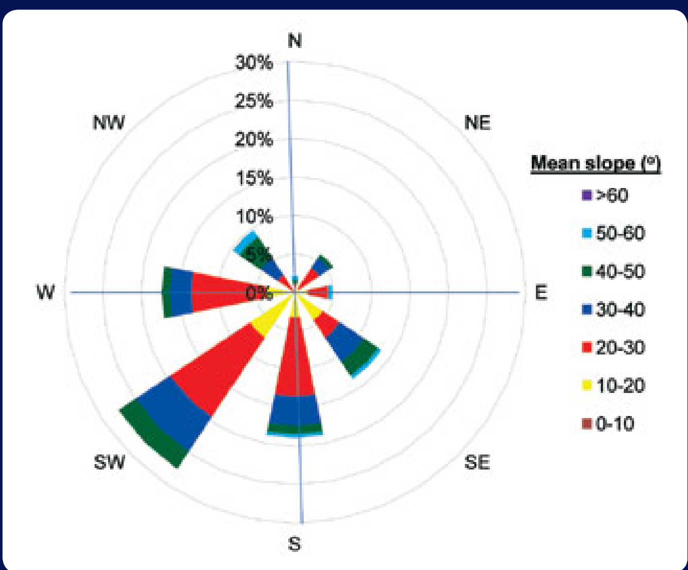


Figure 7.6: Comparative distribution of different glacier types in the Yamuna basin by number, area, and estimated ice reserves

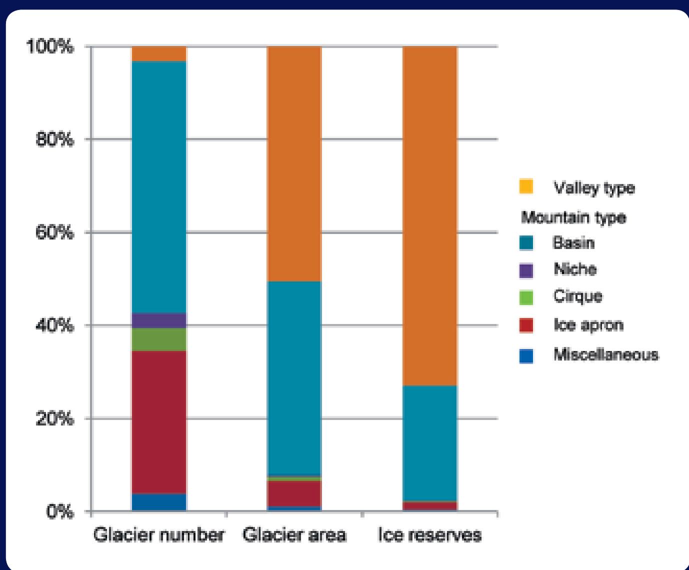


Table 7.5: Morphological classification of glaciers in the Yamuna basin

Glacier type		Number		Area		Estimated ice reserves		Mean area per glacier
		Total	%	km²	%	km³	%	km²
Mountain	Miscellaneous	7	3.8	1.27	1.1	0.034	0.4	0.18
	Ice apron	57	30.8	6.25	5.5	0.141	1.6	0.11
	Cirque	9	4.9	1.01	0.9	0.019	0.2	0.11
	Niche	6	3.2	0.48	0.4	0.008	0.1	0.08
	Basin	100	54.1	47.60	41.6	2.118	24.7	0.48
Valley	Trough	6	3.2	57.82	50.5	6.251	72.9	9.64
	Total	**185**	**100**	**114.42**	**100**	**8.571**	**100**	**0.62**

sub-basin. The glacier area in the Tons sub-basin was more than 5 km² in every 100 m band from 4,600 to 5,600 masl. The maximum glaciated areas were 11 km² at 5,100 masl in the Tons sub-basin, and a little more than 1 km² at an elevation of 4,800 to 4,900 in the Upper Yamuna sub-basin.

Upper Ganga basin

The Upper Ganga basin is drained by the Alaknanda river. There are five glaciated sub-basins, the Alaknanda itself, together with the Bhagirath, Bhilanga, Mandakani, and Pindar (Figure 7.8). The distribution and characteristics of the glaciers in each sub-basin are summarised in Table 7.6.

Number, area, and ice reserves – The Upper Ganga basin has a total area of 34,504 km², with 1,536 glaciers covering 1,627 km², and estimated ice reserves of 162 km³. The number, area, and estimated ice reserves of glaciers in the sub-basins are shown in Figure 7.9. The two major sub-basins Alaknanda and Bhagirathi together contain 1300 glaciers, more than 75% of the total, covering 1430 km², 88% of the total glacier area. The Upper Ganga basin is characterised by many small glaciers, but as a result of the presence of a few large glaciers, the average area of the glaciers in the basin is more than 1 km². The estimated ice reserves in the Alaknanda and Bhagirathi sub-basins are almost equal, a total together of 148 km³ or more than 90% of the reserves in the basin.

Glacier area classes – The number, area, and estimated ice reserves of glaciers in the different size classes are summarised in Table 7.7 and shown as a percentage of the total in Figure 7.10. The great majority of the glaciers, 1138 or 74% of the total, were in class 1 (≤0.5 km²), but together contributed only about 10% of the glacier area and just over 2% of the ice reserves. A further 22% of the glaciers were in class 2 or 3, covering 31% of the glaciated area and containing 17% of the ice reserves. The 27 glaciers in class 5, 2% of the total, covered nearly 44% of the area and contained close to 70% of the basin's ice reserves.

Glacier elevation – The highest glacier elevation was 7,481 masl and the lowest 3,762 masl, both in the Alaknanda sub-basin (Table 7.6 and Figure 7.11). The termini of the glaciers in the Bhagirathi sub-basin were all above 4,000 masl, whereas in the other sub-basins they lay a little below this.

Glacier aspect – Figure 7.12 shows the percentage of glaciers with different aspects and mean slope. More than 20% of the glaciers had a southwest aspect, more than 15% southeast and south aspects, and just under 15% west and east aspects. Only about 2% faced north.

Figure 7.7: Area-altitude distribution of glaciers in the sub-basins of the Yamuna basin

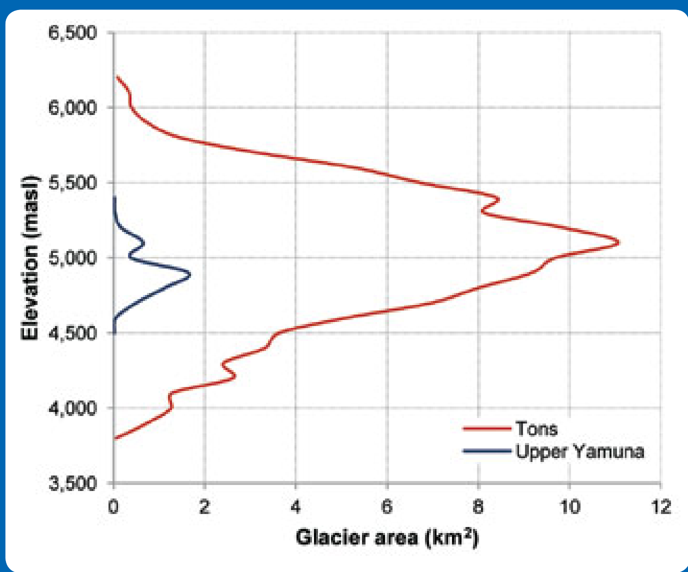


Figure 7.8: Distribution of glaciers in the Upper Ganga basin

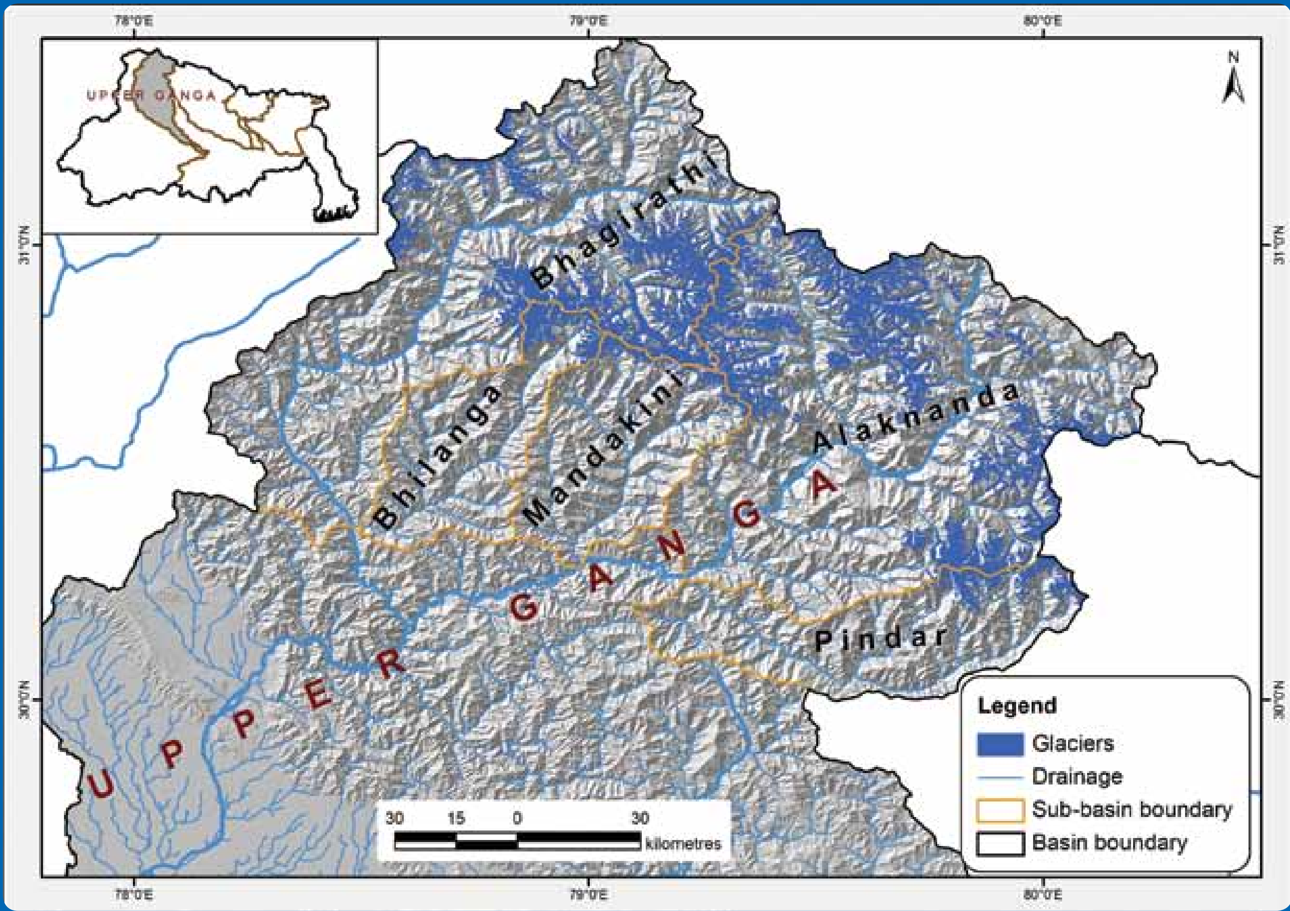


Table 7.6: Glacier characteristics in the Upper Ganga basin

Parameter	Units	Sub-basin					Upper Ganga
		Bhagirathi	Bhilanga	Mandakini	Alaknanda	Pindar	
Basin area	km²	5,832	1,463	1,645	6,416	1,897	34,504*
Latitude	degrees	30.73-31.37	30.73-30.88	30.59-30.80	30.25-31.06	30.19-30.30	30.19-31.37
Longitude	degrees	78.55-79.41	78.83-79.03	78.98-79.35	79.23-80.23	79.76-80.08	78.55-80.23
Number of glaciers	unit	510	46	77	790	113	1,536
CI glacier area	km²	510.98	77.52	35.80	679.16	69.03	1,372.49
DC glacier area	km²	93.42	2.08	4.74	146.85	7.5	254.59
Total glacier area	km²	604.40	79.60	40.54	826.01	76.53	1,627.08
Largest glacier area	km²	176.76	29.67	5.85	43.05	11.15	176.76
Total ice reserves	km³	73.79	7.48	2.13	73.78	4.90	162.08
Highest elevation	masl	6,904	6,572	6,725	7,481	6,683	7,481
Lowest elevation	masl	4,084	3,934	3,828	3,762	3,814	3,762
CI glacier elevation	masl	4,087-6,904	4,151-6,572	3,895-6,725	4,086-7,481	3,973-6,683	3,895-7,481
DC glacier elevation	masl	4,084-5,929	3,934-4,876	3,828-4,892	3,762-5,825	3,814-5,389	3,762-5,929
Mean CI glacier slope	degrees	28	27	32	29	33	30
Mean DC glacier slope	degrees	11	13	18	11	21	15
CI-DC area ratio	unit	5.47	37.23	7.55	4.62	9.20	5.39
Average glacier area	km²	1.19	1.73	0.53	1.05	0.68	1.06

*Includs area of not glaciated sub-basins

Table 7.7: Glacier area classes in the Upper Ganga basin

Area class	Area (km²)	Number		Area		Estimated ice reserves		Mean area per glacier
		Total	%	km²	%	km³	%	km²
1	≤ 0.5	1,138	74.1	167.20	10.3	3.715	2.3	0.15
2	0.51-1.00	153	10.0	105.74	6.5	3.876	2.4	0.69
3	1.01-5.00	184	12.0	399.46	24.6	23.591	14.6	2.17
4	5.01-10.00	34	2.2	230.88	14.2	19.383	12.0	6.79
5	≥10.00	27	1.8	723.81	44.5	111.513	68.8	26.81
	Total	**1,536**	**100**	**1,627.08**	**100**	**162.077**	**100**	**1.06**

Figure 7.9: Glacier number, area, and estimated ice reserves in the sub-basins of the Upper Ganga basin

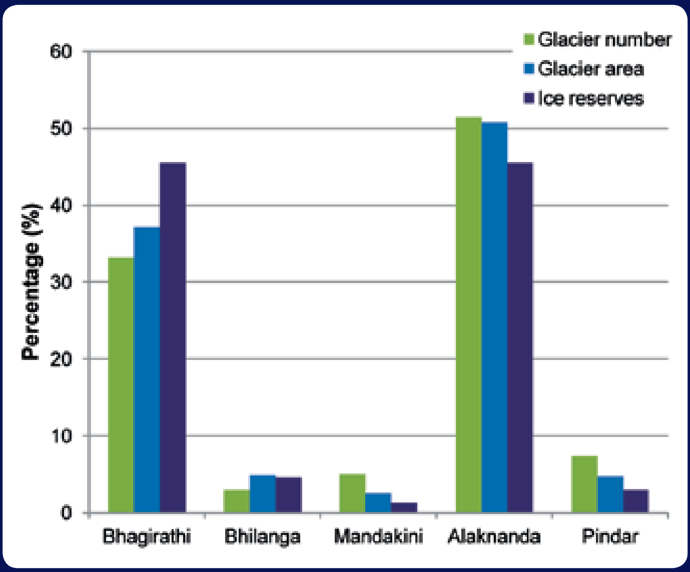


Figure 7.10: Percentage of glacier number, area, and estimated ice reserves in the different glacier size classes in the Upper Ganga basin

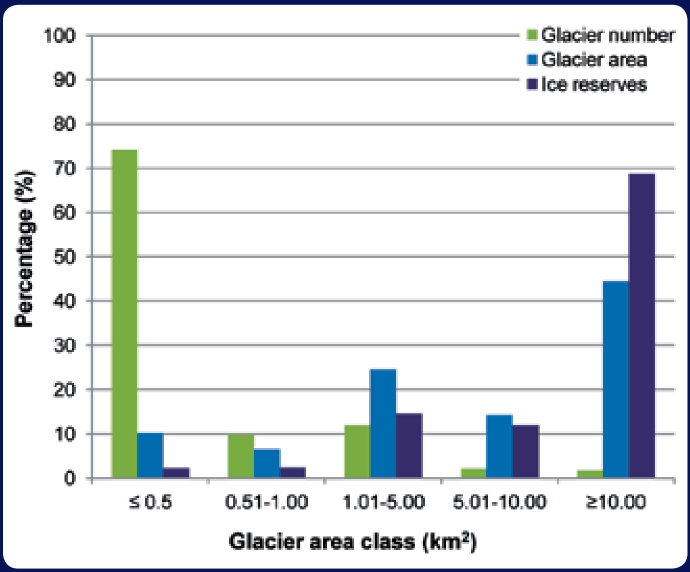


Figure 7.11: Elevation of CI and DC glaciers in the sub-basins of the Upper Ganga basin

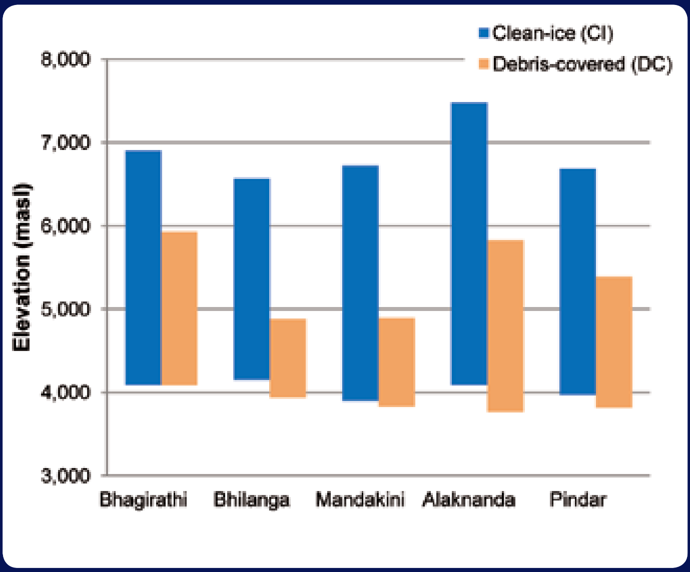
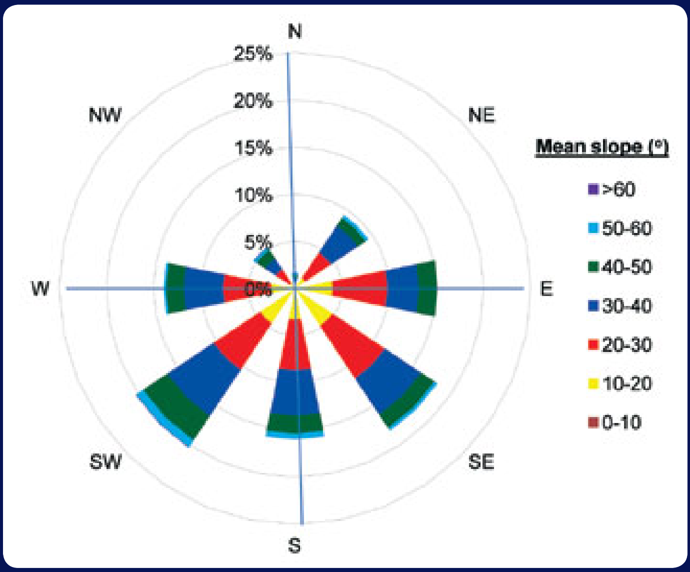


Figure 7.12: Aspect and mean slope of glaciers in the Upper Ganga basin



Slope – The mean slope of the glaciers in the basin ranged from 10° to 60°, with slopes of 20° to 30° and 30° to 40° most common for all aspects (Figure 7.12). Less than 1% of glaciers of all aspects had steep slopes of 50° to 60°. A very few glaciers with a southwest aspect had slopes of more than 60°.

The mean slope of DC glaciers in the different sub-basins ranged from 11° to 21°; and that of CI glaciers from 27° to 33° (Table 7.6 and Figure 7.13). The mean slopes of both CI and DC glaciers were higher in the Pindar and Mandakini sub-basins than in the other sub-basins.

Morphological glacier type – The morphological classification of glaciers in the upper Ganga basin is summarised in Table 7.8; the comparative distribution by number, area, and estimated ice reserves is shown graphically in Figure 7.14.

Close to 96% of the glaciers were identified as mountain type, the majority of them ice apron type, followed closely by basin type. Mountain glaciers contributed 49% of the glacier area, and 28% of estimated ice reserves.

The valley glaciers in the region have both compound basins and simple basins. The 65 valley glaciers, 4% of the total number, contributed more than 50% of glacier area and 71% of ice reserves.

Table 7.8: Morphological classification of glaciers in the Upper Ganga basin

Glacier type		Number		Area		Estimated ice reserves		Mean area per glacier
		Total	%	km²	%	km³	%	km²
Mountain	Miscellaneous	29	1.9	11.08	0.7	0.448	0.3	0.38
	Ice apron	746	48.6	101.48	6.2	2.597	1.6	0.14
	Cirque	3	0.2	0.73	0.04	0.022	0.01	0.24
	Niche	32	2.1	3.54	0.2	0.086	0.05	0.11
	Basin	661	43.0	689.70	42.4	43.187	26.7	1.04
Valley	Trough	65	4.2	820.55	50.4	115.74	71.4	12.62
	Total	**1,536**	**100**	**1,627.08**	**100**	**162.077**	**100**	**1.06**

Figure 7.13: Mean slope of CI and DC glaciers in the sub-basins of the upper Ganga basin

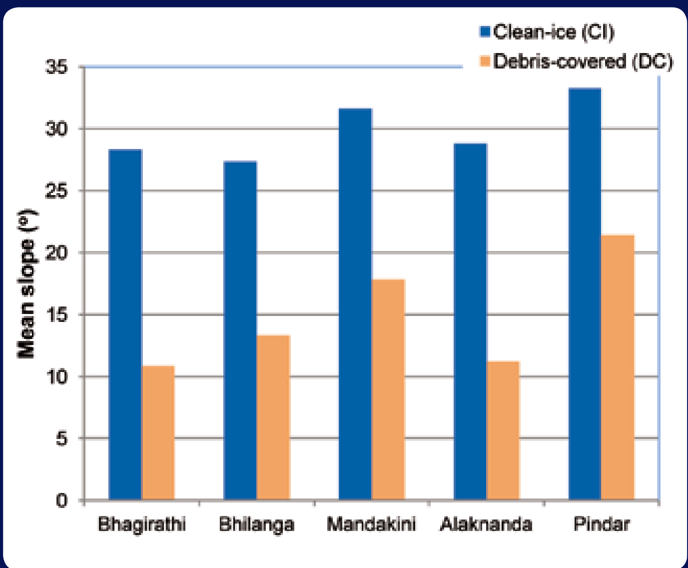
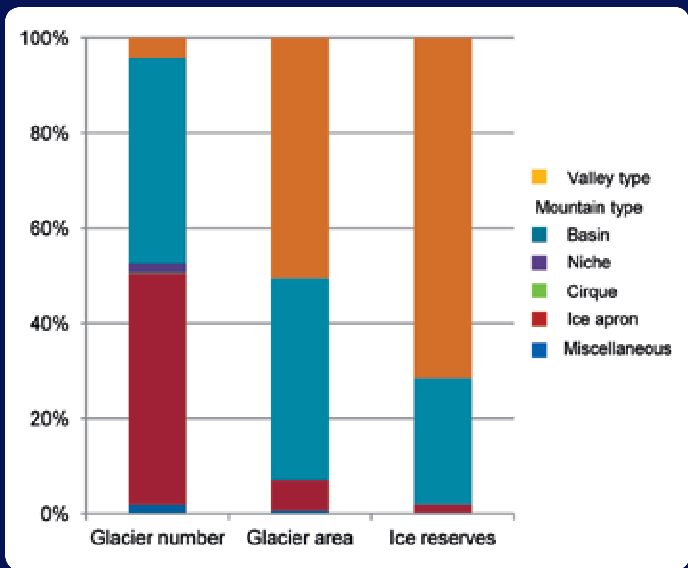


Figure 7.14: Comparative distribution of different glacier types in the Upper Ganga basin by number, area, and estimated ice reserves



Clean-ice and debris-covered glaciers – The DC glaciated area was 254 km², close to 17% of the total, almost all (239 km²) in the highly glaciated Bhagirathi and Alaknanda sub-basins (Table 7.6). The actual proportion of DC glaciers in the different sub-basins was similar, with the exception of the Bhilganga sub-basin which had a very small proportion of DC glaciers (Figure 7.15).

Hypsography – The glacier area-altitude distribution in the sub-basins is shown in Figure 7.16. The maximum glaciated areas were 67.8 km² at 5,500-5,600 masl in the Alaknanda sub-basin and 51.3 km² at 5,300-5,400 masl in the Bhagirathi sub-basin. The Alaknanda sub-basin had glacier areas of more than 50 km² in all hundred metre elevation bands between 5,100 and 5,800 masl, and areas of 20 to 50 km² in all bands from 4,600 to 5,100 masl and 5,800 to 6,000 masl. The glacier area below 3,900 masl and above 6,900 masl was less than 1 km² (Figure 7.16).

Karnali (Ghaghara) basin

The Karnali river originates in the Tibetan Plateau near Lake Mansarovar. The catchment lies between longitudes 80.00° and 83.66° E and latitudes 28.67° and 30.58° N (Figure 7.17). The Karnali is joined by the Kali (Mahakali in Nepal), West Seti, Humla, Kawari, Tila, Mugu Karnali, and Bheri rivers. The major part of the Mugu Karnali flows from east to west, and of the Humla Karnali from west to east, unlike most rivers on the southern flanks of the Himalayas, which generally flow from north to south. The Karnali river is called the Ghaghara in India, and is one of the major tributaries of the Ganges. The glaciers are mostly found in the northern part of the basin (Figure 7.17). The distribution and characteristics of the glaciers in each sub-basin are summarised in Table 7.9.

Number, area, and ice reserves – The Karnali basin extends across three countries, Nepal, India, and China and is the largest river basin in Nepal (Table 7.9). A total of 2417 glaciers were identified in the basin with an area of 1,872 km² and estimated ice reserves of 122 km³. The Kali sub-basin had the most glaciers (758) and the Kawari sub-basin the least (48).

The number, area, and estimated ice reserves of glaciers in the sub-basins are shown in Figure 7.18. The Kali, Bheri, and Humla sub-basins had the greatest number of glaciers and proportion of the glaciated area, and contributed most to the estimated ice reserves (34%, 28%, and 23% of the total, respectively). The largest glacier was the compound basin type glacier of GLIMS ID G080065E30534N with an area of about 46 km² located in the Kali sub-basin, and extending from 6,780 to 4,234 masl.

Figure 7.15: Percentage distribution by area of CI and DC glaciers in the sub-basins of the Upper Ganga basin

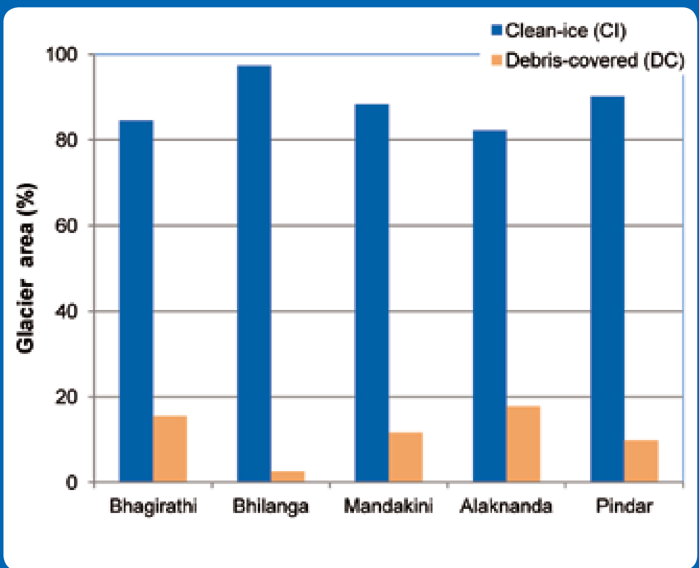


Figure 7.16: Area-altitude distribution of glaciers in the sub-basins of the Upper Ganga basin

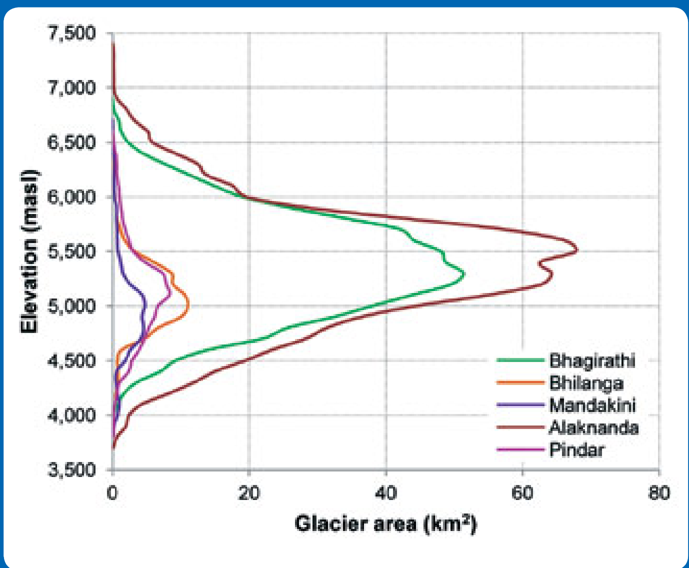


Figure 7.17: Distribution of glaciers in the Karnali (Ghaghara) basin

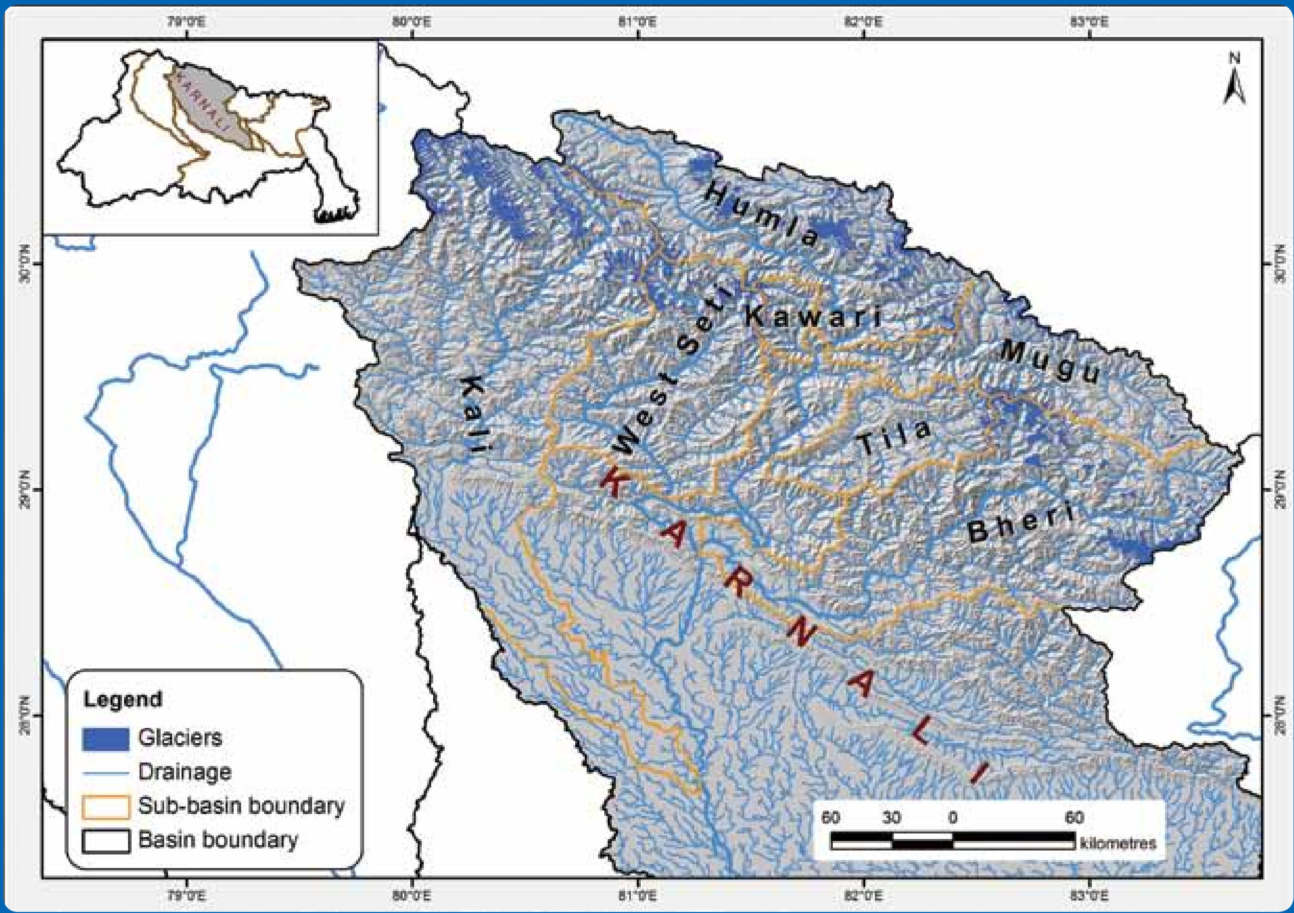


Figure 7.18: Glacier number, area, and estimated ice reserves in the sub-basins of the Karnali basin

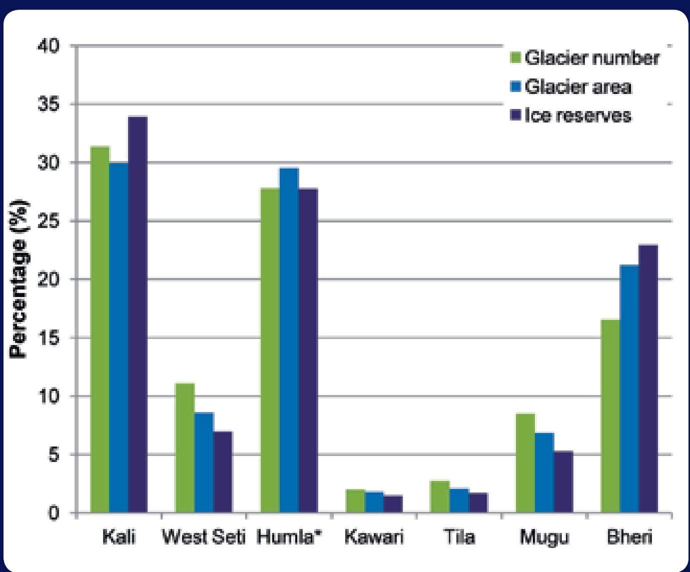


Figure 7.19: Percentage of glacier number, area, and estimated ice reserves in the different glacier size classes in the Karnali basin

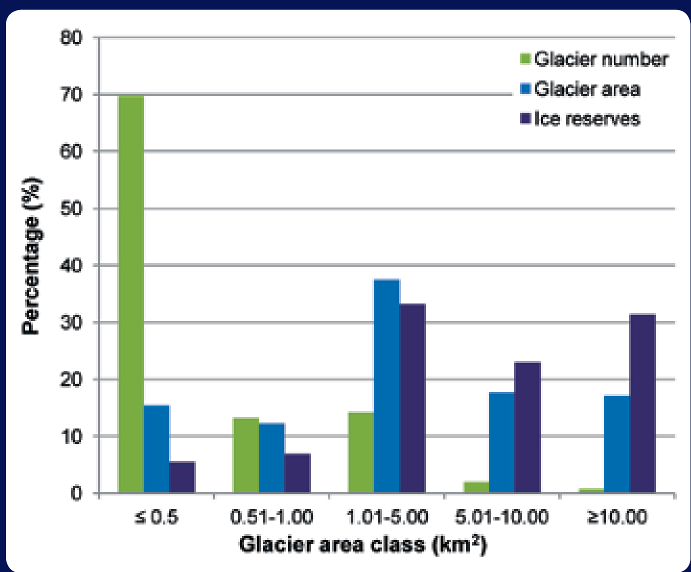


Table 7.9: Glacier characteristics in the Karnali (Ghaghara) basin

Parameter	Units	Sub-basin							Karnali
		Kali	West Seti	Humla*	Kawari	Tila	Mugu	Bheri	
Basin area	km^2	17,325	7,372	8,989	822	3,327	5,374	13,686	81,711**
Latitude	degrees	29.83-30.58	29.66-30.05	29.68-30.50	29.68-29.94	29.19-29.48	29.11-29.95	28.67-29.42	28.67-30.58
Longitude	degrees	80.00-81.11	81.00-81.56	80.64-82.48	81.51-81.73	82.34-82.58	82.24-83.51	82.40-83.66	80.00-83.66
Number of glaciers	unit	758	268	672	48	66	205	400	2,417
CI glacier area	km^2	465.15	138.26	326.18	30.18	37.34	108.05	383.96	1,489.12
DC glacier area	km^2	95.32	22.59	35.54	3.19	1.87	19.73	13.37	191.61
Total glacier area	km^2	560.47	160.86	552.95	33.37	39.21	127.78	397.33	1,871.98
Largest glacier area	km^2	46.34	14.25	14.14	8.56	8.08	8.57	24.79	46.34
Total ice reserves	km^3	41.23	8.47	33.72	1.78	2.05	6.40	27.91	121.56
Highest elevation	masl	6,850	6,982	7,678	6,795	6,408	6,837	7,515	7,678
Lowest elevation	masl	3,476	4,064	4,249	3,631	4,043	4,473	4,096	3,476
CI glacier elevation	masl	3,610-6,850	4,393-6,982	4,315-7,678	3,877-6,795	4,407-6,408	4,650-6,837	4,440-7,515	3,610-7,678
DC glacier elevation	masl	3,476-5,406	4,064-5,839	4,249-5,721	3,631-4,013	4,043-4,455	4,473-5,659	4,096-5,499	3,476-5,839
Mean CI glacier slope	degrees	30	30	24	25	31	28	30	28
Mean DC glacier slope	degrees	10	15	14	7	8	13	11	11
CI-DC area ratio	unit	4.88	6.12	9.18	9.46	19.99	5.48	28.71	7.77
Average glacier area	km^2	0.74	0.60	0.82	0.70	0.59	0.62	0.99	0.77

*extends into China (area in China contains 198 glaciers with an area of 191 km^2, all in the Humla sub-basin; CI/DC differentiation excludes these); **includes area of not glaciated sub-basins

Glacier area classes – The number, area, and estimated ice reserves of glaciers in the different size classes are summarised in Table 7.10 and shown as a percentage of the total in Figure 7.19. The small class 1 glaciers (≤0.5 km²) were the most numerous (1,686, about 70% in the basin) but contributed only 15% of the glacier area and 5% of the ice reserves. The large glaciers in class 5 had an average area of 17 km² and contributed about 17% of the glacier area and 31% of the ice reserves.

Glacier elevation – The highest glacier elevation was 7,678 masl, in the Humla sub-basin, and the lowest 3,476 masl, in the Kali sub-basin (Figure 7.20). CI glaciers were found from 7,678 to 3,610 masl and DC glaciers from 5,839 to 3,476 masl .

Glacier aspect – Figure 7.21 shows the percentage of glaciers with different aspects and mean slope. Similar numbers of glaciers (16 to 18%) had west, southwest, south, southeast, and east aspects. Only 1% had a northern aspect.

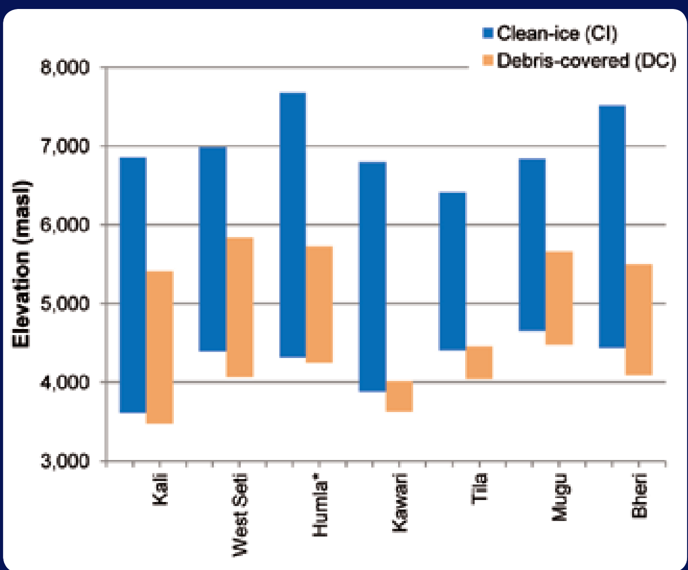
Slope – The mean slope of the glaciers in the basin ranged from 10° to 60°. The majority of glaciers with all aspects had slopes of 20° to 40°, with the two classes 20° to 30° and 30° to 40° almost equally represented. Less than 1% of glaciers had mean slopes of 50° to 60°, and all with north, northwest or west aspects.

The average slope of the CI glaciers in the sub-basins ranged from 24° to 31°, and of DC glaciers from 7° to 15° with slight basin to basin variations (Figure 7.22).

Table 7.10: Glacier area classes in the Karnali basin

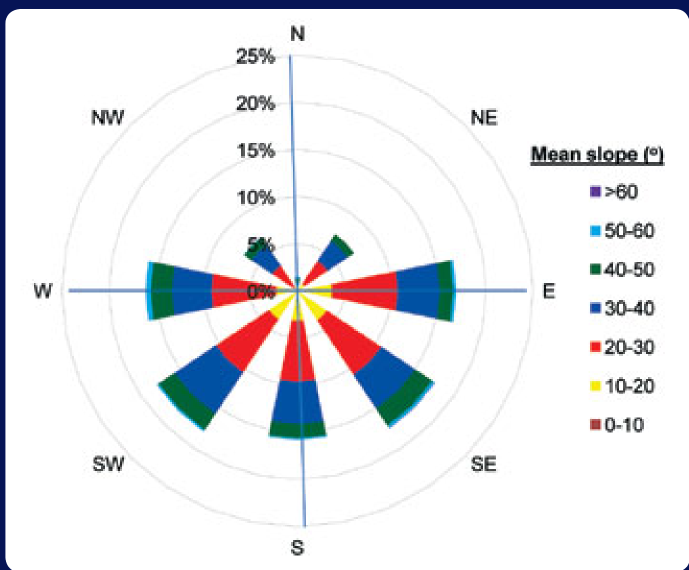
Area class	Area (km²)	Number		Area		Estimated ice reserves		Mean area per glacier
		Total	%	km²	%	km³	%	km²
1	≤ 0.5	1,686	69.8	288.95	15.4	6.721	5.5	0.17
2	0.51-1.00	321	13.3	228.54	12.2	8.474	7.0	0.71
3	1.01-5.00	343	14.2	701.60	37.8	40.339	33.2	2.05
4	5.01-10.00	48	2.0	331.67	17.7	27.954	23.0	6.91
5	≥10.00	19	0.8	321.21	17.2	38.073	31.3	16.91
	Total	**2,417**	**100**	**1,871.97**	**100**	**121.560**	**100**	**0.77**

Figure 7.20: Elevation of CI and DC glaciers in the sub-basins of the Karnali basin



Excluding glaciers in China

Figure 7.21: Aspect and mean slope of glaciers in the Karnali basin



Morphological glacier type – The morphological classification of glaciers in the Karnali basin is summarised in Table 7.11; the comparative distribution by number, area, and ice reserves is shown graphically in Figure 7.23. The part of the Humla sub-basin in China has a total of 198 glaciers. These glaciers were not classified morphologically, and are not included here.

More than 98% of the glaciers were identified as mountain type, the majority basin type (66%), followed by apron type (23%). Mountain type glaciers covered 81% of the glaciated area and contained 69% of the total ice reserves (Table 7.11). The 41 valley glaciers comprised less than 2% of the total by number, but with an average area of 7.86 km², contributed 19% of the total glacier area and 31% of the total estimated ice reserves

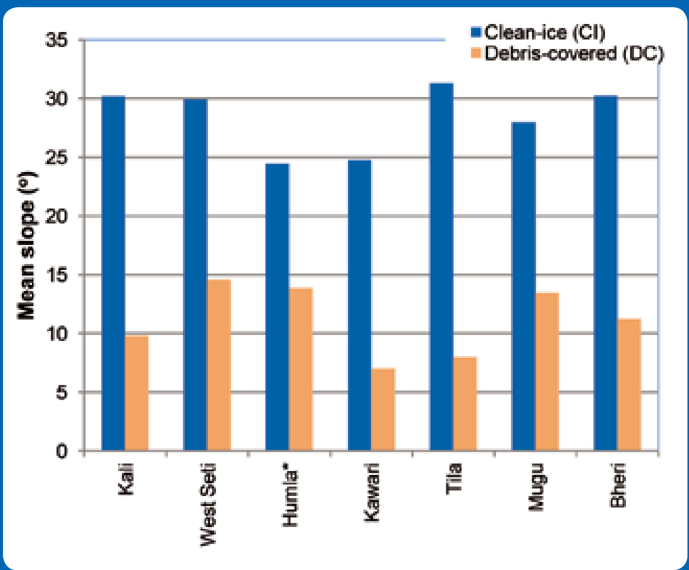
Clean-ice and debris-covered glaciers – In total, 126 of the 2,219 glaciers classified had a debris-covered component, covering about 12% of the total glacier area. Figure 7.24 shows the area distribution of CI and DC glaciers in the sub-basins. The Bheri and Tila sub-basins had the lowest proportion of DC glaciers and the Kali and Mugu the highest. Overall the CI to DC ratio in the Karnali basin was close to 8:1 (Table 7.9), which is comparatively higher than in the other basins of the HKH region.

Hypsography – The glacier area-altitude distribution in the sub-basins is shown in Figure 7.25. The maximum glaciated area in the basin overall was 172 km² at 5,300-5,400 masl; glaciated areas of greater than 10 km² within a 100 m band were found at all elevations from 4,200 to 6,600 masl. The maximum glaciated areas in the sub-basins were 59.4 km² at 5,400-5,500 in the Humla sub-basin; 47 km² at 5,200-5,300 in the Kali sub-basin,

Table 7.11: Morphological classification of glaciers in the Karnali basin (exclusing glaciers in China)

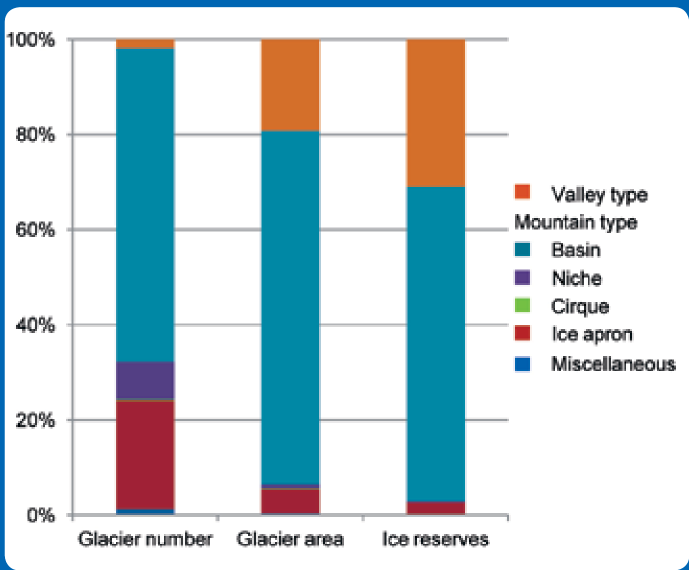
Glacier type		Number		Area		Estimated ice reserves		Mean area per glacier
		Total	%	km²	%	km³	%	km²
Mountain	Miscellaneous	28	1.3	6.05	0.4	0.202	0.2	0.22
	Ice apron	508	22.9	85.76	5.1	2.615	2.4	0.17
	Cirque	4	0.2	1.65	0.1	0.054	0.1	0.41
	Niche	176	7.9	16.00	1.0	0.273	0.3	0.09
	Basin	1,462	65.9	1,248.90	74.3	71.938	66.2	0.85
Valley	Trough	41	1.9	322.38	19.2	33.658	31.0	7.86
	Total	**2,219**	**100**	**1,680.73**	**100**	**108.740**	**100**	**0.76**

Figure 7.22: Mean slope of CI and DC glaciers in the sub-basins of the Karnali basin



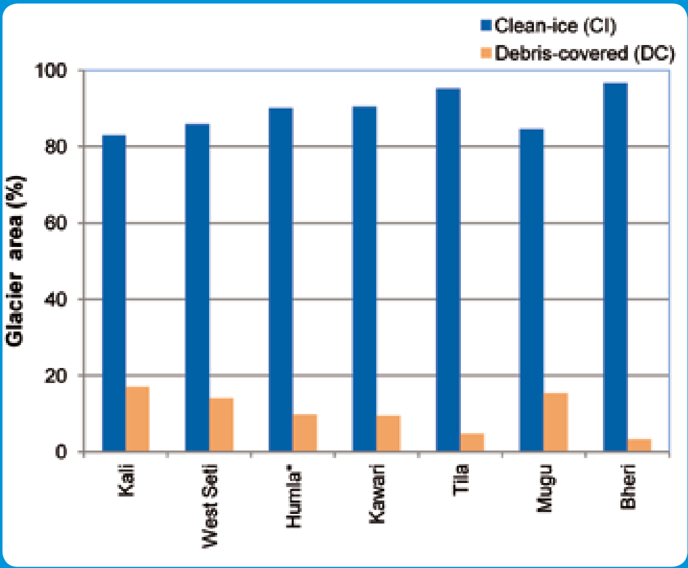
Excluding glaciers in China

Figure 7.23: Comparative distribution of different glacier types in the Karnali basin by number, area, and estimated ice reserves



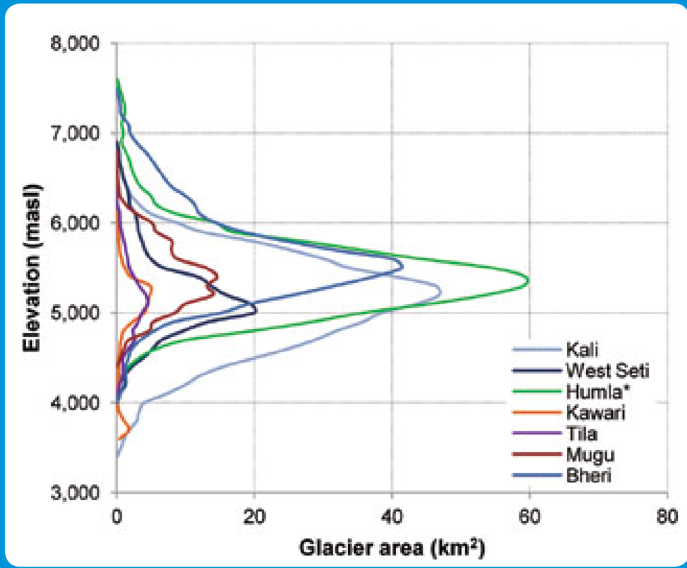
Excluding glaciers in China

Figure 7.24: Percentage distribution by area of CI and DC glaciers in the sub-basins of the Karnali basin



Excluding glaciers in China

Figure 7.25: Area-altitude distribution of glaciers in the sub-basins of the Karnali basin



Excluding glaciers in China

41.4 km² at 5,500-5,600 masl in the Bheri sub-basin, 20 km² at 5,000-5,100 in the West Seti sub-basin, 14.6 km² at 5,400-5,500 in the Mugu sub-basin, 4.9 km² at 5,300-5,400 in the Kawari sub-basin, and 4.5 km² at 5,100-5,200 in the Tila sub-basin.

Gandaki basin

The Gandaki river is also known as the Sapta Gandaki and in the lower reaches as the Narayani. The Gandaki basin lies in central Nepal between the Karnali and Koshi basins between longitudes 83.25° and 85.74° E and latitudes 28.11° and 29.33° N, with a catchment area extending into China (Figure 7.26). The river has seven major tributaries, but only five have catchment areas with glaciers: the Trishuli (the main tributary), Budhi Gandaki, Marsyangdi, Seti, and Kali Gandaki (Figure 7.26). The Budhi Gandaki and Marsyangdi rivers flow from north-central Nepal, and the Seti and Kali Gandaki rivers from western Nepal. The Gandaki has an immense annual discharge, which flows towards the southwest into the Ganges in India. The distribution and characteristics of the glaciers in each sub-basin are summarised in Table 7.12.

Number, area, and ice reserves – The Gandaki basin had a total of 1,710 glaciers with an area of 2,285 km² and estimated ice reserves of 194 km³ (Table 7.12). The number, area, and estimated ice reserves of glaciers in the sub-basins are shown in Figure 7.27. The Kali Gandaki sub-basin had the most glaciers (507) and the Seti sub-basin the least (45), while the Trishuli sub-basin had the highest glacier area coverage (639 km²) and estimated ice reserves (59 km³). The largest glacier was the compound basin type glacier with GLIMS ID G085711E28293N (Gtrgr10_106), which had an area of 59 km² extending from 7,168 to 4,467 masl. The Seti is the smallest basin in the Gandaki but had the second largest glacier, GLIMS ID G084129E28507N (Gsegr10_30) with an area of 46 km².

Glacier area classes – The number, area, and estimated ice reserves of glaciers in the different size classes are summarised in Table 7.13 and shown as a percentage of the total in Figure 7.28. The majority of glaciers were in the smallest class (1,043, or 61%); and the least in class 4 (36 or 2%). The class 1 glaciers contributed only 9% of the glacier area and 2% of the ice reserves. The 46 glaciers in class 5 (more than 10 km²) were only 3% of the total number, but had the greatest total area (42% of the total) and contained 62% of the ice reserves.

Table 7.12: Glacier characteristics in the sub-basins of the Gandaki basin

Parameter	Units	Sub-basin					Gandaki
		Kali Gandaki*	Seti	Marsyangdi	Budhi Gandaki*	Trishuli*	
Basin area	km²	10,411	2,950	4,791	4,986	5,756	36,450**
Latitude	degrees	28.49-29.33	28.47-28.58	28.34-28.89	28.27-28.90	28.11-28.99	28.11-29.33
Longitude	degrees	83.25-84.22	83.95-84.21	83.79-84.71	84.48-85.19	84.99-85.74	83.25-85.74
Number of glaciers	unit	507	45	385	357	416	1,710
CI glacier area	km²	547.81	67.15	517.03	349.82	219.24	1,701.05
DC glacier area	km²	15.34	4.95	28.35	37.58	42.25	128.48
Total glacier area	km²	569.53	72.10	545.38	459.28	638.89	2,285.18
Largest glacier area	km²	33.25	45.54	30.21	35.20	59.02	59.02
Total ice reserves	km³	43.47	8.35	44.01	37.60	60.83	194.25
Highest elevation	masl	8,093	7,515	7,878	8,019	7,381	8,093
Lowest elevation	masl	3,861	3,754	3,651	3,273	3,692	3,273
CI glacier elevation	masl	4,149-8,093	4,425-7,515	4,034-7,878	3,734-8,019	3,797-7,381	3,734-8,093
DC glacier elevation	masl	3,861-5,475	3,754-5,262	3,651-5,605	3,273-5,754	3,692-5,522	3,273-5,754
Mean CI glacier slope	degrees	29	30	30	32	34	31
Mean DC glacier slope	degrees	19	10	10	13	13	13
CI-DC area ratio	unit	35.70	13.58	18.24	9.31	5.19	13.24
Average glacier area	km²	1.12	1.60	1.42	1.29	1.54	1.34

*extends into China (area in China contains 371 glaciers with an area of 455 km², CI/DC differentiation excludes these);
**includes area of not glaciated sub-basins

Figure 7.26: Distribution of glaciers in the Gandaki basin

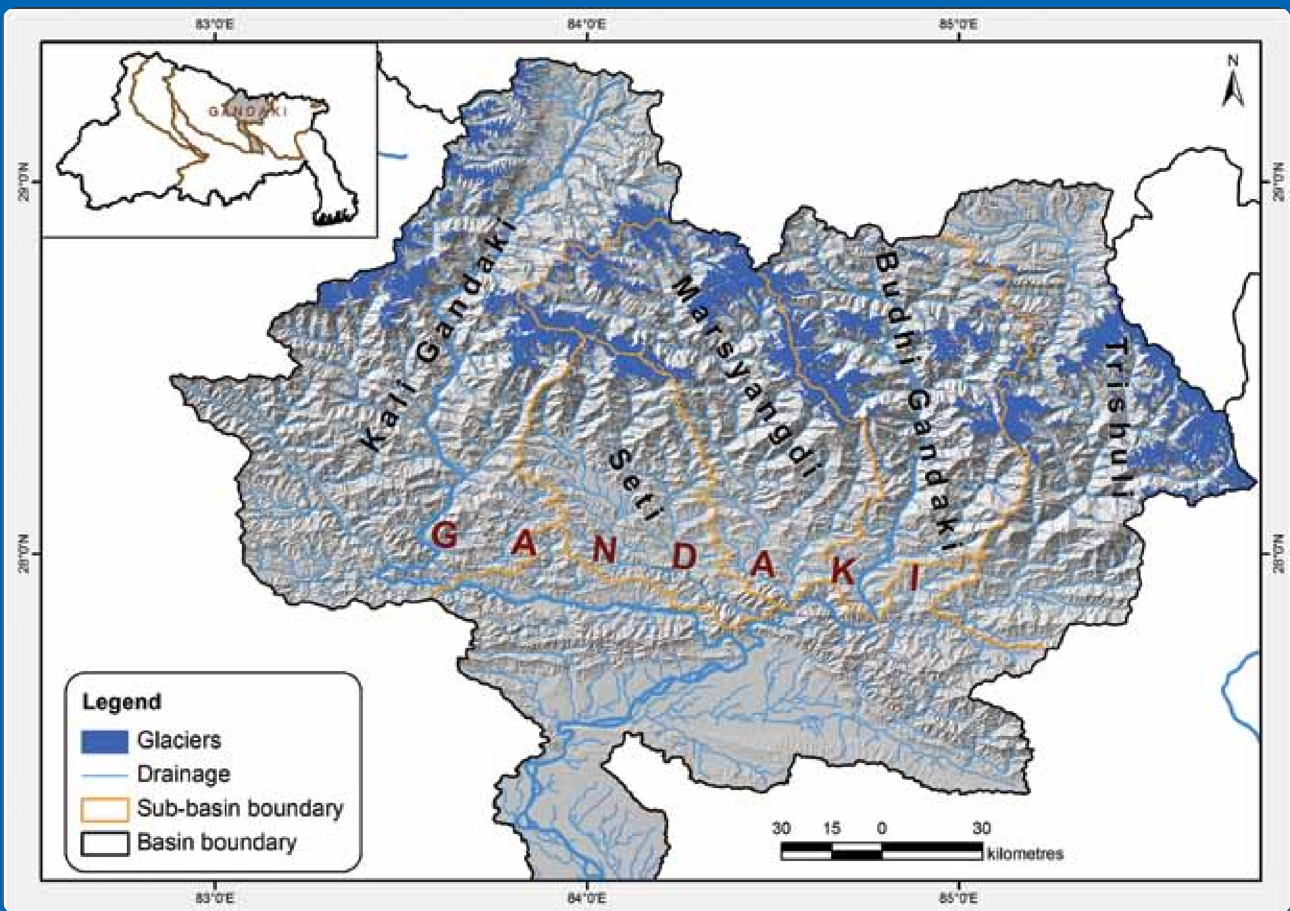


Table 7.13: Glacier area classes in the Gandaki basin

Area class	Area (km²)	Number		Area		Estimated ice reserves		Mean area per glacier
		Total	%	km²	%	km³	%	km²
1	≤0.5	1,043	61.0	203.21	8.9	4.908	2.5	0.19
2	0.51-1.00	256	15.0	178.97	7.8	6.592	3.4	0.70
3	1.01-5.00	329	19.2	697.99	30.5	40.539	20.9	2.12
4	5.01-10.00	36	2.1	253.27	11.1	21.617	11.1	7.04
5	≥10.00	46	2.7	951.74	41.7	120.594	62.1	20.69
	Total	**1,710**	**100**	**2,285.18**	**100**	**194.249**	**100**	**1.34**

Figure 7.27: Glacier number, area, and estimated ice reserves in the sub-basins of the Gandaki basin

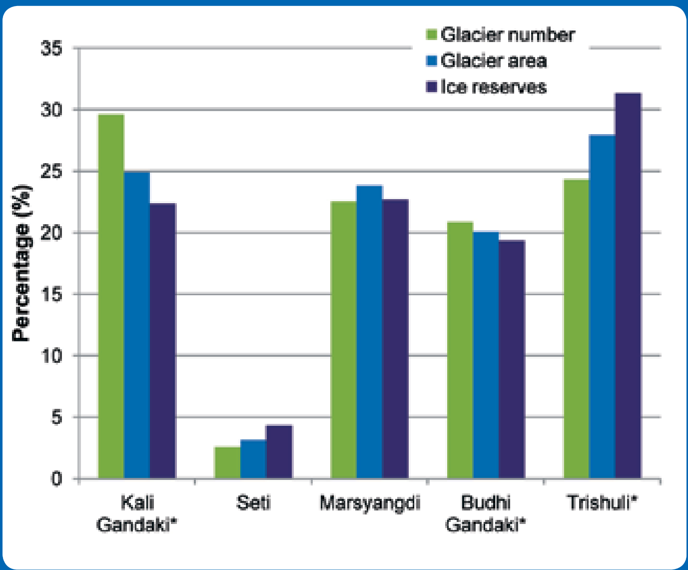


Figure 7.28: Percentage of glacier number, area, and estimated ice reserves in the different glacier size classes in the Gandaki basin

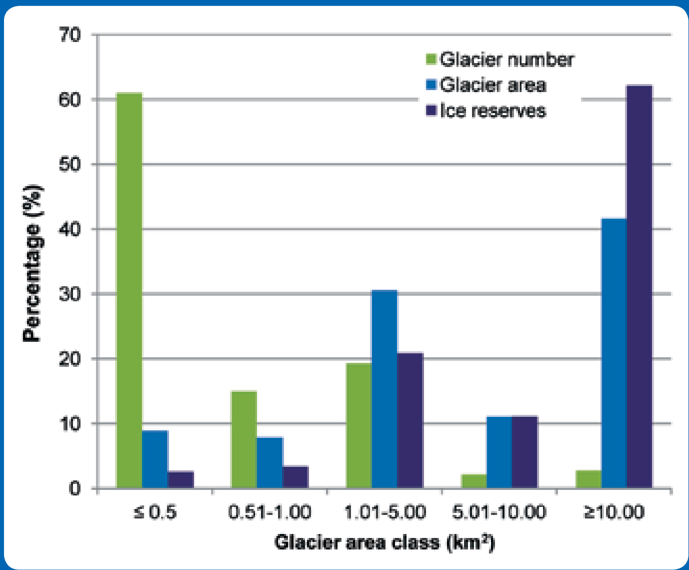


Figure 7.29: Elevation of CI and DC glaciers in the sub-basins of the Gandaki basin

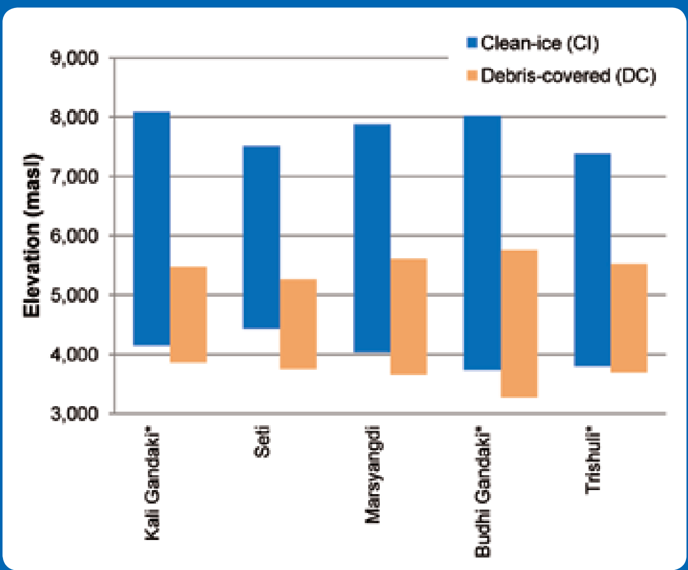
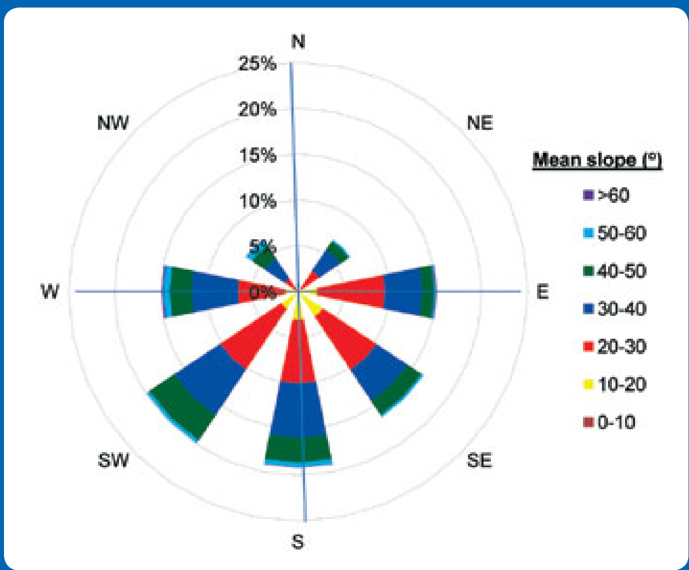


Figure 7.30: Aspect and mean slope of glaciers in the Gandaki basin



Excluding glaciers in China

Table 7.14: Morphological classification of glaciers in the Gandaki basin (excluding glaciers in China)

Glacier type		Number		Area		Estimated ice reserves		Mean area per glacier
		Total	%	km²	%	km³	%	km²
Mountain	Miscellaneous	3	0.2	1.37	0.1	0.048	0.03	0.46
	Ice apron	412	30.8	161.88	8.9	6.838	4.4	0.39
	Cirque	8	0.6	1.86	0.1	0.049	0.03	0.23
	Niche	102	7.6	14.87	0.8	0.372	0.2	0.15
	Basin	786	58.7	1,086.77	59.4	76.986	49.4	1.38
Valley	Trough	28	2.1	562.78	30.8	71.688	46.0	20.10
	Total	**1,339**	**100**	**1,829.52**	**100**	**155.981**	**100**	**1.37**

Glacier elevation – The highest glacier elevation was 8,093 masl in the Kali Gandaki sub-basin and the lowest 3,273 masl in the Budhi Gandaki sub-basin. CI glaciers were found from 8,093 to 3,734 masl and DC glaciers from 5,754 to 3,273 masl (Figure 7.29) (glaciers in China were not analysed).

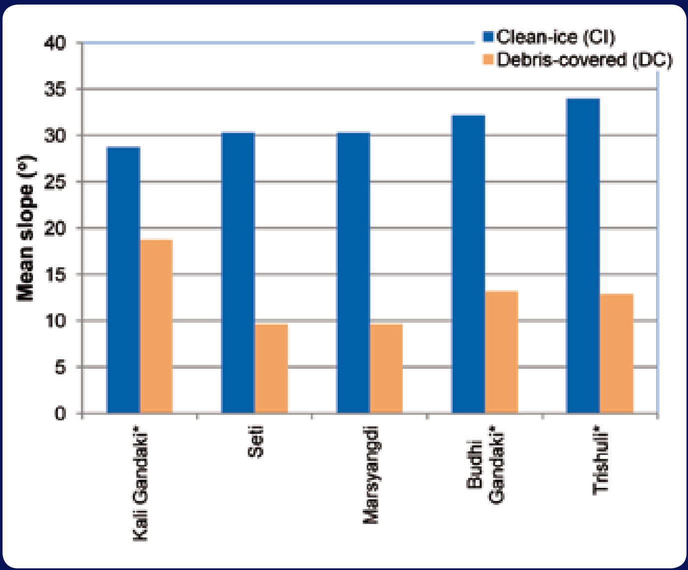
Glacier aspect – Figure 7.30 shows the percentage of glaciers with different aspects and mean slope. The glaciers in the Gandaki basin are distributed in all cardinal directions. Approximately 20% of the glaciers faced southwest and 19% south. Around 15% had a southeast, east, or west aspect. Only 1% had a north aspect.

Slope – The mean slope of the glaciers ranged from 10° to more than 60°, with slopes of 20° to 40° most common, but slopes of 20° to 30° slightly more common in glaciers with a southwest, south, southeast, or east aspect, and slopes of 30° to 40° more common in glaciers with a west or more northerly aspect. A very few glaciers had slopes of less than 10° or more than 50°.

Figure 7.31 shows the mean slope of CI and DC glaciers in the different basins. As elsewhere, the mean slope of CI glaciers was considerably higher than those of DC glaciers in all sub-basins except the Kali Gandaki, where the difference was less marked.

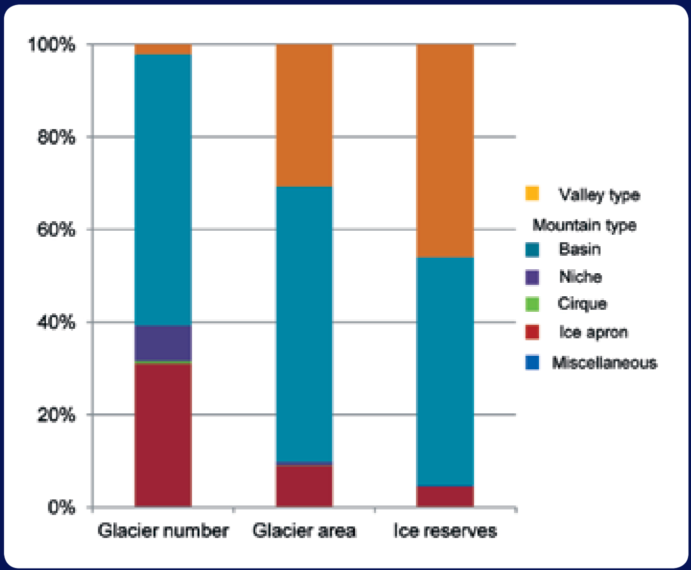
Morphological glacier type – The morphological classification of glaciers in the Gandaki basin is summarised in Table 7.14; the comparative distribution by number, area, and ice reserves is shown graphically in Figure 7.32. The 371 glaciers in China were not classified morphologically, and are not included here.

Figure 7.31: Mean slope of CI and DC glaciers in the sub-basins of the Gandaki basin



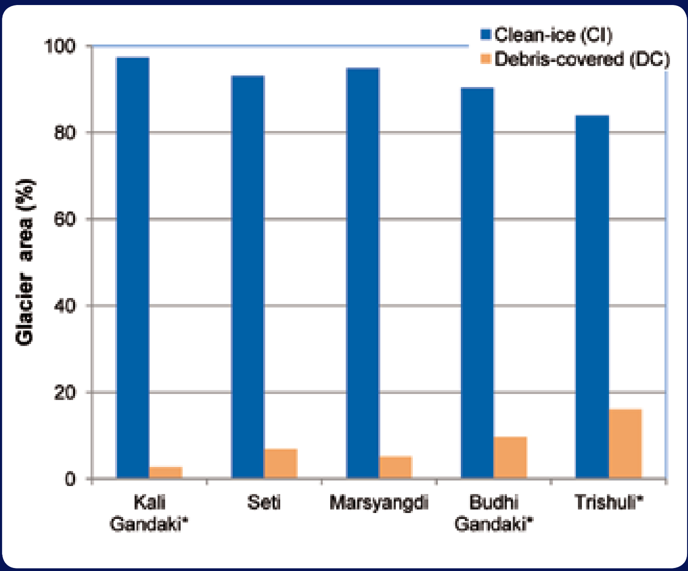
Excluding glaciers in China

Figure 7.32: Comparative distribution of different glacier types in the Gandaki basin by number, area, and estimated ice reserves



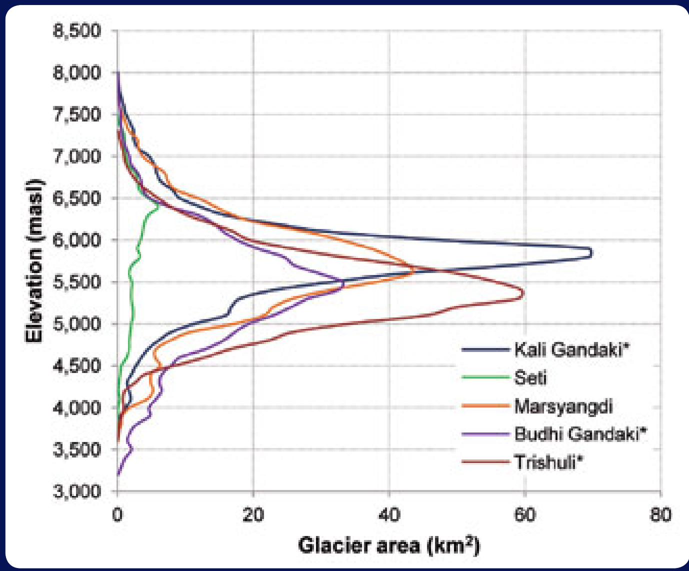
Excluding glaciers in China

Figure 7.33: Percentage distribution by area of CI and DC glaciers in sub-basins of the Gandaki basin.



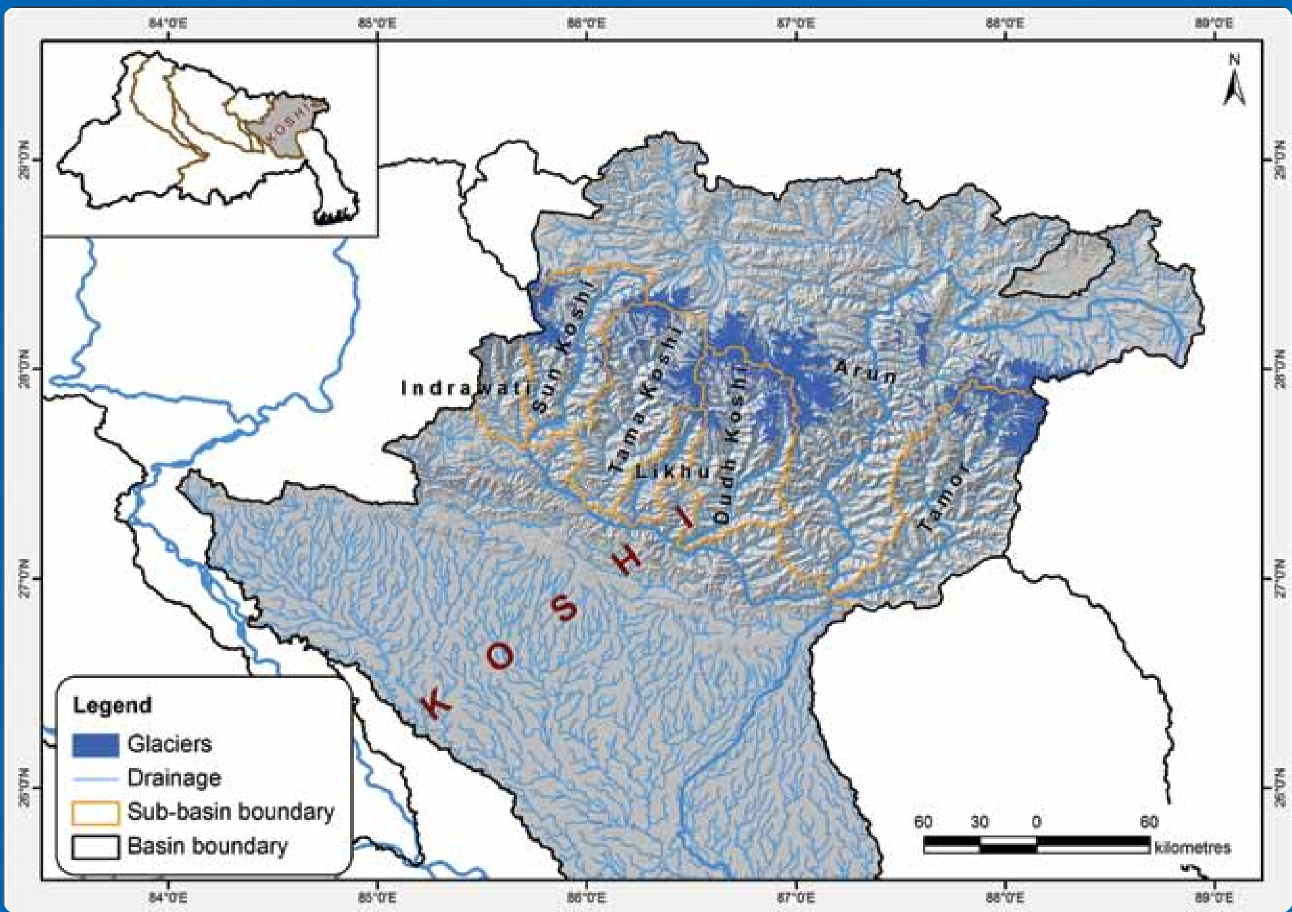
Excluding glaciers in China

Figure 7.34: Area-altitude distribution of glaciers in the sub-basins of the Gandaki basin



Excluding glaciers in China

Figure 7.35: Distribution of glaciers in the Koshi basin



Close to 98% of the glaciers were mountain type, the majority of them mountain basin type (59%) or ice apron type (31%). Mountain glaciers covered an area of 1,266 km^2, 69% of the basin total, and had estimated ice reserves of 84 km^3, 54% of the basin total. The 28 valley glaciers represented only 2% of the total number, but with an average area of 20 km^2, they covered 31% of the glaciated area and contained 46% of the ice reserves.

Clean-ice and debris-covered glaciers – This section refers to the 1339 glaciers in Nepal. The DC glacier components covered a total area of 128 km^2 out of the 1,830 km^2 glacier area investigated. Figure 7.33 shows the area distribution in the sub-basins; the proportional area of DC glaciers was very low in all sub-basins, with the smallest proportion in the Kali Gandaki.

Hypsography – The glacier area-altitude distribution in the sub-basins is shown in Figure 7.34. The maximum glaciated area in the basin overall was 171 km^2 at 5,700-5,800 masl; with glaciated areas found from 3,200 to 8,100 masl. The maximum glaciated areas in the sub-basins were 69.50 km^2 at 5,800-5,900 masl for the Kali Gandaki sub-basin, 59.54 km^2 at 5,400-5,500 masl for the Trishuli sub-basin, 43.35 km^2 at 5,600-5,700 masl for the Marsyangdi sub-basin, 33.16 km^2 at 5,500-5,600 masl for the Budhi Gandaki sub-basin, and 5.98 km^2 at 6,400-6,500 masl for the Seti sub-basin.

Koshi basin

The Koshi river basin lies in eastern Nepal and neighbouring areas of China from longitude 85.48° to 88.70° E and latitude 27.53° to 28.95° N (Figure 7.35). It has seven major sub-basins: the Tama Koshi, Arun, Dudh Koshi, Likhu, Tama, Sun Koshi, and Indrawati. The Arun, Tama, and Sun Koshi rivers originate in Tibet AR, China, and flow south through the Himalayas to Nepal; the other rivers originate within Nepal. The Indrawati merges with the Sun Koshi which flows to the southeast, is then joined by the Tama Koshi, Likhu, and Dudh Koshi from the north, and after confluence with the Arun and Tamor rivers becomes the Sapta (seven) Koshi river and flows towards the southwest as a tributary of the Ganges in India.

The distribution and characteristics of the glaciers in each sub-basin are summarised in Table 7.15. The glaciers in China were not classified morphologically or differentiated into CI and DC glaciers; information related to these is limited to the glaciers within the part of the basin in Nepal.

Number, area, and ice reserves – The Koshi basin had 2,073 glaciers, of which 1,230 glaciers were in China in the sub-basins of the upper catchments of the Sun Koshi, Tama Koshi, and Arun rivers. The total glaciated area was 2,984 km^2 with estimated ice reserves of 295 km^3 (Table 7.15).

The Arun sub-basin is the largest sub-basin with the most glaciers (964), highest glacier area coverage (1,429 km^2), and greatest ice reserves (141 km^3). The Tamor, Dudh Koshi, Tama Koshi, and Sun Koshi sub-basins also had significant numbers and areas of glaciers (Figure 7.36).

The largest single glacier was the Ngojumba glacier in the Dudh Koshi sub-basin with an area of 81 km^2.

Glacier area classes – The number, area, and estimated ice reserves of glaciers in the different size classes are summarised in Table 7.16 and shown as a percentage of the total in Figure 7.37. Nearly 64% of the glaciers were in small class 1, but they contributed only 8% of the glacier area and 2% of the estimated ice reserves. The 49 large glaciers of class 5 were only 2% of the total number, but they contributed about 47% of the glacier area and contained almost 70% of the ice reserves in the basin.

Glacier elevation – The glaciated area extended from just below the peak of Mt. Everest (8,850 masl) to 3,719 masl (Table 7.15), both points in the Arun sub-basin. CI glaciers were found from 8,806 to 3,962 masl and DC glaciers from 6,009 to 3,977 masl (Figure 7.38).

Glacier aspect – Figure 7.39 shows the percentage of glaciers with different aspects and mean slope. Around 19% of the glaciers had a southwest aspect, and approximately 16-17% a west, south, southeast, or east aspect. Less than 1% had a north aspect.

Table 7.15: Glacier characteristics in the Koshi basins

Parameter	Unit	Sub-basin							Koshi
		Indrawati	Sun Koshi*	Tama Koshi*	Likhu	Dudh Koshi	Arun*	Tamor	
Basin area	km²	1,229	3,365	4,127	1,050	4,062	30,125	6,052	71,047**
Latitude	degrees	28.10-28.16	27.95-28.46	27.77-28.29	27.71-27.82	27.64-28.10	27.65-28.95	27.53-27.92	27.53-28.95
Longitude	degrees	85.48-85.70	85.70-86.28	86.07-86.56	86.42-86.55	86.52- 87.00	85.73-88.70	87.62-88.18	85.48-88.70
Number of glaciers	unit	37	204	294	26	287	964	261	2,073
CI glacier area	km²	17.91	52.86	80.18	20.13	304.42	151.55	333.40	960.44
DC glacier area	km²	0	4.80	13.57	4.17	110.68	12.26	73.93	219.42
Total glacier area	km²	17.91	284.00	405.64	24.30	415.09	1,429.33	407.33	2,983.60
Largest glacier area	km²	4.43	40.62	43.75	9.32	80.72	75.72	77.10	80.72
Total ice reserves	km³	0.79	25.11	38.32	1.53	41.62	141.49	45.66	294.53
Highest elevation	masl	5,911	7,974	7,335	6,698	8,222	8,806	8,437	8,806
Lowest elevation	masl	4,694	3,962	4,328	4,334	4,344	3,719	4,176	3,719
CI glacier elevation	masl	4,694-5,911	3,962-7,974	4,328-7,335	4,590-6,698	4,588-8,222	4,443-8,806	4,588-8,437	3,962-8,806
DC glacier elevation	masl	0	3,977-5,134	4,555-5,593	4,334-5,463	4,344-5,996	4,182-5,840	4,176-6,009	3,977-6,009
Mean CI glacier slope	degrees	24	33	29	24	31	29	27	28
Mean DC glacier slope	degrees	0	15	14	21	14	12	16	15
CI-DC area ratio	unit	0	11.01	5.91	4.83	2.75	12.36	4.51	4.38
Average glacier area	km²	0.48	1.39	1.38	0.93	1.45	1.48	1.56	1.44

*Extends into China (area in China contains 1,230 glaciers with an area of 1,803 km², including almost all of those in the Arun sub-basin; CI/DC excludes these)
**includes area of not glaciated sub-basins

Table 7.16: Glacier area classes in the Koshi basin

Area class	Area (km²)	Number		Area		Estimated ice reserves		Mean area per glacier
		Total	%	km²	%	km³	%	km²
1	≤ 0.5	1,320	63.68	243.98	8.18	5.826	1.98	0.18
2	0.51-1.00	303	14.62	214.87	7.20	7.963	2.70	0.71
3	1.01-5.00	355	17.12	769.33	25.78	45.280	15.37	2.17
4	5.01-10.00	46	2.22	340.69	11.42	29.446	10.00	7.41
5	≥10.00	49	2.36	1,414.75	47.42	206.013	69.95	28.87
	Total	**2,073**	**100.00**	**2,983.61**	**100.00**	**294.528**	**100.00**	**1.44**

Figure 7.36: Glacier number, area, and estimated ice reserves in the sub-basins of the Koshi basin

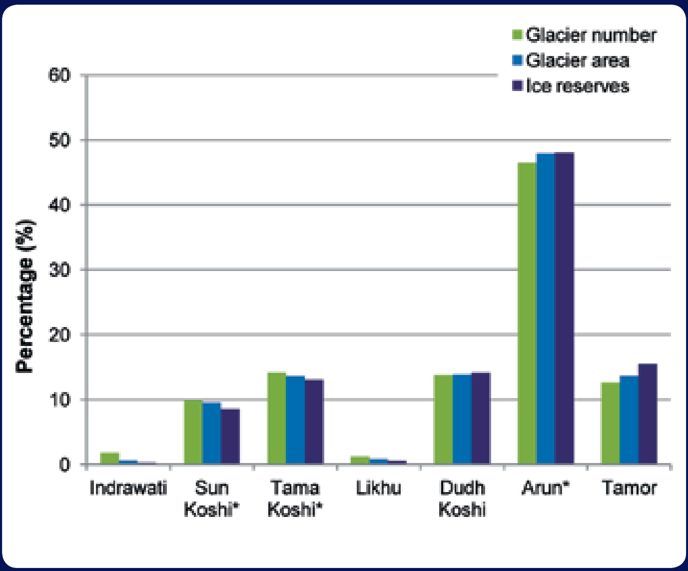


Figure 7.37: Percentage of glacier number, area, and estimated ice reserves in the different glacier size classes in the Koshi basin

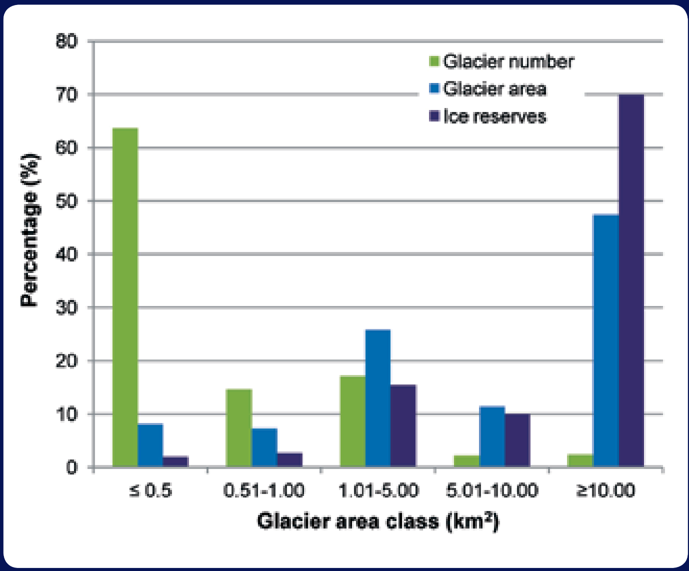


Figure 7.38: Elevation of CI and DC glaciers in the sub-basins of the Koshi basin

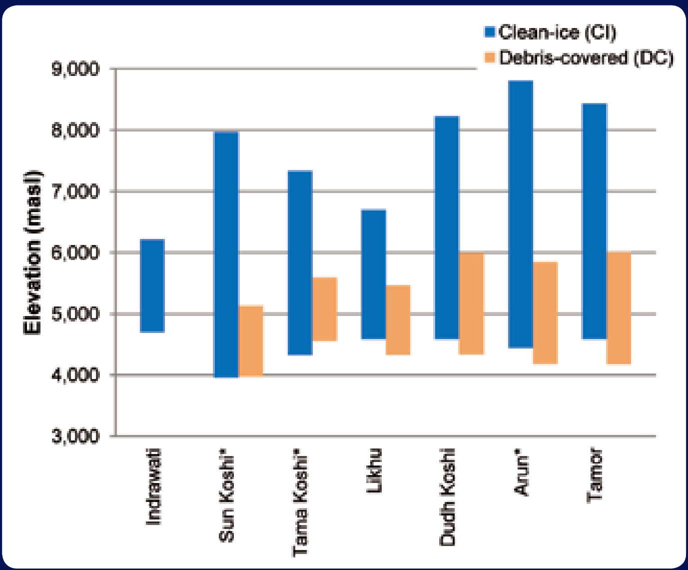
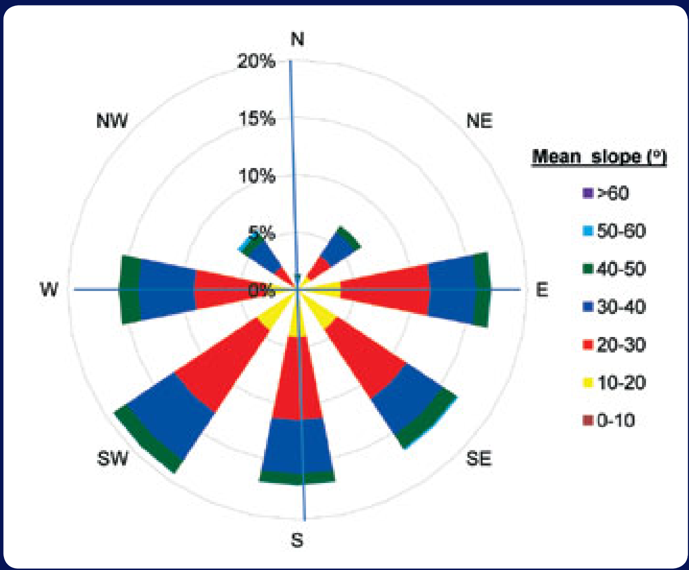


Figure 7.39: Aspect and mean slope of glaciers in the Koshi basin



Excluding glaciers in China

Slope – The mean slope of almost all the glaciers in the basin ranged from 10° to 50°, with slopes of 20° to 30° slightly more common than slopes of 30° to 40° in all aspect directions. Less than 1% of glaciers had slopes above 50°, all with a northwest aspect (Figure 7.39).

The mean slope of CI glaciers in the different basins ranged from 24° to 33°, and the mean slope of DC glaciers from 12° to 21° (Figure 7.40). The mean slope of DC glaciers was much less than that of CI glaciers in all basins except the Likhu.

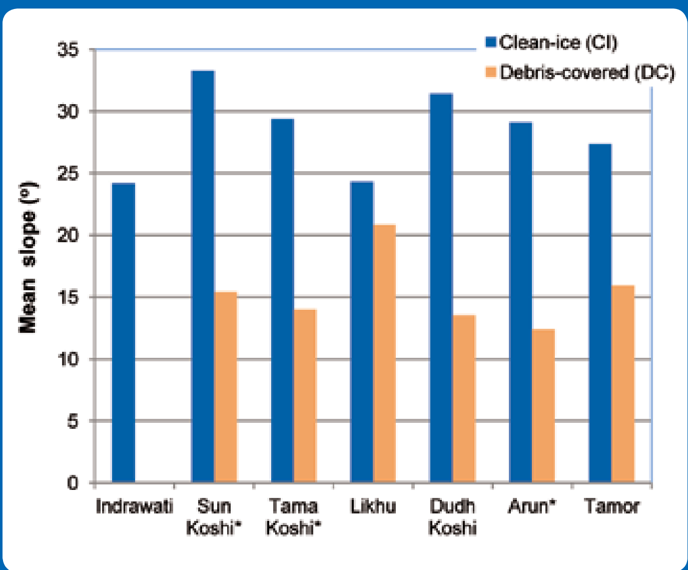
Morphological glacier type – The morphological classification of glaciers in the Koshi basin is summarised in Table 7.17; the comparative distribution by number, area, and ice reserves is shown graphically in Figure 7.41. The part of the Koshi basin in China had a total of 1230 glaciers. These glaciers were not classified morphologically, and are not included here. This section refers to the 843 glaciers within Nepal.

Almost 95% of the glaciers were identified as mountain type, mainly mountain basin (49%) and apron type (30%) with a fairly large number of niche type (12%). The mountain basin glaciers covered 31% of the glaciated area and contained 15% of the estimated ice reserves (Table 7.17). The 45 valley type glaciers were only 5% of the total number, but contributed 60% of the glacier area and 81% of the estimated ice reserves (Figure 7.41).

Table 7.17: Morphological classification of glaciers in Koshi basin (excluding glaciers in China)

Glacier type		Number		Area		Estimated ice reserves		Mean area per glacier
		Total	%	km²	%	km³	%	km²
Mountain	Miscellaneous	17	2.0	17.38	1.5	0.932	0.8	1.02
	Ice Apron	255	30.3	79.85	6.8	3.024	2.5	0.31
	Cirque	12	1.4	1.45	0.1	0.026	0.02	0.12
	Niche	100	11.9	14.17	1.2	0.322	0.3	0.14
	Basin	414	49.1	360.32	30.5	18.306	15.2	0.87
Valley	Trough	45	5.3	706.68	59.9	97.537	81.2	15.70
	Total	**843**	**100**	**1,179.85**	**100**	**120.147**	**100**	**1.40**

Figure 7.40: Mean slope of CI and DC glaciers in the sub-basins of the Koshi basin



Excluding glaciers in China

Figure 7.41: Comparative distribution of different glacier types in the Koshi basin by number, area, and estimated ice reserves

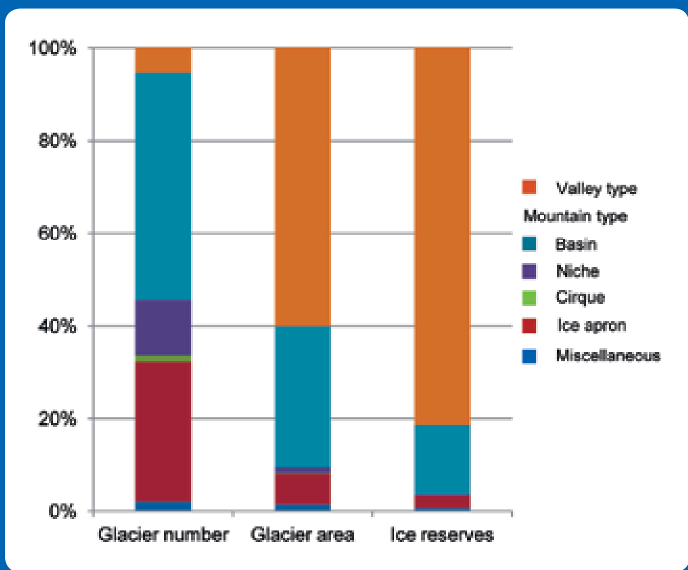
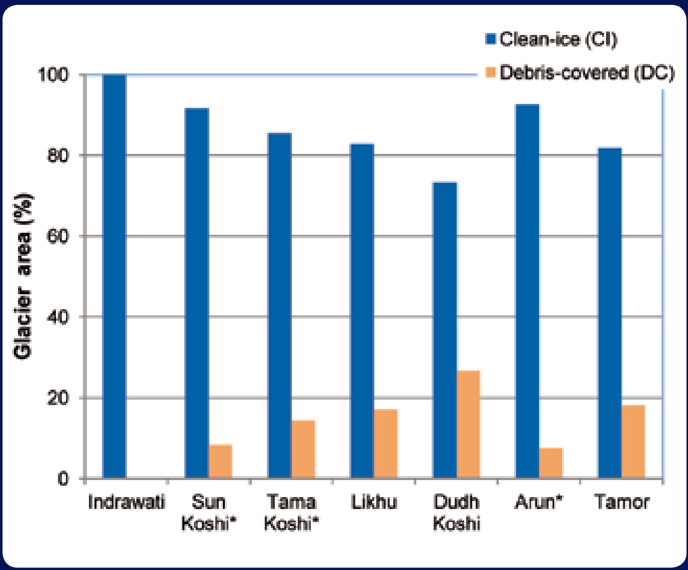
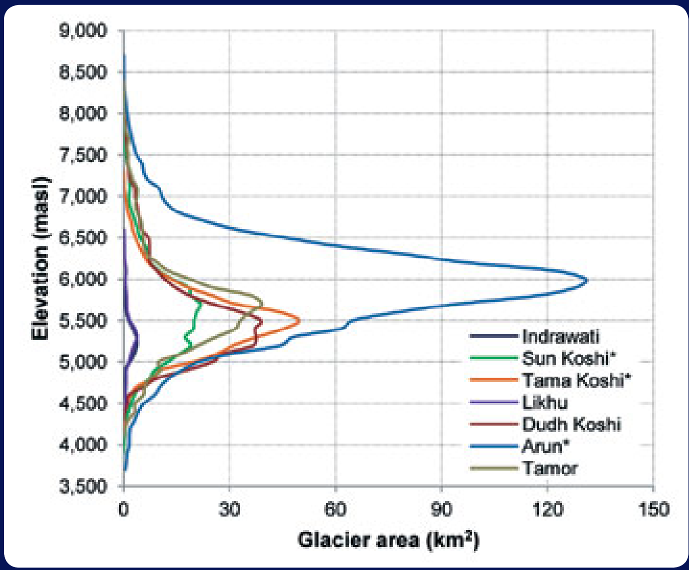


Figure 7.42: Percentage distribution by area of CI and DC glaciers in sub-basins of the Koshi



Excluding glaciers in China

Figure 7.43: Area-altitude distribution of glaciers in the sub-basins of the Koshi basin



Excluding glaciers in China

Clean-ice and debris-covered glaciers – This section refers only to the 843 glaciers within Nepal. The total DC glacier area was 220 km² (19% of the total), 110 km² of which was in the Dudh Koshi sub-basin (Table 7.15). Figure 7.42 shows the area distribution in the sub-basins. The Likhu, Dudh Koshi, and Tamor sub-basins all had a reasonable proportion of DC glaciers; the Indrawati sub-basin had no DC glaciers.

Hypsography – The greatest concentration of glaciers overall in the Koshi basin was 217.24 km² at an elevation 5,800-5,900 masl. Amounts of more than 50 km² within a 100 m band were found from 4,900 to 6,500 masl. The glacier area-altitude distribution in the seven sub-basins is shown in Figure 7.43. The maximum glaciated areas were 130.90 km² at 6,000-6,100 masl in the Arun sub-basin; 49.60 km² at 5,500-5,600 masl in the Tama sub-basin; 39.15 km² at 5,700-5,800 masl in the Tamor sub-basin; 38.91 km² at 5,500-5,600 masl in the Dudh Koshi sub-basin; 21.75 km² at 5,700-5,800 masl in the Sun Koshi sub-basin; 3.81 km² at 5,300-5,400 masl in the Likhu sub-basin; and 3.63 km² at 5,200-5,300 masl in the Indrawati sub-basin. The glaciers of the Arun sub-basin are characterised by high altitude accumulation areas and far-reaching tongues and had the greatest extension over different elevations (3,700-8,700 masl). The Indrawati sub-basin had the shortest elevation band (4,694-5,911 masl).

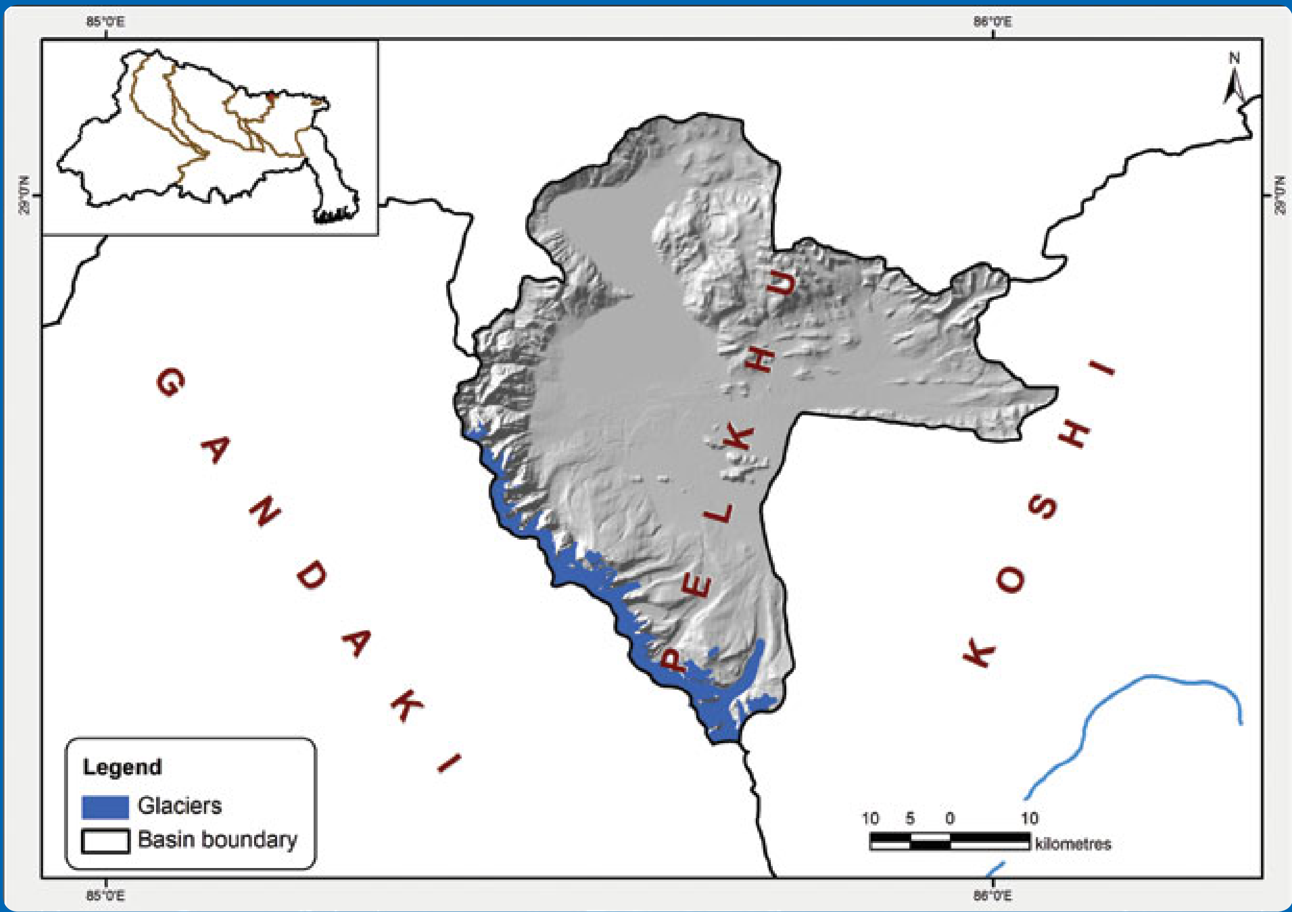
Pelkhu basin

The Pelkhu is a small interior basin at the head of the Arun sub-basin in China extending from 28.42° to 28.74° N latitude and 85.40° to 85.74° E longitude. The sub-basin is elongated and has high concentrations of glaciers in the southern part of the upper catchment and some glaciers at the centre of the sub-basin (Figure 7.44). The distribution and characteristics of the glaciers in the basin are summarised in Table 7.18.

Table 7.18: Glacier characteristics in the Pelkhu basin

Parameter	Unit	
Basin Area	km²	2,405
Latitude	degrees	28.42-28.74
Longitude	degrees	85.40-85.74
Number of glaciers	unit	42
CI glacier area	km²	129.27
DC glacier area	km²	0
Total glacier area	km²	129.27
Largest glacier area	km²	36.26
Total ice reserves	km³	12.55
Highest elevation	masl	7,228
Lowest elevation	masl	4,985
CI glacier elevation	masl	4,985-7,228
DC glacier elevation	masl	0
Mean CI glacier slope	degrees	24°
Mean DC glacier slope	degrees	0
CI-DC area ratio	unit	0
Average glacier area	km²	3.08

Figure 7.44: Distribution of glaciers in the Pelkhu basin



Number, area, and ice reserves – Altogether 42 glaciers were identified in the basin, covering a total area of 129.27 km², and containing estimated ice reserves of 12.55 km³. The largest glacier was GLIMS ID G085694E28430N (Gpegr10_31) located at 28.43° N latitude and 85.69° E longitude, which had an area of 36.26 km², and extended from 7,109 to 5,283 masl.

Glacier area classes – The number, area, and estimated ice reserves of glaciers in the different size classes are summarised in Table 7.19 and shown as a percentage of the total in Figure 7.45. The majority of glaciers (38%) were in class 1, whereas nearly half the area and 66% of the ice reserves were contributed by the three glaciers in Class 5, which had a mean glacier area of 21.49 km².

Glacier elevation – The highest glacier elevation was 7,228 and the lowest 4,985 masl. The elevation range for individual glaciers ranged from 1,890

Figure 7.45: Percentage of glacier number, area, and estimated ice reserves in the different glacier size classes in the Pelkhu basin

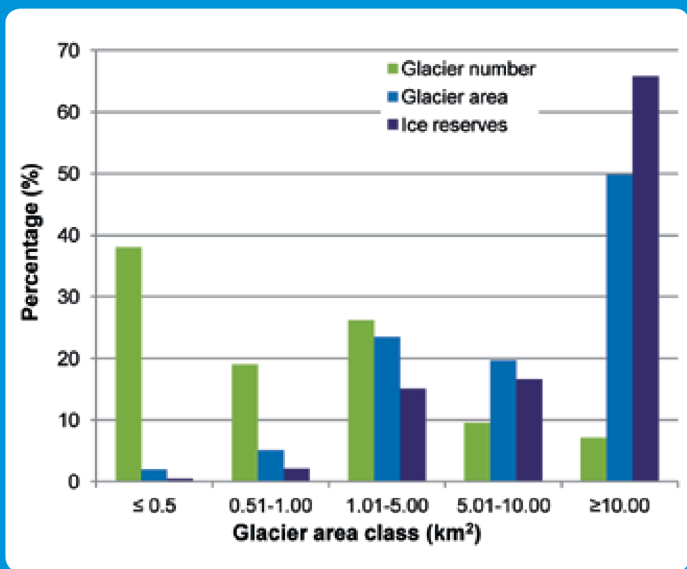


Figure 7.46: Aspect and mean slope of glaciers in the Pelkhu basin

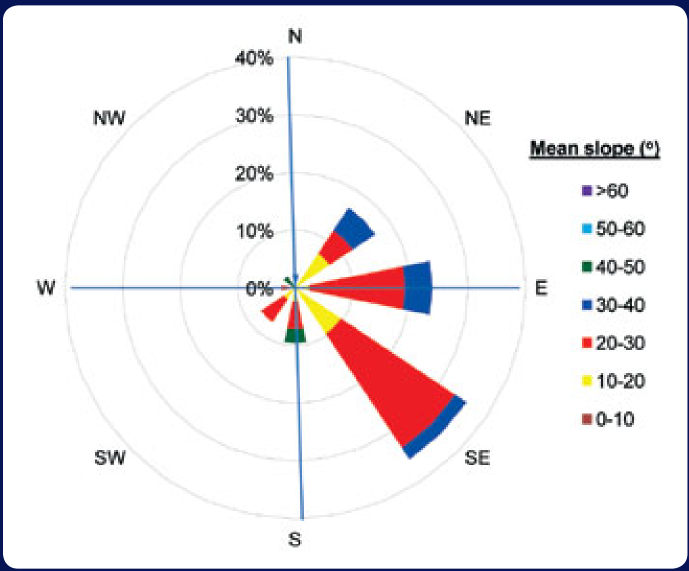


Figure 7.47: Area-altitude distribution of glaciers in the Pelkhu basin

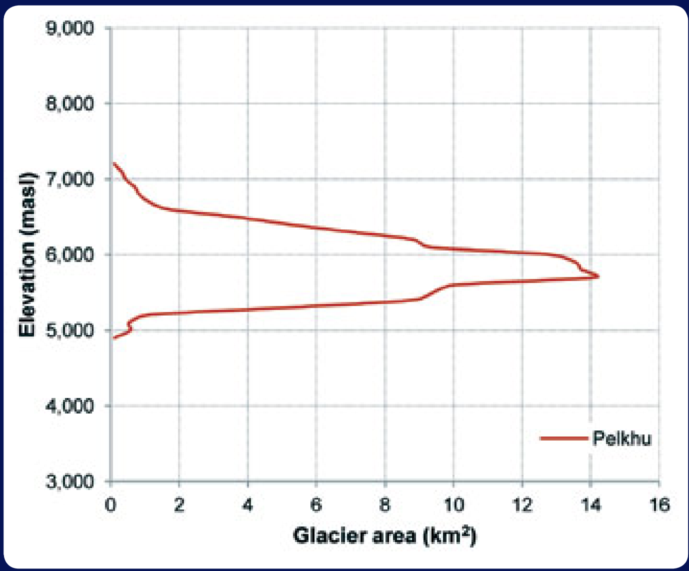


Table 7.19: Glacier area classes in the Pelkhu basin

Area class	Area (km^2)	Number		Area		Estimated ice reserves		Mean area per glacier
		Total	%	km^2	%	km^3	%	km^2
1	≤ 0.5	16	38.1	2.48	1.9	0.056	0.5	0.15
2	0.51 - 1.00	8	19.1	6.62	5.1	0.259	2.1	0.83
3	1.01 - 5.00	11	26.2	30.32	23.5	1.891	15.1	2.76
4	5.01 - 10.00	4	9.5	25.40	19.7	2.086	16.6	6.35
5	≥10.00	3	7.1	64.46	49.9	8.256	65.8	21.49
	Total	**42**	**100**	**129.27**	**100**	**12.548**	**100**	**3.08**

to 32 m. The greatest elevation range (7,064-5,174 masl) was for glacier GLIMS ID G085520E28579N (Gpegr10_20).

Glacier aspect – Figure 7.46 shows the percentage of glaciers with different aspects and mean slope. The predominant aspect (37%) was southeast, followed by east (24%) and northeast (17%). Only 2% of glaciers had a northwest or north aspect.

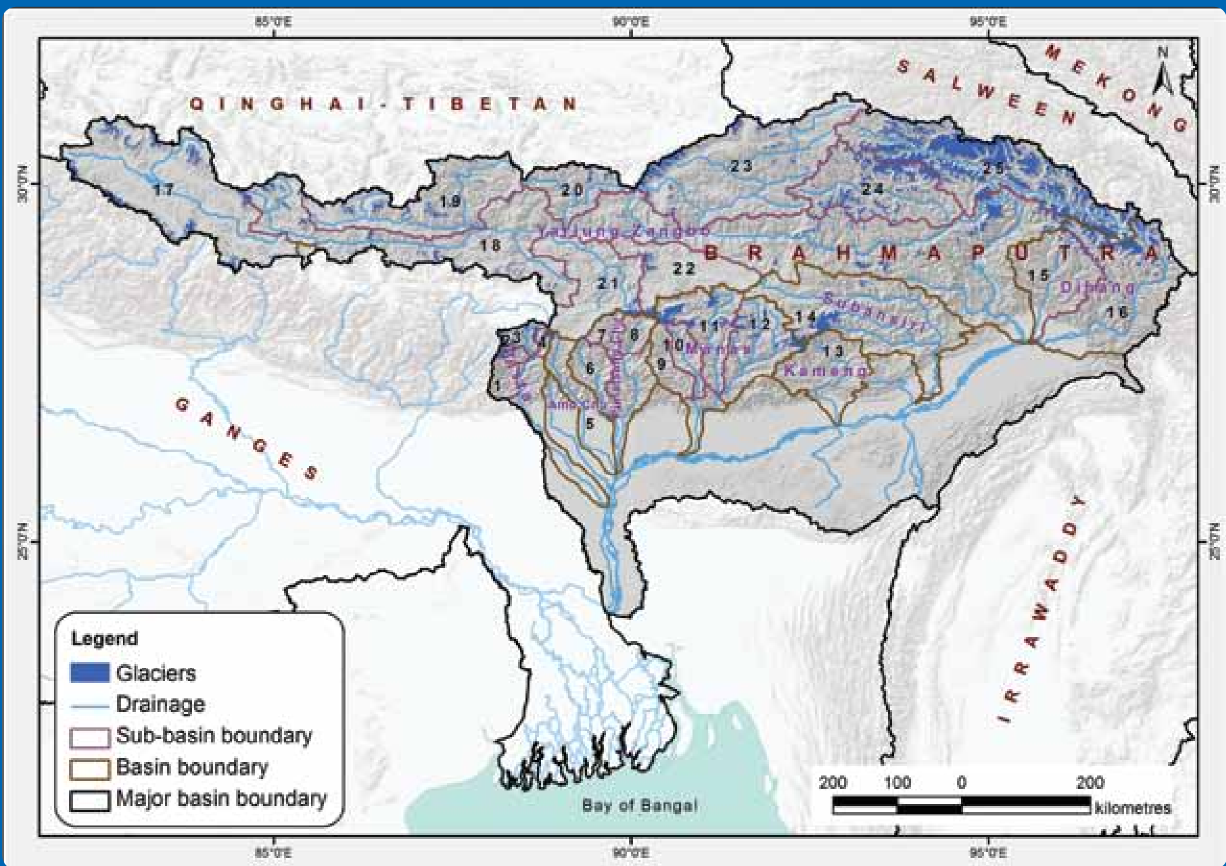
Slope – The average mean slope of the glaciers was 24°. The mean glacier slope ranged from 10 to 60° with slopes from 20 to 30° the most common in all aspect classes, followed by 30° to 40°. A very few south-facing glaciers had slopes of more than 50°.

Hypsography – The glacier area-altitude distribution in the basin is shown in Figure 7.47. The maximum glaciated area was 14.16 km^2 at 5,700-5,800 masl. Amounts of more than 5 km^2 in every 100 m band was found from 5,300 to 6,400 masl.

8 Brahmaputra Basin

The Brahmaputra River is one of the major rivers of Central and South Asia. It originates in the Mansarovar lake and passes through the Tibet Autonomous Region of China, the Indian states of Arunachal Pradesh and Assam, and Bangladesh. The river has many names: Jamuna in Bengali, Dihang in Assamese, Tsangpo ('Purifier') in Tibetan, and Yarlung Zangbo Jiang in Chinese (Pinyin). The source of the river is the Chemayungdung Glacier in southwestern Tibet. The river runs for nearly 1,100 km from its source in a generally easterly direction between the main range of the Himalayas to the south and the Kailash range to the north; at Namcha Barwa it enters India and bends to take a westerly path through Arunachal Pradesh and Assam, where it is joined by several tributaries such as the Subansiri and Kameng from Arunachal; Manas, Punatsang, and Amo from Bhutan; and the Tista from Sikkim, travelling a further 1800 km to its confluence with the Ganges River (Figure 8.1).

Figure 8.1: The Brahmaputra river system showing major basins and sub basins and distribution of glaciers



Tista	Amo*	Punatsang	Manas*	Kameng	Subansiri*	Dihang	Yarlung Zangbo*
1. East Rathong	5.Amo*	6. Wang	9. Mangde	13. Kameng	14. Subansiri*	15. Dibhang	17. Maquan
2. Talung		7. Mo	10. Chamkhar			16. Lohit	18. Yarlung Zangbo
3. Zemu		8. Pho	11. Kuri*				19. Dogxung Zangbo
4. Changme Khangpu			12. Dangme*				20. Xiangqu
							21. Nianchu
							22. Langkamu
							23. Lhasa
							24. Nyang
							25. Yigongzongbo

*extends into China

The Brahmaputra has a total catchment area of 528,079 km² of which 432,480 km² lies within the HKH region (Figure 8.1). Across the Tibetan Plateau, the river has a relatively low flow and receives little silt, but in India, it passes through a region of heavy rainfall and carries a large amount of rainfall runoff with considerable sediment loads. It has a braided channel throughout most of its length in Assam, with a few large islands within the channel. Shifting of river channels is common. During the monsoon, regular flooding occurs in Assam and Bangladesh causing significant damage and human casualties.

Data

The mapping and inventory of the glaciated areas in the sub-basins of the Brahmaputra was carried out using ETM+ images from 2005 to 2008. The topographic characteristics were derived using the SRTM DEM. The list of images used is shown in Table 8.1.

Mapping and Inventory of Glaciers

The Brahmaputra basin had 11,497 glaciers with a total glaciated area of 14,020 km² and estimated ice reserves of about 1,303 km³, distributed between 27.49°–31.03° N latitude and 82.03°–97.76° E longitude at elevations of 2,435-8,331 masl (Figure 8.1). The glaciers are concentrated in the northeastern part of the basin; the largest covered an area of 204 km².

The distribution and characteristics of the glaciers in each sub-basin are summarised in Table 8.2. Descriptions of the typology, morphological classification, and hypsography of the part of the basin in China, the greater part of the glaciated area, are not yet available and not included in the description here. Only 1,444 glaciers have detailed information on CI/DC type and morphological classification.

Table 8.1: Landsat images used for the Brahmaputra basin (for areas outside China)

Path-Row	Image	Date	Used for	Basin/ Sub-basin
139-41	LE71390412007348PFS00	12/14/2007	analysis	East Rathong, Talung, Zemu, Changme Khangpu
	L71139041_04120051208	12/8/2005	analysis	
138-41	LE71380412007357SGS01	23/12/2007	analysis	Pa , Thim, Mo, and Pho Chu
137-41	LE71370412006027EDC00	27/01/2006	analysis	Kameng, Mangde, Chamkhar, Kuri, Dangme Chu
136-41	L71136041_04120050101	1/1/2005	correction	Kameng, Dangme, Subansiri
	LE71360412006212PFS00	7/31/2006	analysis	
	LE71360412007279EDC00	10/6/2007	analysis	
	LE71360412008314SGS00	11/9/2008	analysis	
136-40	LE71360402008314SGS00	11/9/2008	analysis	Subansiri
	LE71360402007279EDC00	10/6/2007	analysis	
	LE71360402006212PFS00	7/31/2006	analysis	
	L5136040_04020051024	10/24/2005	analysis	
135-40	LE71350402008339EDC00	12/4/2008	analysis	Dibhang
	LE71350402008323EDC00	11/18/2008	analysis	
	LE71350402008307SGS00	11/2/2008	analysis	
134-40	LE71340402009270SGS00	9/27/2009	analysis	Dibhang, Lohit
	LE71340402007265PFS00	9/22/2007	analysis	
	L5135040_04020061223	12/23/2006	analysis	
	L5134040_04020051111	11/11/2005	correction	

Table 8.2: Glacier characteristics in the Brahmaputra basin within the HKH region

Parameter	Units	Basin								Brahmaputra
		Tista	Amo*	Punatsang	Manas*	Kameng	Subansiri*	Dihang*	Yarlung Zangbo*	
Basin area	km^2	8,665	3,773	14,365	28,574	10,347	26,343	34,412	256,779	432,480**
Latitude	degrees	27.50-28.06	27.49-27.91	27.60-28.24	27.70-28.60	27.71-27.98	27.80-28.79	28.20-29.54	27.82-31.03	27.49-31.03
Longitude	degrees	88.07-88.88	88.79-89.26	89.24-90.35	90.26-92.45	92.41-92.77	91.89-93.50	95.77-97.76	82.03-97.09	82.03-97.76
Number of glaciers	unit	398	32	433	1,090	21	493	955	8,075	11,497
CI glacier area	km^2	399.02	NA	351.93	278.35	10.63	51.53	94.18	NA	1,185.65
DC glacier area	km^2	53.88	NA	62.33	31.31	NA	NA	NA	NA	147.52
Total glacier area	km^2	452.96	40.06	414.26	1,156.93	10.63	486.23	1,305.10	10,153.67	14,019.84
Largest glacier area	km^2	77.24	19.49	34.73	68.16	2.30	53.33	96.22	204.36	204.36
Total ice reserves	km^3	40.50	3.45	30.18	84.98	0.44	35.94	110.97	996.17	1,302.63
Highest elevation	masl	8,331	5,975	7,084	7,223	6,205	6,514	5,902	6,536	8,331
Lowest elevation	masl	3,882	4,712	4,080	4,388	4,465	4,223	2,435	3,348	2,435
CI glacier elevation	masl	4,102-8,331	4,712 - 5,975	4,442-7,084	4,391-7,223	4,465 - 6,205	4,223-6,514	3,707-5,693	NA	3,707-8,331
DC glacier elevation	masl	3,882-5,828	NA	4,085-5,368	4,524-5,548	NA	NA	NA	NA	3,882-5,828
Mean CI glacier slope	degrees	28	30	26	20	21	25	25	NA	25
Mean DC glacier slope	degrees	9	NA	13	17	NA	NA	NA	NA	13
CI-DC area ratio	unit	7.41	NA	5.65	8.89	NA	NA	NA	NA	8.04
Average glacier area	km^2	1.14	1.25	0.96	1.06	0.51	0.99	1.37	1.26	1.22

* extends into China (area in China contains 10,028 glaciers with an area of 12,686 km^2; CI/DC differentiation refers to the remaining 1469 glaciers with an area of 1,333 km^2); **includes area of not glaciated sub-basins

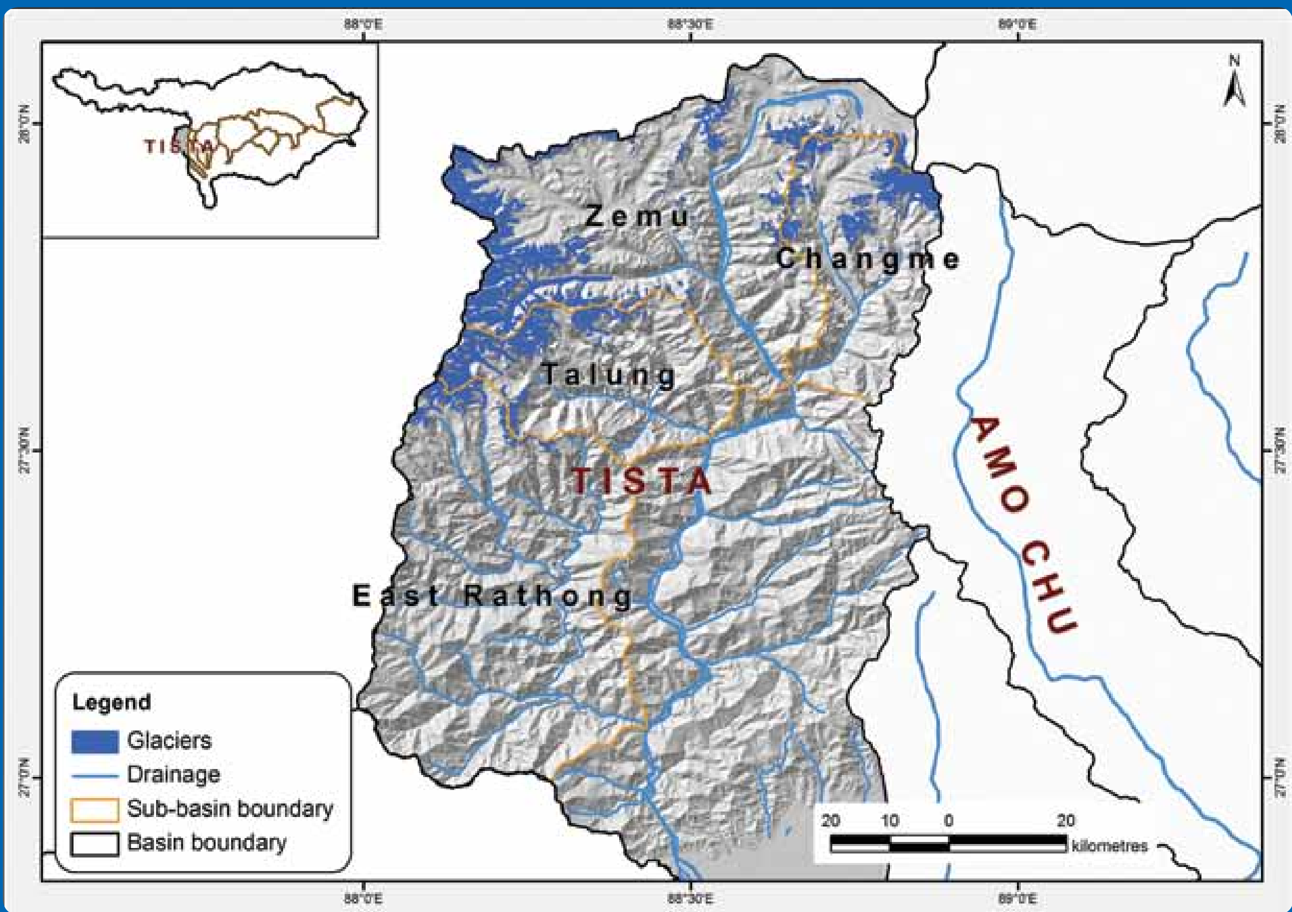
Tista basin

The Tista River has its origin in the Chombu glacial lake of Tista Khangse glacier just above the Lachen Monastery (>5,800 m) in Sikkim, India. The river initially flows northwest and then towards the south, finding its way down through deep, narrow meandering gorges. The Tista is joined by the Rangit river, which originates in the Rathong glacier, at the border between Sikkim and West Bengal. It is then joined by many tributaries before flowing into the Brahmaputra in Bangladesh. The glaciated area of the Tista river lies within four sub-basins: East Rathong, Talung, Changme Khangpu, and Zemu (Figure 8.2). The distribution and characteristics of the glaciers in each sub-basin are summarised in Table 8.3.

Number, area, and ice reserves – The Tista basin had 398 glaciers all in the northern part (193 in the Zemu sub-basin, and less than 100 glaciers each in the other sub-basins), with a total area of 453 km² and estimated ice reserves of 41 km³ (Table 8.3). The number, area, and estimated ice reserves of glaciers in the sub-basins are shown in Figure 8.3. The Zemu sub-basin had the most glaciers, greatest glacier area, and greatest estimated ice reserves; and East Rathong sub-basin the least. The largest glacier in the Tista basin is the Zemu Glacier with an area of 77 km². The average area per glacier overall was 1.1 km², a little more in the Zemu and Talung sub-basins and less in the East Rathong and Changme Khangpu sub-basins.

Glacier area classes – The number, area, and estimated ice reserves of glaciers in the different size classes are summarised in Table 8.4 and shown as a percentage of the total in Figure 8.4. The great majority of the glaciers, 252 or 66% of the total, were in the smallest class 1 (≤0.5 km²), but together contributed only 11% of the glacier area and just over 3% of the ice reserves. A further 30% of the glaciers were in class 2 or 3, covering 32% of the glaciated area and containing 20% of the ice reserves. The 8 glaciers in class 5, 2% of the total, covered nearly 40% of the glaciated area and contained 64% of the basin's ice reserves. Four of these large glaciers were in the Zemu sub-basin, three in the Talung sub-basin, and one in the Changme-Khangpu sub-basin.

Figure 8.2: Distribution of glaciers in the Tista basin



Glacier elevation – The highest glacier elevation was 8,331 masl and the lowest 3,882 masl, both in the Talung sub-basin (Table 8.3 and Figure 8.5). The Changme-Khangpu sub-basin had the smallest range of glacier elevation, reflecting the absence of valley glaciers.

As elsewhere in the HKH the CI glaciers were found at higher elevations than the DC glaciers.

Glacier aspect – Figure 8.6 shows the percentage of glaciers with different aspects and mean slope. The majority faced southeast (24%), east (22%), southwest (19%) or south (16%). Only about 5% had a more northerly aspect.

Table 8.3: Glacier characteristics in the Tista basin

Parameter	Units	Sub-basin				Tista
		East Rathong	Talung	Zemu	Changme Khangpu	
Basin area	km^2	2,132	819	1,969	770	8,665*
Latitude	degrees	27.50-27.61	27.53-27.73	27.69-28.06	27.72-27.98	27.50-28.06
Longitude	degrees	88.07-88.30	88.13-88.50	88.14-88.82	88.65-88.88	88.07-88.88
Number of glaciers	unit	49	64	193	92	398
CI glacier area	km^2	29.93	84.46	207.70	76.93	399.02
DC glacier area	km^2	3.72	13.79	31.98	4.40	53.88
Total glacier area	km^2	33.70	98.25	239.69	81.32	452.96
Largest glacier area	km^2	6.65	26.70	77.24	20.29	77.24
Total ice reserves	km^3	1.91	8.55	24.52	5.53	40.51
Highest elevation	masl	7,258	8,331	8,139	6,708	8,331
Lowest elevation	masl	4,335	3,882	4,266	4,455	3,882
CI glacier elevation	masl	4,639-7,258	4,102-8,331	4,337-8,139	4,693-6,708	4,102-8,331
DC glacier elevation	masl	4,335-5,203	3,882-5,210	4,266-5,828	4,455-5,400	3,882-5,828
Mean CI glacier slope	degrees	31	32	25	22	28
Mean DC glacier slope	degrees	8	12	7	10	9
CI-DC area ratio	unit	8.05	6.13	6.49	17.50	7.41
Average glacier area	km^2	0.69	1.54	1.24	0.88	1.14

*Includesw area of not glaciated sub-basins

Figure 8.3: Glacier number, area, and estimated ice reserves in the sub-basins of the Tista basin

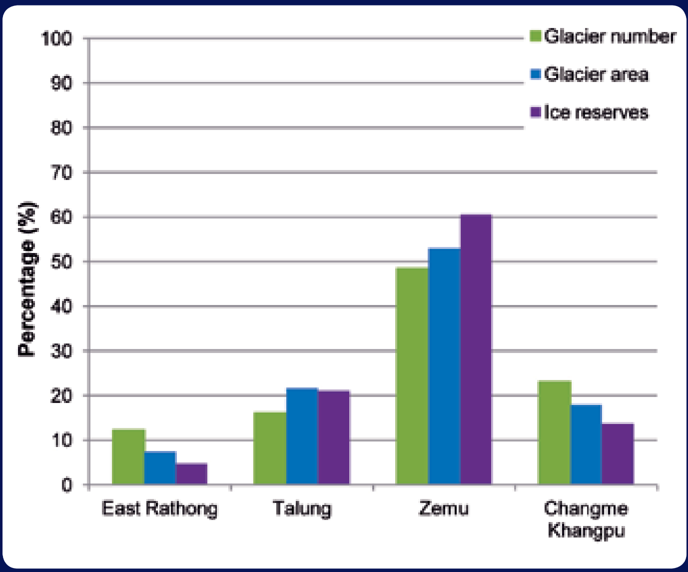


Figure 8.4: Percentage of glacier number, area, and estimated ice reserves in the different glacier size classes in the Tista basin

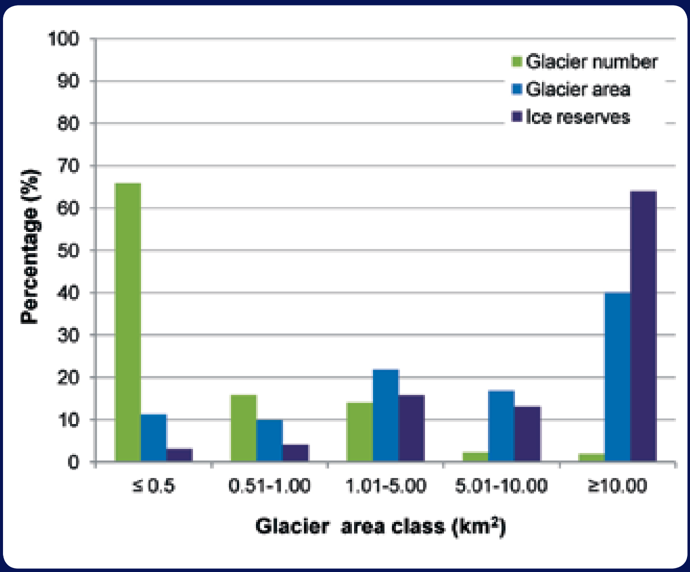


Table 8.4: Glacier area classes in the Tista basin

Area class	Area (km^2)	Glacier		Area		Estimated ice reserves		Mean area per glacier
		Number	%	km^2	%	km^3	%	km^2
1	≤ 0.5	262	65.8	51.10	11.3	1.236	3.1	0.20
2	0.51-1.00	63	15.8	44.65	9.9	1.654	4.1	0.71
3	1.01-5.00	56	14.1	98.84	21.8	6.367	15.7	1.76
4	5.01-10.00	9	2.3	76.70	16.9	5.320	13.1	8.52
5	≥10.00	8	2.0	181.62	40.1	25.921	64.0	22.70
	Total	**398**	**100**	**452.91**	**100**	**40.497**	**100**	**1.14**

Slope – The mean slope of the glaciers in the basin ranged from 10° to 60°. Slopes of 20° to 30° were most common followed by 30° to 40° (Figure 8.6).

The average slope of the CI glaciers in the sub-basins ranged from 22° to 32°, and of DC glaciers from 7° to 12° with slight basin to basin variations (Figure 8.7).

Morphological glacier type – The morphological classification of glaciers in the Tista basin is summarised in Table 8.5; the comparative distribution by number, area, and estimated ice reserves is shown graphically in Figure 8.8. More than 94% of glaciers were mountain type, with basin type (45%), and apron type (41%) almost equally represented. The mountain basin type glaciers covered 35% of the glaciated area and contained 20% of the estimated ice reserves. The 22 valley glaciers comprised less than 6% of the total by number, but with an average area of 11.15 km^2, contributed 54% of the total glacier area and 75% of the total ice reserves.

Clean-ice and debris-covered glaciers – In total, 20 of the 398 glaciers had a debris-covered component, covering about 14% of the total glacier area. Figure 8.9 shows the area distribution of CI and DC glaciers in the sub-basins. The proportional area occupied by DC glaciers was similar in all the sub-basins at around 10-15%, except the Changme Khangpu sub-basin where they occupied only 5%.

Hypsography – The area-altitude distribution in the sub-basins is shown in Figure 8.10. The maximum glaciated area in the basin overall was 39.35 km^2 at 5,400-5,500 masl; overall the highest concentration of glaciers was between

Figure 8.5: Elevation of CI and DC glaciers in the sub-basins of the Tista basin

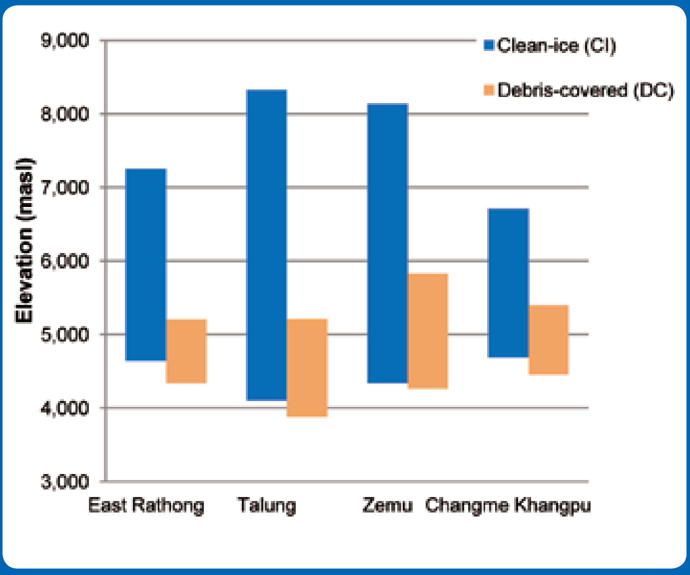


Figure 8.6: Aspect and mean slope of glaciers in the Tista basin

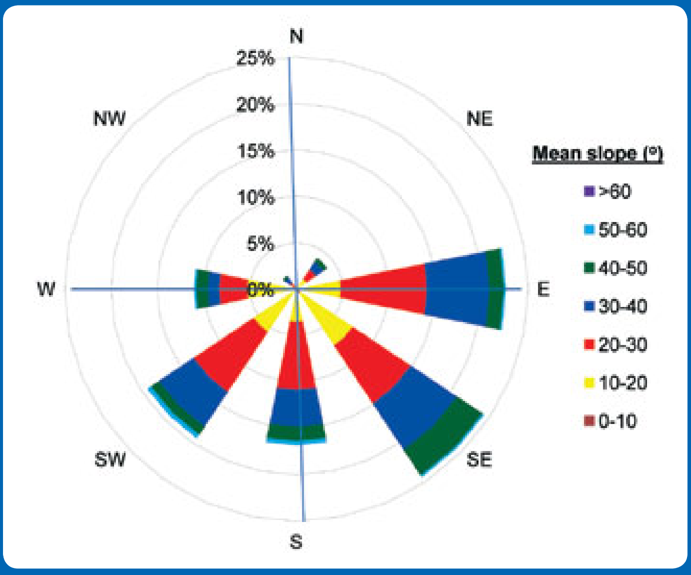


Table 8.5: Morphological classification of glaciers in the Tista basin

Glacier type		Number		Area		Estimated ice reserves		Mean area per glacier
		Total	%	km²	%	km³	%	km²
Mountain	Miscellaneous	10	2.5	4.03	0.9	0.147	0.4	0.40
	Ice apron	163	41.0	44.15	9.8	1.555	3.8	0.27
	Cirque	6	1.5	1.54	0.3	0.041	0.1	0.26
	Niche	17	4.3	1.75	0.4	0.031	0.1	0.10
	Basin	180	45.2	156.17	34.5	8.100	20.0	0.87
Valley	Trough	22	5.5	245.28	54.2	30.623	75.6	11.15
	Total	**398**	**100**	**452.9**	**100**	**40.497**	**100**	**1.14**

Figure 8.7: Mean slope of CI and DC glaciers in the sub-basins of the Tista basin

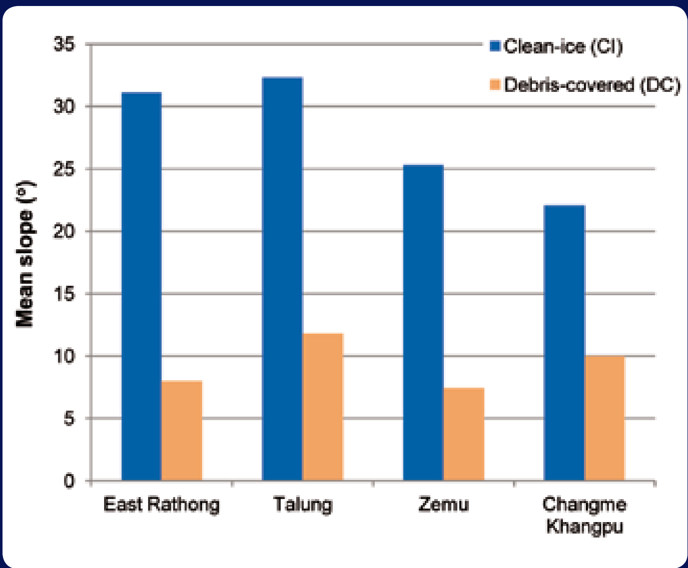


Figure 8.8: Comparative distribution of different glacier types in the Tista basin by number, area, and estimated ice reserves

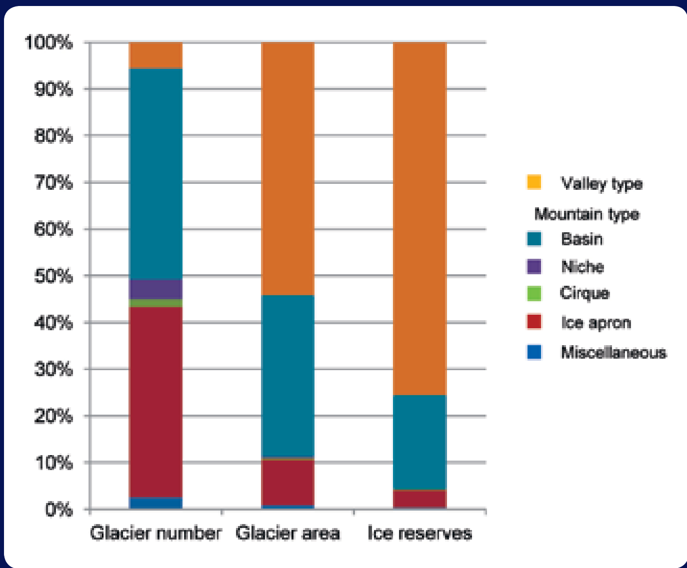


Figure 8.9: Percentage distribution by area of CI and DC glaciers in the sub-basins of the Tista basin

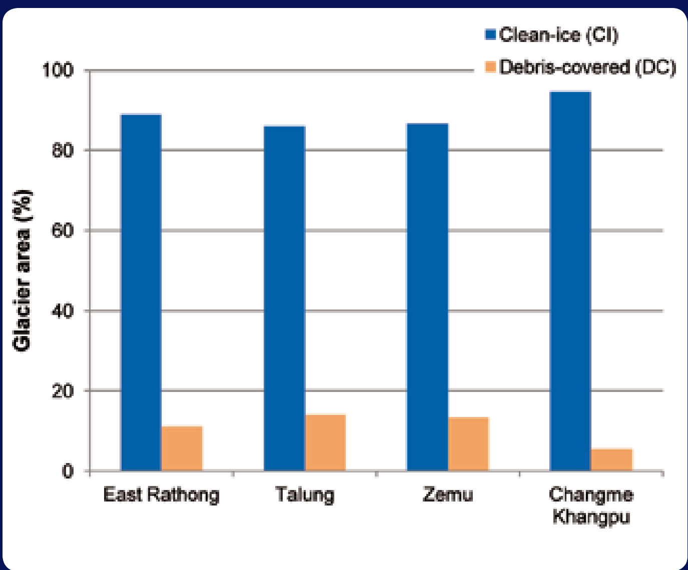
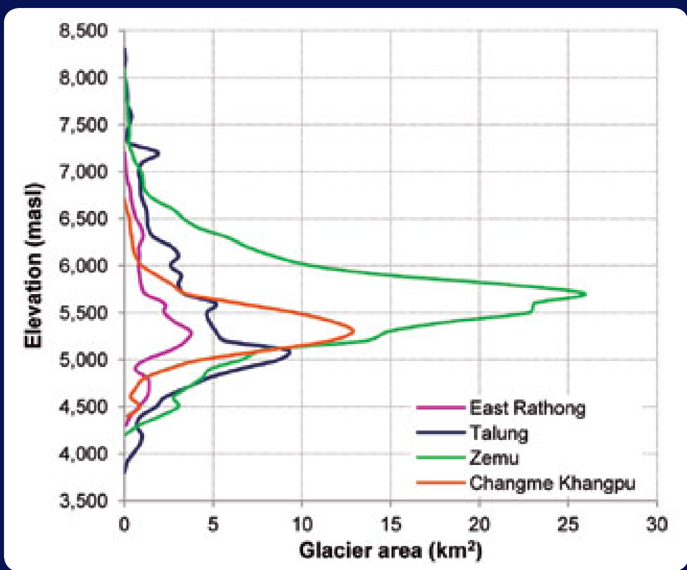


Figure 8.10: Area-altitude distribution of glaciers in the sub-basins of the Tista basin



5,000 and 6,000 masl. The maximum glaciated areas in the sub-basins were 25.93 km² at 5,700 to 5,800 masl in the Zemu sub-basin; 12.88 km² at 5,300 to 5,400 masl in the Changme Khampu sub-basin; 9.21 km² at 5,100 to 5,200 masl in the Talung sub-basin; and 3.72 km² at 5,300 to 5,400 masl in the East Rathong sub-basin.

Amo basin

The Amo Chu river and its three main tributaries, the Tangka Chu, the Khangphu Chu, and the Tromo Chu, originate in Tibet AR and flow south (Figure 8.11). The main branch of the Tromo Chu originates west of Phari Dzong, flows south to the Bhutan-Tibet border at Trakarpo, and along the border until it joins the Amo Chu at Yatung. The Amo Chu flows eastwards into Bhutan and southeast for about 170 km until it enters the Indian flood plains of West Bengal near Phuntsholing (a Bhutanese border town). The Amo Chu drains a catchment area of around 16,000 km² in Tibet AR, which contains all the glaciated areas (Figure 8.11). The distribution and characteristics of the glaciers in the basin are summarised in Table 8.6. As they all lie in China, they were not differentiated into CI/DC glaciers or classified morphologically.

Number, area, and ice reserves – A total of 32 glaciers were identified in the Amo basin with an area of 40 km² and estimated ice reserves of 3.5 km³ (Table 8.6). The largest single glacier had an area of just under 20 km².

Glacier area classes – The number, area, and estimated ice reserves of glaciers in the different size classes are summarised in Table 8.7 and shown as a percentage of the total in Figure 8.12.

Figure 8.11: Distribution of glaciers in the Amo basin

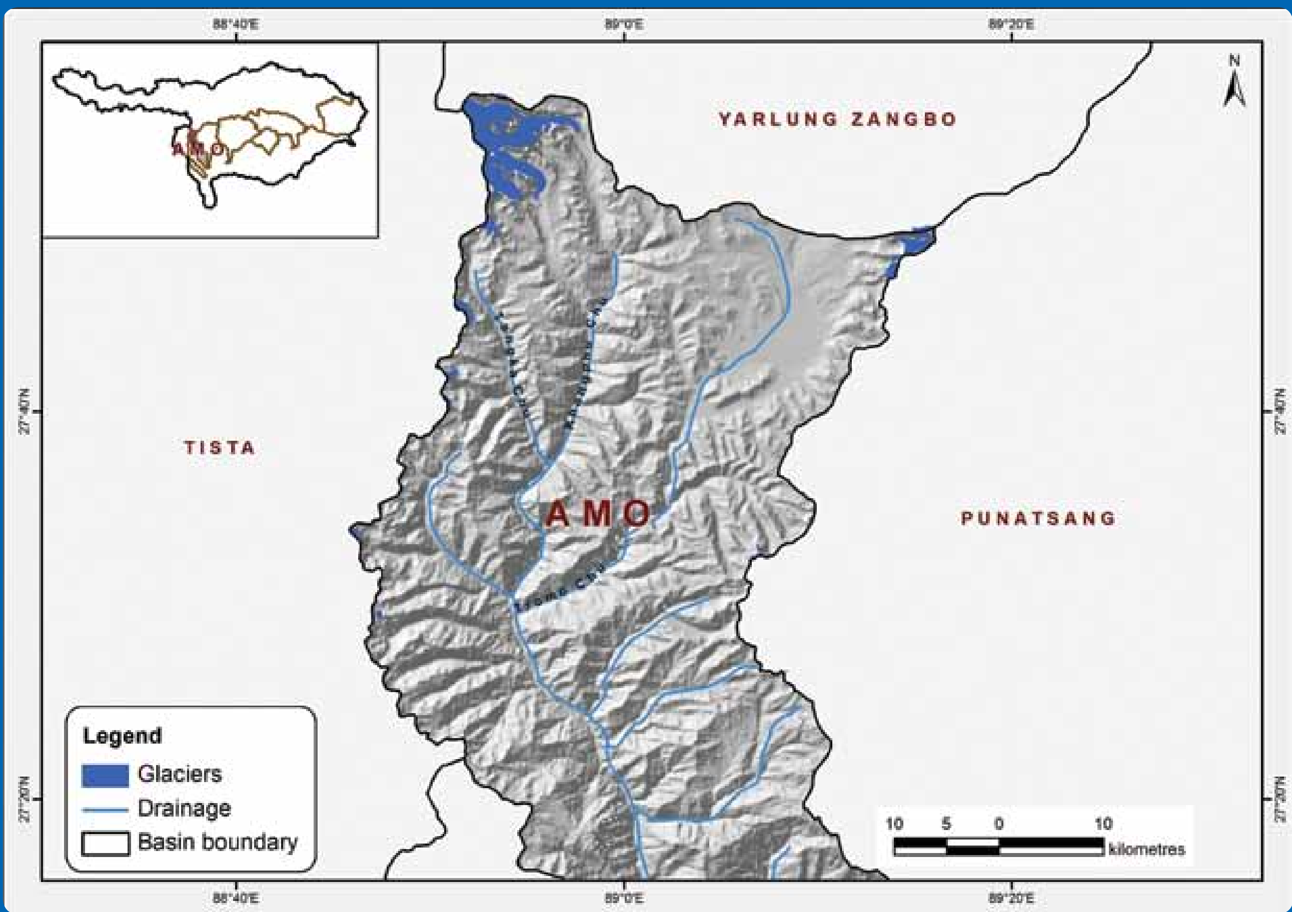


Figure 8.12: Percentage of glacier number, area, and estimated ice reserves in the different glacier size classes in the Amo basin

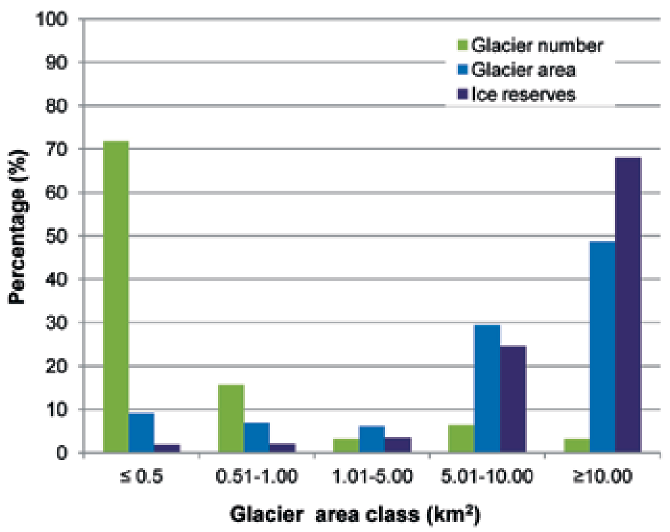
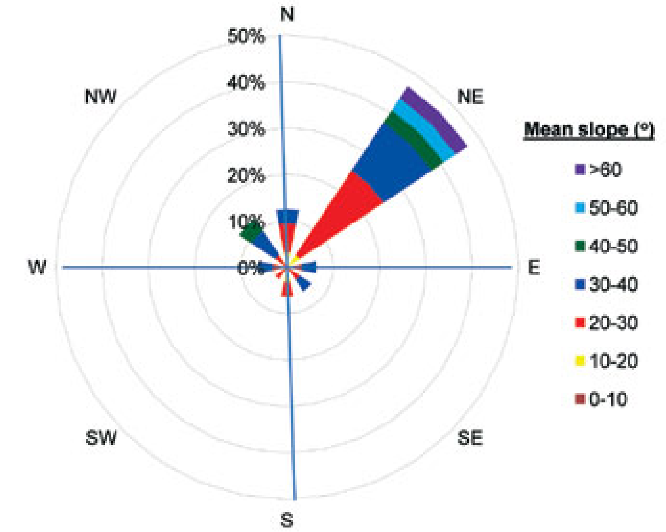


Figure 8.13: Aspect and mean slope of glaciers in the Amo basin



The great majority of the glaciers, 23 or 72% of the total, were in the small class 1 (≤0.5 km²), but together contributed only about 9% of the glacier area and less than 2% of the ice reserves. A further 16% of the glaciers were in class 2, covering 7% of the glaciated area and also containing 2% of the ice reserves. The single large class 5 glacier, 3% of the total, covered nearly half the glaciated area and contained close to 70% of the basin's ice reserves.

Glacier elevation – The highest glacier elevation was 5,975 masl (GLIMS ID G089256E27818N or Aamgr10_18) and the lowest 4,712 masl (GLIMS ID G088852E27699N or Aamgr10_23).

Table 8.6: Glacier characteristics in the Amo basin

Parameter	Units	
Basin area	km²	3,773
Latitude	degrees	27.49-27.91
Longitude	degrees	88.79-89.26
Number of glaciers	unit	32
Total glacier area	km²	40.06
Largest glacier area	km²	19.49
Total ice reserves	km³	3.45
Highest elevation	masl	5,975
Lowest elevation	masl	4,712
Mean glacier slope	degrees	30
Average glacier area	km²	1.25

Table 8.7: Glacier area classes in the Amo basin

Area class	Area (km²)	Number		Area		Estimated ice reserves		Mean area per glacier
		Total	%	km²	%	km³	%	km²
1	≤ 0.5	23	71.9	3.63	9.1	0.064	1.9	0.16
2	0.51-1.00	5	15.6	2.76	6.9	0.072	2.1	0.55
3	1.01-5.00	1	3.1	2.42	6.0	0.119	3.4	2.42
4	5.01-10.00	2	6.3	11.76	29.4	0.850	24.6	5.88
5	≥10.00	1	3.1	19.49	48.7	2.349	68.0	19.49
	Total	**32**	**100**	**40.06**	**100**	**3.454**	**100**	**1.25**

Aspects – Figure 8.13 shows the percentage of glaciers with different aspects and mean slope. The majority of glaciers (more than 45%) had a northeast aspect. Around 12% each faced north or northwest. Very few had a south trending aspect.

Slope – The mean slope of the glaciers in the basin ranged from 10° to more than 60°, with slopes of 20° to 30° and 30° to 40° the most common. The average slope of all glaciers was 30°.

Punatsang basin

The Punatsang Chu is formed from the Mo Chu and Pho Chu rivers in Bhutan and is later joined by the Wang Chu river in India, where it is called the Sankosh river (Figure 8.14), finally merging with the Brahmaputra in Assam. This is the most important glaciated basin in Bhutan, extending from 89.24° to 90.35° E longitude and 27.60° to 28.24° N latitude. The distribution and characteristics of the glaciers in each sub-basin are summarised in Table 8.8.

Number, area, and ice reserves – The Punatsang basin has a total area of 14,365 km², with 433 glaciers covering an area of about 414 km² and containing estimated ice reserves of 30 km³ (Table 8.8). The number, area, and estimated ice reserves of glaciers in the sub-basins are shown in Figure 8.15. The two major glaciated basins of Pho Chu and Mo Chu have catchment areas of 2,335 km² and 2,364 km², with 213 and 163 glaciers, respectively, covering areas of 257 and 123 km², and containing estimated ice reserves of 21 and 7 km³.

Table 8.8: Glacier characteristics in the Punatsang basin

Parameter	Units	Sub-basin			Punatsang
		Wang	Mo	Pho	
Basin area	km²	4,602	2,367	2,337	14,365*
Latitude	degrees	27.60-27.84	27.73-28.24	27.82-28.17	27.60-28.24
Longitude	degrees	89.24-89.57	89.35-89.91	89.86-90.35	89.24-90.35
Number of glaciers	unit	57	163	213	433
CI glacier area	km²	29.03	113.25	209.65	351.93
DC glacier area	km²	4.96	9.57	47.80	62.33
Total glacier area	km²	33.99	122.81	257.45	414.26
Largest glacier area	km²	7.01	10.35	34.73	34.73
Total ice reserves	km³	1.86	7.06	21.26	30.18
Highest elevation	masl	7,062	6,574	7,084	7,084
Lowest elevation	masl	4,354	4,092	4,080	4,080
CI glacier elevation	masl	4,537-7,062	4,447-6,574	4,442-7,084	4,442-7,084
DC glacier elevation	masl	4,354-5,034	4,091-5,324	4,080-5,368	4,080-5,368
Mean CI glacier slope	degrees	27	26	23	26
Mean DC glacier slope	degrees	12	15	13	13
CI-DC area ratio	unit	5.85	11.84	4.39	5.65
Average glacier area	km²	0.60	0.75	1.21	0.96

*Includes area of not glaciated sub-basins

Table 8.9: Glacier area classes in the Punatsang basin

Area class	Area (km²)	Number		Area		Estimate ice reserves		Mean area per glacier
		Total	%	km²	%	km³	%	km²
1	≤ 0.5	271	62.6	47.45	11.5	1.095	3.6	0.18
2	0.51-1.00	80	18.5	55.50	13.4	2.041	6.8	0.69
3	1.01-5.00	68	15.7	143.02	34.5	8.263	27.4	2.10
4	5.01-10.00	8	1.9	54.51	13.2	4.723	15.7	6.81
5	≥10.00	6	1.4	113.76	27.5	14.056	46.6	18.96
	Total	**433**	**100**	**414.25**	**100**	**30.178**	**100**	**0.96**

Figure 8.14: Distribution of glaciers in the Punatsang basin

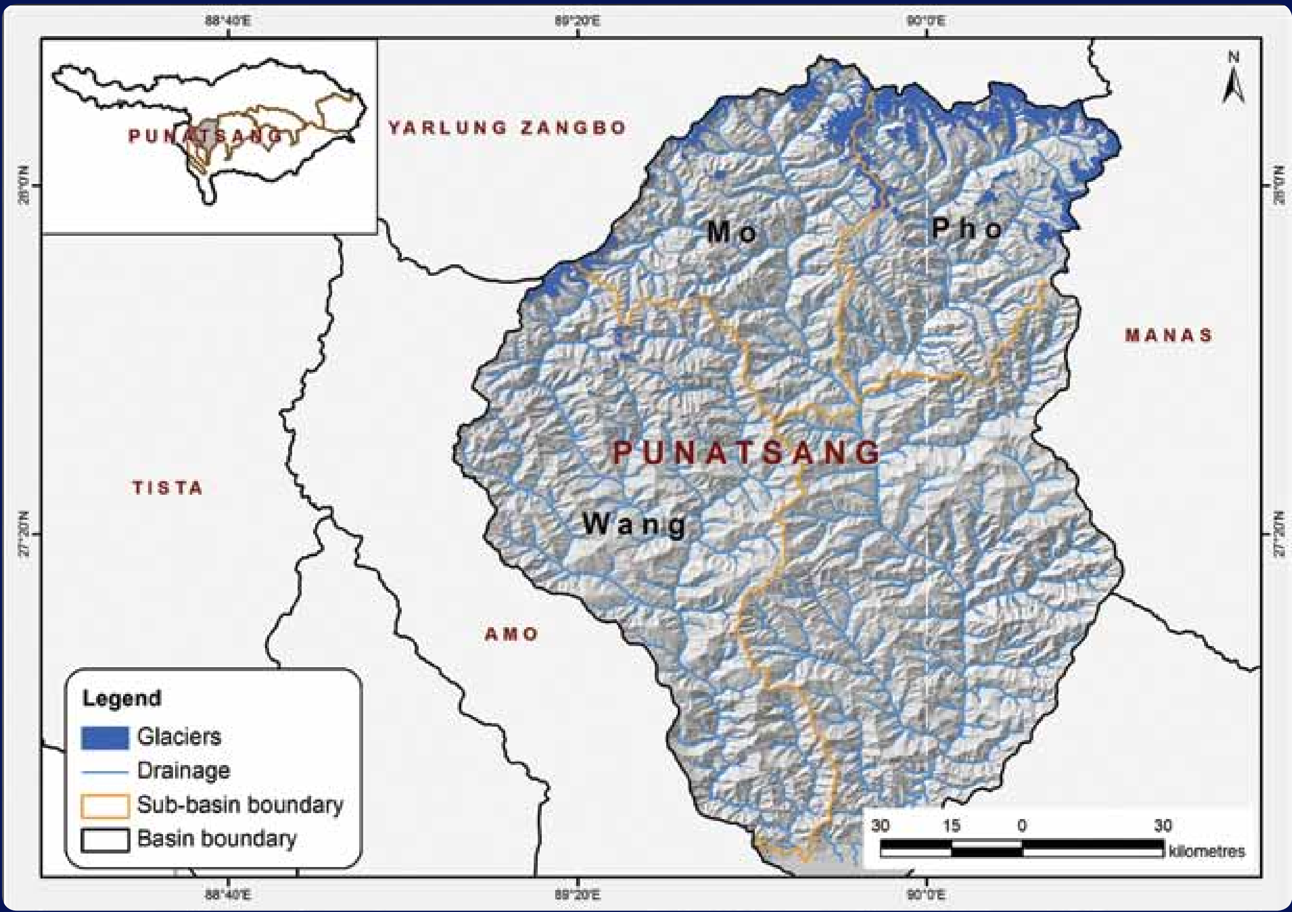


Figure 8.15: Glacier number, area, and estimated ice reserves in the sub-basins of the Punatsang basin

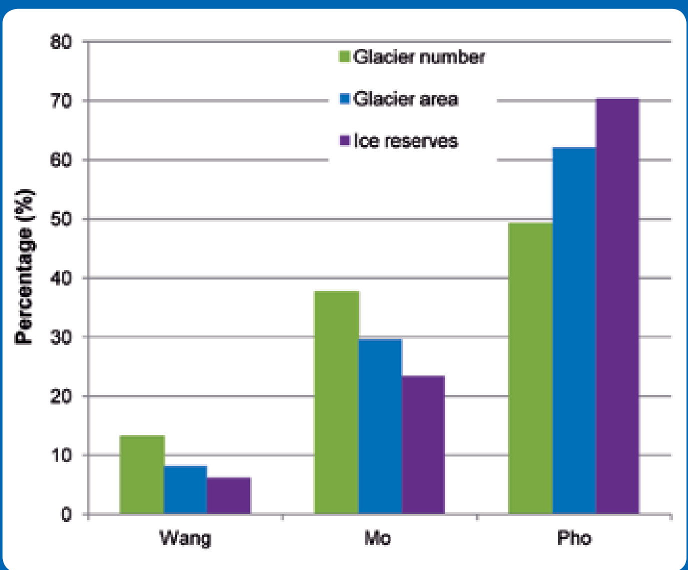


Figure 8.16: Percentage of glacier number, area, and estimated ice reserves in the different glacier size classes in the Punatsang basin

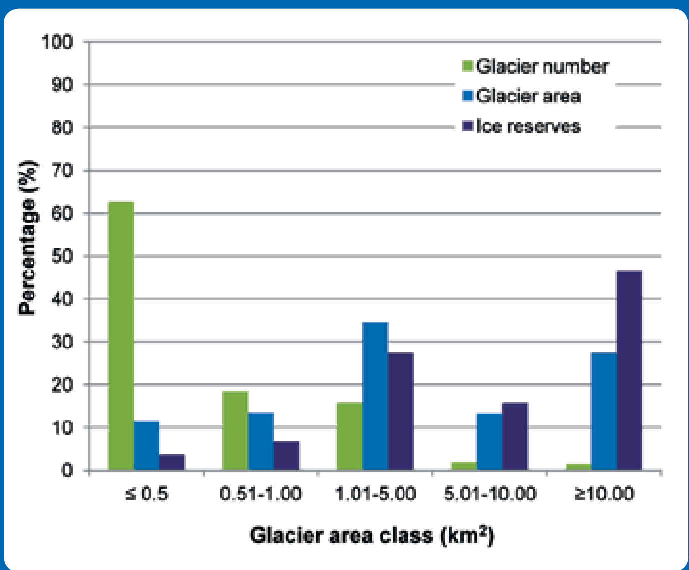


Figure 8.17: Elevation of CI and DC glaciers in the sub-basins of the Punatsang basin

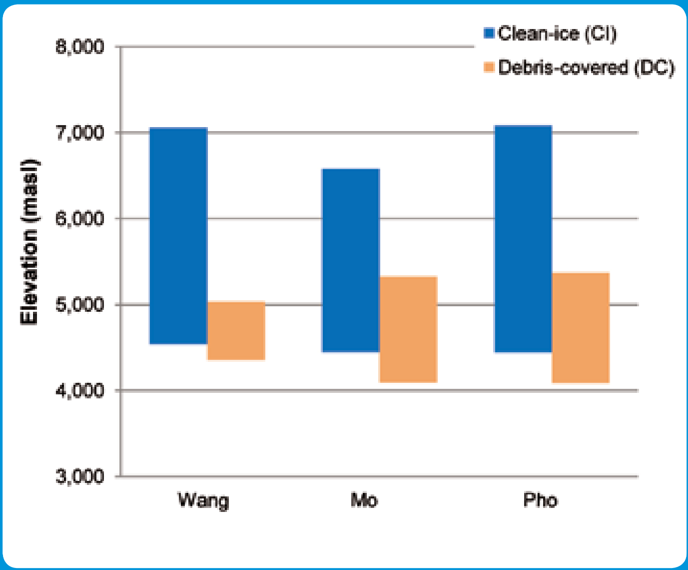
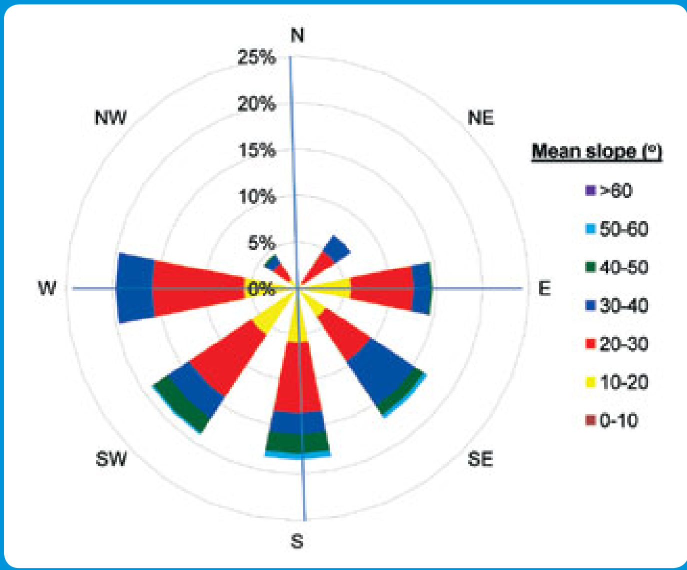


Figure 8.18: Aspect and mean slope of glaciers in the Punatsang basin



Glacier area classes – The number, area, and estimated ice reserves of glaciers in the different size classes are summarised in Table 8.9 and shown as a percentage of the total in Figure 8.16. The average glacier area was about 0.96 km². The majority of the glaciers, 271 or 63% of the total, were in the smallest class 1 (≤0.5 km²), but together contributed only about 11% of the glacier area and just under 4% of the ice reserves. The 6 glaciers in class 5, less than 2% of the total, covered 27% of the glaciated area and contained 47% of the basin's ice reserves. Unusually, the 68 glaciers in class 3, 16% of the total, contributed the most to the area, 35% of the total, and contained the second highest amount of ice reserves (27%).

Glacier elevation – The highest glacier elevation was 7,084 masl and the lowest 4,080 masl, both in the Pho sub-basin (Table 8.8 and Figure 8.17). As elsewhere, the DC glaciers lay at lower elevations overall then the CI glaciers.

Glacier aspect – Figure 8.18 shows the percentage of glaciers with different aspects and mean slope. Between 18 and 20% of glaciers had a south, southwest, or west aspect, and around 15% a southeast or east aspect. Only one glacier had a north aspect.

Slope – The mean slope of the glaciers in the basin ranged from 10° to 60°, with slopes of 20° to 30° the most common for all aspects (45% of all glaciers) followed by slopes of 30° to 40° (28% of glaciers). Less than 1% of glaciers had steep slopes 50° to 60°, all with southern aspects. The mean slope of DC glaciers was 13°; and that of CI glaciers 26° (Table 8.8 and Figure 8.19).

The average slopes of the valley glaciers ranged from 13° to 15° which is favourable to the formation of glacial lakes, especially at lower elevations; the valley glaciers of the Mo and Pho sub-basins give rise to many glacial lakes.

Morphological glacier type – The morphological classification of glaciers in the Punatsang basin is summarised in Table 8.10; the comparative distribution by number, area, and estimated ice reserves is shown graphically in Figure 8.20.

Table 8.10: Morphological classification of glaciers in the Punatsang basin

Glacier type		Number		Area		Estimated ice reserves		Mean area per glacier
		Total	%	km²	%	km³	%	km²
Mountain	Miscellaneous	1	0.2	0.43	0.1	0.013	0.04	0.43
	Ice apron	163	37.6	44.87	10.8	1.611	5.3	0.28
	Cirque	0	0.0	0.00	0.0	0.000	0.0	0.00
	Niche	14	3.2	0.75	0.2	0.009	0.03	0.05
	Basin	236	54.5	189.28	45.7	9.252	30.7	0.80
Valley	Trough	19	4.4	178.92	43.2	19.294	63.9	9.42
	Total	**433**	**100**	**414.25**	**100**	**30.178**	**100**	**0.96**

Figure 8.19: Mean slope of CI and DC glaciers in the sub-basins of the Punatsang basin

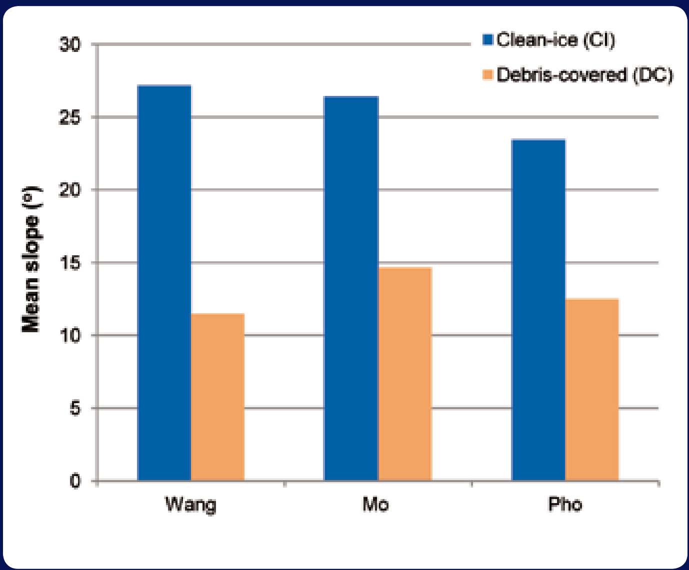


Figure 8.20: Comparative distribution of different glacier types in the Punatsang basin by number, area, and estimated ice reserves

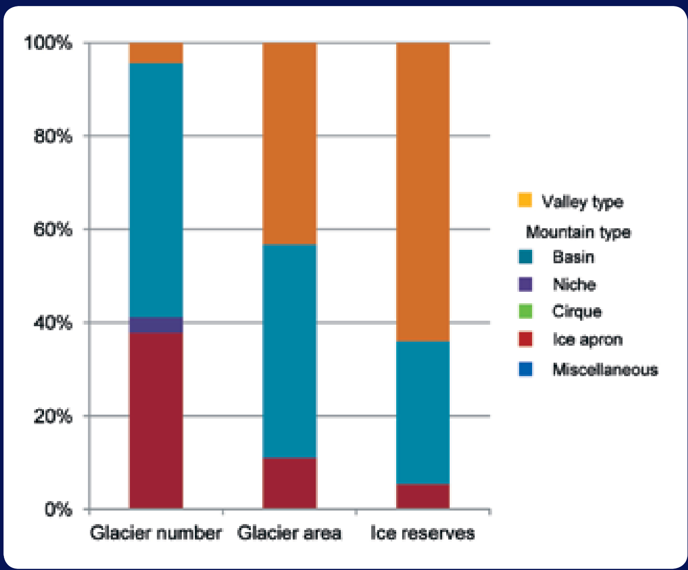


Figure 8.21: Percentage distribution by area of CI and DC glaciers in the sub-basins of the Punatsang basin

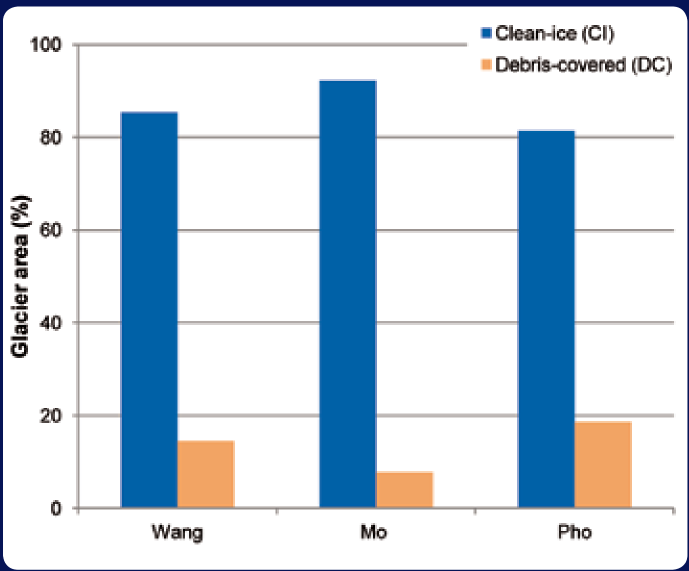


Figure 8.22: Area-altitude distribution of glaciers in the sub-basins of the Punatsang basin

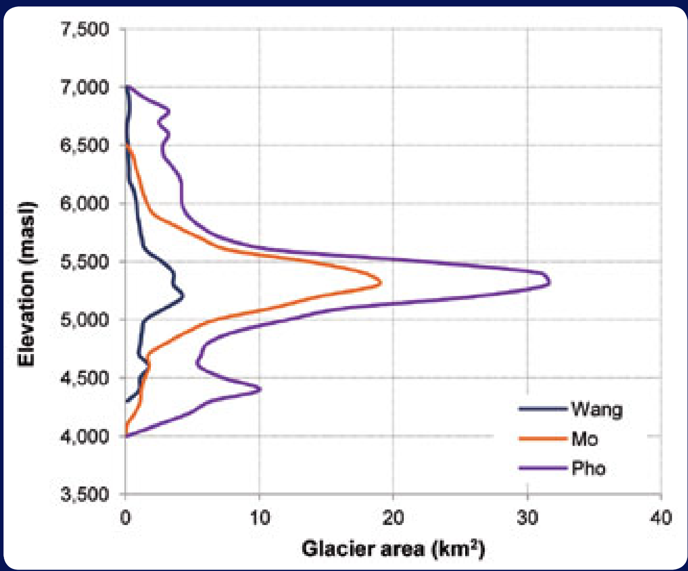


Table 8.11: Glacier characteristics in the Manas basin

Parameter	Units	Sub-basin (Chu)				Manas
		Mangde	Chamkhar	Kuri*	Dangme*	
Basin area	km²	3,818	3,167	9,636	10,488	28,574**
Latitude	degrees	27.82-28.06	27.77-28.06	27.85-28.60	27.70-28.37	27.70-28.60
Longitude	degrees	90.26-90.57	90.49-90.81	90.32-91.48	91.37-92.45	90.26-92.45
Number of glaciers	unit	137	109	518	326	1,090
CI glacier area	km²	94.02	65.78	64.67	53.89	278.35
DC glacier area	km²	16.47	9.67	3.72	1.45	31.31
Total glacier area	km²	110.49	75.44	691.38	279.62	1,156.93
Largest glacier area	km²	20.67	16.85	68.16	15.46	68.16
Total ice reserves	km³	7.65	5.16	56.46	15.71	84.98
Highest elevation	masl	7,223	6,279	6,816	6,380	7,223
Lowest elevation	masl	4,678	4,617	4,404	4,388	4,388
CI glacier elevation	masl	4,791-7,223	4,617-6,279	4,553-6,816	4,391-6,380	4,391-7,223
DC glacier elevation	masl	4,678-5,548	4,699-5,242	4,524-5,139	5,051-5,448	4,524-5,548
Mean CI glacier slope	degrees	19	20	23	20	20
Mean DC glacier slope	degrees	11	11	14	31	17
CI-DC area ratio	unit	5.71	6.80	17.38	37.17	8.89
Average glacier area	km²	0.81	0.69	1.33	0.86	1.06

* extends into China (area in China contains 694 glaciers with a total of 847 km²; CI/DC applies only to the remaining 396 glaciers with an area of 309 km²); **includes area of not glaciated sub-basins

More than 95% of the glaciers were identified as mountain type, the majority of them basin type, followed by ice apron type. Mountain glaciers contributed 57% of the glacier area, and 36% of estimated ice reserves. The average valley glacier area was 9.42 km², compared to between 0.05 to 0.80 km² for the different mountain types. The 19 valley glaciers contributed 43% of the glaciated area and contained 64% of the ice reserves.

Clean-ice and debris-covered glaciers – CI glaciers covered an area of 352 km², 60% of it in the Pho sub-basin, and 85% of the total glaciated area (Table 8.8 and Figure 8.21).

Hypsography – The glacier area-altitude distribution in the sub-basins is shown in Figure 8.22. More than 50% of the glacier area lay between 5100 and 5600 masl. The maximum glaciated areas were 31.5 km² In the Pho sub-basin and 18.92 km² in the Mo sub-basin, both at 5,300 to 5400 masl.

Manas basin

The Manas basin is located in the eastern part of Bhutan at 27.70° to 28.60° N latitude and 90.26° to 92.45° E longitude (Figure 8.23). The river merges with the Brahmaputra river in Assam, India. It has four glaciated sub-basins, the Mangde, Chamkhar, Kuri, and Dangme. The distribution and characteristics of the glaciers in each sub-basin are summarised in Table 8.11.

Number, area, and ice reserves – The Manas basin had 1,090 glaciers (518 in the Kuri, 326 in the Dangme, 137 in the Mangde, and 109 in the Chamkhar sub-basins) with a total area of 1,157 km² and estimated ice reserves of 85 km³ (Table 8.11). The number, area, and estimated ice reserves of glaciers in the sub-basins are shown in Figure 8.24. The Kuri sub-basin has the greatest glacier area (691 km²) and estimated ice reserves (56 km³), and the Chamkhar the least (glacier area 75 km², ice reserves 5 km³).

Glacier area classes – The number, area, and estimated ice reserves of glaciers in the different size classes are summarised in Table 8.12 and shown as a percentage of the total in Figure 8.25. There were 711 glaciers in class 1 (≤0.5 km²), 65% of the total number but with less than 12% of the total area and just over 3% of the ice reserves.

Figure 8.23: Distribution of glaciers in the Manas basin

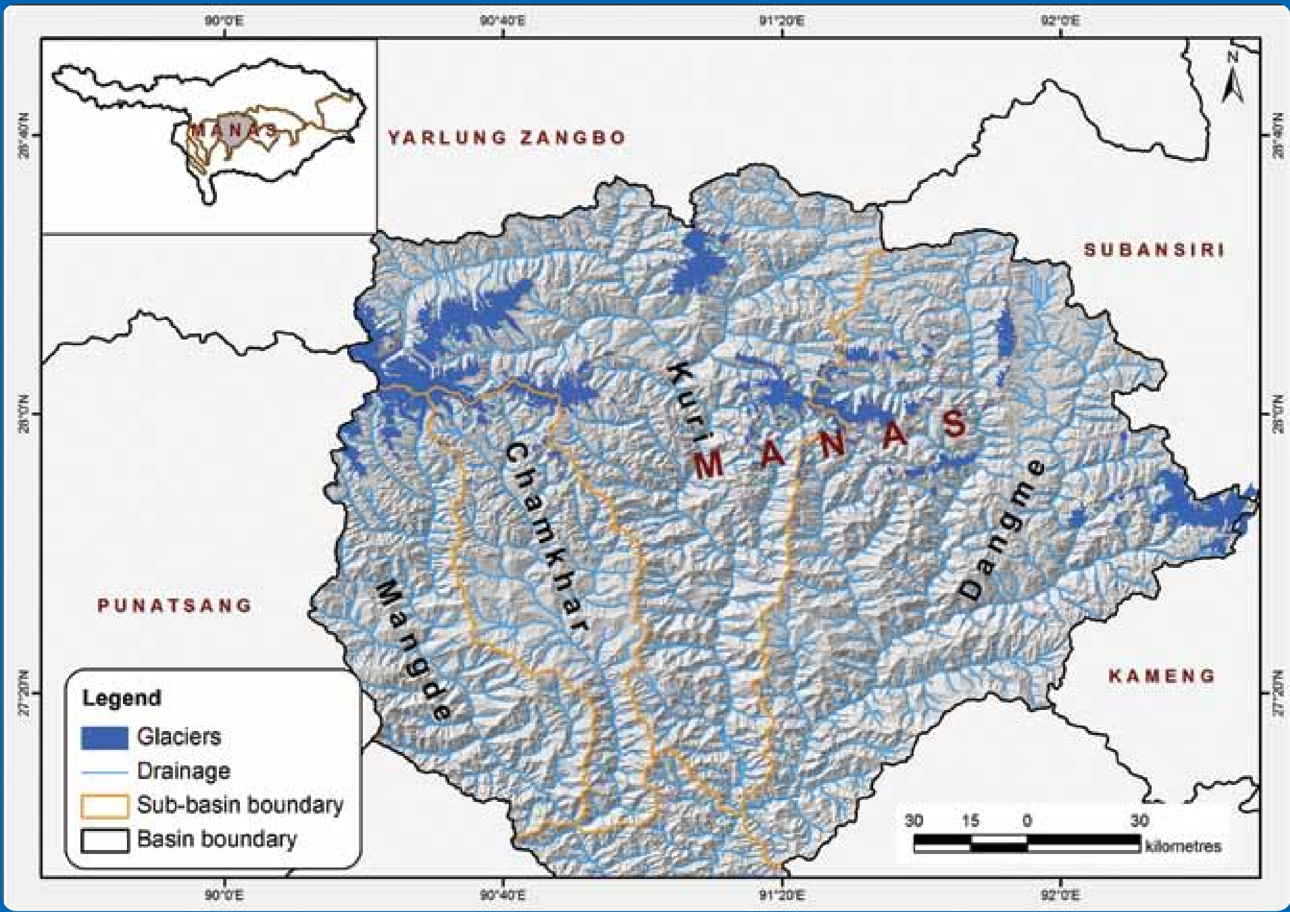


Table 8.12: Glacier area classes in Manas basin

Area class	Area (km²)	Number		Area		Estimated ice reserves		Mean area per glacier
		Total	%	km²	%	km³	%	km²
1	≤ 0.5	711	65.2	133.92	11.6	2.807	3.3	0.19
2	0.51-1.00	150	13.8	106.77	9.2	3.387	4.0	0.71
3	1.01-5.00	184	16.9	402.07	34.8	21.060	24.8	2.19
4	5.01-10.00	30	2.8	223.14	19.3	18.316	21.6	7.44
5	≥10.00	15	1.4	291.04	25.2	39.414	46.4	19.40
	Total	**1,090**	**100**	**1,156.94**	**100**	**84.984**	**100**	**1.06**

The medium-sized class 3 glaciers (1 to 5 km²) had 17% of the total number, but the greatest total area (35%), and the second largest ice reserves (25%). The 15 large glaciers, a little more than 1% of the total number, covered 25% of the total area and contained 46% of the ice reserves. The average area per glacier was just over 1 km².

Glacier elevation – The highest glacier elevation was 7,223 masl and the lowest 4,388 masl (Table 8.11). Among the glaciers differentiated, CI glaciers were found from 7,223 to 4,391 masl and DC glaciers from 5,548 to 4,524 masl (Figure 8.26).

Glacier aspect – Figure 8.27 shows the percentage of glaciers with different aspects and mean slope. Similar numbers of glaciers (11 to 15%) had aspects in all directions except northwest, with 6%.

Figure 8.24: Glacier number, area, and estimated ice reserves in the sub-basins of the Manas basin

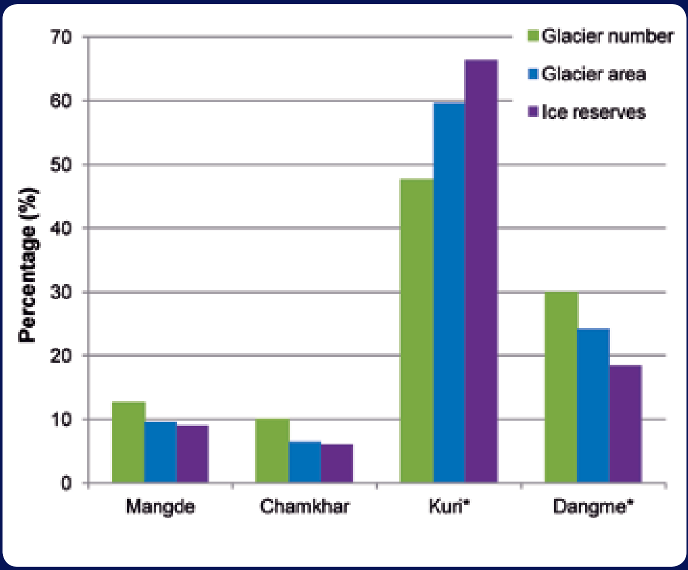


Figure 8.25: Percentage of glacier number, area, and estimated ice reserves in the different glacier size classes in the Manas basin

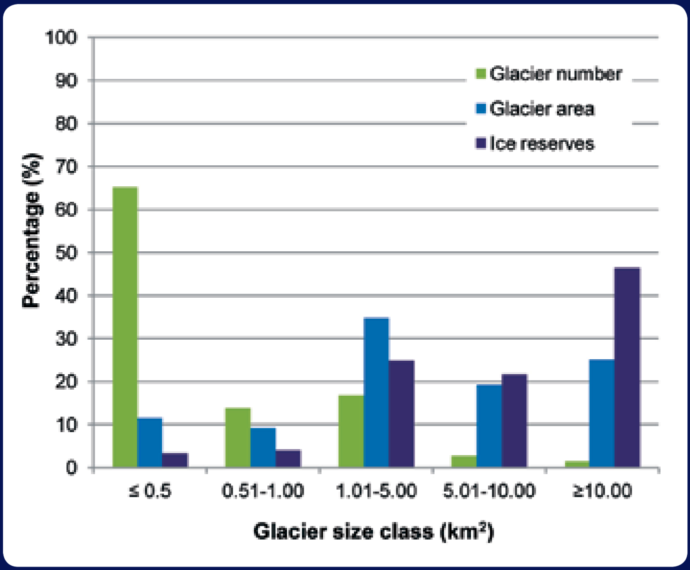


Figure 8.26: Elevation of CI and DC glaciers in the sub-basins of the Manas basin

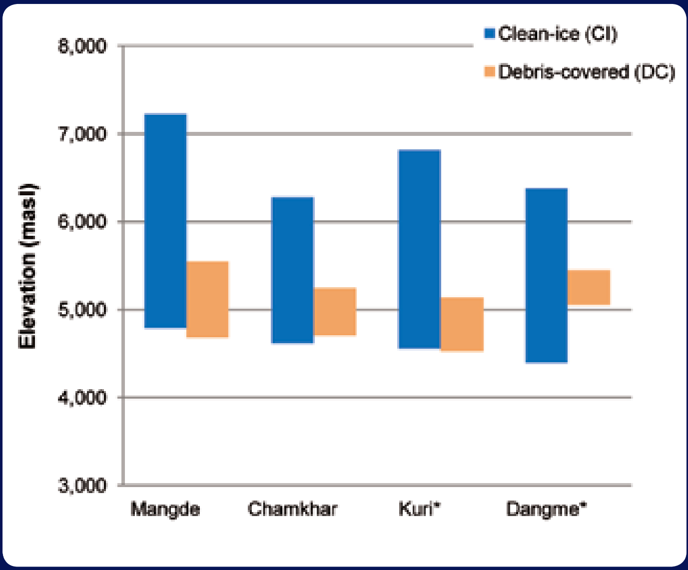
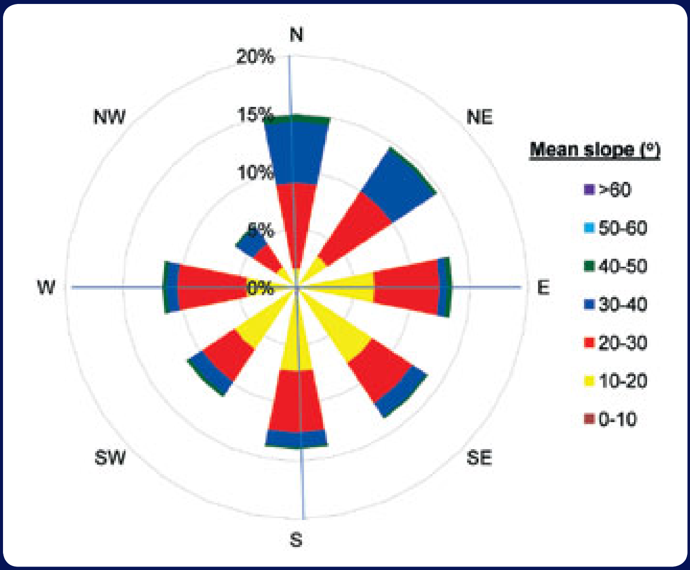


Figure 8.27: Aspect and mean slope of glaciers in the Manas basin



Excluding glaciers in China

Slope – The mean slope of the glaciers in the basin ranged from 10° to 50°. Towards the south, slopes from 10° to 20° and 20° to 30° predominated, whereas towards the north, slopes from 20° to 30° and 30° to 40° predominated (Figure 8.27).

The mean slope of the CI glaciers analysed in the sub-basins of the Manas basin ranged from 19° to 26° with an average slope of 21° while that of the DC glaciers varied from 11° to 31° with an average slope of 17° (Table 8.11 and Figure 8.28). The mean slope of the DC glaciers in the Dangme sub-basin was markedly higher than that in the other sub-basins.

Morphological glacier type – A large proportion of the glaciers were in TAR, China, and thus not classified morphologically, thus the results are not included here.

Clean-ice and debris-covered glaciers – Around 10% of the glacier area analysed, was covered by DC glaciers, with 15% and 13% in the Chamkhar and Mangde sub-basins, and only 3% and 5% in the Dangme and Kuri sub-basins (where many glaciers were not analysed) (Table 8.11 and Figure 8.29).

Hypsography – The glacier area-altitude distribution in the parts of the sub-basins outside China is shown in Figure 8.30. More than 75% of the glaciated area was between 5000 and 5700 masl. The maximum glaciated areas in the sub-basins were 24.3 km² (9.1%) at 5400 to 5500 masl in Mangde sub-basin, and 14.3 km² (5.3%) at 5300-5400 masl in Chamkhar sub-basin. The maximum glaciated area of the part of the Kuri and Dangme sub-basins within Bhutan was 9.93 km² (3.7%) at 5100-5200 masl and less than 1.7 km² (<1%) at 5000 to 5100 masl, respectively.

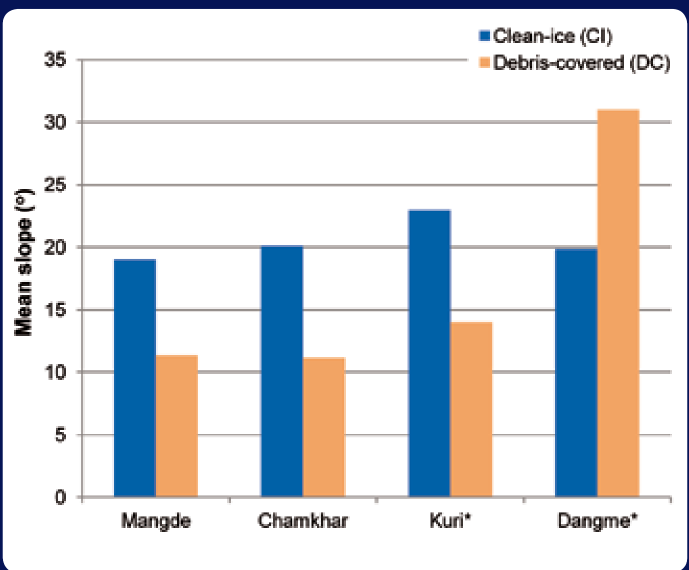
Kameng basin

The Kameng river originates in Tawang district from the glacial lake below the snow-capped Gori Chen mountain on the border between India and Tibet AR, China, in the eastern Himalayan mountains, and flows through Bhalukpong circle of West Kameng District, Arunachal Pradesh, and Sonitpur District of Assam, India (Figure 8.31). It is one of the major tributaries of the Brahmaputra river, joining it at Tezpur, just east of the Kolia Bhomora Setu bridge. The catchment area of the basin is about 10,347 km². The distribution and characteristics of the glaciers in the basin are summarised in Table 8.13.

Number, area, and ice reserves – The Kameng basin contained 21 glaciers with a total glaciated area of close to 11 km² and estimated ice reserves of 0.44 km³ (Table 8.13). The largest single glacier had an area of 2.3 km². All glaciers were CI type.

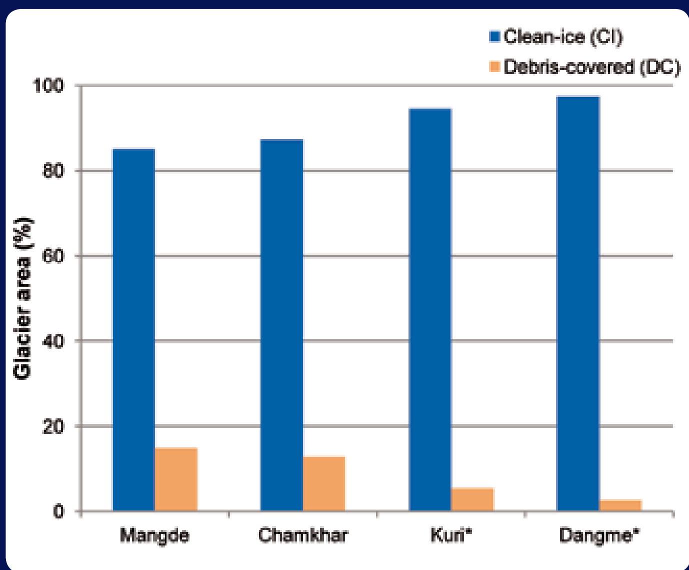
Glacier area classes – The number, area, and estimated ice reserves of glaciers in the different size classes are summarised in Table 8.14 and shown as a percentage of the total in Figure 8.32. The 15 small class 1 glaciers (≤0.5 km²), about 70% of the total, contributed about 30% of the glacier area and contained 18% of the estimated ice reserves. There were three glaciers each in classes 2 and 3, with class 3 glaciers contributing 50% of the glacier area and 65% of the ice reserves. There were no large class 4 or 5 glaciers. The average area per glacier was 0.5 km².

Figure 8.28: Mean slope of CI and DC glaciers in the sub-basins of the Manas basin



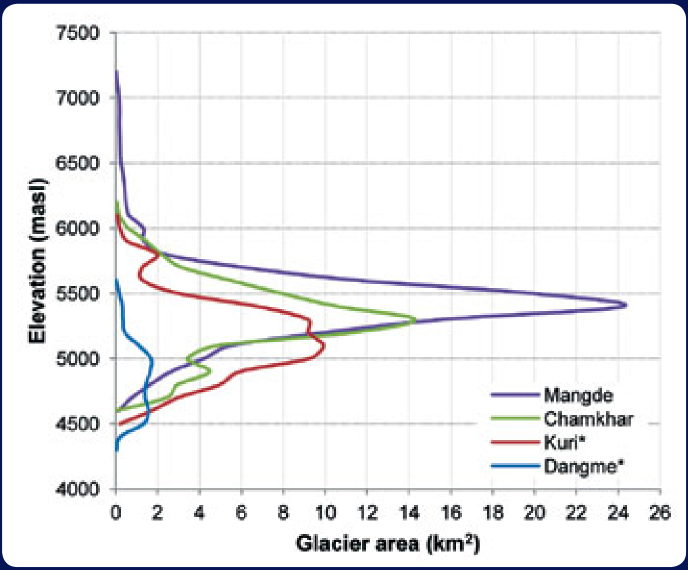
Excluding glaciers in China

Figure 8.29 Percentage distribution by area of CI and DC glaciers in the sub-basins of the Manas basin



Excluding glaciers in China

Figure 8.30: Area-altitude distribution in the sub-basins of Manas basin



Excluding glaciers in China

Table 8.13: Glacier characteristics in the Kameng basin*

Parameter	Units	
Basin area	km²	10,347
Latitude	degrees	27.71-27.98
Longitude	degrees	92.41-92.77
Number of glaciers	unit	21
Total glacier area	km²	10.63
Largest glacier area	km²	2.30
Total ice reserves	km³	0.44
Highest elevation (CI)	masl	6,205
Lowest elevation (CI)	masl	4,465
Mean glacier slope (CI)	degrees	21
Average glacier area	km²	0.51

*all glaciers in the basin were CI type

Figure 8.31: Distribution of glaciers in the Kameng basin

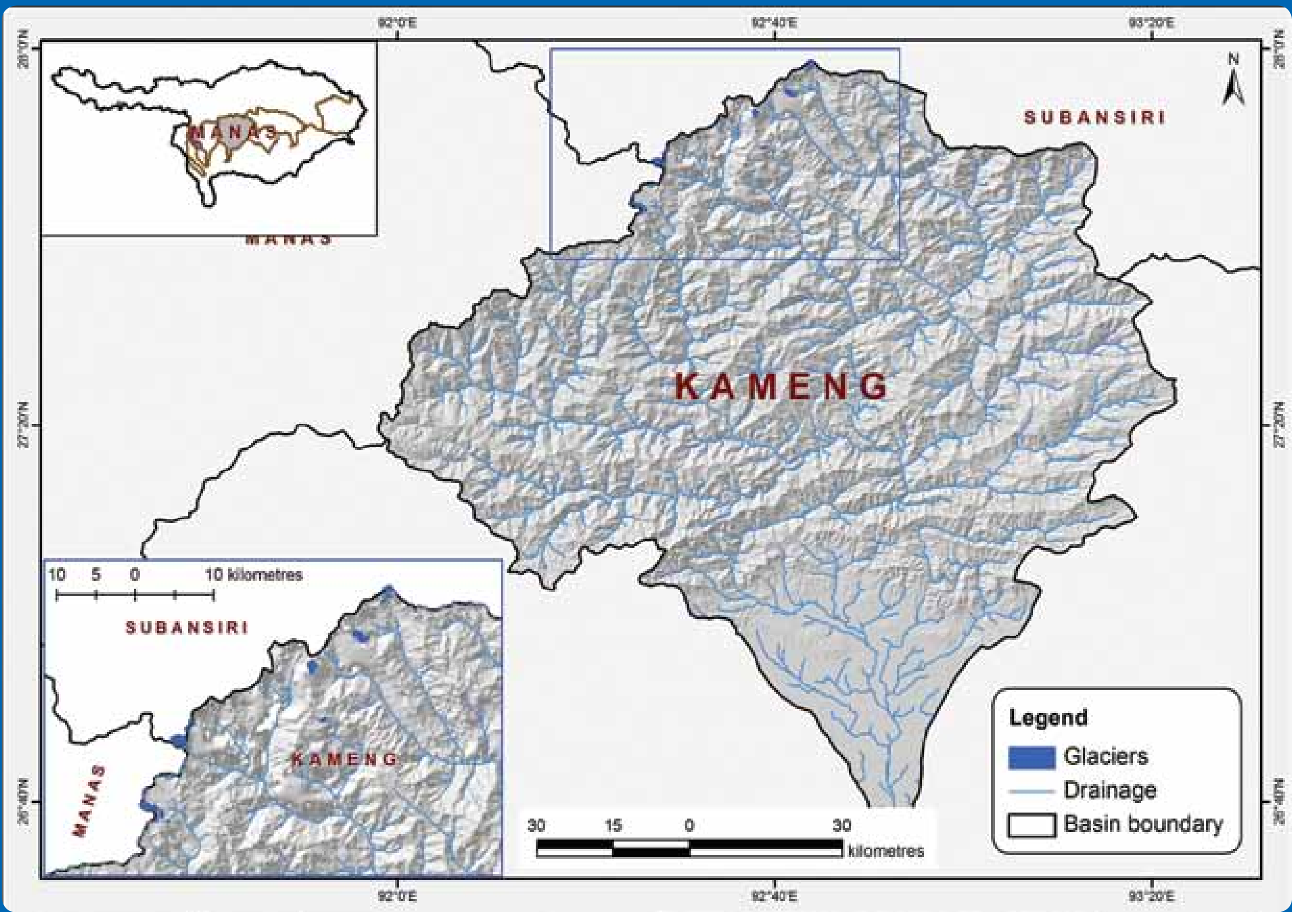


Table 8.14: Glacier area classes in the Kameng basin

Area class	Area (km²)	Number		Area		Estimated ice reserves		Mean area per glacier
		Total	%	km²	%	km³	%	km²
1	≤ 0.5	15	71.4	3.21	30.2	0.080	18.2	0.21
2	0.51-1.00	3	14.3	2.02	19.0	0.074	16.8	0.67
3	1.01-5.00	3	14.3	5.40	50.8	0.286	65.0	1.80
4	5.01-10.00	0	0.0	0.00	0.0	0.000	0.0	0.00
5	≥10.00	0	0.0	0.00	0.0	0.000	0.0	0.00
	Total	**21**	**100**	**10.63**	**100**	**0.440**	**100.00**	**0.51**

Figure 8.32: Percentage of glacier number, area, and estimated ice reserves in the different glacier size classes in the Kameng basin

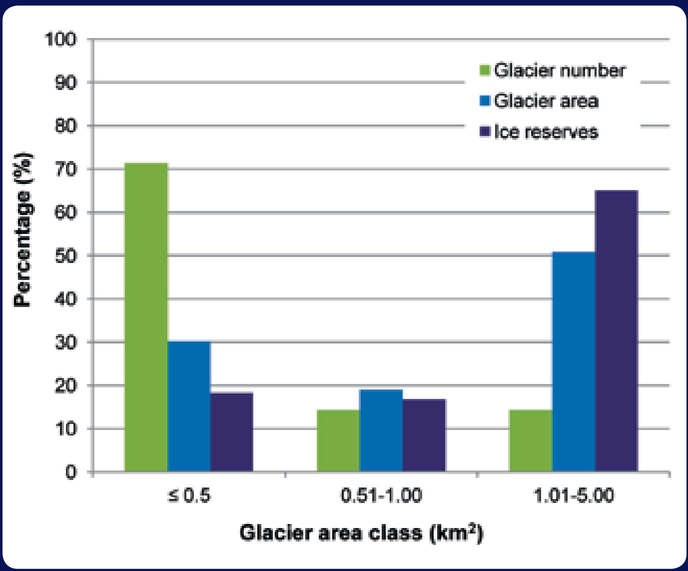


Figure 8.33: Aspect and mean slope of glaciers in the Kameng basin

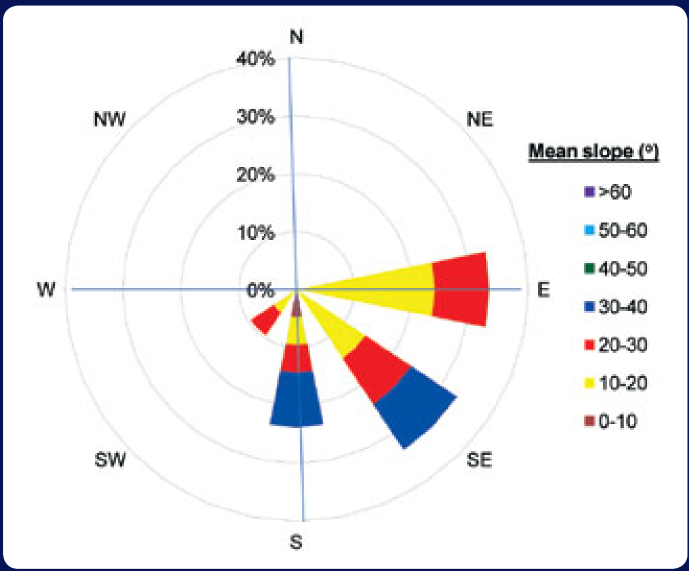


Figure 8.34: Comparative distribution of different glacier types in the Kameng basin by number, area, and estimated ice reserves

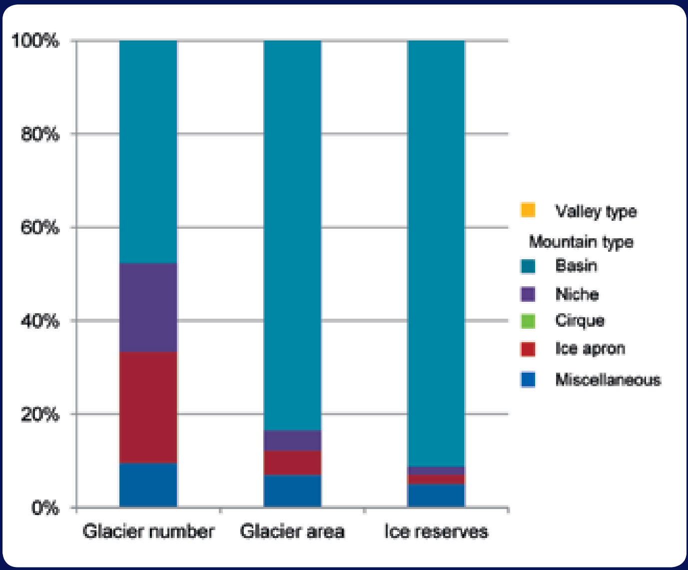


Figure 8.35: Area-altitude distribution of glaciers in the Kameng basin

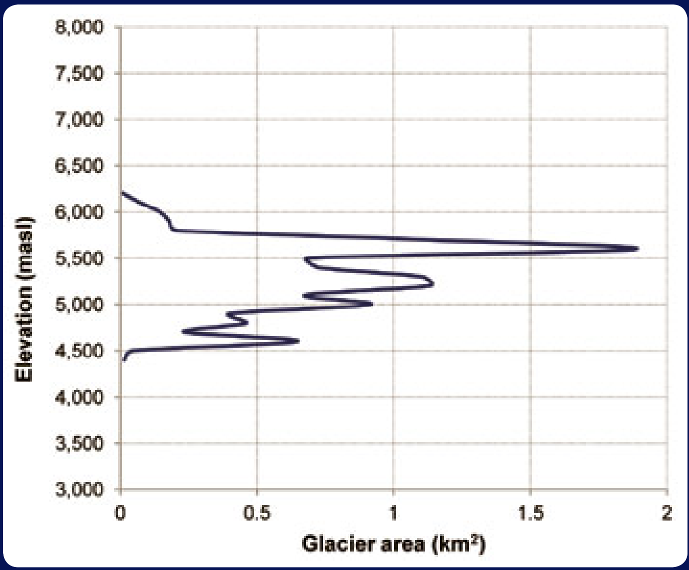


Table 8.15: Morphological classification of glaciers in the Kameng basin

Glacier type		Number		Area		Estimated ice reserves		Mean area per glacier
		Total	%	km²	%	km³	%	km²
Mountain	Miscellaneous	2	9.5	0.75	7.1	0.022	5.0	0.38
	Ice apron	5	23.8	0.54	5.1	0.009	2.1	0.11
	Cirque	0	0.0	0.00	0.0	0.000	0.0	0.00
	Niche	4	19.1	0.47	4.4	0.008	1.8	0.12
	Basin	10	47.6	8.88	83.5	0.401	91.1	0.89
Valley	Trough	0	0.0	0.00	0.0	0.000	0.0	0.00
	Total	**21**	**100**	**10.63**	**100**	**0.440**	**100**	**0.51**

Glacier elevation – The highest glacier elevation was 6,205 masl and the lowest 4,465 masl, both CI glaciers as there were no debris covered areas.
Glacier aspect – Figure 8.33 shows the percentage of glaciers with different aspects and mean slope. The majority of glaciers faced southeast or east (33% each), with a further 24% facing south and 9% southwest.

Slope – The mean slope of the glaciers in the basin was 21°. Slopes of 10° to 20°, followed by slopes of 20° to 30°, were most common in east and southeast facing glaciers, and slopes of 30° to 40° in south facing glaciers. Some 5% of glaciers had slopes of less than 10%, all facing south (Figure 8.33).

Morphological glacier type – The morphological classification of glaciers in the Kameng basin is summarised in Table 8.15; the comparative distribution by number, area, and estimated ice reserves is shown graphically in Figure 8.34. All the glaciers in this basin were of mountain type, the majority basin type (48%), followed by ice apron (24%) and niche type (19%) glaciers. Mountain basin type glaciers contribute 83% of the glaciated area and contained 91% of the estimated ice reserves.

Table 8.16: Glacier characteristics in the Subansiri basin*

Parameter	Units	
Basin area	km²	26,343
Latitude	degrees	27.80-28.79
Longitude	degrees	91.89-93.50
Number of glaciers	unit	493*
CI glacier area	km²	51.53
Total glacier area	km²	486.23
Largest glacier area	km²	53.33
Total ice reserves	km³	35.94
Highest elevation	masl	6,514
Lowest elevation	masl	4,223
Glacier elevation	masl	4,223-6,514
Glacier slope	degrees	25
Average glacier area	km²	0.99

* most of the basin lies in China, CI/DC differentiation, and hypsography were only evaluated for the 62 glaciers within India; there were no DC glaciers in this area.

Hypsography – The glacier area-altitude distribution is shown in Figure 8.35. The distribution was heterogeneous. The maximum glaciated area was about 1.88 km² at 5,600-5,700 masl, 18% of the total.

Subansiri basin

The Subansiri river originates in China, flows east and southeast into India, then south to the Assam valley, where it joins the Brahmaputra (Figure 8.36). It has a drainage area of 26,343 km². The distribution and characteristics of the glaciers in each sub-basin are summarised in Table 8.16.

Number, area, and ice reserves – The Subansiri basin had 493 glaciers, with a total glaciated area of 486 km² and estimated ice reserves of 36 km³ (Table 8.16). The largest individual glacier had an area of about 53 km².

Glacier area classes – The number, area, and estimated ice reserves of glaciers in the different size classes are summarised in Table 8.17 and shown as a percentage of the total in Figure 8.37. There were 326 glaciers, 66% of the total, in the smallest class 1 (≤0.5 km²), covering 12% of the glaciated area and containing 3 % of the estimated

Figure 8.36: Distribution of glaciers in the Subansiri basin

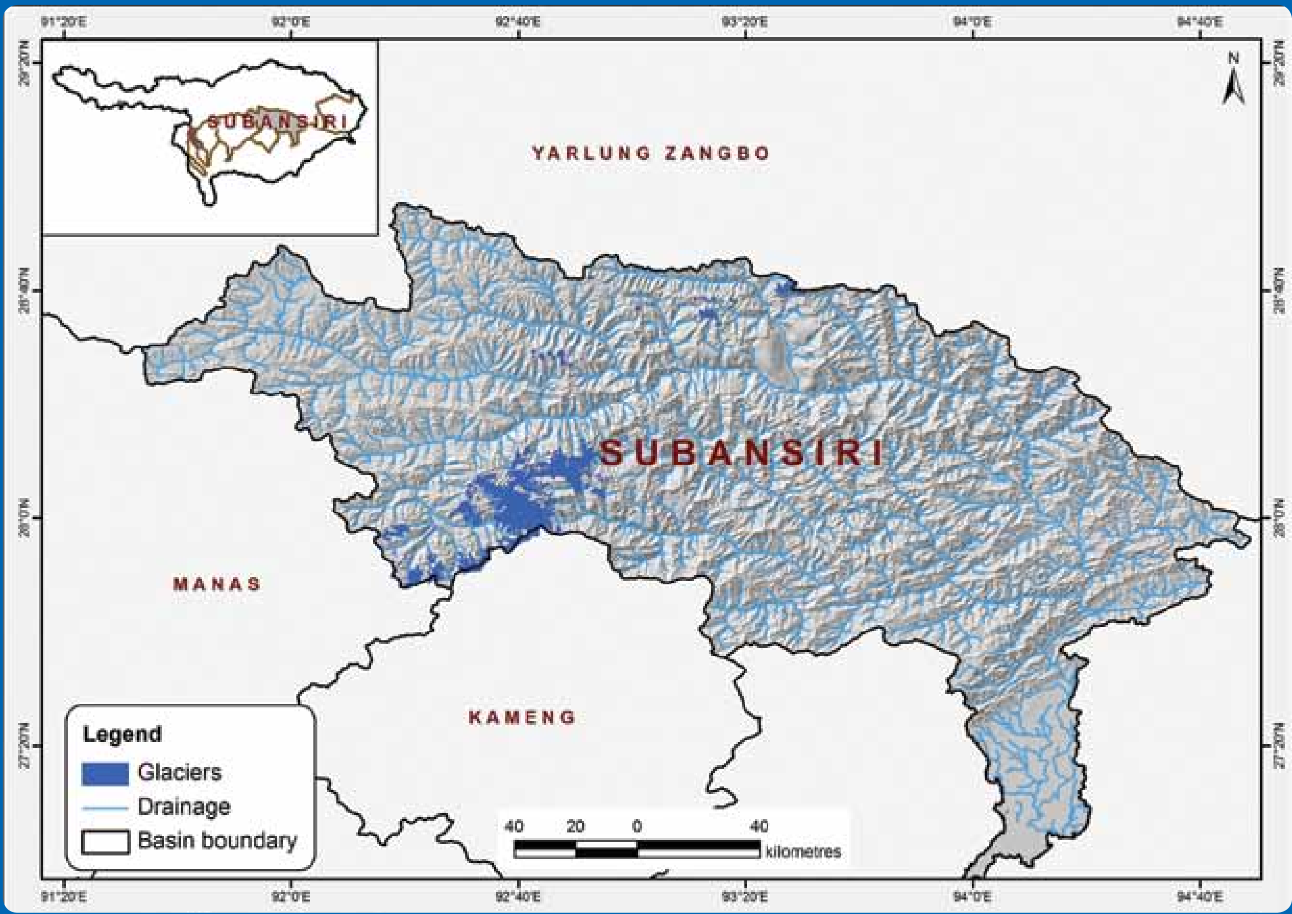


Table 8.17: Glacier area classes in the Subansiri basin

Area class	Area (km²)	Number		Area		Estimated ice reserves		Mean area per glacier
		Total	%	km²	%	km³	%	km²
1	≤ 0.5	326	66.1	59.85	12.3	1.173	3.3	0.18
2	0.51-1.00	78	15.8	55.77	11.5	1.713	4.8	0.72
3	1.01-5.00	70	14.2	152.04	31.3	7.800	21.7	2.17
4	5.01-10.00	14	2.8	100.86	20.7	8.072	22.5	7.20
5	≥10.00	5	1.0	117.70	24.2	17.185	47.8	23.54
	Total	**493**	**100**	**486.23**	**100**	**35.943**	**100**	**0.99**

ice reserves. The 5 glaciers in class 5 (≥10.00 km²) contributed about 24 % of the glacier area and 48% of the estimated ice reserves. The average area per glacier overall was 0.99 km².

Glacier elevation – The highest glacier was at 6,514 masl and the lowest at 4,223 masl.

Glacier aspect – Figure 8.38 shows the percentage of glaciers with different aspects and mean slope. The majority of glaciers faced east (24%), southeast (27%), or south (24%), and about 16% southwest.

Slope – The glacier slopes ranged from 10° to 40° with a mean of 25°. Slopes of 20° to 30° were most common in glaciers of all aspects, followed by slopes of 30° to 40°. Less than 5% of glaciers with all aspects had slopes of 10° to 20°.

Figure 8.37: Percentage of glacier number, area, and estimated ice reserves in the different glacier size classes in the Subansiri basin

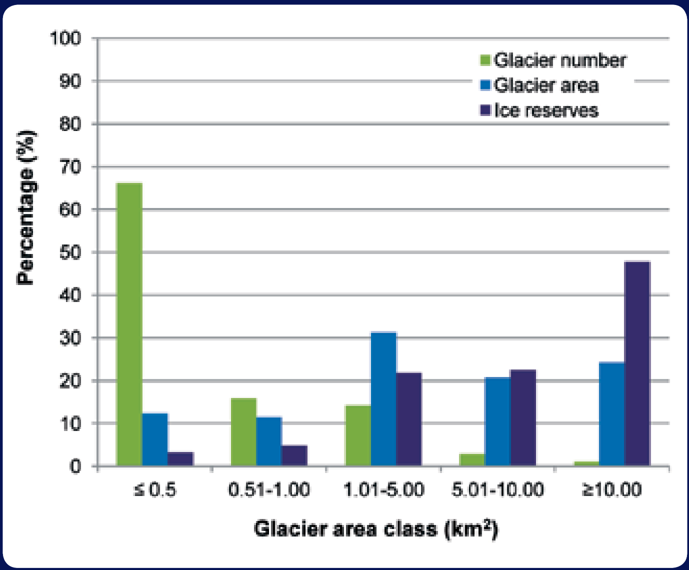
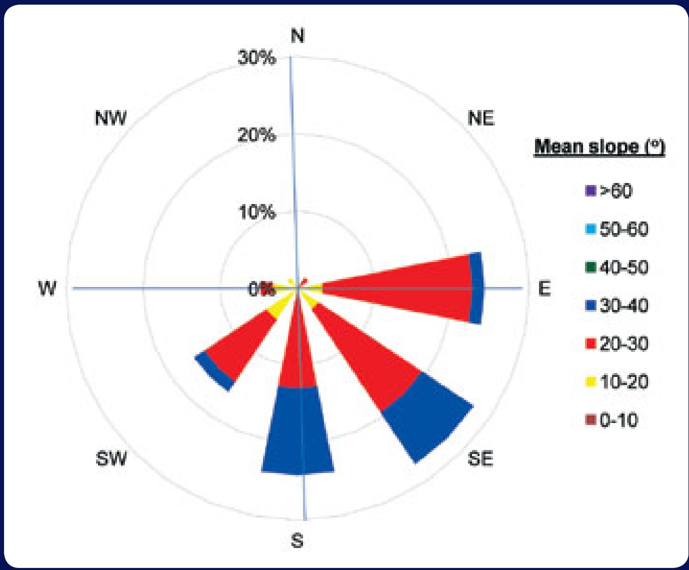


Figure 8.38: Aspect and mean slope of glaciers in the Subansiri basin



Hypsography – The glacier area-altitude distribution of the 62 glaciers evaluated is shown in Figure 8.39. Among these, the maximum glaciated area was 6.85 km² at 5,300 to 5,400 masl, 13% of the total area. Glaciated areas of more than 1 km² were found from 4600 masl to 6,300 masl.

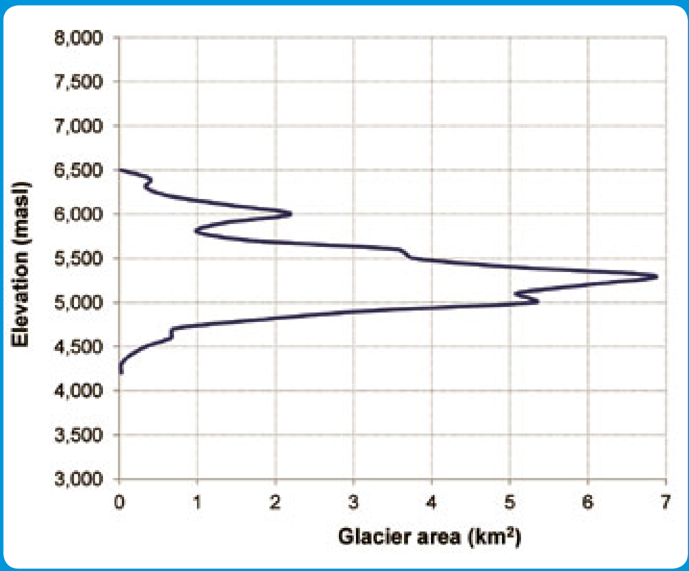
Dihang basin

The Dihang is a large tributary of the Brahmaputra in Upper Assam. The river originates in Arunachal Pradesh and flows through Assam to its confluence with the Brahmaputra. It has two glaciated sub-basins, the Dibhang (11,345 km²) and the Lohit (23,067 km²) (Figure 8.40). The distribution and characteristics of the glaciers in the two sub-basins are summarised in Table 8.18.

Number, area, and ice reserves – The Dihang basin had 955 glaciers with a total glaciated area of 1,305 km² and estimated ice reserves of about 111 km³ (Table 8.18). The number, area, and estimated ice reserves of glaciers in the sub-basins are shown in Figure 8.41. The Lohit sub-basin had 87% of the glaciers, 95% of the area, and 97% of the estimated ice reserves.

Glacier area classes – The number, area, and estimated ice reserves of glaciers in the different size classes are summarised in Table 8.19 and shown as a percentage of the total in Figure 8.42. The majority of glaciers were in the smallest class (547, or 57%); but contributed only 8% of the glacier area and less than 2% of the estimated ice reserves. There were 25 glaciers in each of the largest classes (5-10 km² and more than 10 km²), but the largest class contributed 38% of the glaciated area and contained 64% of the estimated ice reserves. The average glacier area was 1.37 km².

Figure 8.39: Area-altitude distribution of glaciers in the Subansiri basin



The 62 glaciers in India only

Figure 8.40: Distribution of glaciers in the Dihang basin

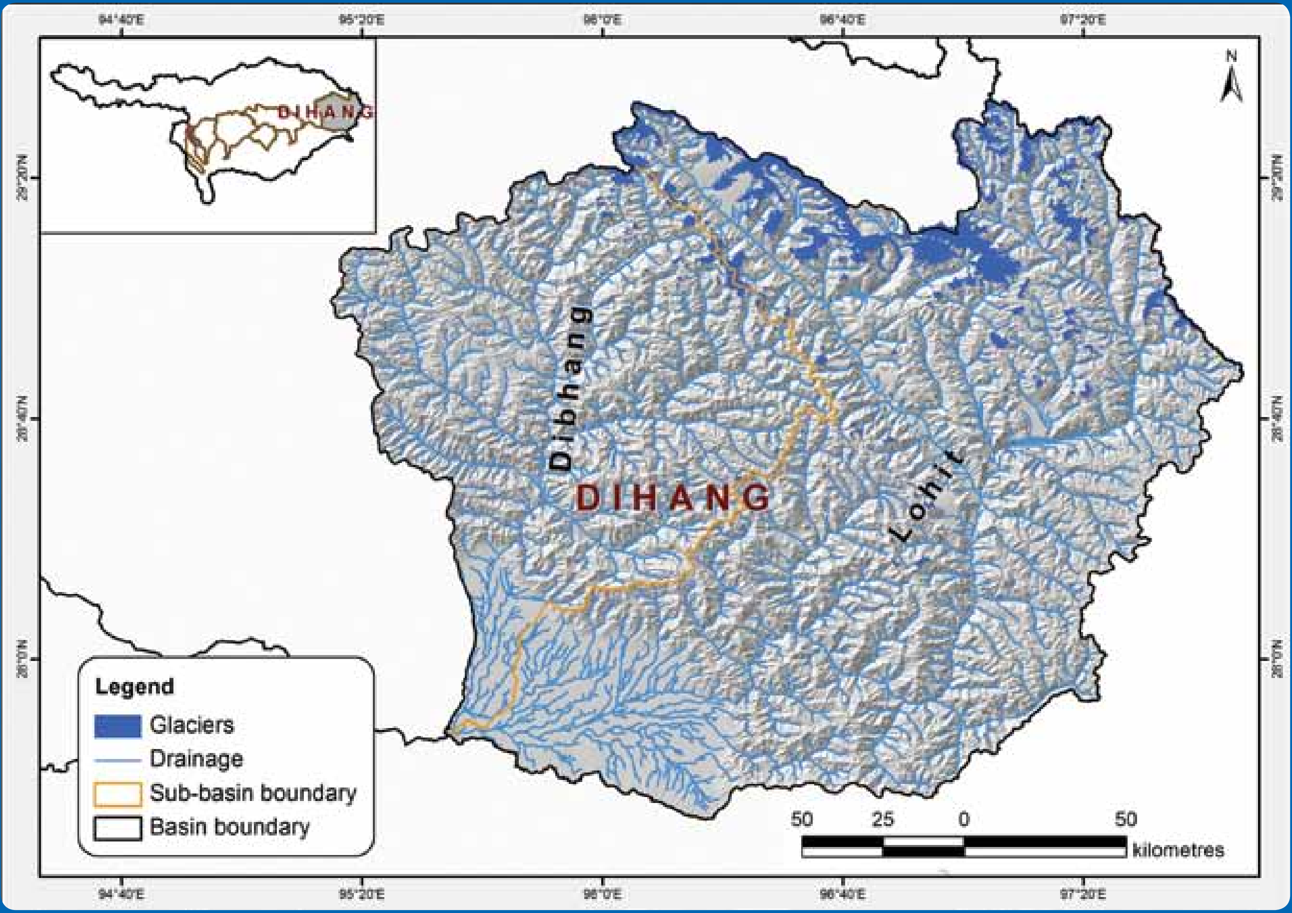


Table 8.18: Glacier characteristics in the Dihang basin

Parameter	Units	Sub-basin		Dihang
		Dibhang	Lohit*	
Basin area	km²	11,345	23,067	34,412**
Latitude	degrees	28.85-29.37	28.20-29.54	28.20-29.54
Longitude	degrees	95.77-96.51	96.03-97.76	95.77-97.76
Number of glaciers	unit	124	831	955
CI glacier area	km²	71.65	22.54	94.18
Total glacier area	km²	71.65	1,233.45	1,305.10
Largest glacier area	km²	3.64	96.22	96.22
Total ice reserves	km³	3.31	107.66	110.97
Highest elevation	masl	5,310	5,902	5,902
Lowest elevation	masl	3,707	2,435	2,435
Glacier elevation	masl	3,707-5,310	4,211-5,693*	2,435-5,902
Mean glacier slope	degrees	22	27	24
Average glacier area	km²	0.58	1.48	1.37

*extends into China (area in China contains 784 glaciers, CI/DC differentiation, and hypsography refers to the remaining 171 glaciers, all the glaciers in the Dibhang sub-basin and 47 glaciers in the Lohit sub-basin; there were no DC glaciers in this area);
** includes area of non-glaciated sub-basins

Figure 8.41: Glacier number, area, and estimated ice reserves in the sub-basins of the Dihang basin

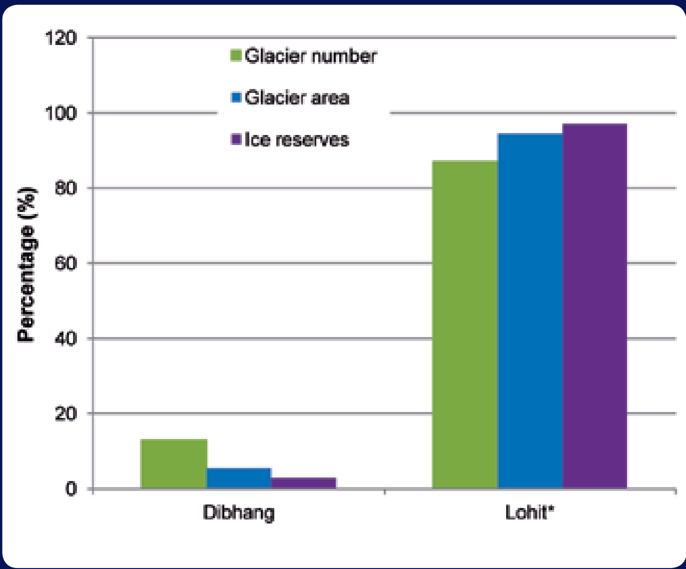


Figure 8.42: Percentage of glacier number, area, and estimated ice reserves in the different glacier size classes in the Dihang basin

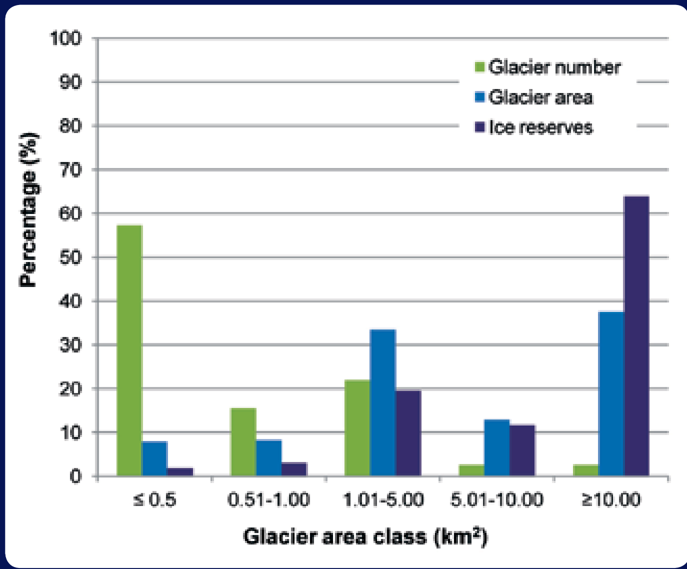


Table 8.19: Glacier area classes in the Dihang basin

Area class	Area (km^2)	Number		Area		Estimated ice reserves		Mean area per glacier
		Total	%	km^2	%	km^3	%	km^2
1	≤ 0.5	547	57.3	103.60	7.9	2.056	1.9	0.19
2	0.51-1.00	148	15.5	107.41	8.2	3.345	3.0	0.73
3	1.01-5.00	210	22.0	436.91	33.5	21.769	19.6	2.08
4	5.01-10.00	25	2.6	167.37	12.8	12.926	11.7	6.69
5	≥10.00	25	2.6	489.80	37.5	70.874	63.9	19.59
	Total	**955**	**100**	**1,305.10**	**100**	**110.971**	**100**	**1.37**

Glacier elevation – Glaciers were found from 5,902 to 2,435 masl in the Lohit basin and from 5,310 to 3,707 masl in the Dihang basin (Table 8.18).

Glacier aspect – Figure 8.43 shows the percentage of glaciers with different aspects and mean slope. More than 22% of glaciers faced north, 18% northeast, and between 11 and 13%, east, southeast, and northwest. Only a small number had southern aspects.

Slope – The mean slope of the glaciers ranged from 10° to 50° (Figure 8.43) with an overall average of 24°. Slopes of 20° to 30° were most common in glaciers of all aspects, followed by slopes of 30° to 40°.

Hypsography – The glacier area-altitude distribution of the 124 glaciers in the Dibhang sub basin and 47 glaciers in the Lohit sub-basin within India is shown in Figure 8.44. The maximum glaciated area in the Dihang basin was 18.0 km^2, 18% of the total, at 4,700 to 4,800 masl. The highest concentration of glaciers was at 4700-4800 masl in the Dibhang sub-basin and 5000-5100 masl in the Lohit sub-basin.

Yarlung Zangbo basin

The Yarlung Zangbo river originates in the vicinity of Mansarovar in southern Tibet in China, passes through the state of Arunachal Pradesh in India, widens out, and eventually becomes the Brahmaputra river. It has nine sub-basins: the Maquan (33,201 km^2), Yarlung Zangbo (90,555 km^2), Dogxung Zangbo (20,097 km^2), Xiangqu (7,443 km^2),

Figure 8.43: Aspect and mean slope of glaciers in the Dihang basin

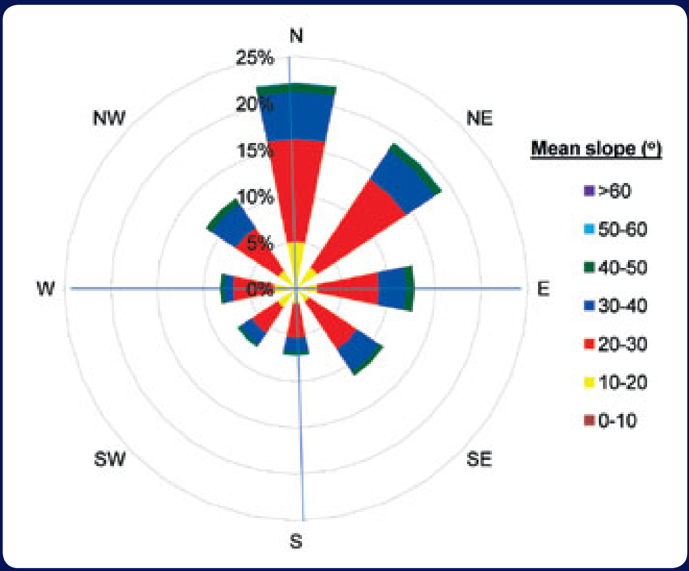
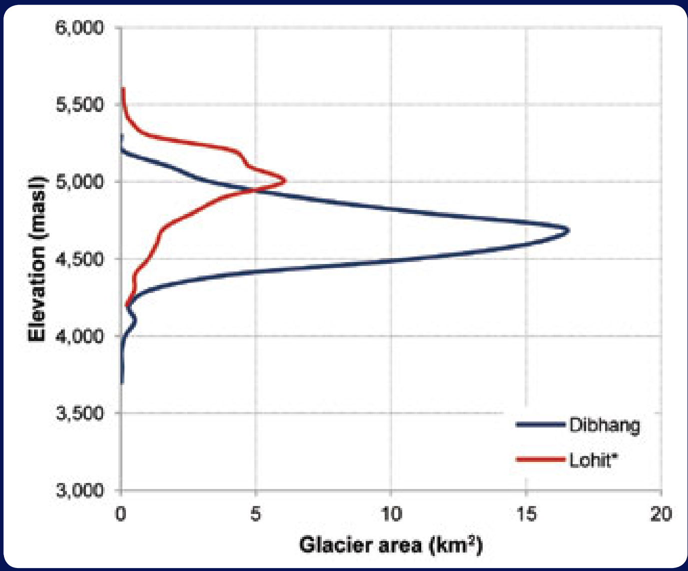


Figure 8.44: Area-altitude distribution of glaciers in the sub-basins of the Dihang basin



Only for the 47 glaciers outside China

Figure 8.45: Distribution of glaciers in the Yarlung Zangbo basin

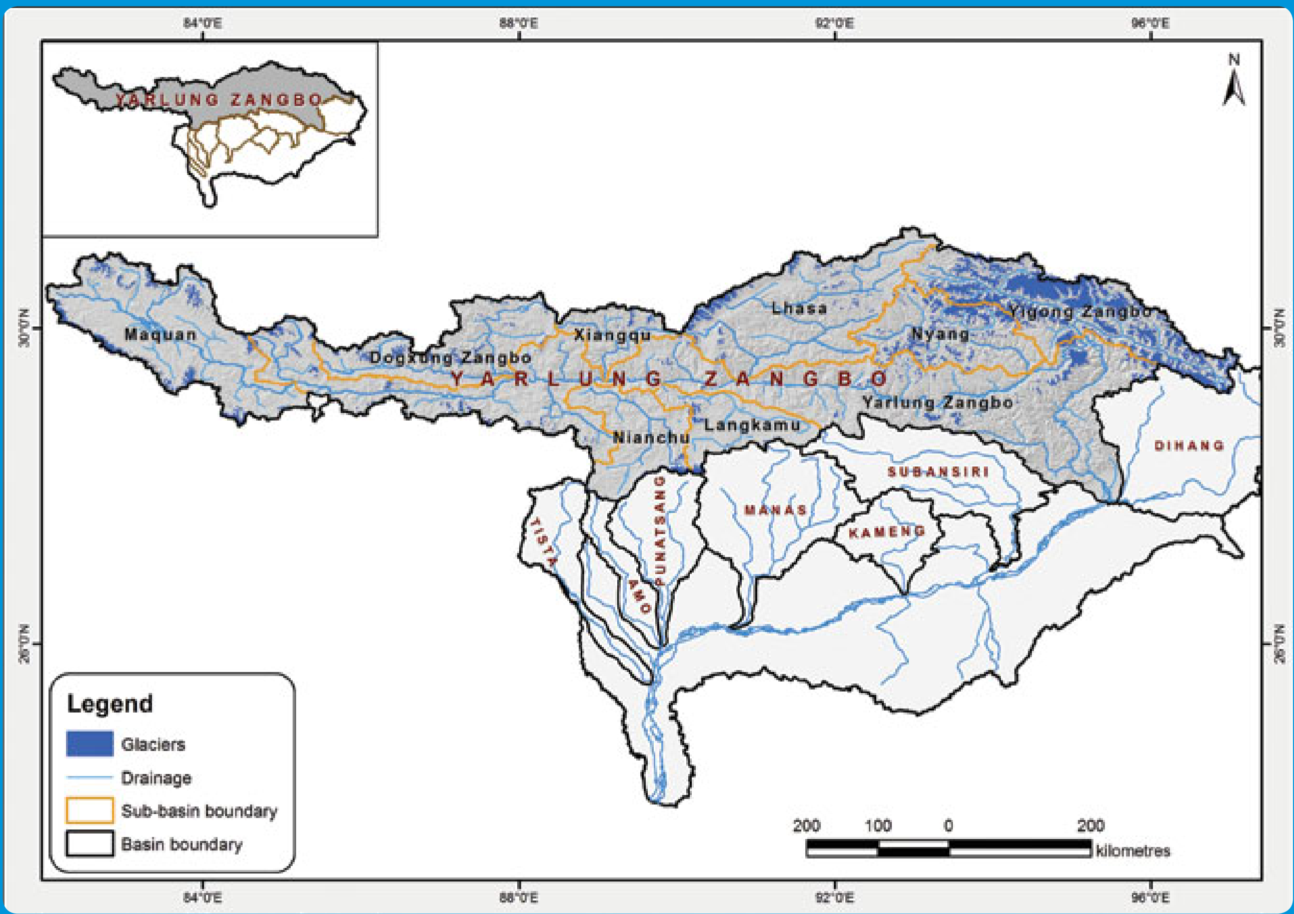


Figure 8.46: Glacier number, area, and estimated ice reserves in the sub-basins of the Yarlung Zangbo basin

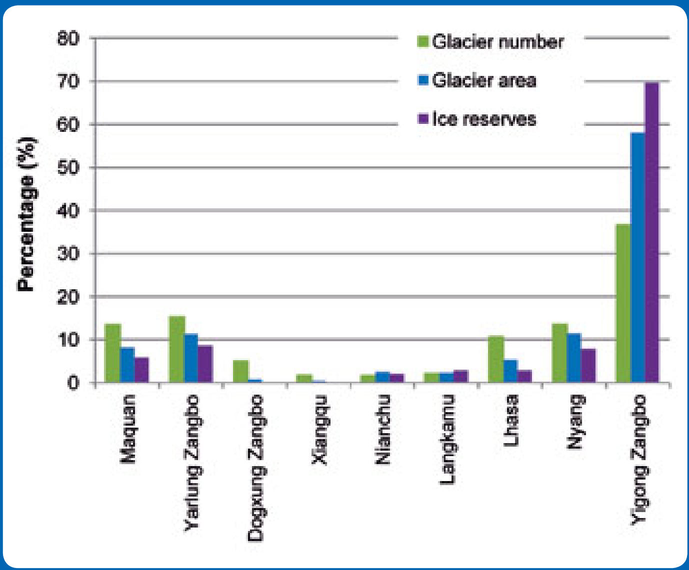
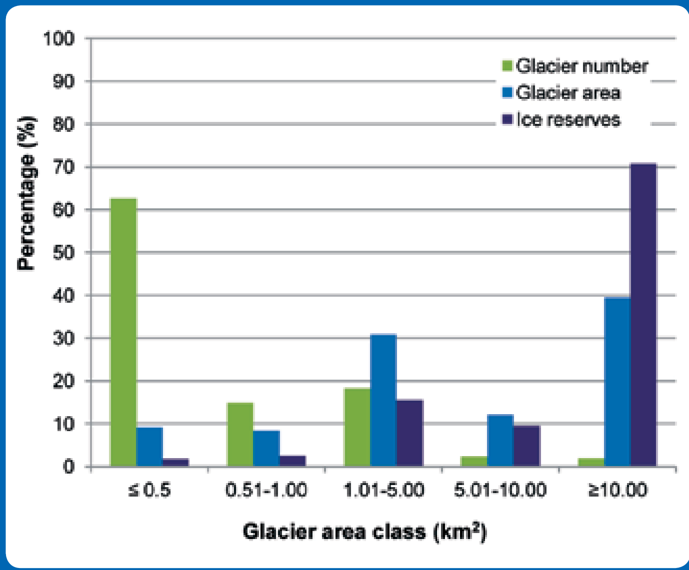


Figure 8.47: Percentage of glacier number, area, and estimated ice reserves in the different glacier size classes in the Yarlung Zangbo basin



Nianchu (14,270 km²), Langkamu (11,505 km²), Lhasa (32,826 km²), Nyang (17,866 km²), and Yigong Zangbo (29,016 km²) (Figure 8.45).

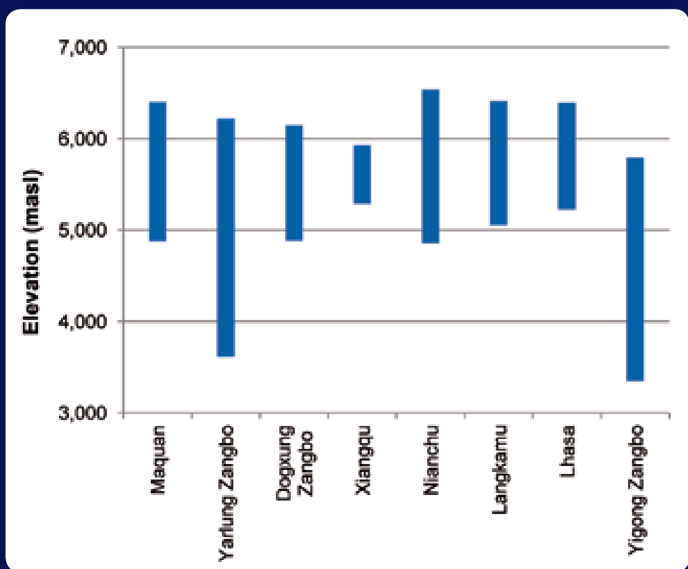
The distribution and characteristics of the glaciers in each sub-basin are summarised in Table 8.20. The glaciers all lie in China and were therefore not classified morphologically or differentiated into CI and DC glaciers.

Number, area, and ice reserves – The Yarlung Zangbo basin had 8,075 glaciers with a total area of 10,154 km² and estimated ice reserves of 996 km³ (Table 8.20). The number, area, and estimated ice reserves of glaciers in the sub-basins are shown in Figure 8.46. The Yigong Zangbo basin had the most glaciers, greatest glaciated area, and greatest estimated ice reserves. The largest individual glacier had an area of 204 km², the biggest in the whole Brahmaputra basin.

Glacier area classes – The number, area, and estimated ice reserves of glaciers in the different size classes are summarised in Table 8.21 and shown as a percentage of the total in Figure 8.47. More than 77% of glaciers were in the smallest class (≤1.0 km²) but contributed only 9% of the glacier area and less than 2% of the ice reserves. The 149 glaciers in the biggest class (≥10.00 km²), less than 2% of the total, contributed 40% of the area, and contained more than 70% of the estimated ice reserves. The average glacier area was 1.26 km².

Glacier elevation – The highest glacier elevation was 6,536 masl in the Nianchu sub-basin and the lowest 3,348 masl in the Yigong Zangbo sub-basin (Figure 8.48). The Yigong Zangbo basin had the lowest glaciers, both top and terminus, of all the sub-basins and the Yarlung Zangbo the greatest range.

Figure 8.48: Elevation of glaciers in the Yarlung Zangbo basin



Elevation data for Nyang sub-basin not available.

Table 8.20: Glacier characteristics in the Yarlung Zangbo basin

Parameter	Units	Sub-basin									Yarlung Zangbo
		Maquan	Yarlung Zangbo	Dogxung-Zangbo	Xiangqu	Nianchu	Langkamu	Lhasa	Nyang	Yigong-Zangbo	
Basin area	km^2	33,201	90,555	20,097	7,443	14,270	11,505	32,826	17,866	29,016	256,779
Latitude	degrees	28.79-30.93	28.55-30.14	29.33-30.36	29.87-30.25	27.82-28.98	28.19-29.07	29.56-31.01	29.44-30.58	29.19-31.03	27.82-31.03
Longitude	degrees	82.03-85.35	84.57-96.08	85.40-88.46	89.24-90.02	88.85-90.18	90.08-91.29	90.09-93.14	92.24-94.33	93.02-97.09	82.03-97.09
Number of glaciers	unit	1,089	1,235	401	137	133	165	861	1,095	2,959	8,075
Total glacier area	km^2	830.30	1,139.06	77.04	42.35	256.38	223.33	537.59	1,154.79	5,892.83	10,153.67
Largest glacier area	km^2	33.31	60.15	3.03	4.71	30.20	85.97	27.35	50.03	204.36	204.36
Total ice reserves	km^3	58.23	85.98	2.05	1.47	20.16	27.63	27.71	78.76	694.18	996.17
Highest elevation	masl	6,402	6,223	6,145	5,930	6,536	6,410	6,392	NA	5,796	6,536
Lowest elevation	masl	4,877	3,616	4,883	5,289	4,858	5,055	5,224	NA	3,348	3,348
Mean slope	degrees	25	26	24	26	26	26	23	NA	27	25
Average glacier area	km^2	0.76	0.92	0.19	0.31	1.93	1.35	0.62	1.05	1.99	1.26

NA = Not available

Figure 8.49: Aspect and mean slope of glaciers in the Yarlung Zangbo basin

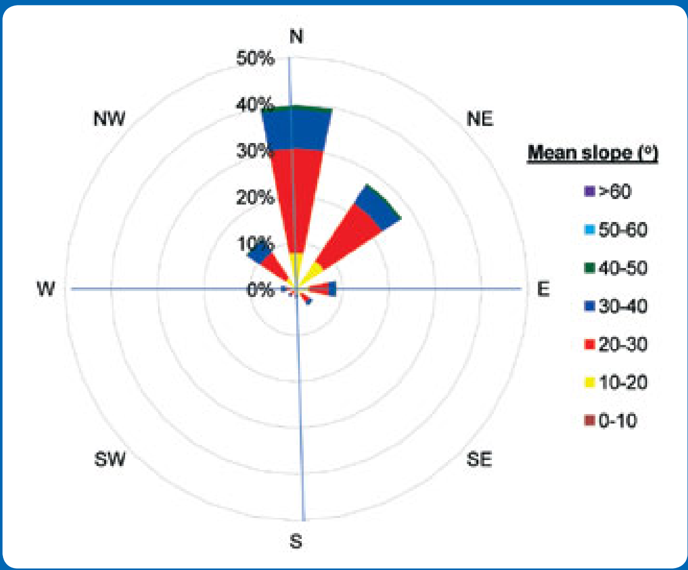


Figure 8.50: Mean slope of glaciers in the Yarlung Zangbo sub-basins

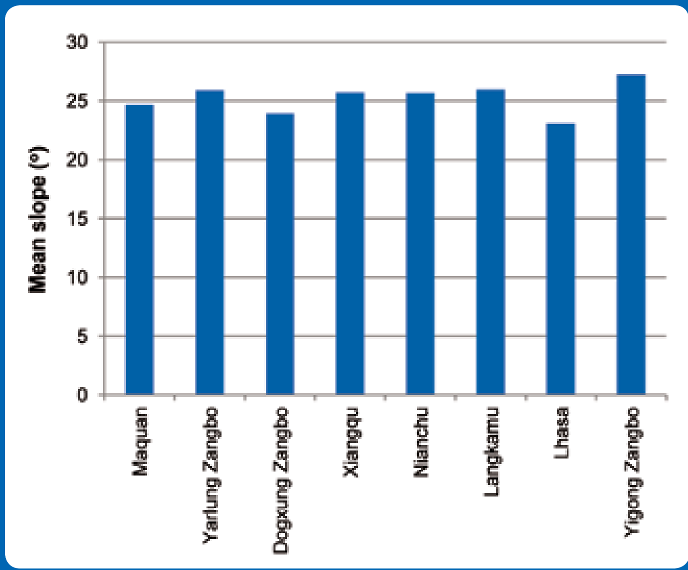


Table 8.21: Glacier area classes in the Yarlung Zangbo basin

Area class	Area (km²)	Number		Area		Estimated ice reserves		Mean area per glacier
		Total	%	km²	%	km³	%	km²
1	≤ 0.5	5,064	62.7	935.54	9.2	17.525	1.8	0.18
2	0.51-1.00	1,202	14.9	847.40	8.4	24.794	2.5	0.70
3	1.01-5.00	1,477	18.3	3,125.88	30.8	154.378	15.5	2.12
4	5.01-10.00	183	2.3	1,228.58	12.1	94.679	9.5	6.71
5	≥10.00	149	1.9	4,016.27	39.6	704.792	70.8	26.95
	Total	**8,075**	**100**	**10,153.67**	**100**	**996.167**	**100**	**1.26**

Glacier aspect – Figure 8.49 shows the percentage of glaciers with different aspects and mean slope. The great majority of glaciers faced north (40%) or northeast (27%), with very few having a generally southern aspect.

Slope – The mean slope of the glaciers ranged from 10° to 60°. Slopes of 20° to 30° were the most common in glaciers of all aspects, followed by slopes of 30° to 40° (Figure 8.49). The average slope of the glaciers in the individual sub-basins ranged from 23° to 27° (Figure 8.50), with an overall average slope of 25° (Table 8.20).

9 Irrawaddy Basin

The Irrawaddy (Irawadi) is the principal river of Myanmar and fed by tributaries from Myanmar and China. The river forms in Kachin State at the confluence of the Mali and Nmai rivers north of Myitkyina. The western branch of the Mali river originates north of Putao from the end of the southern Himalayas, and is called Nam Kiu locally. The easternmost branch of the Nmai river originates in the Languela glacier north of Putao in China. The area has a mainly tropical climate; the watershed area is covered by clouds and fog most of the time and perennial ice and snow are only found in a limited area. The Irrawaddy flows through the country from north to south bisecting the centre and empties through a nine-armed delta into the Indian Ocean. From Myitkyina, the river is about 2,050 km long; the catchment area is about 426,501km² of which 202,745 km² falls within the HKH region. The Nmai river is not navigable because of the strong current, whereas the smaller western river, the Mali, is navigable despite having a few rapids. The Chindwin river is the largest tributary of the Irrawaddy. It flows 840 km before joining the Irrawaddy river close to Mandalay.

Data

The mapping and inventory of the glacierised areas was carried out using ETM+ images from 2004, 2005, and 2009. The topographic characteristics were derived using the SRTM DEM. A single Landsat image was sufficient to map the glaciers, which are confined to the northern part of the basin. The list of images used is shown in Table 9.1.

Table 9.1: Landsat images used for the Irrawady basin (for areas outside China)

Path-Row	Images	Date	Used for	Sub-basin
133-40	l72133040_04020041211	11/12/2004	correction	Maikha
133-40	l72133040_04020091107	07/11/2009	analysis	Maikha
133-41	l72133041_04120091107	01/11/2009	analysis	Maikha
133-41	l72133041_04120051112	12/11/2005	correction	Maikha

Mapping and Inventory of Glaciers

The glaciers are limited to the northern part of the Irrawaddy basin in the watershed of the Mai river (Figure 9.1). The distribution and characteristics of the glaciers are summarised in Table 9.2

Number, area, and ice reserves

The Irrawaddy basin had 133 glaciers with a total area of 35 km² and estimated ice reserves of 1 km³ (Table 9.2). There are no previous published reports describing mapping results for the 87 glaciers within the territory of Myanmar.

Glacier area classes

The number, area, and estimated ice reserves of glaciers in the different size classes are summarised in Table 9.3 and shown as a percentage of the total in Figure 9.2. There were no glaciers in the largest size

Table 9.2: Glacier characteristics in the Irrawaddy basin*

Parameter	Units	Unit/column
Basin area	km²	202,745
Latitude	degrees	28.06-28.77
Longitude	degrees	97.32-98.17
Number of glaciers	unit	133
Total glacier area (CI)	km²	35.46
Largest glacier area	km²	2.91
Total ice reserves	km³	1.29
Highest elevation	masl	5,695
Lowest elevation	masl	4,256
Mean glacier slope	degrees	25
Average glacier area	km²	0.27

*extends into China (area in China contains 46 glaciers; CI/DC diffeentiation was only applied to the remaining 87 glaciers, there were no DC glaciers among these)

Figure 9.1: Distribution of glaciers in the Irrawaddy basin

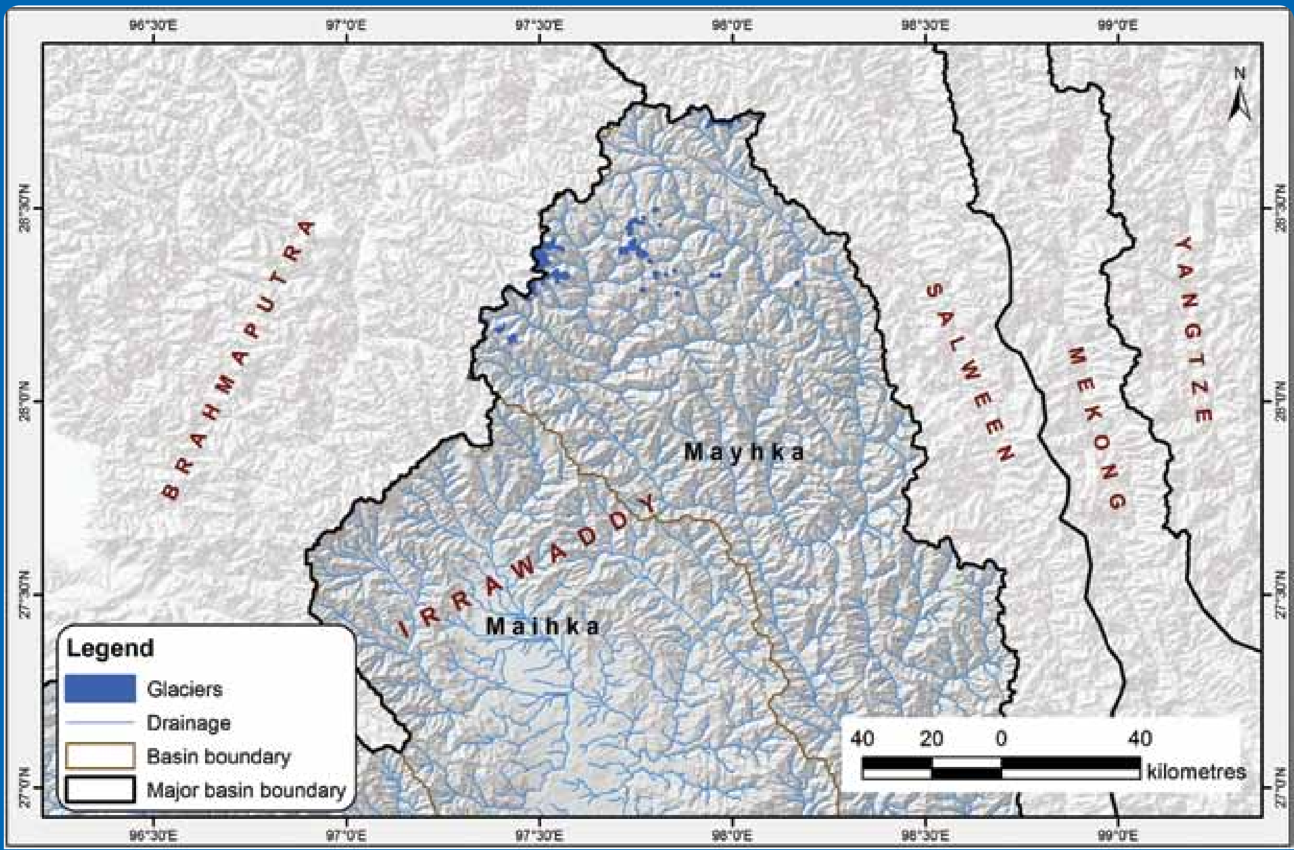


Table 9.3: Glacier area classes in the Irrawaddy basin

Area class	Area (km^2)	Number		Area		Estimated ice reserves		Mean area per glacier
		Total	%	km^2	%	km^3	%	km^2
1	≤ 0.5	115	86.5	14.49	40.9	0.301	23.4	0.13
2	0.51-1.00	10	7.5	7.50	21.2	0.284	22.0	0.75
3	1.01-5.00	8	6.0	13.47	38.0	0.703	54.6	1.68
4	5.01-10.00	0	0.0	0.00	0.0	0.000	0.0	0.00
5	≥10.00	0	0.0	0.00	0.0	0.000	0.0	0.00
	Total	**133**	**100**	**35.46**	**100**	**1.287**	**100**	**0.27**

classes, and almost all were smaller than 3 km^2. Around 86% of the glaciers were in the smallest class 1 (≤0.5 km^2), covering 41% of the glaciated area and containing 23% of the estimated ice reserves. The largest glacier was GLIMS ID G097509E28365N (Imaygr10_53) with an area 2.91 km^2 located at 28.37° N latitude and 97.51° E longitude. The average area per glacier was 0.27 km^2.

Elevations of glaciers

The highest elevation in Myanmar is at Hkakabo Razi (5,881 masl) in Kachin State. The glaciers extended from 5,695 masl to 4,256 masl. The largest glacier extended from 5,548 masl to 4,292 masl.

Aspects

Figure 9.3 shows the percentage of glaciers with different aspects and mean slope. More than 40% of the glaciers had a south aspect, with about 15% each facing southeast and southwest. There were no glaciers facing north, indicating the strong orographic control of moist airflows coming from the south.

Slope

The mean slope of the glaciers in the basin ranged from 10° to 50°, with slopes of 20° to 30° most common regardless of aspect, followed by slopes of 10° to 20° and 30° to 40°.

Morphological glacier type

Only the 87 glaciers within Myanmar were classified morphologically. The classification is summarised in Table 9.4 and the comparative distribution by number, area, and estimated ice reserves is shown graphically in Figure 9.4. All the classified glaciers were mountain type, the great majority basin type (71%) followed by ice apron type (18%). Mountain basin type glaciers covered 89% of the glaciated area and contained 94% of the estimated ice reserves.

Table 9.4: Morphological classification of glaciers in the Irrawaddy basin*

Glacier type		Number		Area		Estimated ice reserves		Mean area per glacier
		Total	%	km²	%	km³	%	km²
Mountain	Miscellaneous	0	0.0	0.0	0.0	0.000	0.0	0.0
Mountain	Ice apron	16	18.4	2.16	9.0	0.054	5.9	0.13
Mountain	Cirque	4	4.6	0.32	1.3	0.005	0.5	0.08
Mountain	Niche	5	5.8	0.09	0.4	0.000	0.04	0.02
Mountain	Basin	62	71.3	21.43	89.3	0.870	93.6	0.35
Valley	Trough	0	0.0	0.00	0.0	0.000	0.0	0.0
	Total	**87**	**100**	**23.99**	**100**	**0.929**	**100**	**0.28**

* excluding glaciers in China, relates to 87 glaciers within Myanmar

Figure 9.2: Percentage of glacier number, area, and estimated ice reserves in the different glacier size classes in the Irrawaddy basin

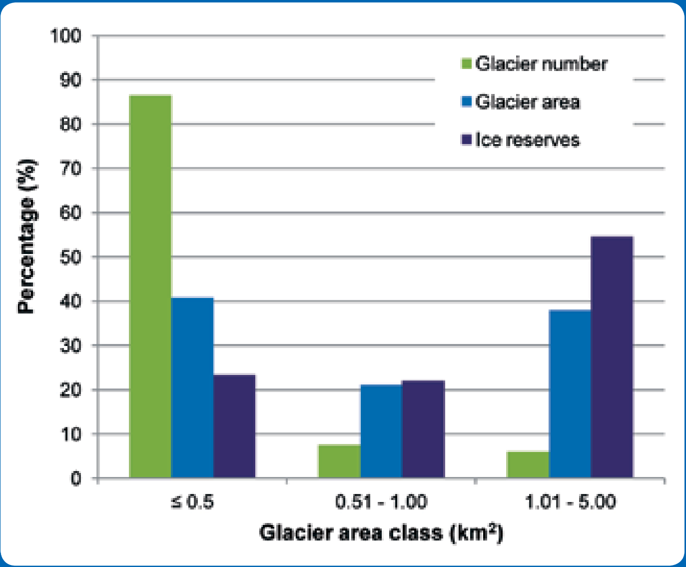


Figure 9.3: Aspect and mean slope of glaciers in the Irrawaddy basin

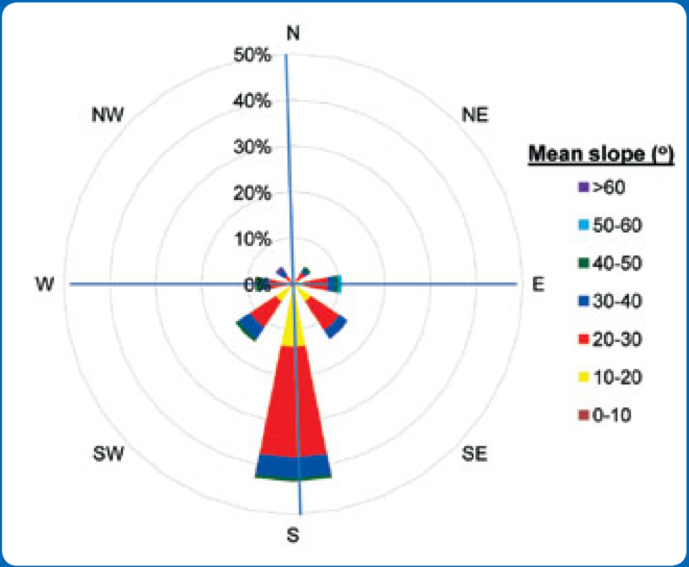


Figure 9.4: Comparative distribution of different glacier types in the Irrawaddy basin by number, area, and estimated ice reserves

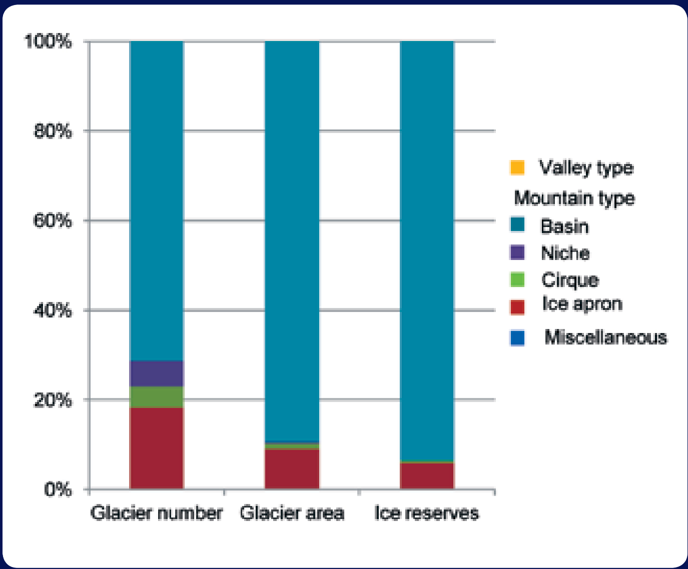
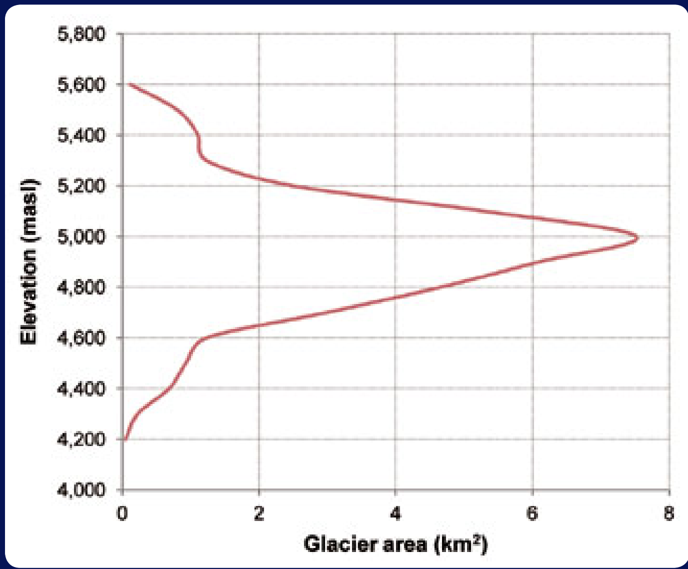


Figure 9.5: Area-altitude distribution of glaciers in the Irrawaddy basin



Excluding glaciers in China

Hypsography

The glacier area-altitude distribution of the glaciers in the basin within Myanmar is shown in Figure 9.5. The maximum glaciated area was 7.52 km^2 at 5,000 to 5,100 masl, 21% of the total. Glaciated areas of more than 1 km^2 were found from 4,600 to 5,500 masl.

10 Salween Basin

The Salween river rises in the Qinghai Mountains on the Tibetan Plateau, near the headwaters of the Mekong and Yangtze rivers. It initially flows west but then makes a great bend to the east, entering the Chinese province of Yunnan and flowing on through Myanmar, and Thailand, before draining into the Andaman Sea (Figure 10.1). For much of its length, the Salween's course runs almost parallel to that of the much larger Mekong in the east. Although the commonly accepted name is Salween, the river is also known by other names: Nu or Nujiang in China, Thanlwin in southern Myanmar, and Salawin at the border of Thailand and Myanmar.

The river basin is one of the largest in Southeast Asia; it covers 363,778 km^2 of which 58% lies in the HKH region. The upper and middle reaches of the basin are glaciated.

Mapping and Inventory of Glaciers

The river flows in a semi-circle and the glaciers are found on both sides of the river within the western part of the basin. They all lie in China (Figure 10.2) within four third-level tributaries with the codes 5N22 (Lower reaches), 5N23 (Naqu), 5N24 (Middle Reaches), and 5N25 (Yuqujiang). The distribution and characteristics of the glaciers in each sub-basin are summarised in Table 10.1.

Number, area, and ice reserves

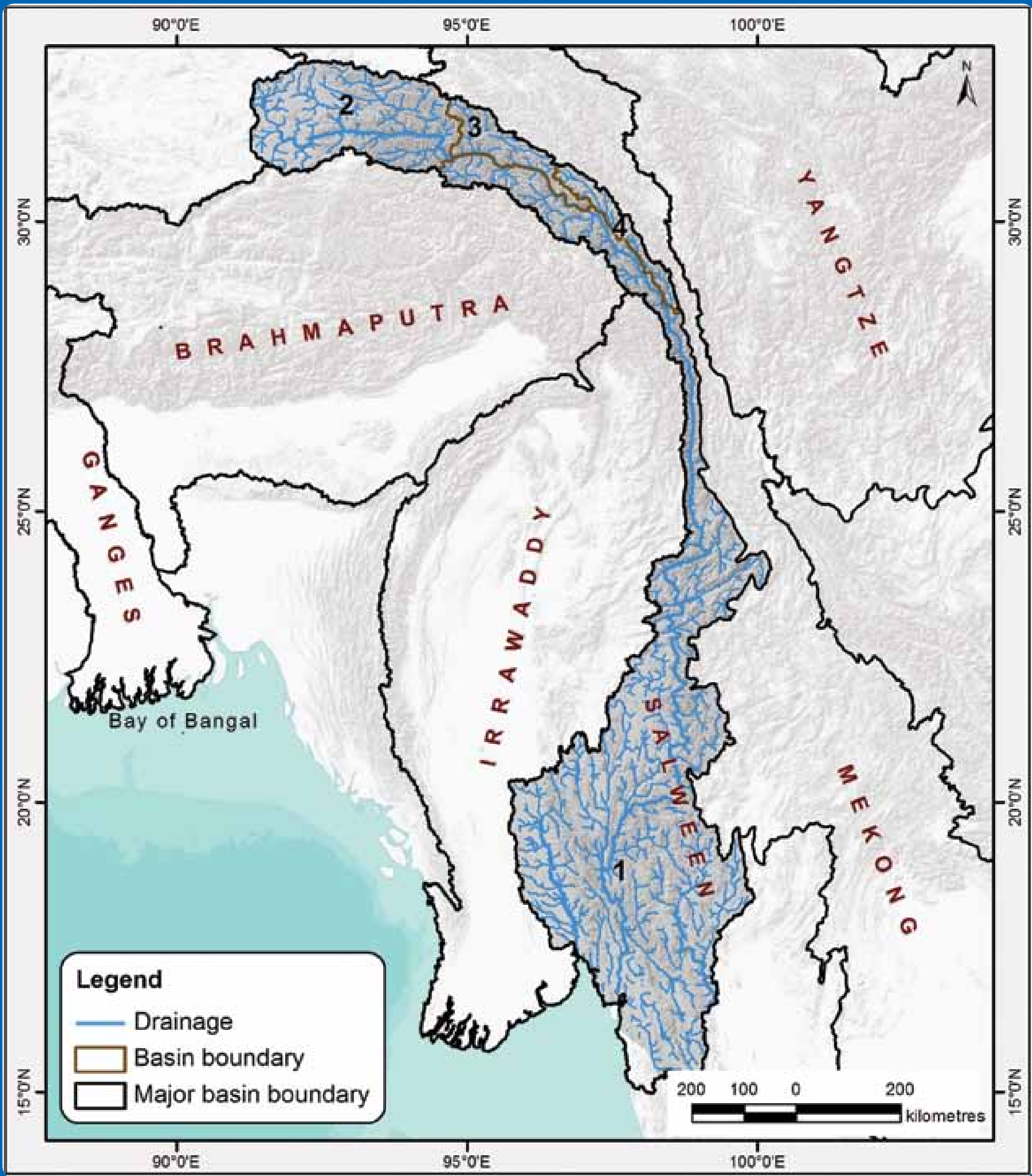
The basin has a total area of 211,122 km^2, with 2,113 glaciers covering an area of 1,352 km^2 and containing estimated ice reserves of 88 km^3 (Table 10.1). The mean glacier area was 0.66 km^2. The number, area, and estimated ice reserves of glaciers in the sub-basins are shown in Figure 10.3. The Lower reaches sub-basin (5N22) had the greatest number of glaciers and largest area and estimated ice reserves and Yuqujiang (5N25) sub-basin the least. The largest glacier was GLIMS ID G094773E30627N (5N22_676) with an area of 40 km^2 and estimated ice reserves of 6.58 km^3, located in sub-basin 5N22.

Table 10.1: Glacier characteristics in the Salween basin

Parameter	Units	Sub-basin				Salween
		Lower reaches (5N22)	Naqu (5N23)	Middle Reaches (5N24)	Yuqujiang (5N25)	
Basin area within HKH	km^2	132,103	56,517	13,123	9,376	211,122*
Latitude	degrees	28.38-30.81	30.80-32.76	30.28-32.13	28.42-30.58	28.38-32.76
Longitude	degrees	94.54-98.71	91.50-94.87	94.65-97.02	96.84-98.68	91.50-98.71
Number of glaciers	unit	892	835	281	105	2,113
Total glacier area	km^2	713.85	438.54	156.25	43.13	1,351.76
Largest glacier area	km^2	40.06	35.49	35.49	9.58	40.06
Total ice reserves	km^3	52.03	23.99	9.41	2.26	87.69
Highest elevation	masl	6,471	5,887	5,985	6,294	6,471
Lowest elevation	masl	4,457	5,257	4,578	3,786	3,786
Mean glacier slope	degrees	23	24	25	27	25
Average glacier area	km^2	0.80	0.53	0.56	0.41	0.64

*includes area of not glaciated sub-basins

Figure 10.1: Basin and drainage systems of the Salween river



1. Lower reaches (5N22) 2. Naqu (5N23) 3. Middle Reaches (5N24) 4. Yuqujiang (5N25)

Glacier area classes

The number, area, and estimated ice reserves of glaciers in the different size classes are summarised in Table 10.2 and shown as a percentage of the total in Figure 10.4. The great majority of the glaciers, 1,596 or 76% of the total, were in class 1 (≤0.5 km^2), and together contributed about 20% of the glacier area and just under 6% of the ice reserves. The 14 glaciers in class 5 (≥10.00 km^2), less than 1% of the total, included 4 with areas greater than 30 km^2; together they contributed 24% of the glacier area and 51% of the estimated ice reserves.

Figure 10.2: Distribution of glaciers in the Salween basin

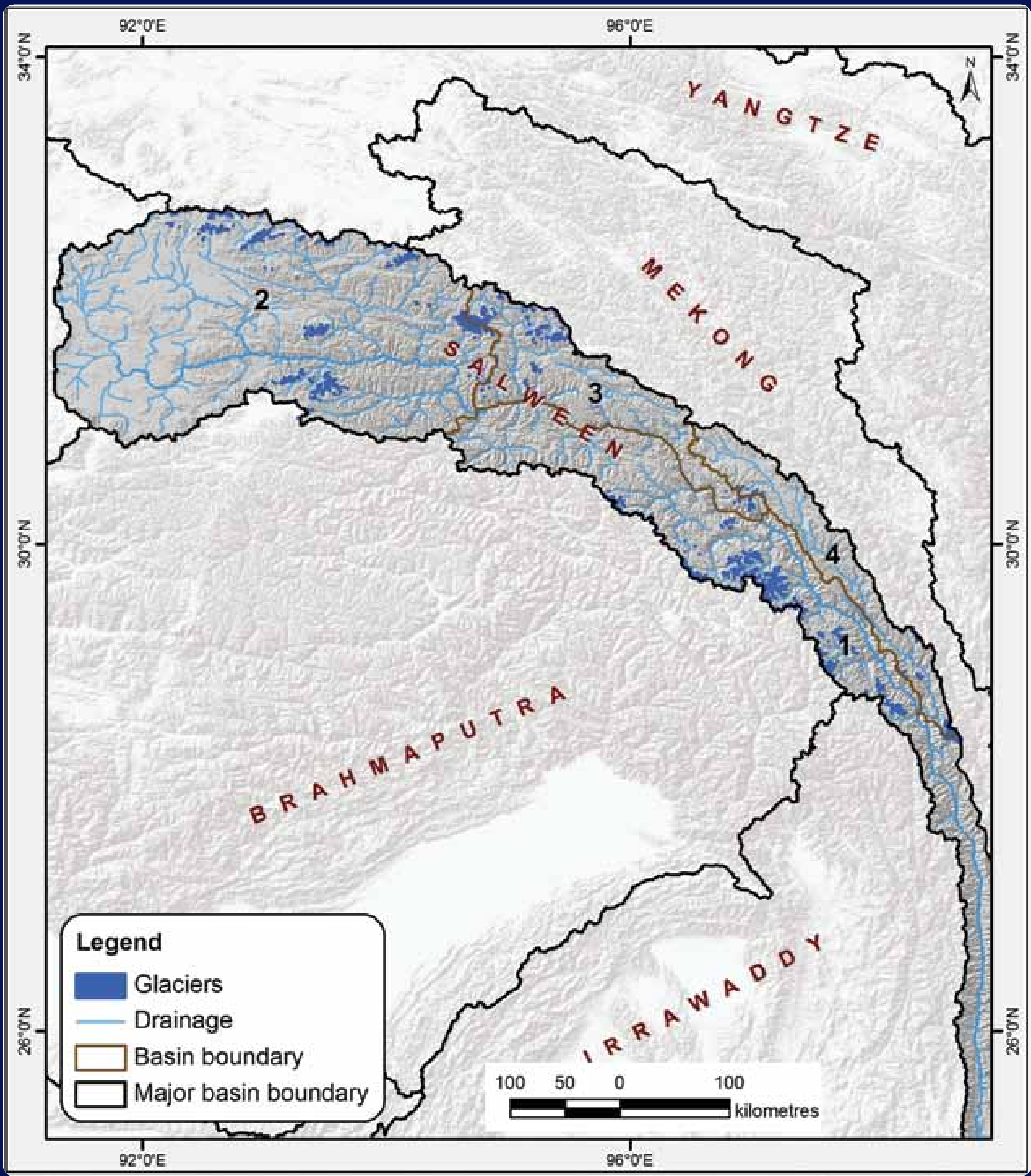


Table 10.2: Glacier area classes in the Salween basin

Area class	Area (km^2)	Number		Area		Estimated ice reserves		Mean area per glacier
		Total	%	km^2	%	km^3	%	km^2
1	≤ 0.5	1,596	75.5	276.92	20.5	5.163	5.9	0.17
2	0.51-1.00	261	12.4	181.57	13.4	5.465	6.2	0.70
3	1.01-5.00	220	10.4	409.54	30.3	19.459	22.2	1.86
4	5.01-10.00	22	1.04	160.64	11.9	13.029	14.9	7.30
5	≥10.00	14	0.7	323.10	23.9	44.573	50.8	23.08
	Total	**2,113**	**100**	**1,351.76**	**100**	**87.689**	**100**	**0.64**

Figure 10.3 Glacier number, area, and estimated ice reserves in the sub-basins of the Salween basin

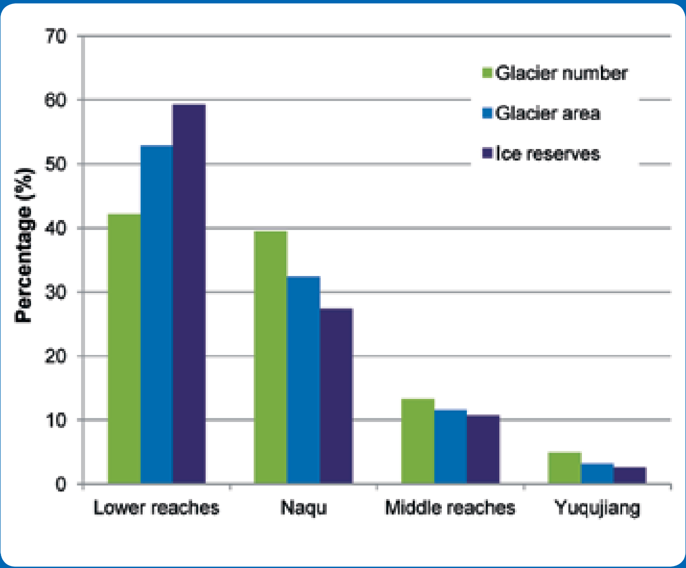
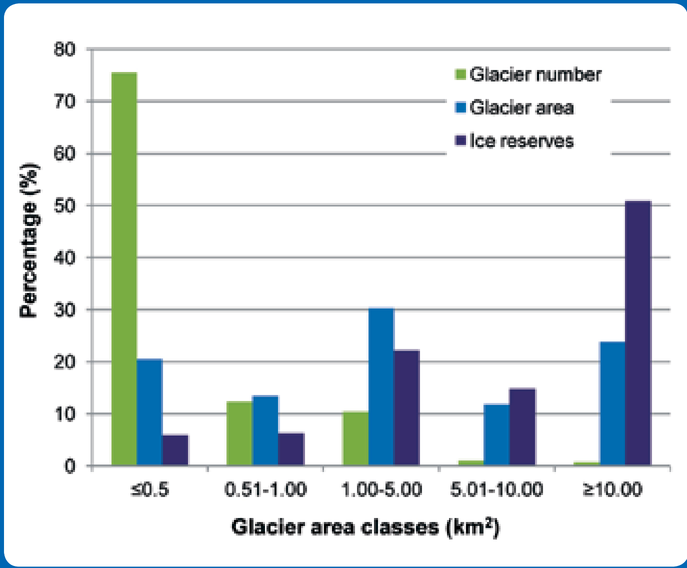


Figure 10.4: Percentage of glacier number, area, and estimated ice reserves in the different glacier size classes in the Salween basin



Glacier elevation

The highest glacier elevation was 6,471 masl in the Lower reaches (5N22) sub-basin and the lowest 3,786 masl in Yuqujiang (5N25) sub-basin (Table 10.1); the majority of the glaciers lay between 4,500 and 6,000 masl. The greatest elevation range was found in Yuqujiang sub-basin and the least in Naqu (5N23) sub-basin.

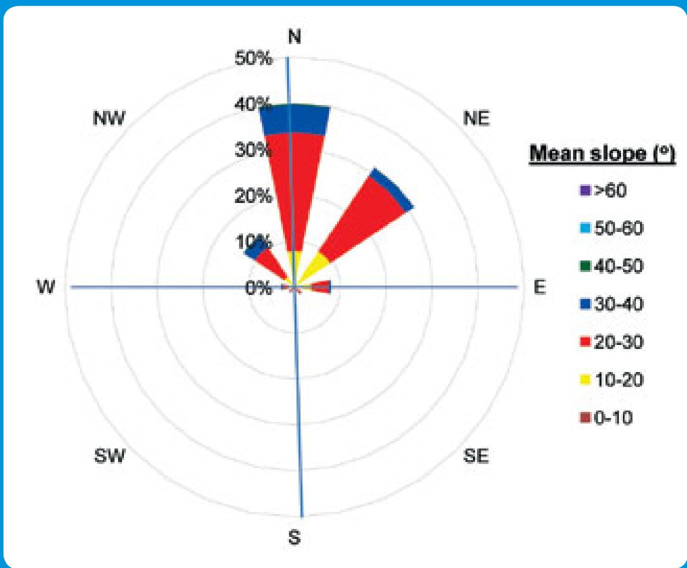
Glacier aspect

Figure 10.5 shows the percentage of glaciers with different aspects and mean slope. Almost 40% of glaciers had a north aspect, and a further 31% a northeast aspect. Very few glaciers had a southern aspect.

Slope

The mean slope of the glaciers in the basin ranged from 10° to 50°, with slopes of 20° to 30° the most common for all aspects, followed by slopes of 10° to 20° and 30° to 40° (Figure 10.5). The average slope of the glaciers in the sub-basins was similar with an overall average of 25° (Table 10.1).

Figure 10.5: Aspect and mean slope of glaciers in the Salween basin



11 Mekong Basin

The Mekong river, originates from the eastern and western Tanggula Range in the central part of the Tibetan Plateau and flows through the three provinces of Qinghai, Tibet, and Yunnan in China, and thence through Burma, Thailand, Cambodia, and Vietnam into the South China Sea (Figure 11.1). Within China it is known as the Lancang river. The Mekong has a total length of 4,880 km and is the 10th longest river in the world and the 7th longest in Asia. The Mekong has two main tributaries: the Zaqu river in the east, and the Ngomqu river in the west. The part of the basin within the HKH region covers an area of 841,322 km², about 17% of the whole basin. The glaciers in the Mekong basin are all located in the upper reaches of the river in China.

Mapping and Inventory of Glaciers

The major Mekong basin has three glaciated basins – Middle Reaches (5L2), Angqu (5L3), and Ziqu (5L4). The distribution and characteristics of the glaciers in each basin (Figure 11.2) are summarised in Table 11.1.

Number, area, and ice reserves

The Mekong major river basin had 482 glaciers with a total area of 235 km² and estimated ice reserves of 11 km³. The number, area, and estimated ice reserves of glaciers in the basins are shown in Figure 11.3. The 5L4 basin had the most glaciers (227), glaciated area, and estimated ice reserves. Glaciers in 5L2 had the largest mean area (0.93 km²); the average glacier area across the basin was 0.49 km². The largest single glacier was GLIMS ID G098723E28450N (M5L0gr_33) located in the 5L2 basin, which covered an area of 9.76 km²

Glacier area classes

The number, area, and estimated ice reserves of glaciers in the different size classes are summarised in Table 11.2 and shown as a percentage of the total in Figure 11.4. There were 384 glaciers in class 1 (≤0.5 km²), 80% of the total number with 27% of the total area and 11% of the ice reserves. The two large glaciers with an area ≥10 km² covered 37% of the total area and contained 60% of the ice reserves. There were no glaciers ≥10.00 km², and the 50 glaciers (10%) with a size of 1 to 5 km² contributed the most to the area (40%) and estimated ice reserves (44%).

Table 11.1: Glacier characteristics in the Mekong basin

Parameter	Units	Basin			Mekong
		Angqu (5L3)	Ziqu (5L4)	Middle Reaches (5L2)	
Basin area within HKH	km²	24,559	36,717	52,330	138,876
Latitude	degrees	30.53-32.48	32.64-33.73	28.30-29.39	28.30-33.73
Longitude	degrees	94.15-97.38	94.24-96.96	98.14-98.76	94.15-98.76
Number of glaciers	unit	196	227	59	482
Total glacier area	km²	65.94	113.91	54.77	234.61
Largest glacier area	km²	5.83	7.62	9.76	9.76
Total ice reserves	km³	2.168	4.927	3.581	10.676
Highest elevation	masl	5,703	5,644	6,361	6,361
Lowest elevation	masl	5,047	4,845	2,891	2,891
Mean glacier slope	degrees	26	26	26	26
Average glacier area	km²	0.34	0.50	0.93	0.49

Figure 11.1: Mekong river basin and drainage system

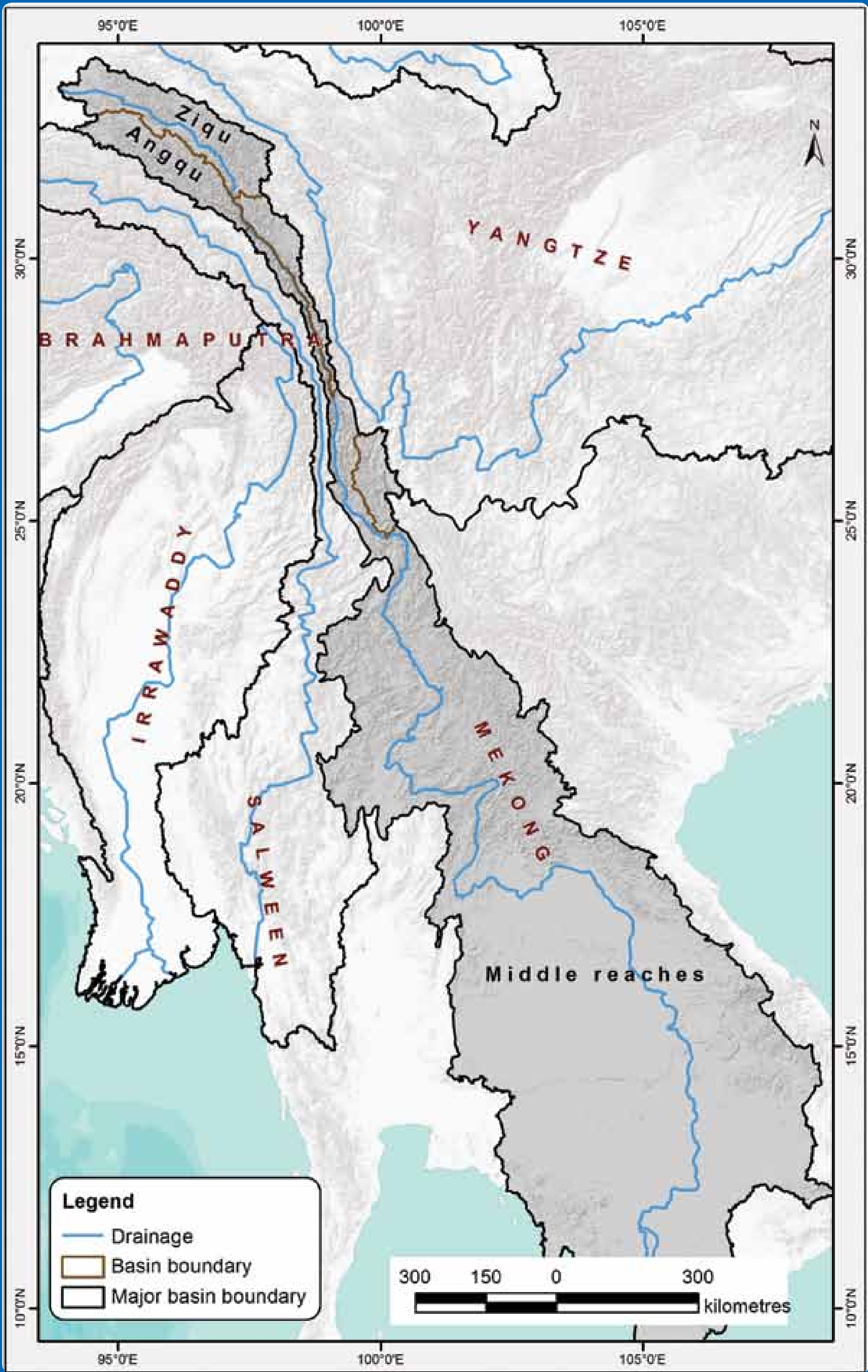


Figure 11.2: Distribution of glaciers in the Mekong (Lancang) basin

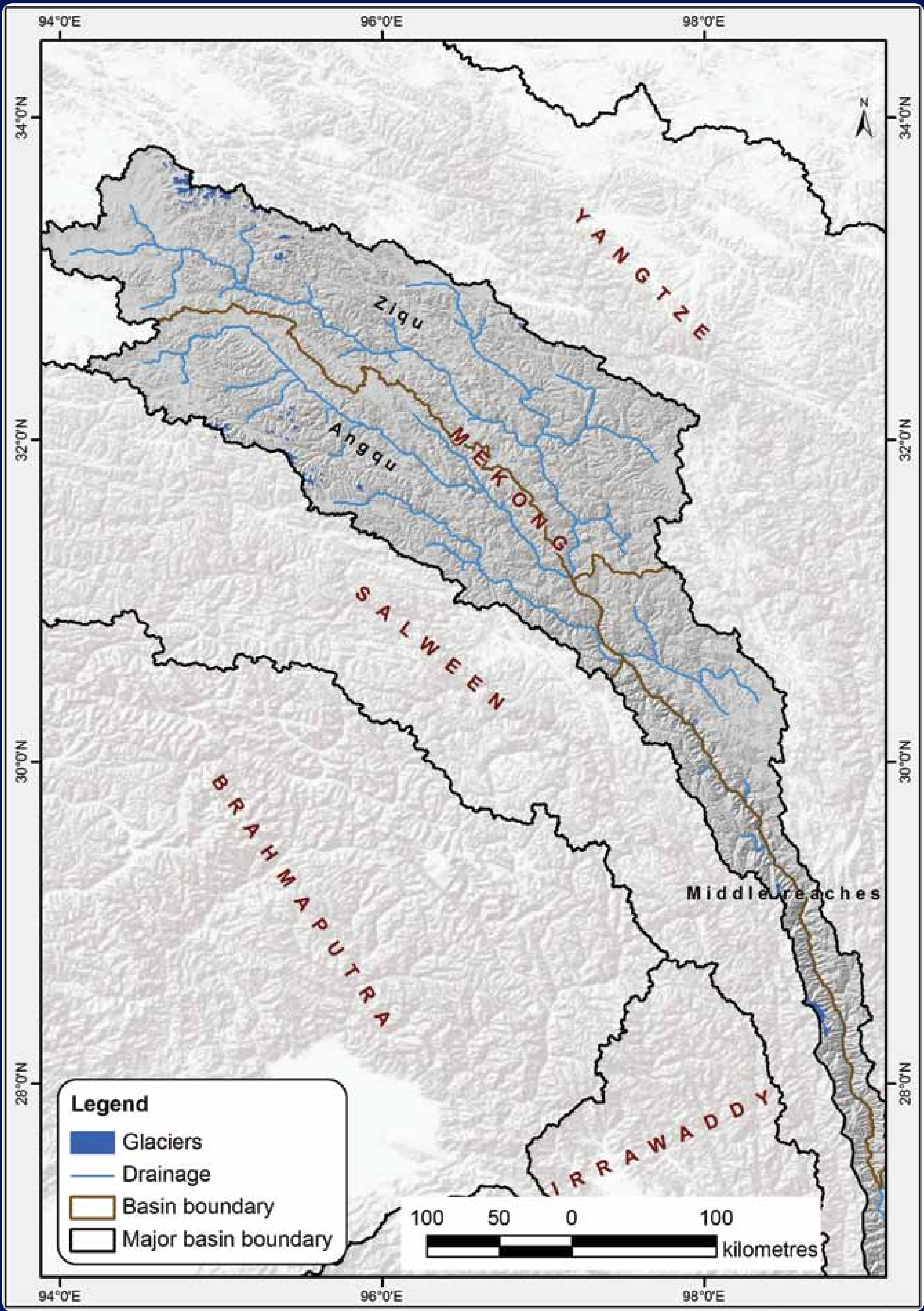


Figure 11.3: Glacier number, area, and ice reserves in the Mekong basin

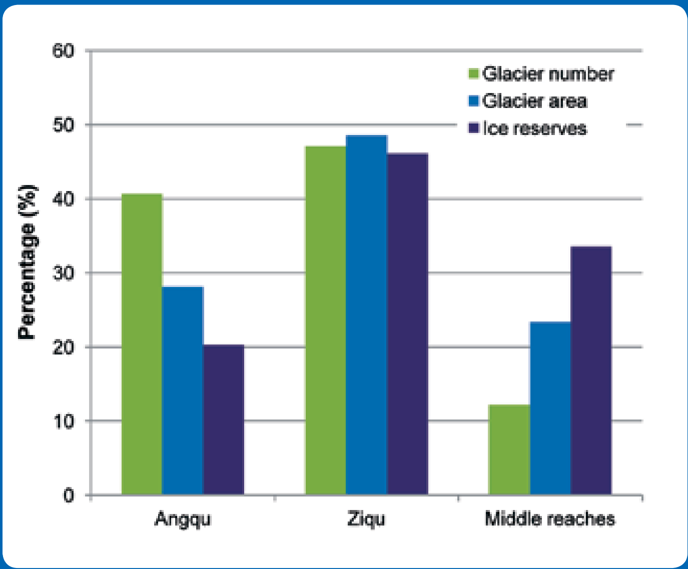


Figure 11.4: Percentage of glacier number, area, and estimated ice reserves in the different glacier size classes in the Mekong basin

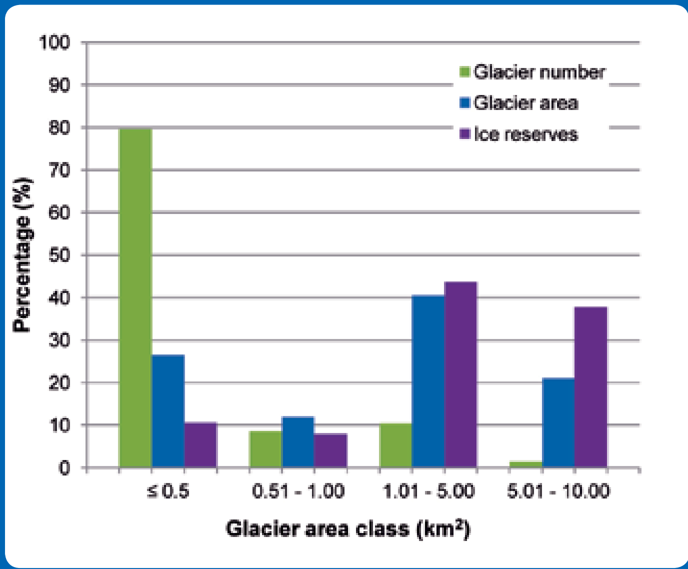


Table 11.2: Glacier area classes in the Mekong basin

Area class	Number		Area		Estimated ice reserves		Mean area per glacier
	Total	%	km²	%	km³	%	km²
≤ 0.5	384	80	62.31	27	1.131	11	0.16
0.51 - 1.00	41	9	28.06	12	0.846	8	0.68
1.01 - 5.00	50	10	94.88	40	4.660	44	1.90
5.01 - 10.00	7	1	49.36	21	4.039	38	7.05
≥10.00	0	0	0.00	0	0.000	0	0.00
Total	**482**	**100**	**234.61**	**100**	**10.68**	**100**	**0.49**

Glacier elevation

The highest glacier elevation was 6,361 and the lowest 2,891 masl both in the Middle Reaches (5L2) basin (Table 11.1). The glacier elevation range in Angqu (5L3) and Ziqu (5L4) basins was less than 1,000 m; most of the glaciers were located between 5,000 and 5,500 masl.

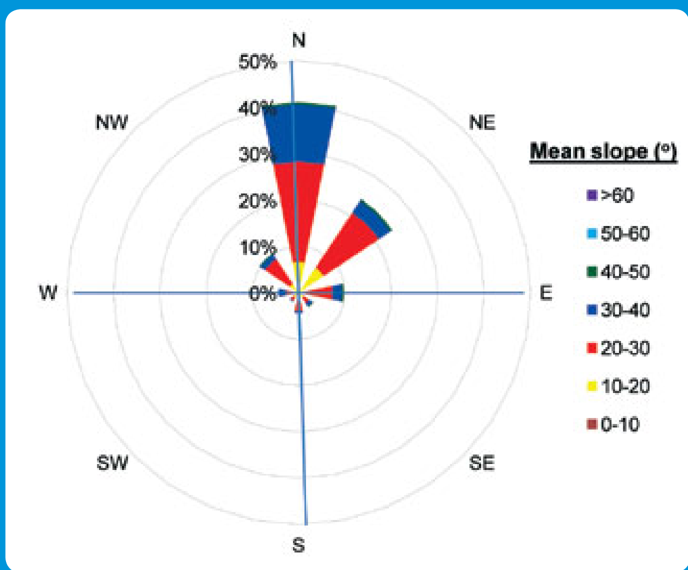
Glacier aspect

More than 40% of glaciers had a north aspect, and 24% a northeast aspect (Figure 11.5). There were very few glaciers with a more southerly aspect.

Slope

The mean slope of almost all the glaciers in the basins ranged from 10° to 50°, with less than 1% having slopes more or less than this. Slopes of 20° to 30° were most common followed by 30° to 40°. The mean slope of glaciers in the three basins was similar; the overall average slope was 25° (Table 11.1).

Figure 11.5: Aspect and mean slope of glaciers in the Mekong basin



12 Yangtze Basin

The Yangtze river rises in the Qinghai-Tibetan Plateau and traverses China from west to east for more than 6000 km before emptying into the East China Sea at Shanghai. It is the longest river in Asia and the third longest in the world. The Yangtze river basin (Figure 12.1) has a total area of 2,065,763 km^2, of which 565,102 km^2 lies in the HKH region, and is the largest of the HKH river basins, draining one-fifth of China's land area (Figure 12.1).

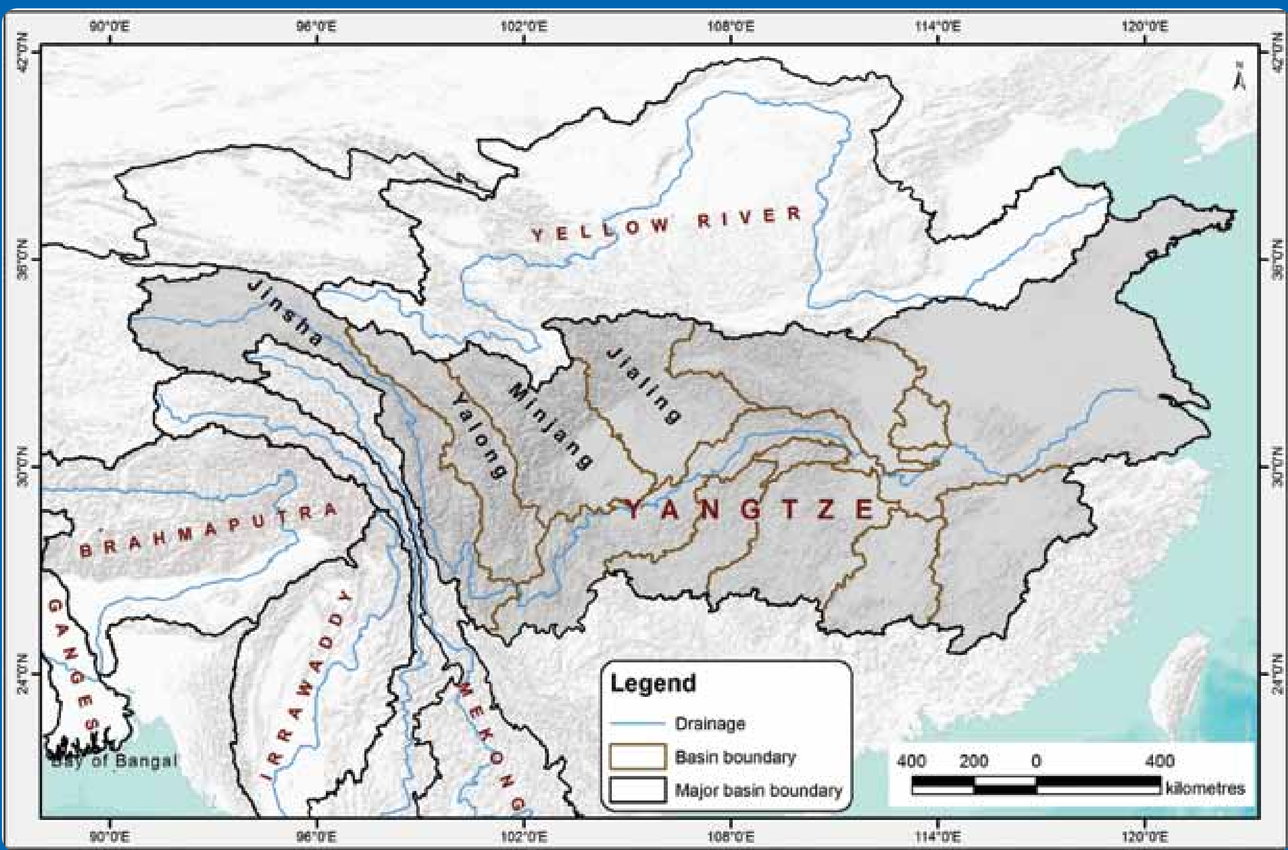
Mapping and Inventory of Glaciers

The area of the major Yangtze basin within the HKH region consists of four glaciated basins: the Jinsha (5K4), Yalong (5K5), Minjiang (5K6), and Jialing (5K7) (Figure 12.2). The distribution and characteristics of the glaciers in each sub-basin are summarised in Table 12.1

Number, area, and ice reserves

The major Yangtze basin contained 1,661 glaciers, with a total area of 1,660 km^2 and estimated ice reserves of 121 km^3 (Table 12.1). The number, area, and estimated ice reserves of glaciers in the basins are shown in Figure 12.3. The Jinsha basin had the most glaciers (1,189 or 70% of the total), and greatest glacier area (75%) and estimated ice reserves (76%). The Jialing basin had only one glacier with an area of 0.12 km^2 and estimated ice reserves of 0.002 km^3. The largest glacier was GLIMS ID G091105E33503N (5K45_96) with an area of 55 km^2.

Figure 12.1: Location of the Yangtze river basin



Glacier area classes

The number, area, and estimated ice reserves of glaciers in the different size classes are summarised in Table 12.2 and shown as a percentage of the total in Figure 12.4.

More than 67% of the glaciers were in the smallest area class size (<1 km²), together contributing 12% to the area and just over 3% of the estimated ice reserves. The 27 glaciers with an area ≥10 km², less than 2% of the total, covered 32% of the area and contained 56% of the basin's ice reserves. Two of these glaciers had an area greater than 30 km². The mean glacier area in the basin was 1.05 km².

Table 12.1: Glacier characteristics in the Yangtze basin

Parameter	Units	Basin				Yangtze
		Jinsha	Yalong	Minjiang	Jialing	
Basin area within HKH	km²	262,892	128,178	107,243	21,790	565,102*
Latitude	degrees	28.21-35.78	29.08-32.07	29.25-33.29	32.64-32.64	28.21-35.78
Longitude	degrees	90.56-100.4	98.79-101.8	101.10-103.9	103.89-103.9	90.56-103.9
Number of glaciers	unit	1,189	193	278	1	1,661
Total glacier area	km²	1243.02	119.49	297.22	0.12	1659.85
Largest glacier area	km²	54.59	18.31	25.81	0.12	54.59
Total ice reserves	km³	92.02	6.71	22.67	0.002	121.40
Highest elevation	masl	6,122	5,779	6,270	5,041	6,270
Lowest elevation	masl	4,479	3,787	2,972	4,951	2,972
Mean glacier slope	degrees	25	26	29	28	27
Average glacier area	km²	1.05	0.62	1.07	0.12	1.00

*includes area of not glaciated sub-basins

Figure 12.2: Distribution of glaciers in the Yangtze basin

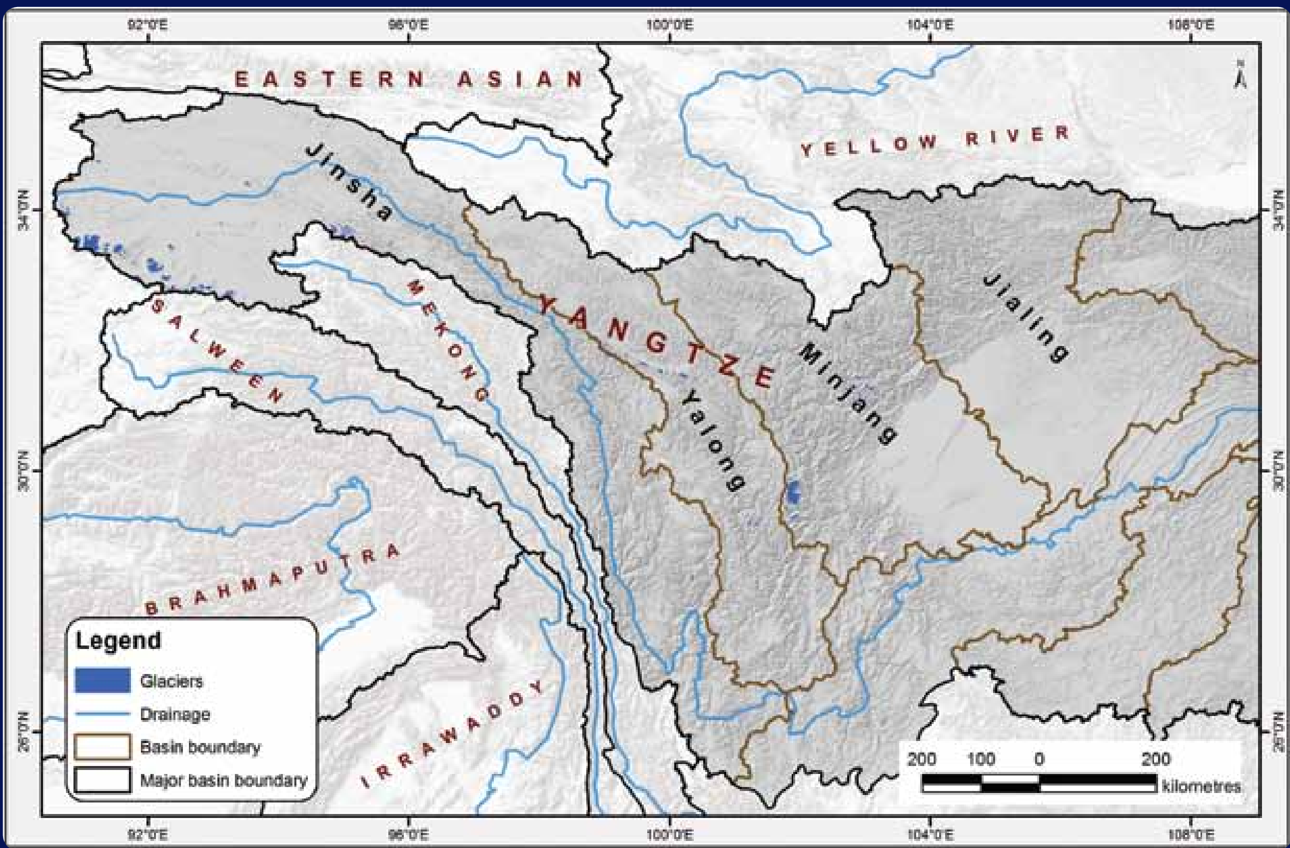


Figure 12.3: Glacier number, area, and estimated ice reserves in the Yangtze basin

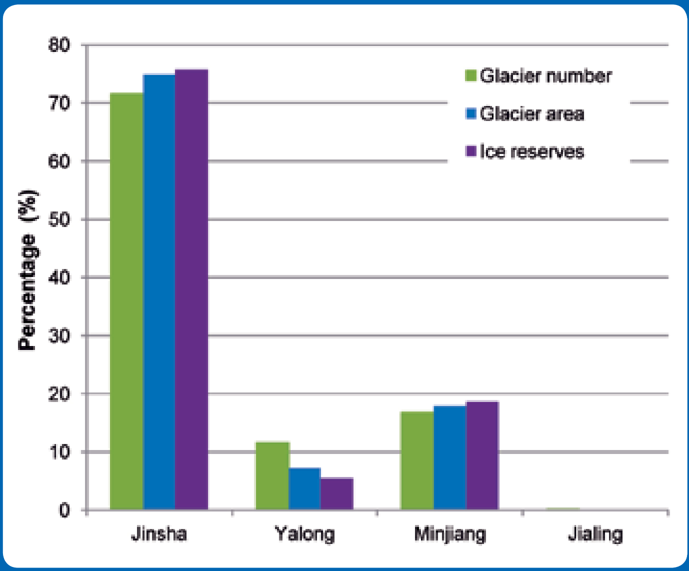


Figure 12.4: Percentage of glacier number, area, and estimated ice reserves in the different glacier size classes in the Yangtze basin

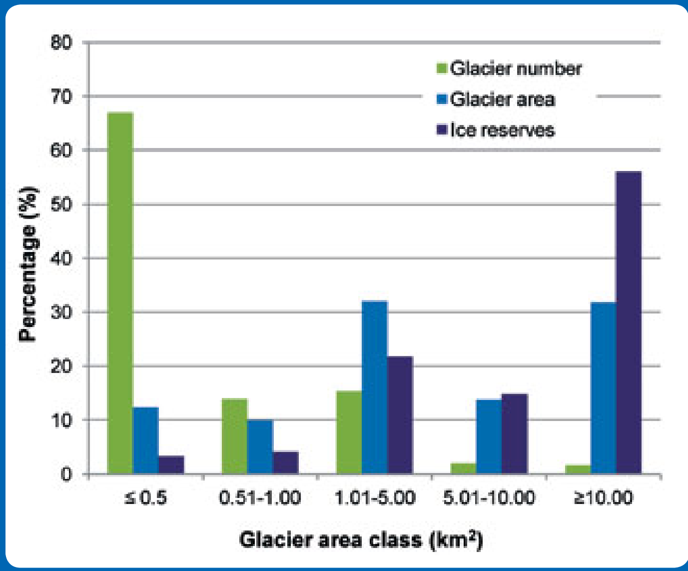


Table 12.2: Glacier area classes in the Yangtze basin

Area class	Area (km²)	Number		Area		Estimated ice reserves		Mean area per glacier
		Total	%	km²	%	km³	%	km²
1	≤ 0.5	1,113	67.0	205.23	12.4	3.952	3.3	0.18
2	0.51-1.00	232	14.07	164.45	9.9	4.986	4.1	0.71
3	1.01-5.00	256	15.4	532.10	32.1	26.494	21.8	2.08
4	5.01-10.00	33	2.0	229.04	13.8	17.984	14.8	6.94
5	≥10.00	27	1.6	529.03	31.9	67.979	56.0	19.59
	Total	**1,661**	**100**	**1,659.85**	**100**	**121.395**	**100**	**1.00**

Glacier elevation

The highest glacier elevation was 6,270 masl and the lowest 2,972 masl, both in the Minjiang basin (Table 12.1). The one glacier in the Jialing basin had an elevation range of less than 100 m.

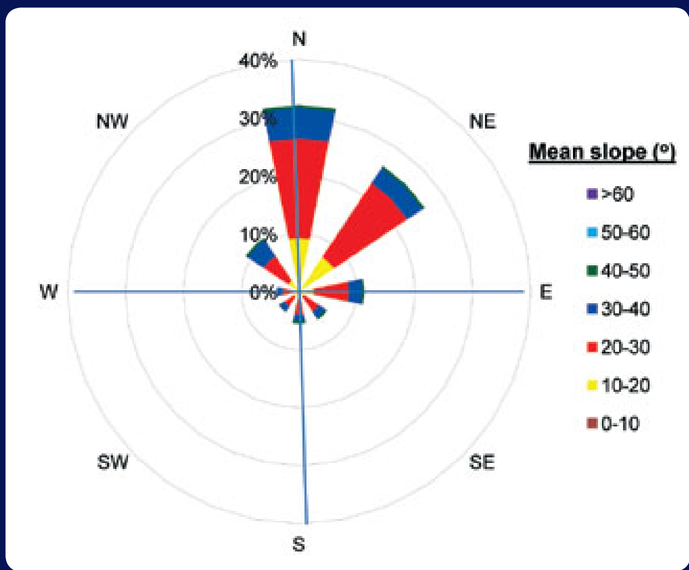
Glacier aspect

Figure 12.5 shows the percentage of glaciers with different aspects and mean slope. Close to 32% of the glaciers had a north aspect, and 26% a northeast aspect Only a few glaciers had more south facing aspects.

Slope

The mean slope of almost all the glaciers in the basin ranged from 10° to 60°, with slopes of 20° to 30° most common (Figure 12.5). A few glaciers in the Minjiang basin had slopes above 60°. The mean slopes of glaciers in the basins ranged from 25° to 29°, with an overall average of 27°.

Figure 12.5: Aspect and mean slope of glaciers in the Yangtze basin



13 Yellow River Basin

The Yellow River (Hwang Ho) is the second-longest river in China with an estimated length of close to 5,500 kilometres. The river originates in the Bayan Har mountains in Qinghai Province in western China, and flows through nine provinces in China before emptying into the Bohai Sea. The Yellow River basin extends 1,900 km from east to west and 1,100 km from north to south. The total basin area is 1,073,168 km² of which 250,540 km² lies within the HKH region (Figure 13.1).

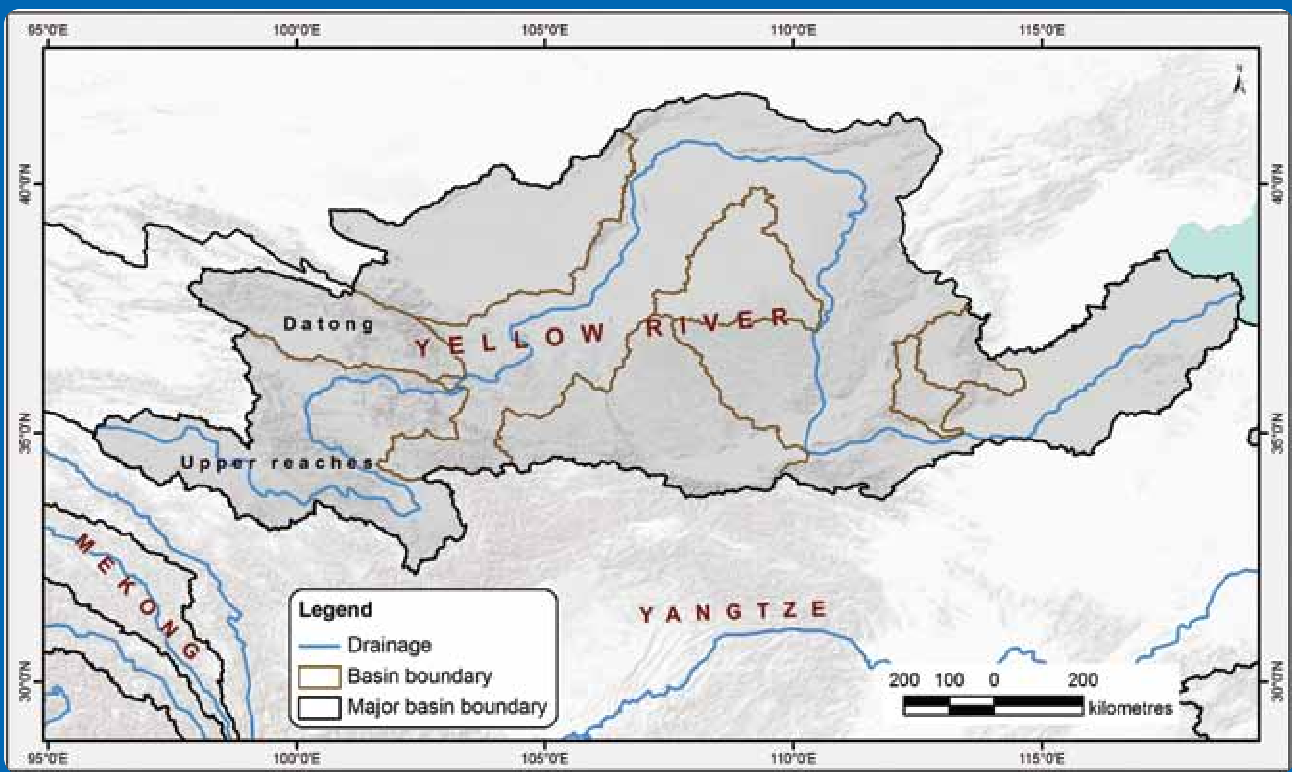
Mapping and Inventory of Glaciers

The HKH part of the Yellow River major basin has two basins, the Upper reaches (5J3) and Datong (5J4). The basins are divided into three third level tributary sub-basins with the codes 5J31, 5J32, and 5J42 (Table 13.1). The glaciers in the basin are found near the source in the Anyemaqen range in the east Kunlun Mountains and along a tributary rising in the Lenglong range in the eastern Qilian mountains (Figure 13.2). The distribution and characteristics of the glaciers in each basin are summarised in Table 13.1.

Number, area, and ice reserves

The Yellow River basin is not heavily glaciated (Figure 13.2); the 189 glaciers had a total area of 137 km² and estimated ice reserves of approximately 9.2 km³. The number, area, and estimated ice reserves of glaciers in the two basins are shown in Figure 13.3. The two basins had similar numbers of glaciers, but the glaciated area of the Upper

Figure 13.1: Yellow River basin and drainage system



reaches (5J3) was much higher (108 km²) than that in the Datong (5J4) (30 km²) as were the estimated ice reserves (8.3 and 0.9 km³, respectively). The largest glacier, with an area of 21 km², was also located in the Upper reaches basin. The mean glacier area in the Upper reaches basin was 1.16 km², and in the Datong basin 0.31 km².

Glacier area classes

The number, area, and estimated ice reserves of glaciers in the different size classes are summarised in Table 13.2 and shown as a percentage of the total in Figure 13.4. The majority of the glaciers, 142 or 75% of the total, were in class 1 (≤0.5 km²), but together contributed only about 15% of the glacier area and just under 4% of the ice

Table 13.1: Glacier characteristics in the Yellow River basin (5J)

Parameter	Units	Basin		Yellow River
		Upper reaches (5J3)	Datong (5J4)	
Basin area within HKH	km²	168,419	58,428	250,540*
Latitude	degrees	33.29-35.99	36.01-38.25	33.29-39.25
Longitude	degrees	99.37-101.13	98.61-101.87	98.61-101.87
Number of glaciers	unit	93	96	189
Total glacier area	km²	107.87	29.56	137.43
Largest glacier area	km²	20.82	2.29	20.82
Total ice reserves	km³	8.333	0.906	9.239
Highest elevation	masl	5,710	5,033	5,710
Lowest elevation	masl	4,442	4,151	4,151
Mean glacier slope	degrees	28	25	26
Average glacier area	km²	1.16	0.31	0.73

* includes non-glaciated sub-basins

Figure 13.2: Glacier distribution in the Yellow River basin

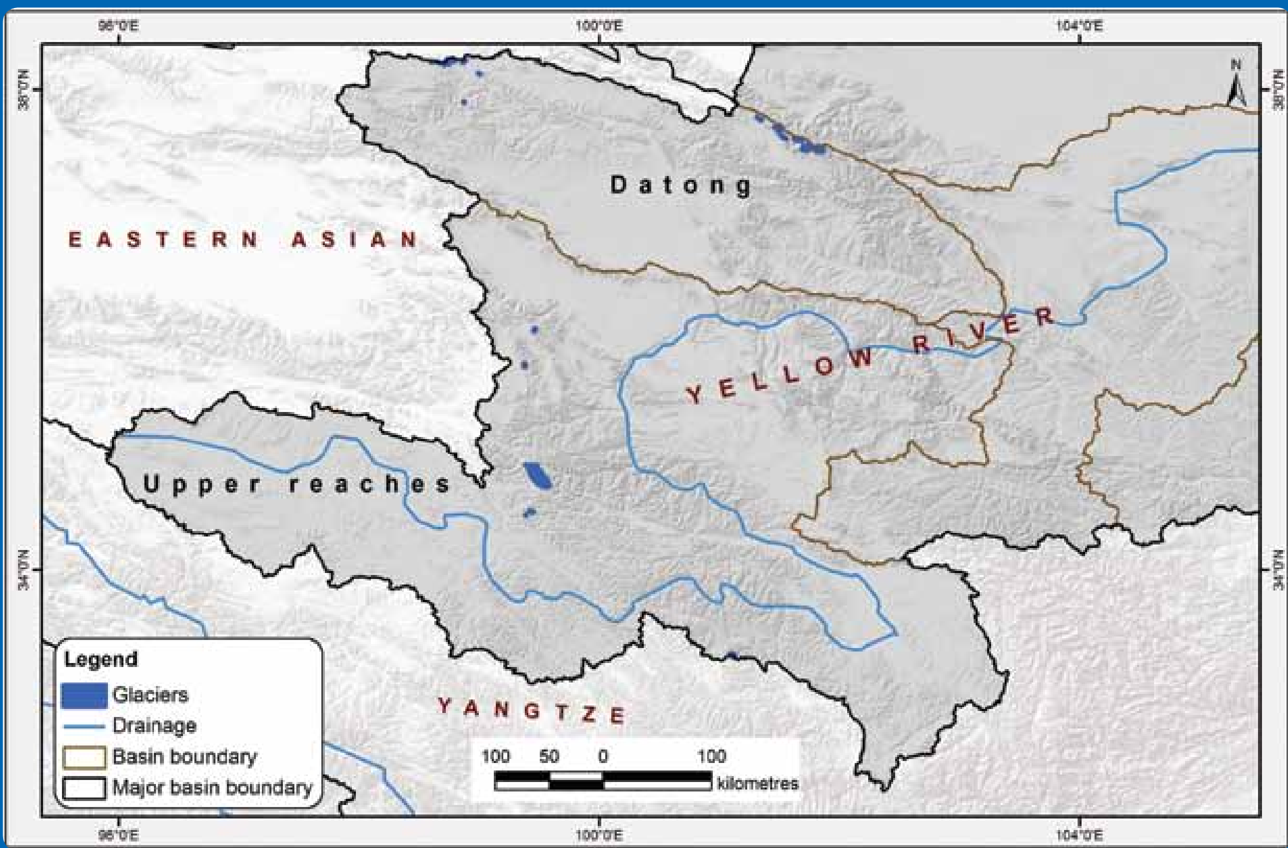


Figure 13.3: Glacier number, area, and estimated ice reserves in the basins of the Yellow River basin

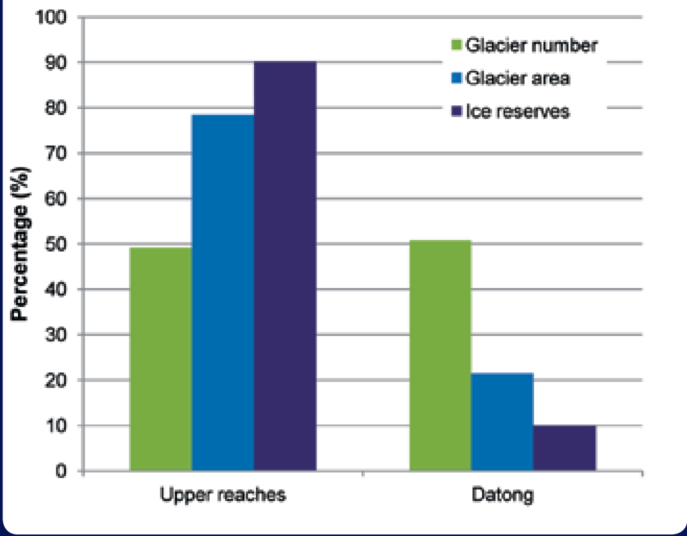


Figure 13.4: Percentage of glacier number, area, and estimated ice reserves in the different glacier size classes in the Yellow River basin

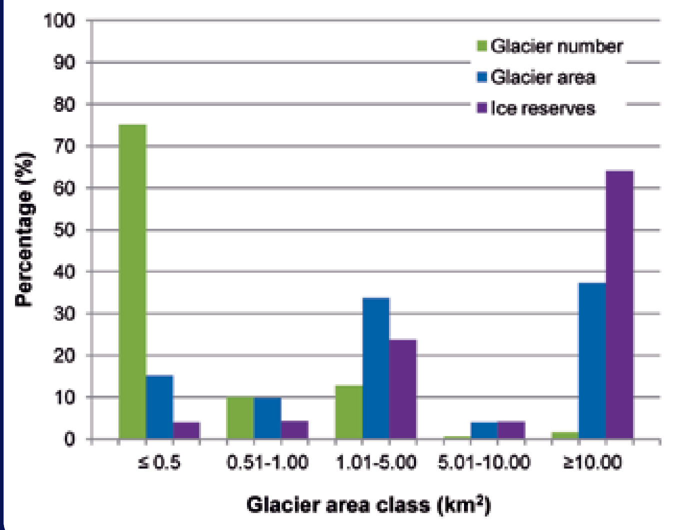


Table 13.2: Glacier area classes in the Yellow River basin

Area class	Area (km²)	Number		Area		Estimated ice reserves		Mean area per glacier
		Total	%	km²	%	km³	%	km²
1	≤ 0.5	142	75.1	20.91	15.2	0.362	3.9	0.15
2	0.51-1.00	19	10.15	13.49	9.8	0.395	4.3	0.71
3	1.01-5.00	24	12.7	46.28	33.7	2.188	23.7	1.93
4	5.01-10.00	1	0.5	5.40	3.9	0.375	4.1	5.40
5	≥10.00	3	1.6	51.36	37.4	5.919	64.1	17.12
	Total	**189**	**100**	**137.43**	**100**	**9.239**	**100**	**0.73**

reserves. A further 23% of the glaciers were in class 2 or 3, covering 43% of the glaciated area and containing 28% of the ice reserves. The 3 glaciers in class 5, less than 2% of the total, covered 51% of the area and contained 64% of the basin's ice reserves. The average area per glacier overall was 0.73 km².

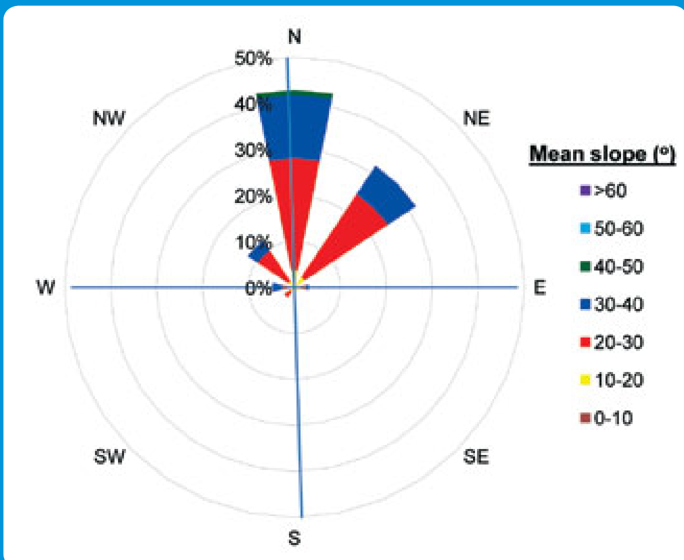
Glacier elevation

The highest glacier elevation was 5,710 masl in the Upper reaches basin and the lowest 4,151 masl in the Datong basin (Table 13.1).

Glacier aspect

Figure 13.5 shows the percentage of glaciers with different aspects and mean slope. Close to 43% of the glaciers had a north aspect, and 32% a northeast aspect. Less than 1% faced south or southeast.

Figure 13.5: Aspect and mean slope of glaciers in the Yellow River basin



Slope

About 60% of the glaciers had a mean slope of 20° to 30°, 27% slopes of 30° to 40° (Figure 13.5), and 12% slopes of 10° to 20°. The average slope of glaciers in the Upper reaches basin was higher than in the Datong basin (28° and 25° respectively, Table 13.1).

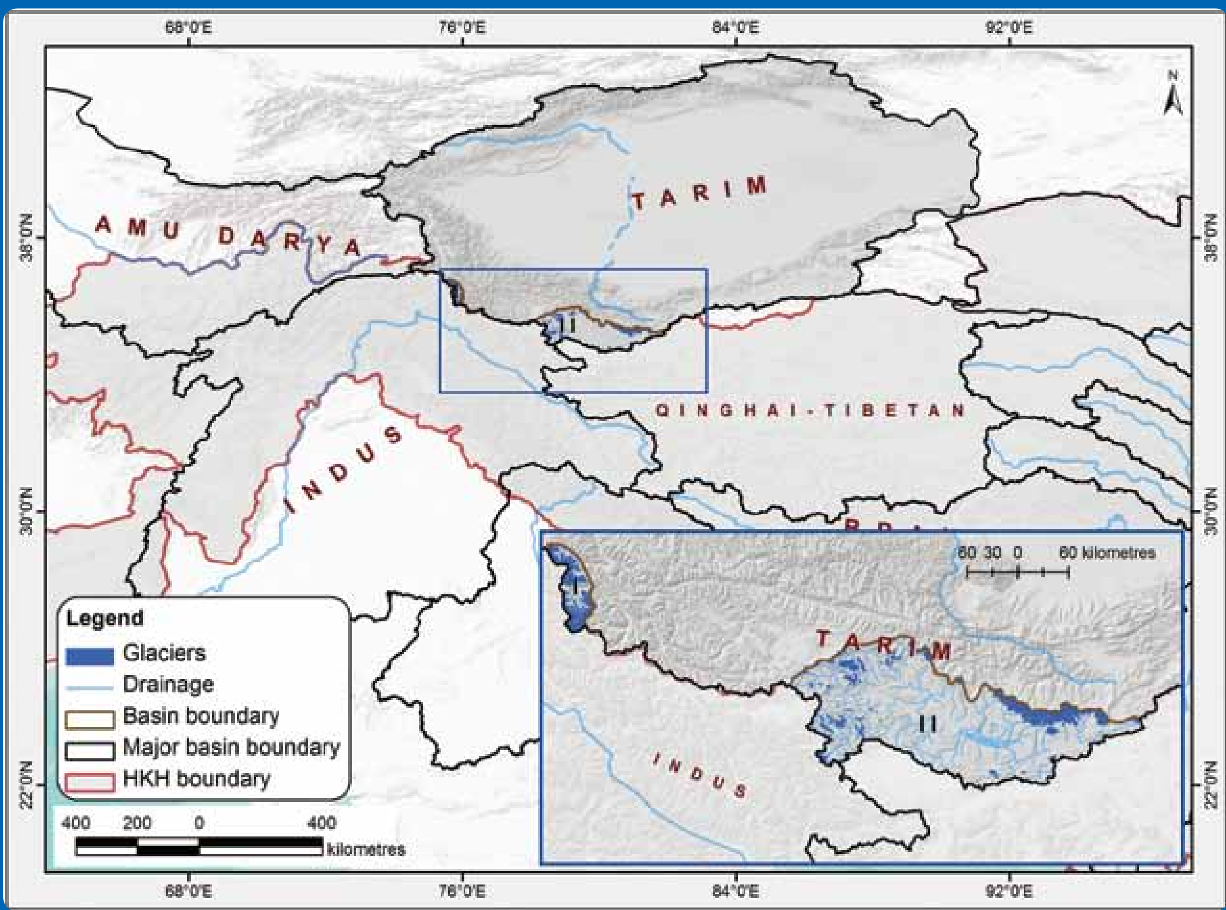
14 Tarim Interior Basin

The Tarim river is the principal river of the Xinjiang Uygur Autonomous Region in western China and the longest inland river in the country. It gives its name to the great Tarim basin (5Y6) between the Tian Shan and Kunlun mountain systems of Central Asia (the northern edge of the Tibetan Plateau), which extends from 34.634° to 43.352° N latitude and 73.634° to 91.112° E longitude (Figure 14.1). The Tarim river is formed after the confluence of the Aksu river flowing from the north and the Yarkand river coming from the southwest, close to Aral City in western Xinjiang. A third river, the Khotan, reaches the same junction area from the south but is usually dry at this location as it has to cross through the Taklamakan Desert. The Tarim flows in an eastward direction around the northern edge of the Taklamakan Desert, where it is joined by a further tributary, the Muzat river from the north. Of these four rivers (Aksu, Yarkand, Khotan, and Muzart) only the Aksu flows into the Tarim year-round (Aizen and Aizen 1998). It is the most important tributary of the river, supplying 70-80 percent of its water volume. The Tarim basin has a total area of 929,003 km², of which only 26,729 km² lies within the the HKH region.

Mapping and Inventory of Glaciers

The Tarim River basin is elliptical with the long axis lying more or less east-west. The basin covers a large area of which only a small part lies within the HKH region. This part has around 0.09% glacier cover concentrated on the northern and southern flank and mapped in two sub-basins: I and II (Figure 14.1). The distribution and characteristics

Figure 14.1: The Tarim Interior basin and distribution of glaciers within the part lying within the HKH region

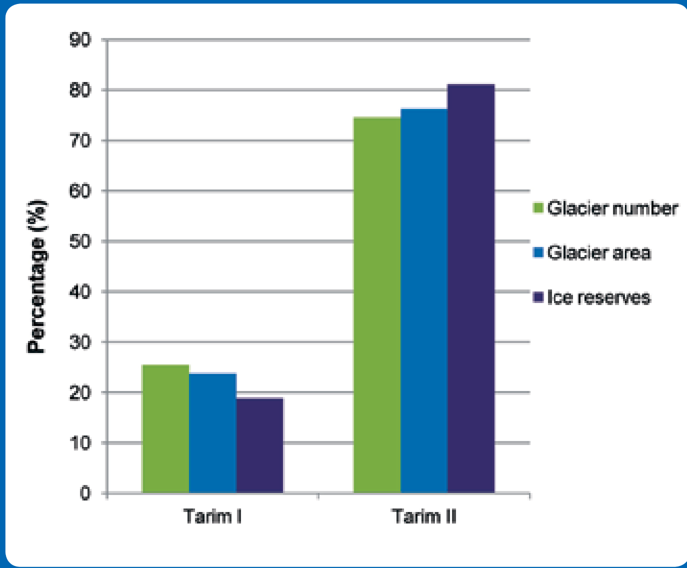


of the glaciers in each sub-basin are summarised in Table 14.1. CI/DC and morphological differentiation, and hypsography were only analysed for the glaciers in sub-basin I; sub-basin II is located in China and this information is not yet available for these glaciers.

Number, area, and ice reserves

A total of 1,091 glaciers were identified in the basin with an area of 2,310 km² and estimated ice reserves of 379 km³ (Table 14.1). The number, area, and estimated ice reserves of glaciers in the sub-basins are shown in Figure 14.2. Sub-basin II had the greatest number of glaciers, glaciated area, and estimated ice reserves. The largest glacier in the basin was GLIMS ID G080880E35286N located at 35.286° N latitude and 80.880° E longitude in sub-basin II at an elevation of 6,144 to 5,341 masl and with an area of 239 km² and estimated ice reserves of 86 km³.

Figure 14.2: Glacier number, area, and estimated ice reserves in the Tarim Interior basin



Glacier area classes

The number, area, and estimated ice reserves of glaciers in the different size classes are summarised in Table 14.2 and shown as a percentage of the total in Figure 14.3. The majority of glaciers were in the smallest class (694, or 64%); and the least number in class 4 (24 or 2%). The class 1 glaciers contributed less than 6% of the glacier area and less than 1% of the ice reserves. The 37 glaciers in class 5 (≥10 km²) were only 3% of the total number, but had 66% of the total area and contained 90% of the estimated ice reserves. The mean glacier area in the basin was 2.12 km².

Table 14.1: Glacier characteristics in the Tarim Interior basin within the HKH

Parameter	Units	Sub-basin		Tarim
		I	II*	
Basin area	km²	1,955	24,774	26,729
Latitude	degrees	36.07-36.75	34.74-36.30	34.74-36.75
Longitude	degrees	75.56-76.01	78.18-86.82	75.56-86.82
Number of glaciers	unit	278	813	1,091
CI glacier area	km²	516.95	NA	NA
DC glacier area	km²	32.00	NA	NA
Total glacier area	km²	548.93	1,761.32	2,310.26
Largest glacier area	km²	166.42	239.23	239.23
Total ice reserves	km³	71.34	307.30	378.64
Highest elevation	masl	6,462	6,399	6,462
Lowest elevation	masl	3,940	5,127	3,940
CI glacier elevation	masl	4,277-6,462	NA	NA
DC glacier elevation	masl	3,940-5,235	NA	NA
Mean CI glacier slope	degrees	27	26 (all glaciers)	27 (all glaciers)
Mean DC glacier slope	degrees	10	NA	NA
CI-DC area ratio	unit	16.16	NA	NA
Average glacier area	km²	1.97	2.17	2.12

*lies in China, no CI/DC differentiation

Glacier elevation

The highest glacier elevation was 6,462 masl and the lowest 3,940 masl both in sub-basin I. In sub-basin I, CI glaciers were found from 6,462 to 4,277 masl and DC glaciers from 5,235 to 3,940 masl (glaciers in sub-basin II not analysed).

Glacier aspect

Figure 14.4 shows the percentage of glaciers with different aspects and mean slope The majority of glaciers had a northeast (30%) or north (27%) aspect, with around 10% each facing east, southeast, and south.

Slope

The mean slopes of the glaciers ranged from 10° to 50°, with slopes of 20° to 30° most common, followed by slopes of 30° to 40°. Only a very few glaciers had slopes of less than 10° or greater than 40° (Figure 14.4).

The mean slope of CI and DC glaciers in sub-basin I was 27° and 10°, respectively; the average mean slope of the glaciers in the basin was 27° (Table 14.1).

Morphological glacier type

The morphological classification of glaciers in Tarim Interior sub-basin I is summarised in Table 14.3; the comparative distribution by number, area, and estimated ice reserves is shown graphically in Figure 14.5.

Table 14.2: Glacier area classes in the Tarim Interior basin

Area class	Area (km²)	Number		Area		Estimated ice reserves		Mean area per glacier
		Total	%	km²	%	km³	%	km²
1	≤ 0.5	694	63.6	131.67	5.7	2.610	0.7	0.19
2	0.51-1.00	159	14.6	111.37	4.8	3.446	0.9	0.70
3	1.01-5.00	177	16.2	370.79	16.1	19.058	5.0	2.09
4	5.01-10.00	24	2.2	167.61	7.3	13.594	3.6	6.98
5	≥10.00	37	3.4	1,528.82	66.2	339.930	89.78	41.32
	Total	**1,091**	**100**	**2,310.26**	**100**	**378.64**	**100**	**2.12**

Figure 14.3: Percentage of glacier number, area, and estimated ice reserves in the different glacier size classes in the Tarim Interior basin

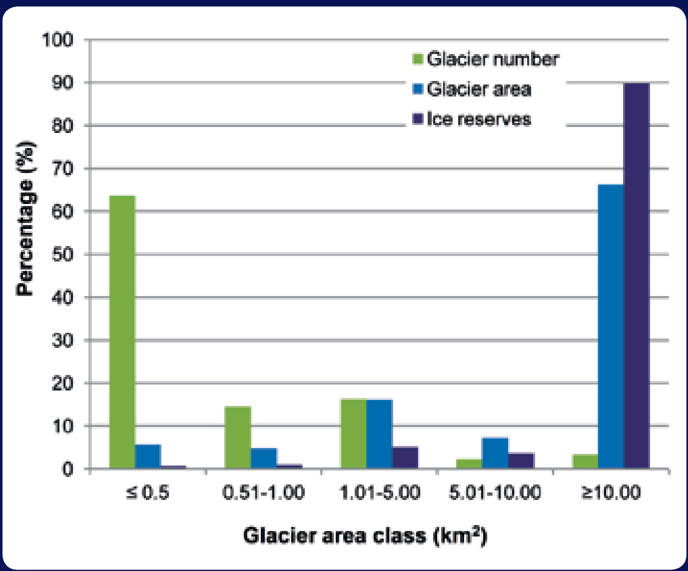


Figure 14.4: Aspect and mean slope of glaciers in the Tarim Interior basin

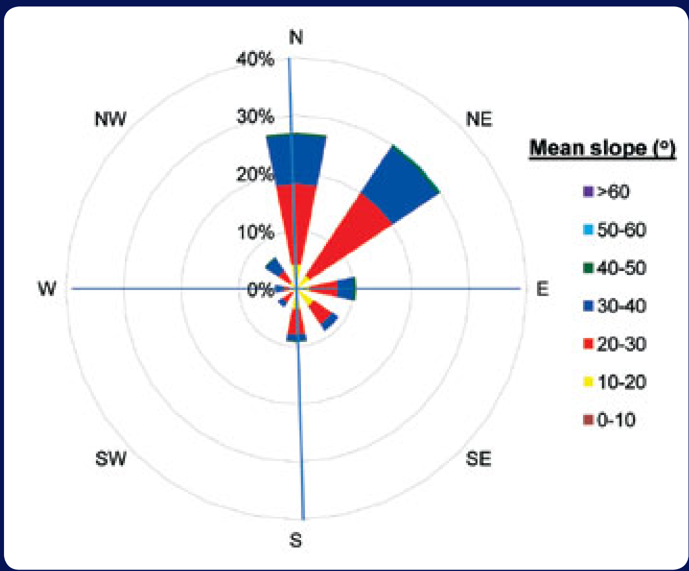
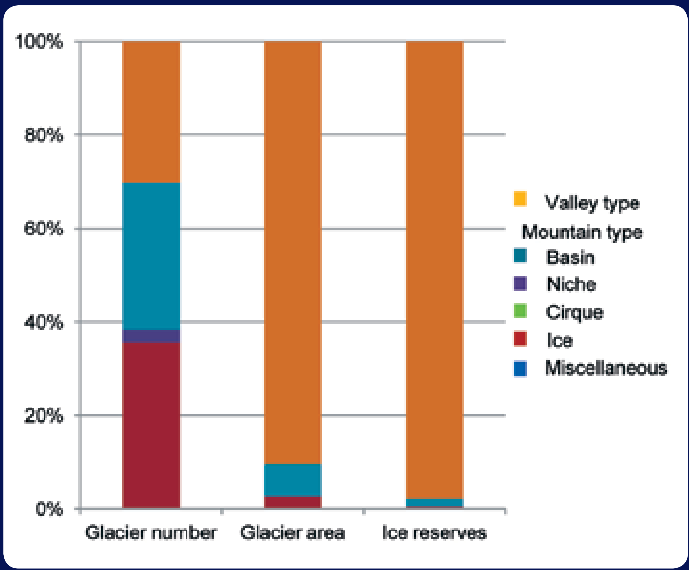
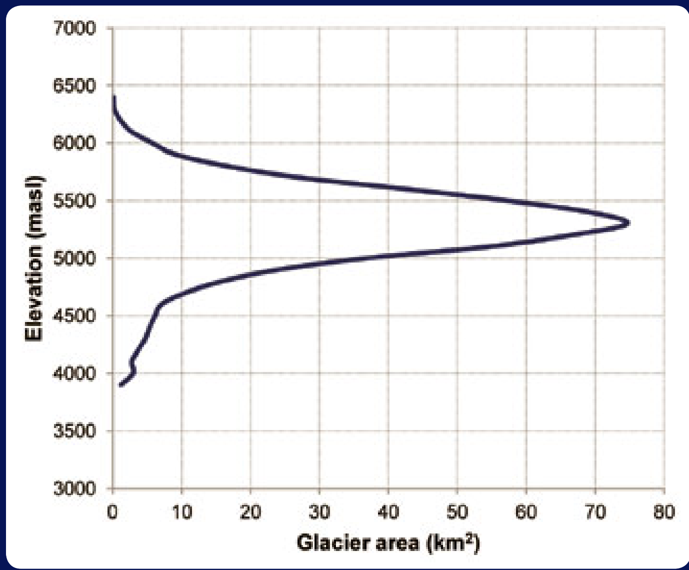


Figure 14.5: Comparative distribution of different glacier types in Tarim Interior basin by number, area, and estimated ice reserves



glaciers in basin II not analysed

Figure 14.6: Area-altitude distribution of glaciers in Tarim Interior basin



glaciers in basin II not analysed

Table 14.3: Morphological classification of glaciers in Tarim Interior sub-basin*

Glacier type		Number		Area		Estimated ice reserves		Mean area per glacier
		Total	%	km²	%	km³	%	km²
Mountain	Miscellaneous	0	0.0	0.00	0.0	0.000	0.0	0.0
	Ice apron	99	35.6	14.34	2.6	0.310	0.4	0.14
	Cirque	0	0.0	0.00	0.0	0.000	0.0	0.0
	Niche	8	2.9	0.80	0.1	0.013	0.02	0.10
	Basin	87	31.3	37.41	6.8	1.314	1.8	0.43
Valley	Trough	84	30.2	496.38	90.4	69.710	97.7	5.91
	Total	**278**	**100**	**548.93**	**100**	**71.343**	**100**	**1.97**

*glaciers in sub-basin II not analysed

Close to 67% of the glaciers were mountain type, the majority of them ice apron type (36%) or mountain basin type (31%), but they covered only 10% of the glaciated area and contained a little more than 2% of the estimated ice reserves. The 84 valley glaciers represented only 30% of the total number, but covered 90% of the glaciated area and contained 98% of the ice reserves.

Clean-ice and debris-covered glaciers

CI and. DC type glaciers were differentiated in sub-basin I. DC glacier components covered an area of 32 km², less than 6% of the total area (Table 14.1).

Hypsography

The glacier area-altitude distribution in sub-basin I is shown in Figure 14.6. Altogether 99% of the glacier area lay between 4,500 masl and 6,100 masl. The highest glacier concentration was 74.63 km² (14%), at an elevation of 5,300 to 5,400 masl.

15 Eastern Asian Qinghai-Tibetan Interior Basins

In addition to the ten major river basins, the HKH region contains a huge interior (endhoreic) basin in the central and northern part of the region that retains water without allowing outflow to other water bodies. The basin extends from 28.18° to 39.32° N latitude and 78.29° to 101.16°E longitude and covers an area of 909,824 km². It is divided into two parts, the Qinghai-Tibetan Interior and Eastern Asian Interior, linked by a small corridor (Figure 15.1).

Mapping and Inventory of Glaciers

The glaciated part of the interior basin extends from 29.69° to 39.28° N latitude and 78.31° to 100.54° E longitude. The distribution and characteristics of the glaciers in each part are summarised in Table 15.1. The basin lies entirely in China, thus descriptions of the typology, morphological classification, and hypsography are not yet available.

Figure 15.1: The glaciers in the HKH region interior basin

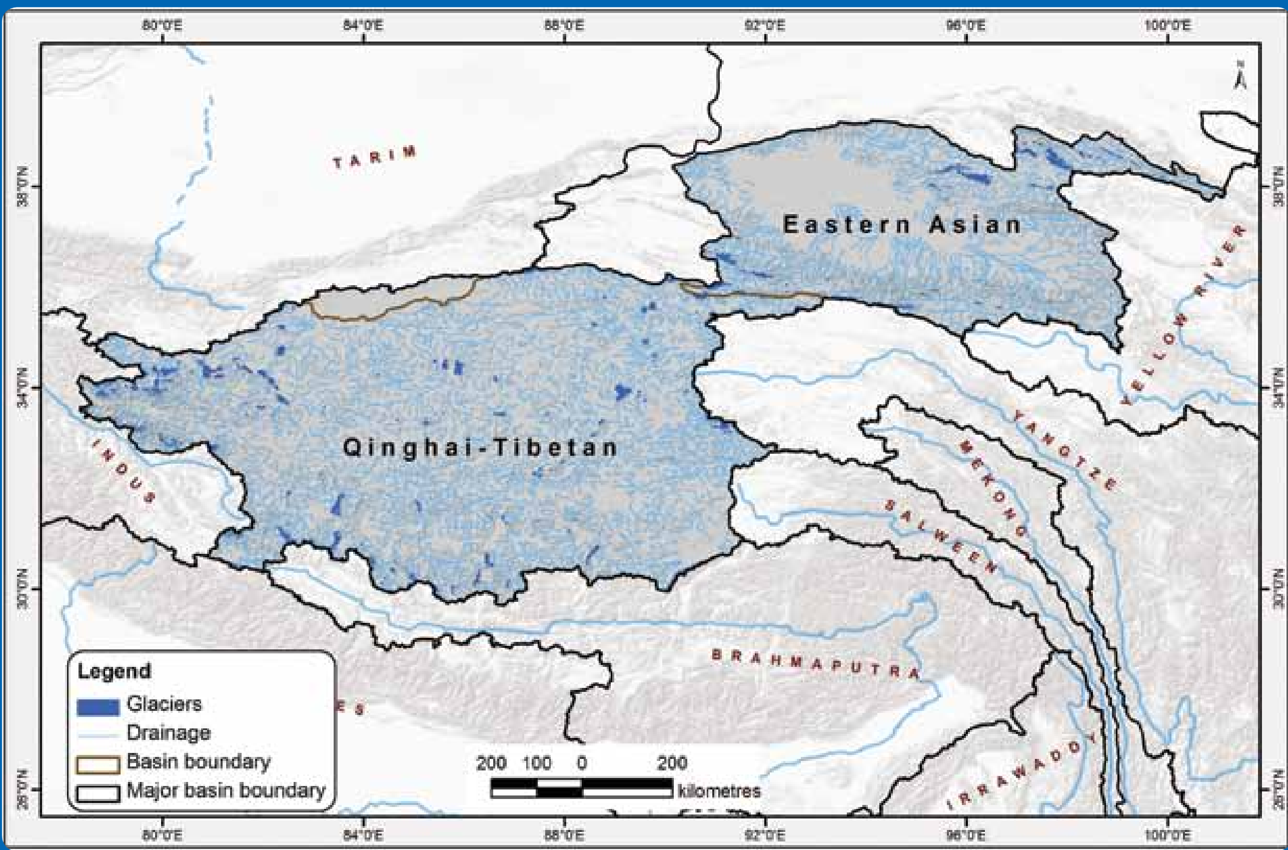


Table 15.1: Glacier characteristics in the HKH region interior basin

Items	Units	Interior basin		Interior basin
		Qinghai-Tibetan	Eastern-Asian	
Basin area	km²	629,378	280,446	909,824
Latitude	degrees	29.69-36.75	35.40-39.28	29.69-39.28
Longitude	degrees	78.31-93.06	90.54-100.54	78.31-100.54
Number of glaciers	unit	5,033	2,318	7,351
Total glacier area	km²	5,493.32	2,041.32	7,534.64
Largest glacier area	km²	69.12	83.94	83.94
Total ice reserves	km³	423.893	130.207	563.1
Highest elevation	masl	6,609	6,052	6,609
Lowest elevation	masl	4,930	3,994	3,994
Mean glacier slope	degree	23	25	24
Average glacier area	km²	1.09	0.88	1.02

No information on CI and DC glaciers

Number, area, and ice reserves

The interior basin had a total of 7,351 glaciers with a total area of 7,535 km² and estimated ice reserves of 563 km³ (Table 15.1).

The number, area, and estimated ice reserves of glaciers in each part of the interior basin are shown in Figure 15.2. The Qinghai-Tibetan basin had the most glaciers (5,033), largest glaciated area (5,493.32 km²), and highest estimated ice reserves (433 km³). The largest glacier in this basin was GLIMS ID: G085873E34310N (5Z63_42) with an area of 69 km² and estimated ice reserves of 14 km³, and extending from 5,988 to 5,462 masl. The largest individual glacier overall was GLIMS ID G091021E36065N (5Y54_324) in the Eastern Asian basin with an area of 84 km² and estimated ice reserves of 19 km³, and extending from 5,569 to 4,858 masl. The average glacier size in the Qinghai-Tibetan basin was 1.09 km², and in the Eastern Asian basin 0.88 km².

Glacier area classes

The number, area, and estimated ice reserves of glaciers in the different size classes are summarised in Table 15.2 and shown as a percentage of the total in Figure 15.3. The majority of glaciers were in the smallest class (4,894, or 67%); and the least in class 5 (109 or 1.5%). The class 1 glaciers contributed only 11% of the glacier area and less than 3% of the ice reserves. The large class 5 glaciers (more than 10 km²) were less than 2% of the total number, had the second highest total area (30% of the total) and contained 54% of the ice reserves.

Glacier elevation

The highest glacier elevation was 6,609 masl in the Qinghai-Tibetan basin and the lowest 3,994 masl in the Eastern-Asian basin, with the majority of glaciers lying between 5000 and 6500 masl (Table 15.1).

Figure 15.2: Glacier number, area, and estimated ice reserves in the two parts of the interior basin

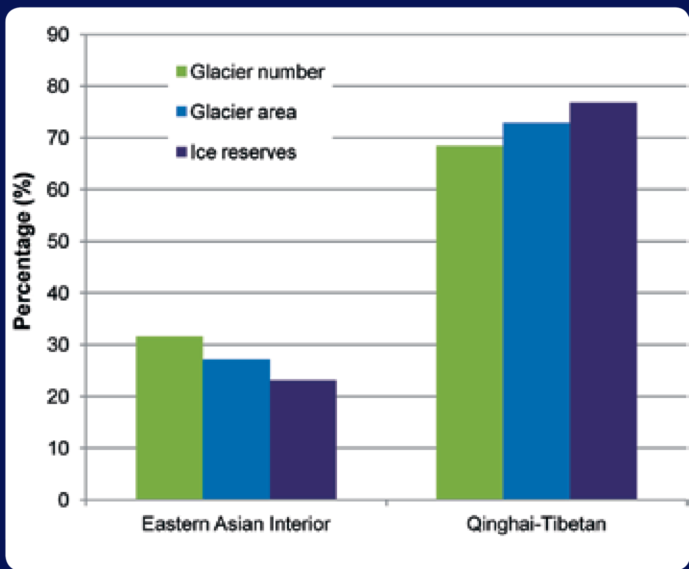


Figure 15.3: Percentage of glacier number, area, and estimated ice reserves in the different glacier size classes in the interior basin

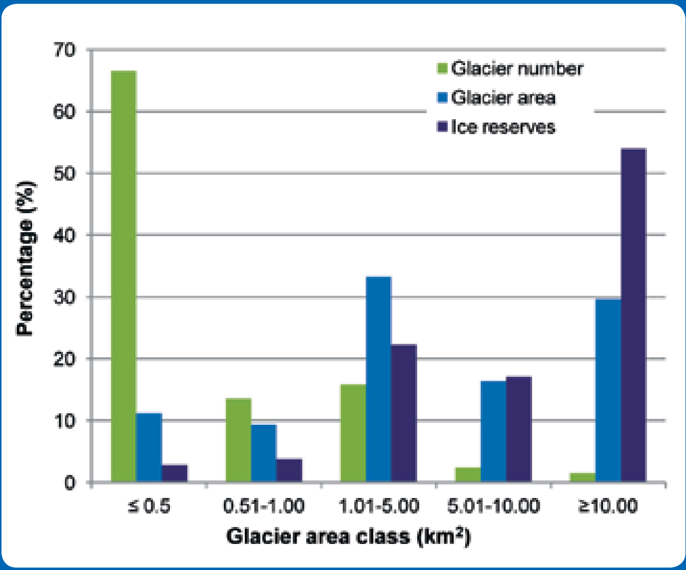


Figure 15.4: Aspect and mean slope of glaciers in the interior basin

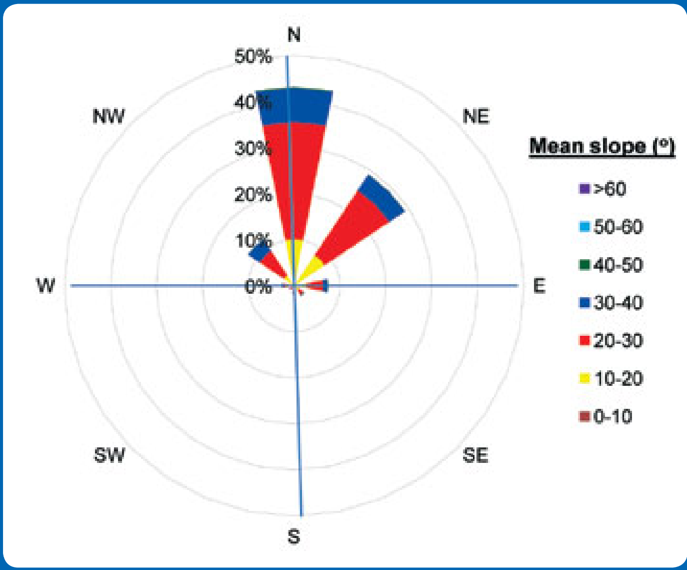


Table 15.2: Glacier area classes in the HKH region interior basin

Area class	Area (km²)	Number		Area		Estimated ice reserves		Mean area per glacier
		Total	%	km²	%	km³	%	km²
1	≤ 0.5	4,894	66.6	844.17	11.2	15.991	2.8	0.17
2	0.51-1.00	1,000	13.6	708.34	9.4	21.166	3.8	0.71
3	1.01-5.00	1,167	15.9	2,506.02	33.3	125.600	22.3	2.15
4	5.01-10.00	181	2.5	1,239.36	16.5	96.455	17.1	6.85
5	≥10.00	109	1.5	2,236.76	29.7	303.889	54.1	20.52
	Total	**7,351**	**100**	**7,534.64**	**100**	**563.100**	**100**	**1.02**

Aspect

Figure 15.4 shows the percentage of glaciers with different aspects and mean slope. More than 43% of glaciers had a north aspect, close to 30% a northeast aspect, and 12% a northwest aspect. The largest glaciers in both parts of the interior basin faced east.

Slope

The mean slope of most of the glaciers ranged from 10° to 40°, with slopes of 20° to 30° most common, followed by slopes of 30° to 40° and 10° to 20° (Figure 15.4). Less than 15% of glaciers had slopes of less than 10° and greater than 40°. The average slope of glaciers in the basin was 24°, slightly higher in the Eastern Asian basins (25°) and slightly lower in the Qinghai-Tibetan basin (23°). The mean slope of the largest glacier in the Eastern Asian basins was 14° and in the Qinghai-Tibetan basin 11°.

Conclusion

The HKH Glacier Inventory

Ten major Asian rivers – the Amu Darya, Indus, Ganges, Brahmaputra, Irrawaddy, Salween, Mekong, Yangtze, Yellow and Tarim – have their source in the glaciers of the HKH region. Glaciers play an important role in sustaining the perennial water supply to downstream areas, in storing water, and in climate processes. Information about them is important for assessing regional water resources, hazard management applications, and climate change impact studies. The present study provides the first comprehensive inventory of glaciers for the entire HKH region prepared using a common methodology and presented at the river basin level. This seems likely to be the first report with details of glaciers in Myanmar.

A consistent semi-automated methodology based on remote sensing was used, with manual corrections carried out by a team of remote sensing specialists, glaciologists, and geologists. Extensive use was made of medium resolution Landsat ETM+ imagery, mostly from around the year 2005 and high resolution images of Google Earth, in combination with SRTM digital elevation models. A systematic approach was followed and for each glacier a set of parameters was derived consistent with the international guidelines formulated by the World Glacier Monitoring Service. Within each basin, glaciers were analysed for area, elevation range, slope, and aspect, and in addition debris cover, morphology, and hypsometry, except for glaciers in China. Efforts are underway to complete this part of the classification in collaboration with the Chinese Glacier Inventory.

Status of Glaciers in the HKH Region

Number and distribution

A total of 54,000 individual glaciers were identified with an overall area of 60,000 km², and an estimated 6,000 km³ of ice reserves. In total, 1.4% of the HKH region is glaciated, but the total ice reserves are equal to roughly three times the annual precipitation over the entire HKH region (Bookhagen and Burbank 2006; Immerzeel et al. 2009).The average size of individual glaciers was relatively small (1.1 km²), but most of the ice reserves are found in the larger glaciers as a result of the non-linear volume-area relationship. The largest individual glacier was the Siachen glacier in the Karakoram mountains in the Indus basin with a total area of 926 km².

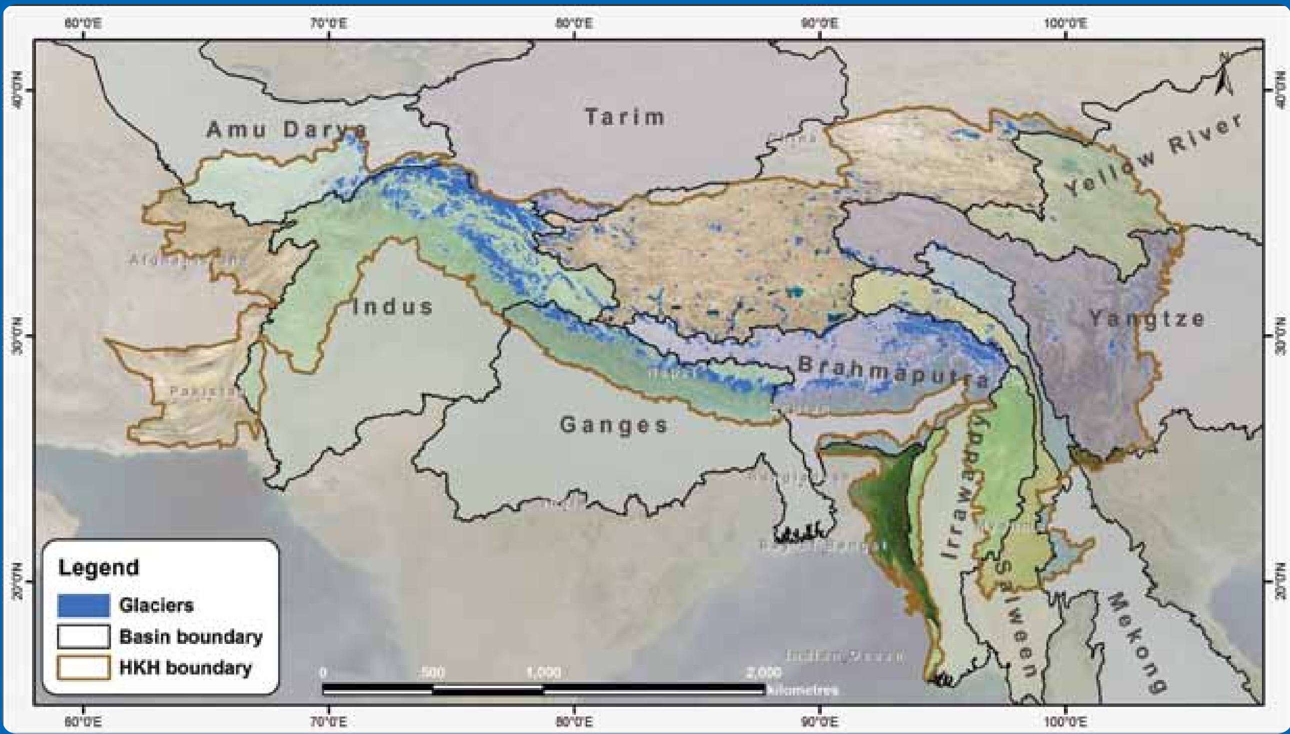
The distribution of glaciers across the region is shown in Figure 1 and the level of glaciation in individual basins in Figure 2. There was a large variation in the glaciated areas found within each basin with the greatest proportions in the Indus (3.8% of the total basin area within the HKH region), Brahmaputra (3.2% of the total basin area within the HKH region), and Ganges basins (3.7% of the total basin area within the HKH region) (Figures 1 and 2).

Summary of characteristics

The overall results for individual parameters across the region are summarised in Table 1.

Altogether 28,500 glaciers with a glaciated area of 32,000 km² were analysed in terms of debris cover or clean-ice type. Overall 9.7% of the total glacier area was debris-covered, with higher values of 12.6% and 9.3% in the Ganges and Indus basins respectively. The debris-covered glaciers are mostly valley glaciers with a thick debris cover on the glacier tongue. They had an average slope of around 12°, whereas clean-ice glaciers were much steeper with average slopes of around 25°. The debris cover plays an important role as it has an insulating effect and reduces melting rates.

Figure 1: Distribution of glaciers in the ten major river basins of the Hindu Kush-Himalayas



There was a large variation in glacier elevation range, with the lowest glacier terminus identified at 2,409 masl in the Indus basin and the highest at 8,806 masl in the Koshi basin. Overall, the largest glaciated area concentration in the HKH was found at altitudes of 5,000-6,000 masl. The elevation range, and more specifically the hypsometric curves, are very important as they largely determine how sensitive glaciers are to changes in temperature. This study provides detailed hypsometric curves at the sub-basin level for all the parts of the major river basins outside the region in China.

Making the information available

The data generated in this study including the attribute information is being made publically available and can be used by decision makers, scientists, and governments in different fields of application. The data are provided through a web portal accessible at http://geoportal.icimod.org/HKHGlacier/ that allows easy access, spatial sub-setting, and online analysis.

Future developments

This inventory can now serve as a baseline and will be continuously updated during the coming years with a particular focus on quantifying changes and especially any impact of climate change. It is hoped that this open approach and the use of a transparent methodology will help in avoiding future misunderstandings related to the Hindu Kush-Himalayan glaciers.

Figure 2: Percentage of glaciated area within the HKH part of the major river basins

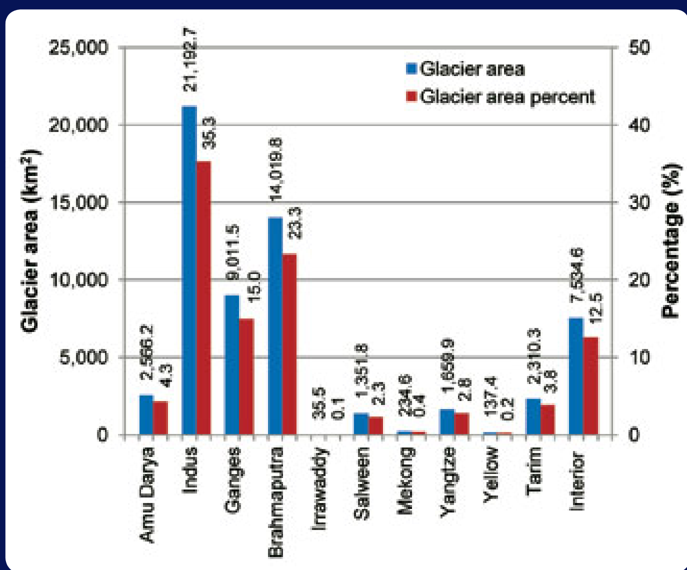


Table 1: Glacier characteristics in the basins of the HKH region

Parameter	Units	Basin											HKH
		Amu Darya	Indus	Ganges	Brahmaputra	Irrawaddy	Salween	Mekong	Yangtze	Yellow	Tarim	Interior	
Basin area total	km^2	645,726	1,116,086	1,001,019	528,079	426,501	363,778	841,322	2,065,763	1,073,168	929,003	NA	8,990,445
Basin area in HKH	km^2	166,686	555,450	244,806	432,480	202,745	211,122	138,876	565,102	250,540	26,729	909,824	3,705,721
Latitude minimum	degrees	34.58	30.45	27.53	27.49	28.06	28.38	28.30	28.21	33.29	34.74	29.69	27.49
Latitude maximum	degrees	38.35	37.08	31.42	31.03	28.77	32.76	33.73	35.78	38.25	36.75	39.28	39.28
Longitude minimum	degrees	67.63	69.36	77.98	82.03	97.32	91.50	94.15	90.56	98.61	75.56	78.31	67.63
Longitude maximum	degrees	74.88	81.65	88.7	97.76	98.17	98.71	98.76	103.89	101.87	86.82	100.54	103.89
Number of glaciers	unit	3,277	18,495	7,963	11,497	133	2,113	482	1,661	189	1,091	7,351	54,252
CI glacier area	km^2	2,405.59	18,631.04*	5,621.68*	1,185.65*	35.46	NA	NA	NA	NA	516.95*	NA	NA
DC glacier area	km^2	160.59	1,970*	809.92*	147.52*	0.0	NA	NA	NA	NA	32.00 *	NA	NA
Total glacier area	km^2	2,566.18	21,192.67	9,011.53	14,019.84	35.46	1,351.76	234.61	1,659.85	137.43	2,310.26	7,534.64	60,054.23
Largest glacier area	km^2	39.72	925.93	176.76	204.36	2.91	40.06	9.76	54.59	20.82	239.23	83.94	926
Total ice reserves	km^3	162.61	2,696.05	793.53	1,302.63	1.29	87.69	10.68	121.40	9.24	378.64	563.1	6,126.85
Highest elevation	masl	7,213	8,566	8,806	8,331	5,695	6,471	6,361	6,270	5,710	6,462	6,609	8,806
Lowest elevation	masl	3,131	2,409	3,273	2,435	4,256	3,786	2,891	2,972	4,151	3,940	3,994	2,409
CI elevation minimum*	masl	3,415	2,723	3,610	3,707	4,256	NA	NA	NA	NA	4277	NA	NA
CI elevation maximum*	masl	7,213	8,566	8,806	8,331	5,695	NA	NA	NA	NA	6462	NA	NA
DC elevation minimum*	masl	3,131	2,409	3,273	3,882	NA	NA	NA	NA	NA	3940	NA	NA
DC elevation maximum*	masl	5,466	5,913	6,009	5,828	NA	NA	NA	NA	NA	5235	NA	NA
Mean CI glacier slope*	degrees	25	25	28	25	25	NA	NA	NA	NA	27	NA	NA
Mean DC glacier slope*	degrees	12	10	13	13	NA	NA	NA	NA	NA	10	NA	NA
Mean slope	degrees	24	24	28	25	25	25	26	27	26	27	24	25
Average glacier area	km^2	0.78	1.15	1.13	1.22	0.27	0.64	0.49	1.00	0.73	2.12	1.02	1.11

Note: Based on UTM, WGS 84 projection. HKH area= 4,192,446 km^2; ten basins area in HKH region=2,795,898 km^2 (excluding interior basin), part of HKH area is not included in either the ten basins or the interior

* excluding glaciers in China, NA = not applicable (as not evaluated)

References

Aizen, VB; Aizen EM (1998) 'Estimation of glacial runoff to the Tarim river, Central Tien Shan.' In *Proceedings of International Symposium 'WaterHead'98'*, Merano, ITALY, IAHS Publication 248, pp191-199. Wallingford, UK: IAHS Press

Armstrong RL (2011) *The glaciers of the Hindu Kush-Himalayan region – A summary of the science regarding glacier melt/retreat in the Himalayan, Hindu Kush, Karakoram, Pamir, and Tien Shan mountain ranges*. Kathmandu, Nepal: ICIMOD

Bajracharya, SR; Mool, PK (2007) 'Melting glaciers in the Himalaya.' *Mountain Forum Secretariat Bulletin 7*(2): 5-6

Bajracharya, SR; Mool, PK; Shrestha, BR (2007) *Impact of climate change on Himalayan glaciers and glacial lakes: Case studies on GLOF and associated hazards in Nepal and Bhutan*. Kathmandu, Nepal: ICIMOD

Barnett, TP; Adam, JC; Lettenmaier, DP (2005) 'Potential impacts of a warming climate on water availability in snow-dominated regions.' *Nature* 438: 303-309

Bishop, MP; Barry, RG; Bush, ABG; Copeland, L; Dwyer, JL; Fountain, AG; Haeberli, W; Hall, DK; Kääb, A; Kargel, JS; Molina, BF; Olsenholler, JA; Paul, F; Raup, BH; Shroder, JF; Trabant, DC; Wessels, R (2004) 'Global Land Ice Measurements from Space (GLIMS): Remote sensing and GIS investigations of the Earth's cryosphere.' *Geocarto International* 19(2): 57-85

Bolch, T; Buchroithner, MF; Peters J; Baessler, M; Bajracharya, S (2008) 'Identification of glacier motion and potentially dangerous glacial lakes in the Mt. Everest region/Nepal using spaceborne imagery.' *Natural Hazards and Earth System Sciences* 8: 1329-1340

Bookhagen, B; Burbank, DW (2006) 'Topography, relief, and TRMM-derived rainfall variations along the Himalaya.' *Geophysical Research Letters* 33: 1-5

Chao-hai, L; Ya-feng, S; Wang, Z; Zi-chu, X (2000) 'Glacier resources and their distributive characteristics in China: A review on Chinese Glacier Inventory.' *Journal of Glaciology and Geocryology* 22 (2): 106-112

Dyhrenfurth, GO (1955) *To the Third Pole: The history of the High Himalaya* (1st edn). London, UK: Ex Libris, Werner Laurie

GSI (1999) *Inventory of the Himalayan glaciers: A contribution to the International Hydrological Programme*, Special Publication No 34. Calcutta, India: Geological Survey of India

Haeberli, W; Hoelzle, M (1995) 'Application of inventory data for estimating characteristics of and regional climate-change effects on mountain glaciers: A pilot study with the European Alps.' *Annals of Glaciology* 21: 206-212

Hewitt, K (2005) 'The Karakoram anomaly? Glacier expansion and the 'Elevation effect,' Karakoram Himalaya.' *Mountain Research and Development* 25(4): 332-340

Hewitt, K (2010) Understanding glacier changes. http://www.chinadialogue.net/article/show/single/en/3480 (accessed 30 August 2011)

Huggel, C; Zgraggen-Oswald, S; Haeberli, W; Kääb, A; Polkvoj, A; Galushkin, I; Evans, SG (2005) 'The 2002 rock/ice avalanche at Kolka/Karmadon, Russian Caucasus: assessment of extraordinary avalanche formation and mobility, and application of QuickBird satellite imagery.' *Natural Hazards and Earth System Science* 5: 173-187

Immerzeel, WW; Droogers, P; De Jong, SM; Bierkens, M (2009) 'Large-scale monitoring of snow cover and runoff simulation in Himalayan river basins using remote sensing.' *Remote Sensing of Environment* 113: 40-49

IPCC (2001a) *Climate change 2001: Technical summary*, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge University Press

IPCC (2001b) *Climate change 2001: Impacts, adaptation and vulnerability*, Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge University Press

IPCC (2007) *Climate change 2007: The physical science basis*, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge University Press

Ives, JD (1986) *Glacier lake outburst floods and risk engineering in the Himalaya – a review of the Langmoche disaster, Khumbu Himal, 4 August 1985*, Occasional Paper No 5. Kathmandu, Nepal: ICIMOD

Ives, JD; Shrestha, RB; Mool, PK (2010) *Formation of glacial lakes in the Hindu Kush-Himalayas and GLOF risk assessment*. Kathmandu: ICIMOD.

Kääb, A; Wessels, R; Haeberli, W; Huggel, C; Kargel, JS; Khalsa, SJS (2003) 'Rapid ASTER imaging facilitates timely assessment of glacier hazards and disasters.' *EOS, Transactions American Geophysical Union* 84(13): 117-121

Kargel, JS; Abrams, MJ; Bishop, MP; Bush, A; Hamilton, G; Jiskoot, H; Kääb, A; Kieffer, HH; Lee, EM; Paul, F; Rau, F; Raup, B; Shroder, JF; Soltesz, DL; Stearns, L; Wessels, R (2005) 'Multispectral imaging contributions to Global Land Ice Measurements from Space.' *Remote Sensing of Environment* 99: 187-219

Kargel, JS; Furfaro, R; Kaser, G; Leonard, GJ; Fink, W; Huggel, C; Kääb, A; Raup, BH; Reynolds, JM; Zapata, ML (2010) 'ASTER imaging and analysis of glacier hazards.' In Ramachandran, B; Gillespie, A; Abrams, M (eds), *Land remote sensing and global environmental change: NASA'S Earth Observing System, and the science of ASTER and MODIS*, pp 325-374. New York, USA: Springer Verlag

Kattelmann, R (2003) 'Glacial lake outburst floods in the Nepal Himalaya: a manageable hazard?' *Natural Hazards* 28(1): 145-154

Kulkami, AV (1991) 'Glacier inventory in Himachal Pradesh using satellite data.' *Journal of Indian Society of Remote Sensing* 19(3): 195-203

Kulkami, AV (1994) 'A conceptual model to assess effect of climatic variations on distribution of Himalayan glaciers.' In *Global change studies: Scientific results from ISRO Geosphere Biosphere Programme* (ISRO-GBP-SR-42-94), pp 322-326. Bangalore, India: Indian Space Research Organisation

LIGG/WECS/NEA (1988) *Report on first expedition to glaciers and glacier lakes in the Pumqu (Arun) and Poique (Bhote-Sun Kosi) river basins, Xizang (Tibet), China, Sino-Nepalese investigation of glacier lake outburst floods in the Himalaya*. Beijing, China: Science Press

Manley, WF (2008) 'Geospatial inventory and analysis of glaciers: A case study for the eastern Alaska Range.' In Williams, Jr, RS; and Ferrigno, JG (eds), *Satellite image atlas of glaciers of the world: Glaciers of Alaska*, USGS Professional Paper 1386-K, pp 424-439. Washington DC, USA: US Government Printing Office

Mool, PK (1995) 'Glacier lake outburst floods in Nepal.' In *Journal of Nepal Geological Society* 11(special issue): 273-280

Mool, PK; Bajracharya, SR; Joshi, SP (2001a) *Inventory of glaciers, glacial lakes, and glacial lake outburst flood monitoring and early warning systems in the Hindu Kush-Himalayan region: Nepal*. Kathmandu, Nepal: ICIMOD

Mool, PK; Wangda, D; Bajracharya, SR; Joshi, SP; Kunzang, K; Gurung, DR (2001b) *Inventory of glaciers, glacial lakes, and glacial lake outburst flood monitoring and early warning system in the Hindu Kush-Himalayan region: Bhutan*. Kathmandu, Nepal: ICIMOD

Müller, F; Caflish, T; Müller, G (1977) *Instructions for compilation and assemblage of data for a World Glacier Inventory*. Zurich, Switzerland: Swiss Federal Institute of Technology, Temporary Technical Secretariat for World Glacier Inventory

Paul, F (2002) 'Combined technologies allow rapid analysis of glacier changes.' *EOS, Transactions American Geophysical Union* 83(23): 253-261

Paul, F; Kääb A; Rott H; Shepherd, A; Strozzi, T; Volden, E (2009) 'Globglacier: A new ESA project to map the world's glaciers and ice caps from space.' *EARSeL eProceedings* 8: 11-25

Quincey, DJ; Richardson, SD; Luckman, A; Lucas, RM; Reynolds, JM; Hambrey, MJ; Glasser, NF (2007) 'Early recognition of glacial lake hazards in the Himalaya using remote sensing datasets.' *Global and Planetary Change* 56(1-2): 137-152

Racoviteanu, AE; Pau, lF; Raup, B; Khalsa, SJS; Armstrong, R (2009) 'Challenges and recommendations in mapping of glacier parameters from space: Results of the 2008 Global Land Ice Measurements from Space (GLIMS) workshop, Boulder, Colorado, USA.' *Annals of Glaciology* 50(53): 53-69

Raina, VK; Srivastava, D (2008) *Glacier atlas of India. Bangalore*, India: Geological Society of India

Rau, F; Mauz, F; Vogt, S; Khalsa, SJS; Raup, B (2005) Illustrated GLIMS glacier classification manual: Glacier classification guidance for the GLIMS glacier inventory, Version 1.0, 2005-02-10. http://www.glims.org/MapsAndDocs/assets/GLIMS_Glacier-Classification-Manual_V1_2005-02-10.pdf (accessed 30 August 2011)

Raup, B; Kääb, A; Kargel, JS; Bishop, MP; Hamilton, G; Lee, E; Paul, F; Rau, F; Soltesz, D; Khalsa, SJS; Beedle M; Helm, C (2007a) 'Remote sensing and GIS technology in the Global Land Ice Measurements from Space (GLIMS) Project.' *Computers and Geoscience* 33: 104-125

Raup, B; Racoviteanu, A; Khalsa, SJS; Helm, C; Armstrong, R; Arnaud, Y (2007b) 'The GLIMS Geospatial Glacier Database: A new tool for studying glacier change.' *Global and Planetary Change* 56(1-2): 101-110

Reynolds, JM (1998) 'High-altitude glacial lake hazard assessment and mitigation: a Himalayan perspective.' In Maund, JG; Eddleston, M (eds), *Geohazards in engineering geology*, GSL Special Publication 15, pp 25-34. London, UK: Geological Society

Richardson, SD; Reynolds, JM (2000) 'An overview of glacial hazards in the Himalayas.' *Quaternary International*, 65/66(1): 31-47

Rivera A; Casassa, G; Bamber, J; Kääb, A (2005) 'Ice-elevation changes of Glacier Chico, southern Patagonia, using ASTER DEMs, aerial photographs and GPS data.' *Journal of Glaciology* 51(172): 105-112

Scherler,D; Bookhagen, B; Strecker,MR (2011) Spatially variable response of Himalayan glaciers to climate change affected by debris cover. *Nat. Geosci*. 4:156-159,doi:10.1038/NGEO1068, 2572,2583

Shi, Y; Liu, S; Ye, B; Liu, C; Wang, Z (eds) (2008) *Concise glacier inventory of China.* Shanghai, China: Shanghai Popular Science Press

Shrestha, AB; Wake, CP; Mayewski, PA; Dibb, JE (1999) 'Maximum temperature trends in the Himalaya and its vicinity: An analysis based on temperature records from Nepal for the period 1971-94.' *Journal of Climate* 12: 2775-2767

Storey, J; Scaramuzza, P; Schmidt, G (2005) *Landsat 7 scan line corrector-off gap filled product development*. Paper presented at the Pecora 16 Conference, 23-27 October 2005, Sioux Falls, South Dakota, USA

Thomas, RH; Rignot, E; Kanagaratnam, P; Krabill, W; Casassa, G (2004) 'Force perturbation analysis of Pine Island Glacier suggests cause for recent acceleration.' *Annals of Glaciology* 39:133-138

TTS (1978) Instructions for compilation and assemblage of data for a World Glacier Inventory. Supplement: Identification/glacier number. Zurich, Switzerland: Temporary Technical Secretariat for World Glacier Inventory

Wessels, R; Kargel, JS; Kieffer, HH (2002) 'ASTER measurement of supraglacial lakes in the Mount Everest region of the Himalaya.' *Annals of Glaciology* 34: 399-408

WGMS (1989) *World glacier inventory - Status 1988*. Haeberli, W; Bösch, H; Scherler, K; Østrem, G; Wallén, CC (eds). Zurich, Switzerland: IAHS (ICSI) / UNEP / UNESCO, World Glacier Monitoring Service

Yamada, T (1998) *Glacier lake and its outburst flood in the Nepal Himalaya*, Monograph 1. Tokyo, Japan: Japanese Society of Snow and Ice, Data Center for Glacier Research

Yamada, T (2000) 'Glacier lake outburst floods in Nepal.' *Seppyo* 62(2): 137-147 (in Japanese with English summary)

Yamada, T; Sharma, CK (1993) 'Glacier lakes and outburst floods in the Nepal Himalaya.' In *Proceedings of International Symposium Snow and Glacier Hydrology*, Kathmandu, 1992, IAHS Publication 218, pp319-330. Wallingford, UK: IAHS Press

Zimmermann, M; Bischel, M; Kienholz, H (1986) 'Mountain hazards mapping in the Khumbu Himal, Nepal, with prototype map, scale 1:50,000.' *Mountain Research and Development* 6(1): 29-40

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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. Globalisation 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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ISBN 978 92 9115 215 5