RESEARCH REPORT

Glaciers in Afghanistan

Status and changes from 1990 to 2015

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Cover photo: A transitional zone featuring clean-ice and debris-covered sections of a glacier in Noshaq valley, Badakhshan, Afghanistan.
– *Zane Afzali, Aqila Hashimi*

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Authors

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General Directorate of Water Resources

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Contents

About this report

This report provides detailed information about the status of glaciers in Afghanistan in 2015 and decadal changes observed in them from 1990 to 2010. The database on glaciers was generated for clean-ice and debris-covered glaciers as separate entities by adopting semi-automated methods and using an object-based image classification in eCognition software. The same source, Landsat images, was used for 1990, 2000, 2010, and 2015 to ensure that the data generated was consistent, and to increase the accuracy of observations. These databases and information will be a great asset to the Government of Afghanistan in managing water resources and disaster risk reduction in the country. They will also comprise a valuable source for further analysis by researchers all over the world. The database has been shared through ICIMOD's Regional Database System (RDS) (https://doi.org/10.26066/rds.35987;https://doi.org/10.26066/rds.35986; https://doi.org/10.26066/rds.35985 and https://doi.org/10.26066/rds.35984) and the Mountain GeoPortal (http://geoapps.icimod.org/glacier/afglacier).

This glacier database and report was prepared as a part of the SERVIR–HKH project, funded by the United States Agency for International Development (USAID) and the National Aeronautics and Space Administration (NASA) and in collaboration with the General Directorate of Water Resources of the National Water Affairs Regulation Authority (NWARA), Kabul, Afghanistan.

Abbreviations and acronyms

AIMS	Afghanistan Information Management Services
ASTER	Advanced Space-borne Thermal Emission and Reflection Radiometer
CGIAR–CSI	Consultative Group on International Agricultural Research–Consortium for Spatial Information
CI	Clean-ice glacier
DC	Debris-covered glacier
DEM	Digital elevation model
ENVI	Environment for Visualizing Images
ERTS	Earth Resources Technology Satellite
ETM+	Enhanced Thematic Mapper Plus
GDEM	Global Digital Elevation Map
GDWR	General Directorate of Water Resources
GLIMS	Global Land Ice Measurements from Space
GLOF	Glacial lake outburst flood
GloVis	USGS Global Visualization Viewer
HKH	Hindu Kush Himalaya
ICIMOD	International Centre for Integrated Mountain Development
IPCC	Intergovernmental Panel on Climate Change
ISRO	Indian Space Research Organization
LIGG	Lanzhou Institute of Glaciology and Geocryology
MSS	Multispectral scanner
NASA	National Aeronautics and Space Administration
NDVI	Normalized Difference Vegetation Index
NDSI	Normalized Difference Snow Index
NDWI	Normalized Difference Water Index
NEA	Nepal Electricity Authority
NWARA	National Water Affairs Regulation Authority
OBIC	Object-based image classification
OLI	Operational Land Imager
SPOT	Satellite Pour l'Observation de la Terre
SRTM	Shuttle Radar Topography Mission
TM	Thematic Mapper
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
WECS	Water and Energy Commission Secretariat
WGS	World Geodetic System

Foreword

The glaciers and snow-capped high mountains of the Hindu Kush Himalaya (HKH), considered the water towers of Asia, are the headwaters of 10 mighty river systems. They provide water, ecosystem services, and the basis for livelihoods to a population of around 240 million people in the hills and mountains and some 1.65 billion people in the river basins downstream. Together, these river basins support the lives and livelihoods of 1.9 billion people, a fourth of the world's population.

The glaciated high mountains of Afghanistan contribute water to two major river systems, the Amu Darya and the Indus. However, glaciers in the HKH are melting and thinning. Rising temperatures are impacting mountain river flow regimes, disrupting ecosystems, and increasing the risks of rockslides, avalanches, and mountain floods caused by glacial lake outburst floods (GLOFs) and landslide dam outburst floods, among other factors. The findings of our HKH Assessment suggest that if the current emissions scenario does not change, the volume of glaciers in the HKH could decline by 64% by the end of this century even if we limit global warming to 1.5 degrees. The disappearance of glaciers at lower elevations is likely to continue and losses of glacier mass at higher elevations will increase as warming accelerates. As glaciers in the HKH continue to retreat and melt, the formation and enlargement of glacial lakes is increasing, and with it, the risk of GLOFs. The 2018 Panjshir valley GLOF in Afghanistan is one recent example where lives were lost and local livelihoods severely damaged.

Changes in glaciers, glacier environments, and increasing risks can, however, be minimized. Thorough investigations into spatio-temporal changes in glaciers and glacial lakes along with the monitoring and identification of potentially dangerous lakes and the risks they pose can help us plan systematic mitigation and adaptation measures.

Researchers and scientists have worked on glaciers and glacial lakes in Afghanistan since the 1960s. However, a systematic and fundamental spatiotemporal database of glaciers is still unavailable. Although ICIMOD's HKH-wide glacier report and database published in 2011 does cover Afghanistan, the report only provides a single dataset prepared using wider time-period (2005±3 years) satellite images. To bridge this gap, we collaborated with NWARA through our SERVIR–HKH Initiative to study and collect information on glaciers and glacial lakes in Afghanistan. Although ICIMOD has been involved in the systematic collection of information on glaciers and glacial lakes throughout the region since 1986, the present endeavour is a unique one. It has engaged professionals from NWARA in a co-development approach where on-the-job-training and close supervision have ensured the involvement of Afghan government professionals in developing the datasets that have led to this report. We hope this experience has enhanced the capacity of the professionals from NWARA to engage in and sustain future research on glaciers and glacial lakes.

This is the first scientific report to provide detailed information on the status of glaciers in Afghanistan (and changes from 1990 to 2015) from a single, consistent data source. It reveals the shrinkage, retreat, and fragmentation of glaciers in the country. The information and database generated through this collaboration can strengthen integrated water resource management and glacial hazards and risk management in Afghanistan. Our partnership with NWARA also helped further consolidate our ties with the Government of Afghanistan. We thank all the researchers and government personnel involved as well as the authors, coauthors, and contributors for their inputs and generous support.

Pema Gyamtsho, PhD
Director General, ICIMOD

Foreword

This study on the status and decadal changes of glaciers in Afghanistan is the first scientific report to provide detailed information on the status of glaciers in Afghanistan in 2015 and decadal changes in its glaciers from 1990 to 2010. This study has been undertaken by the General Directorate of Water Resources (GDWR), National Water Affairs Regulation Authority (NWARA), Afghanistan, in close collaboration with the International Centre for Integrated Mountain Development (ICIMOD) under the SERVIR–HKH initiative. This report includes a comprehensive assessment of glacial cover in Afghanistan using a semi-automated method based on remote-sensing information.

This study represents a very important step in bridging the gaps in available data and information on the current status of glaciers in Afghanistan. A complete database of glaciers in Afghanistan will be made available online at http://geoapps.icimod.org/glacier/afglacier, which can be accessed and used widely by national and international institutions. The database will contain detailed information on and a current assessment of glaciers in the country. NWARA would like to utilise the findings of this scientific report in integrated water resources management and water-related disaster risk reduction.

NWARA, as the nodal agency for the Integrated Water Resources Management (IWRM), would like to sincerely express its thanks to the United States Agency for International Development (USAID) for its technical and financial support. NWARA would also like to thank ICIMOD for organizing, coordinating, and enabling this valuable document. I also congratulate GDWR colleagues and staff from other ministries who have contributed to its preparation.

I am confident that this valuable publication and the glacier data portal will be a useful resource for all national and international stakeholders and scientific institutions interested in studying glacier dynamics, glacier sensitivity, climate change, and the implications of climate change.

Khan Mohammad Takal
General Director,
National Water Affairs Regulation Authority,
Afghanistan

Debris-covered glaciers on the way from base camp to first camp at the Noshaq valley in Badakhshan; July 2020.

Key findings

This report provides, for the first time, detailed information on the status of and changes in glaciers in Afghanistan. This is essential in order to understand freshwater availability, potential glacial hazards, and future scenarios regarding water availability in Afghanistan. The study deployed a semi-automatic method, using Landsat images from 2015 to map glaciers. For a higher accuracy of the decadal glacier data, glaciers in decadal time periods (1990, 2000, and 2010) were mapped by overlaying glacier boundaries for 2015 against Landsat images of these respective years, and manually editing them where necessary through visual interpretation and cross checking with high-resolution images available on Google Earth.

Altogether, 3,891 glaciers, covering an area of 2,543 km^2, were mapped based on Landsat images for 2015. They cover almost 0.4% of the total land area of the country. There are two glacierized basins in Afghanistan – the Panj Amu River basin and the Kabul River basin. The Panj Amu River basin contains most of the country's glaciers (96%) and the rest (4%) are in the Kabul River basin. Most of the glaciers are concentrated in the northern part of the country in the Wakhan Corridor. The largest glacier covers 39.36 km^2 and is located south of the Pak village (Wakhan Corridor) in the Upper Panj sub-basin of the Panj Amu River basin.

The glaciers are distributed at elevations ranging from 3,201 metres above sea level (masl) to 7,175 masl, with the highest concentration (almost 78% of the total glacier area) in the elevation range 4,500–5,500 masl. About 93% of the glacier area comprises clean-ice glacier portions, distributed over an elevation range of 3,452–7,175 masl. Only 7% of the total glacier area is debris-covered, and to be found from 3,164 to 5,406 masl.

This study shows that there has been an overall reduction in glacier area in Afghanistan of 13.8% (406.16 km^2) over the 25-year period 1990–2015, with the greatest change from 2010 to 2015 (–6.1%), indicating greater glacial shrinkage in recent years. It finds that the number of glaciers has also decreased, for two reasons: small glaciers shrinking below the threshold size (0.02 km^2) and the disappearance of some smaller glaciers. Glacier retreat is prominent in the small glaciers, at their snout and at steeper slopes. Glaciers at lower elevations are very sensitive to changes in temperature. The lowest elevation at which glaciers can be found has changed from 3,114 masl in 1990 to 3,201 masl in 2015, indicating an upward shift of 87 metres. The loss in glacier area is the most at the elevation range 4,500–5,000 masl.

This is the first-ever report providing comprehensive information about the status of glaciers in all of Afghanistan in four time periods and changes in them over a 25-year period, from a single and consistent data source. This report demonstrates the shrinking, retreating, and fragmenting of glaciers in the country, which would directly and adversely impact the long-term availability of freshwater. The information and database provided in this report will be useful for integrated water resource management and glacial hazards and risk management in the country. It will also help understand the impacts of climate change on glaciers, and its effects on mountain ecosystems and downstream riparian areas of the country in terms of water availability.

Acknowledgements

This study has been undertaken by the General Directorate of Water Resources (GDWR), National Water Affairs Regulation Authority (NWARA), Afghanistan in collaboration with ICIMOD under the SERVIR–HKH initiative. We wish to express our sincere gratitude to Birendra Bajracharya, Chief of Party, SERVIR–HKH for his indispensable support from the study's inception to its successful completion. We are very thankful to Fazulhaq Bakhtari, former Director, Water Resources Department, for initiating this research study; to Fayezurahman Azizi, General Director, GDWR for providing management and technical support and guidance during the preparation of the glacier database; and to all the officials and staff members of NWARA who directly or indirectly supported this study.

We express our sincere thanks to Khan Mohammad Takal, General Director, NWARA for his valuable leadership. Thanks also go to Ahmad Wais Basiri, Technical Deputy Minister, NWARA for his kind support.

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Landsat images and Shuttle Radar Topography Mission (SRTM) digital elevation model data were used extensively in this research work. We are deeply indebted to the data provider – NASA, United States Geological Survey (USGS), NASA's Jet Propulsion Laboratory (JPL) and the Consultative Group for International Agriculture Research (CGIAR).

We are also thankful to Sudip Pradhan, coordinator, Regional Database System (RDS) and Sameer Bajracharya, Application Developer, ICIMOD, for their support in structuring the database, developing the web portal, and publishing the database online.

Heartfelt thanks to reviewers Sharad Joshi, Cryosphere Analyst, ICIMOD and Sayed Sharif Shobair, Senior Water Resources Expert, NWARA for their valuable inputs.

Finally, we express our gratitude to our immediate colleagues in the Geospatial Solutions and Mountain Environment Regional Information Systems (MENRIS), ICIMOD for their support and cooperation, which played an important role in the successful completion of this work.

Investigating a source area of the 2018 GLOF in the Panjshir valley.

In the field: Measuring glacier mass balance on Pir Yakh glacier, Panjshir valley.

SECTION 1

Introduction

Glaciers in the high mountains of the Hindu Kush Himalaya (HKH) serve as a massive natural reservoir of freshwater, which provides the basis for the livelihoods of millions of people living downstream. Glaciers are a particularly important source of water for arid and semi-arid regions of the HKH, such as Afghanistan. The melting of glaciers regulates water resource availability (Haritashya et al. 2009) in the river basins, and understanding past and present scenarios of glaciers will help in gauging freshwater availability and glacial hazards in the region in the long run.

Glaciers are very sensitive to changes in temperature and are considered to be one of the key indicators of climate change. The global average surface temperature has been increasing since the end of the Little Ice Age (Bajracharya 2008) in the mid-19th century, and has been successively higher during each of the last decades than any preceding decade since 1850. The change in global surface temperature is predicted to likely exceed 1.5°C by the end of the 21st century (IPCC 2013). For Afghanistan, the reanalysis data for the period 1951–2010 shows that the mean annual temperature across the country has increased substantially, by 1.8°C, with the highest increases of 2.4°C in the east and Hindu Kush region, the figure stands at 1.0°C. It is also observed that the warming in the main glaciated region of Afghanistan, Badakhshan, is between 0.3°C and 0.7°C. Similarly, the projection of rises in mean temperature under the “low emission scenario” representative concentration pathway (RCP) 4.5 indicates the strongest warming, over 2°C, will be in the Wakhan Corridor, followed by the Central Highlands with a warming of 1.75°C–2°C by 2050. (Aich et al. 2017).

Rising temperatures directly influence the melting of glaciers, the variability of snow cover, and changes in other components of the cryosphere. These changes are not consistent throughout the region due to large spatial variability in topography and physical processes. However, the rise in temperatures has undoubtedly contributed to accelerated glacier melt and recession in the region. Cryospheric research indicates that most glaciers across the HKH have been rapidly shrinking and retreating since the 1980s (Bajracharya et al. 2014a; Maurer et al. 2019; Wester et al. 2020), concurrent with a warming climate (Bhambri & Bolch 2009; Bolch et al. 2012; Yao et al. 2012). The rapid melting and recession of glaciers are leading to the formation of glacial lakes behind newly exposed moraines and, at the same time, to the enlargement of existing glacial lakes, which increases the risk of destabilizing the surrounding moraine dam (Cruz et al. 2007; IPCC 2007, 2014; Rosenzweig et al. 2007). It can lead to a sudden breaching of the dam, resulting in glacial lake outburst floods (GLOFs).

In 2011, ICIMOD published a glacier inventory covering the ten major river basins of the HKH. It was the first time baseline data of glaciers mapped from consistent data sources of Landsat images of 2005 (±3 years) had been used and presented, which also covered the Afghan part of the HKH (Bajracharya et al. 2011). Moreover, to understand the current status and trends in changes in glaciers in the region, time series data of decadal time periods for 1980, 1990, 2000, and 2010 from Nepal, Bhutan, and some selected basins in other parts of the HKH were generated based on satellite images. Analyses of this data revealed that the glaciers had lost almost a quarter of their total area over the 30 year period 1980–2010 (Bajracharya et al. 2014b, 2014c, 2015).

In Afghanistan, glaciers serve as the headwaters of the Panj Amu River basin, contributing to Amu Darya River, and the Kabul River basin, which contributes to the Indus River. Despite this significance, there is very little information on glacier extent and periodic changes in them in Afghanistan, because of the challenging topography, the paucity of field work, and geopolitical restrictions. In order to understand future scenarios of freshwater availability, and anticipate and protect against potential glacial hazards, it is necessary to know the present and past status of glaciers and periodic changes in them. Hence, ICIMOD has been working closely with partner institutions in the region to build the database on glaciers in the region since the 1990s. This study was designed in collaboration with the General Directorate of Water Resources (GDWR) of the National Water Affairs Regulation Authority (NWARA) (previously Water Resource Department [WRD] of the Ministry of Energy and Water [MEW]), Afghanistan, under the SERVIR–HKH initiative to provide detailed information on the status of, and changes in glaciers in Afghanistan. The analysis will help to understand the future scenario regarding water availability and potential glacial hazards. Ultimately, the data on, and analyses of changes in glaciers in Afghanistan will support water resources management in the country.

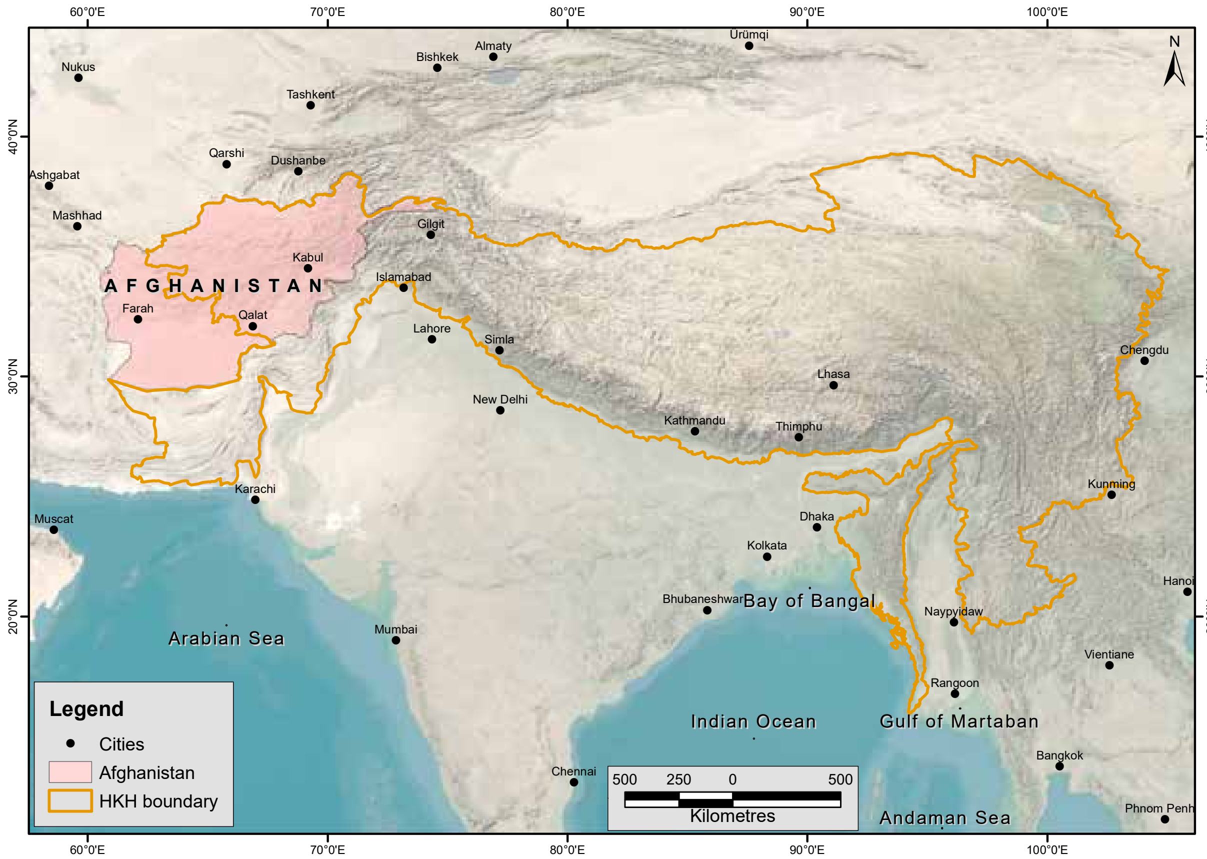
1.1 Study area

Afghanistan is a landlocked country bordered by Iran to the west, Pakistan to the south and east, Turkmenistan, Uzbekistan, and Tajikistan to the north, and China to the far north-east at the tip of Wakhan. It lies between the latitudes 29.21° N and 38.29° N, and longitudes 60.30° E and 74.53° E (Figure 1.1). It encompasses a total area of about 652,000 square kilometres (km^2), dominated by much of the Hindu Kush mountain range (Beekma et al. 2013; Favre and Kamal 2004; Petersen et al. 2013). The country's contours are elliptical, extending north-east to south-west. It is also characterized by the narrow strip of valley, the Wakhan Corridor, to the extreme north-east.

Overall, Afghanistan has an arid and semi-arid continental climate with hot summers and cold winters. The winters are very harsh in the central highlands and the north-eastern region. Maximum temperatures during the summer frequently exceed 38°C, particularly in the south-western region, while the minimum temperature can reach below –25°C during winters. The highlands in the central region influences the local climate with low temperatures at the higher altitudes and by affecting the precipitation regime (Palka 2001).

Afghanistan has varied ecosystems, including glaciers and high-alpine vegetation, particularly in the extreme north-east (including the Wakhan Corridor); montane coniferous and mixed forests; open, dry woodland with juniper, pistachio, and almond trees; semi-desert scrub; sand and stony deserts; rivers, lakes, and marshland. The more closed types of mixed and coniferous forests occur mainly in the eastern part of the country, where the westernmost extension of the Indian monsoon breaks the summer drought. Alpine and subalpine vegetation is generally found at an elevation of 2,800–2,900 metres above mean sea

FIGURE 1.1 AFGHANISTAN AND THE HINDU KUSH HIMALAYA



level (masl) in the central mountains and 3,000–3,500 masl in the east. Sub-alpine vegetation is dominated by juniper in the eastern Hindu Kush and cushion shrublands in central Afghanistan (UNEP 2014). Most of the country appears to be subjected to some degree of land degradation. Almost 47% of its land surface is used as rangeland for grazing livestock (FAO 2016).

1.2 Physiographic divisions of Afghanistan

More than three-quarters of the land is covered by mountains and more than one-quarter of the country lies at or above 2,500 masl. Two mountain arcs rising from the Iranian plateau extend across the country – the northern arc starts from northern Iran with the Elburz mountains and continues through the Hindu Kush in Afghanistan up to the Pamir and the Karakoram chains; the southern arc starts in the Zagros mountains in western Iran, continues through the Baluchistan mountains, the Suleiman mountains across Pakistan and Afghanistan, and ends with the northern arc in the Karakoram mountains (Favre and Kamal 2004). The Hindu Kush mountains form a barrier and divide the country into three physiographic regions: the northern plains, the central highlands, and the southern plateau (Palka 2001).

The Northern Plains

The northern plains cover about 15% of the land and include the extremely fertile foothills and plains. The Amu Darya river flows through the edge of the foothills. The average elevation in this region is about 600 masl (Palka 2001).

The Central Highlands

This region consists primarily of the Hindu Kush mountain range in the central part of the country, covering about 70% of its land area. It is a rugged, snowbound highland that is one of the most impenetrable regions in the world (English 1984; Palka 2001). The Hindu Kush range extends for about 1,000 kilometres (km) in a south-westerly direction, from the Wakhan Corridor in the north-east almost to the border with Iran to the west. From the Hindu Kush, other, lower ranges radiate in all directions. The average elevation of this mountainous region is 2,700 masl and the highest peak, Nowshak, located in the north-east, reaches 7,492 masl. Mountain passes here have always been of profound importance for trade (Palka 2001). This includes the Khyber Pass, one of the most famous routes to the Indian subcontinent.

Southern Plateau

This region of Afghanistan is made up of high plateaus and sandy deserts. It is essentially the lowland area of Afghanistan and includes the Turkistan Plains, the Herat–Farah lowlands to the extreme north-west, the Sistan Basin and the Helmand River Valley to the south-west, and the Rigestan desert in the south (Palka 2001). The soil here is very infertile, except along the rivers in the south-west. The average altitude of this region is about 900 masl.

1.3 River systems in Afghanistan

The river systems in the country play a significant role in the lives and livelihoods of millions of people, and in the country's development. They mostly originate in the central highland regions or in the north-eastern mountains, and drain into inland lakes, irrigation canals, or dry up in sandy deserts. A major exception is the Kabul River, which joins the Indus River in Pakistan and drains into the Indian Ocean. One can identify five major river basins, based on the topography and hydrological flows – the Panj Amu, Kabul, Northern, Harirod–Murghab, and Helmand river basins (Favre and Kamal 2004). These can be grouped into three classes based on its spatial controls – (1) the northern and north-western flows of the Panj Amu and Northern rivers into the Central Asian depressions of the Turkestan endorheic basin; (2) the strong western and south-western flows of the Helmand and Harirod-Murghab rivers to the Afghan–Iran Plateau endorheic basin, with the Helmand River flowing into the Seistan Basin at the Iranian border, largely controlled by geological structures; and (3) the south-eastern exorheic flows by the Kabul River and its tributaries into the Indus Basin system in Pakistan.

The area and elevation distribution of each river basin is given in Table 1.1. Figure 1.2 shows their boundaries.

FIGURE 1.2 RIVER BASINS AND SUB-BASINS IN AFGHANISTAN

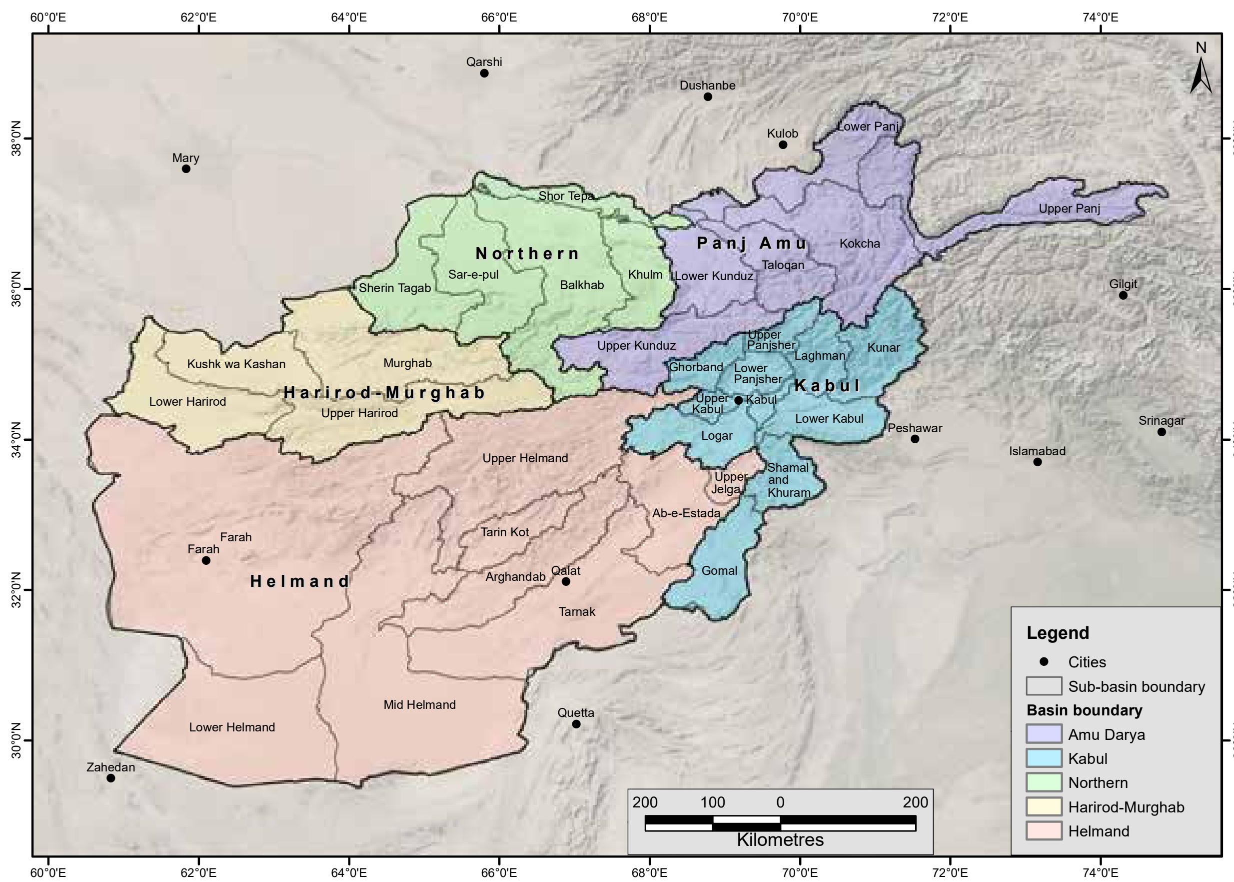


TABLE 1.1 **AREA AND ELEVATION RANGES OF THE FIVE MAJOR RIVER BASINS IN AFGHANISTAN**

River basin	Area		Elevation range (masl)	
	(km²)	%	Minimum	Maximum
Panj Amu	90,941	14	312	7,377
Kabul	71,266	11	388	6,128
Northern	70,000	12	245	4,621
Harirod–Murghab	78,060	12	368	4,448
Hilmand	327,661	51	246	5,048
Total	**637,928**	**100**	–	–

Sources: GDWR, NWARA, River Basin Management Fact Sheet for area; SRTM DEM for elevation.

The Panj Amu River basin

The Panj Amu is the second-largest river basin in Afghanistan. It is demarcated by the Hindu Kush mountains to the south and the Panj and Amu Darya rivers in the north. The Panj contributes to the Amu Darya River (Beekma et al. 2013), one of the longest rivers in Central Asia, with a length of 2,400 km measured from its headwaters originating in the High Pamir mountains of Afghanistan and Tajikistan.

The two main branches of the Amu Darya are the Abi Pamir, which originates from Zor Kul Lake, and Wakhan Rud, which flows from Chaqmaqtin Lake. These two rivers join in the Wakhan to form the Panj River, which flows along most of the national border of Afghanistan with Tajikistan. The Amu Darya begins at the confluence of the Panj and the Kokcha River. It then flows along the entire southern border of Tajikistan and Uzbekistan with Afghanistan, as well as Afghanistan's border with Turkmenistan (Favre and Kamal, 2004).

Relevant for our purposes, the major sources of water in the Amu Darya are glacier melt and snow melt. It drains as much as 57% of Afghanistan's total annual water flow (Beekma et al. 2013; Favre and Kamal 2004). The Panj Amu basin is divided into six sub-basins – the Upper Panj, the Lower Panj, Kokcha, Taloqan, the Upper Kunduz, and the Lower Kunduz (Beekma et al. 2013). Five of them contain glaciers, all but the Lower Kunduz sub-basin.

The Kabul River basin

The Kabul River basin includes all the Afghan rivers that join the Indus River in Pakistan. The Kabul River rises from the mountains in central Afghanistan, west of the city of Kabul. It drains the eastern part of Afghanistan and flows for about 700 km before joining the Indus River near Attock in Pakistan. Of its major tributaries, Panjshir flows from the Hindu Kush to the north-east, and the Kunar originates at the Chiantar glacier in Chitral, Pakistan and enters Afghanistan from north-west Pakistan. It continues as the Kabul River after their confluence near Jalalabad.

This basin covers 12% of Afghanistan's land area (Favre and Kamal 2004; Petersen et al. 2012). Glacier and snow melt water are the major sources of the basin's river flows. The basin generates almost 40% of Afghanistan's total run-off, which irrigates approximately 28% of the land in the country (Petersen et al. 2012). The Kabul basin has eight sub-basins – Kunar, Laghman, Upper Panjsher, Lower Panjsher, Ghorband, Logar, Shamal, and Gomal; the first four sub-basins consist of glaciers.

The Northern River basin

The Northern River rises from the high mountains of the central highlands. It is an endorheic basin; its river dries up in the irrigation canals or desert sands before being able to reach Afghanistan's western border and the Amu Darya river. The river is now separated by a non-drainage area in between the Amu Darya and Northern river basins (Favre and Kamal 2004). The basin consists of four sub-basins – Khulm, Balkhab, Sar-e-pul, and Sherin Tagab.

The Harirod–Murghab River basin

The Harirod River basin is a narrow and elongated basin. The river rises from the chain of high mountains – Sefid Koh on the southern slope, Band-i-Baian and Kasa Murgh on the northern slope, and Koh-i- Bahar on the western slope. It flows nearly straight in the westerly direction towards the Iranian border and then between Iran and Turkmenistan before expending itself in the sands of the Karakumsky desert.

Another river in this basin, the Murghab, originates in the central-western mountain chains of Tirband-I Turkestan, Paropamisus, and Gharjisan mountains in Afghanistan and flows out of the country into the Karakumsky desert. Its main tributary, the Bala Murghab joins with a number of other tributaries in Jawand district to form the main Murghab River.

The Helmand River basin

The Helmand is the largest river basin in Afghanistan and covers almost half (43%) of the country. It rises in the Hindu Kush mountain range about 40 km west of Kabul, crosses south-west through the desert forming the Afghan-Iran border before flowing into the Sistan marshes and the Hamun Lake region around Zabol (King and Sturtewagen 2010). The Helmand basin has nine sub-basins which are mainly fed by snowmelt from the Hindu Kush mountains in east-central Afghanistan. The Helmand's major tributary, the Arghandab, flows from Kandahar and joins the Helmand near Lashkargah (Favre and Kamal 2004).

1.4 Survey of literature on glaciers in Afghanistan

There is a lack of fundamental, reliable spatiotemporal information about glaciers, glacier mass, and glacial hazards in Afghanistan (Dyurgerov and Meier 2004; Haeberli 2004; 2010a, 2010b, Bishop et.al., 2014). Very little information has been collected by scientists and researchers due to geographical, technical, and geopolitical challenges. Shroder (1980, 1989) began to prepare a glacier inventory of Afghanistan in 1974. He used an incomplete set of small-scale topographic maps derived from aerial photographs from 1958 and 1959.

Grotzbach (1964) noted a general retreat in glaciers in the Khwaja Mohammed mountains. Gilbert et al (1969) studied a small glacier near Mir Samir in the central Hindu Kush. Braslau (1972) studied the general recession of the Keshnikhan glacier, which is located at the entrance to the Wakhan Corridor. Breckle and Frey (1976 a, b) pointed to a relatively strong glacierization in eastern and south-eastern Afghanistan near the border with Pakistan. Patzelt (1978), based on research conducted in 1974, measured the orientation, maximum and minimum elevation, length, total area, debris-covered area, and hypsometry of, and changes in the South Issik glacier. He also studied the transient snow lines, the lateral moraine altitude, and daily ablation rates of this glacier (Haritashya et. al. 2009).

Soviet and Russian scholars were very much interested in Afghanistan's glaciers because of the meltwater resources that flow out of Afghanistan to the north. They intensively studied a part of the Wakhan area for a while (Haritashya et al. 2009). They carried out aerial stereo photography covering one-third of northern Afghanistan (Shroder 1980). Shroder (1980) used this data source in comparing the Russian topographic map of 1959 with Kostka's (1974) excellent map of the Keshnikhan glacier in 1970, and found that the glacier had retreated 3.5–4.5 km. He also noted, from fieldwork in 1978 at the Koh-i-Baba mountain range at the extreme western limit of the central Hindu Kush, that the glaciers showed a general retreat since 1959.

In 2011, ICIMOD published a report on the status of glaciers in the HKH region, including in Afghanistan. However, this report did not cover changes in glacier area; it also only provided one-time data. In 2014, Global Land Ice Measurements from Space (GLIMS) published a book comprising varied studies on glaciers at a global scale using remote sensing; it included a chapter on glaciers in Afghanistan and Pakistan. It reported glacier retreat in Afghanistan using satellite images; however, there is no specific digital data set of changes in glaciers covering the whole of Afghanistan. Sakai (2019) updated the GAMDAM glacier inventory over high mountain Asia, in which glaciers from Afghanistan were also included. The inventory used Landsat data from 1994 to 2002 to cover glaciers in Afghanistan.

Pir Yakh is one of the biggest glaciers in Panjshir province with an area of approximately 1.70 km^2.

SECTION 2

Methodology

Remote-sensing methods are more convenient than field-based monitoring to monitor and measure changes in glaciers (Bajracharya et al. 2014a, 2014c). Undoubtedly, field-based monitoring would enable the validation of results and getting more precise information about a glacier, such as its extent, depth, total mass, and mass balance. However, this can be extremely physically challenging, labour- and resource-intensive, and time consuming, especially in a country like Afghanistan due to its rugged terrain, extremely high altitudes, harsh climatic conditions, remoteness, and the geopolitical situation. It is almost impossible without the help of experienced mountaineers and sophisticated logistical support. Importantly, even with such support, one can access and cover only a few, more accessible glaciers that are at lower altitudes. A comprehensive survey of all glaciers in Afghanistan, such as by the present study, necessitates reliance on satellite images.

The development of advanced tools and techniques for remote sensing, the geographic information system (GIS), and the availability of continuous satellite data have significantly augmented the mapping and monitoring of glaciers in the region. Various methodologies have been developed and applied for the rapid mapping of glaciers around the world. This study adopted the semi-automatic method, which was applied in the glacier inventory of the HKH carried out in 2011, and in an assessment of changes in glaciers in Nepal and Bhutan (Bajracharya et al. 2011, 2014a, 2014b). The database of glaciers was prepared based on guidelines adopted by the first World Glacier Inventory (Müller et al. 1977). The method used an automatic object-based image classification with some manual intervention for quality assurance. It is described in detail in the sections that follow.

2.1 Data collection and preparation

Satellite images

This study used Landsat 5, Landsat 7-ETM+, and Landsat 8 images, freely downloadable from the United States Geological Survey's Global Visualization Viewer (GloVis) portal. Altogether, eight Landsat scenes, including full and partial scenes, covering the glaciated areas of Afghanistan were used.

Ideally, for a precise mapping of glaciers from satellite images, it is necessary to acquire good-quality, cloud-free satellite images with minimal snow cover. However, it is quite difficult to get such ideal images for the same year throughout the study area due to the rugged topography and climatic variability across basins. Hence, images are selected from consecutive years of specific time periods rather than single years. Consequently, Landsat 8 images from 2014–2016 were selected and the data prepared as representative of 2015. Similarly, to analyse decadal change, Landsat TM and Landsat 7 ETM+ images from 2009 to 2011 were used to prepare data sets for 2010, Landsat TM images from 1999 to 2001 were used for the year 2000, and images from 1988 to 1992 were used to have data sets for 1990. Altogether, 71 Landsat images were used to prepare decadal data sets of glaciers for 1990, 2000, 2010, and 2015, of which 15 images were from 2015, 21 from 2010, 17 from 2000, and 18 images from 1990. For 2010, Landsat TM data was used for whichever areas available. For other areas, Landsat ETM+ images were used. The Landsat 7 ETM+ images from June 2003 onwards have a scan line dropout, which causes the wedge-shaped scan to scan gaps in the images. These images were corrected using the Landsat Gap fill tool in the ENVI image analysis software (Bajracharya and Shrestha 2011).

The digital elevation model (DEM) used

Topographic information such as elevation and slope play a crucial role in the identification of glaciers. In this study, we used the SRTM version 4.1 DEM from CGIAR at a spatial resolution of 90 m for mapping as well as generating the parameters of glaciers such as their elevation, slope, aspect, and distribution in terms of size and altitude.

SRTM, a specially modified radar system operationalised in February 2000 by NASA, obtained near-global scale elevation data. It represents the most complete high-resolution digital topographic database of the Earth. In 2003, SRTM 90 m (3 arc seconds, or 1/1,200th of a degree latitude and longitude) resolution images covering the whole globe were released. SRTM DEM 30 m (1 arc second) resolution images were released in September 2014, covering the world's landforms (NASA JPL 2014). However, the 30 m resolution data has larger voids for the higher areas of the region under study, and therefore a void-filled SRTM 90 m resolution DEM was used. The void-filled SRTM DEM for the world has been built in a mosaic of seamless near-global coverage (up to 60 degrees latitude north and south). It can be downloaded as 5 x 5-degree tiles in the geographic coordinate system of the World Geodetic System – WGS84 Datum from the CGIAR-CSI portal (http://srtm.csi.cgiar.org/Index.asp).

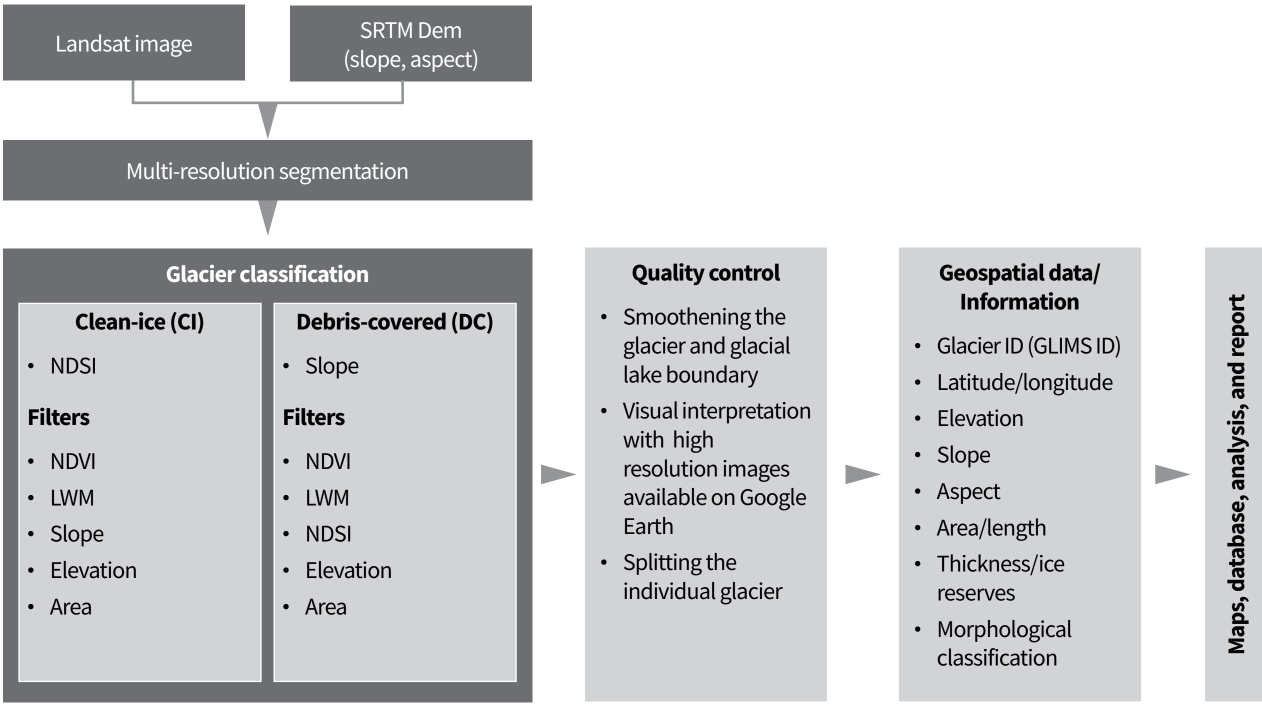
2.2 Semi-automatic method

Glacier mapping through an automated multispectral classification of optical satellite data, in combination with a digital elevation model, is a well-established procedure (Bhambri and Bolch 2009; Bolch et al. 2010; Frey and Paul 2012; Paul and Andreassen 2009; Paul and Kaab 2005; Racoviteanu et al. 2009). However, the automatic mapping process is mostly valid for clean-ice (CI) glaciers only, whereas regions of the HKH are dominated by debris-covered (DC) glaciers. The automatic method developed for debris-covered glaciers tends to produce some errors. Generating quality data sets for DC glaciers therefore requires manual intervention.

The current study adopted the semi-automatic method using an object-based image classification (Bajracharya et al. 2011, 2014a, 2018) to map clean-ice and debris-covered glaciers as separate entities for 1990, 2000, 2010, and 2015. The mapping process consists of a separate algorithm for clean-ice and debris-covered glaciers and some manual intervention. The multi-stage process of mapping glaciers is summarised in Figure 2.1.

This method is able to deliver data consistent with established international glacier inventory standards. The multispectral image classification was processed using eCognition Developer software. Primarily, the image was segmented using multi-resolution segmentation, which creates image-objects based on spectral reflectance, shape, relation to neighbouring objects, and textural characteristics. Image-objects are a group of pixels having homogeneous characteristics.

FIGURE 2.1 FLOW CHART OF THE METHODOLOGY TO MAP GLACIERS



These image-objects were classified by developing rule sets based on spectral and spatial characteristics. A rule set uses the mean value of the defined areas instead of the individual pixel value. It is developed separately for the classification of CI and DC glaciers. The clean ice part of a glacier was mapped using the normalized difference snow index (NDSI). However, the threshold value of NDSI also captures the snow cover and other features such as shadows and water bodies as well. These misclassified features were eliminated by using filters such as the normalized difference vegetation index (NDVI), land and water mask (LWM), slope, etc. Similarly, the debris-covered part of a glacier was mapped using the slope, and filters such as NDVI, LWM, NDSI, etc were used to eliminate the misclassified features (Figure 2.1).

All the classified CI and DC image-objects were merged, and the raster products were then exported to a vector file. The vector-based glacier polygons were manually separated to distinguish individual glaciers based on their hydrological catchments by overlaying them on images and hill shades generated from the DEM using the architecture geographic information system, ArcGIS. These steps used for the delineation of clean-ice and debris-covered glaciers are described in further detail in literature published earlier by ICIMOD (Bajracharya et al. 2011; Bajracharya et al. 2017; Maharjan et al. 2017).

First, Landsat 8 images were used to derive the status of glaciers in Afghanistan in 2015. The glacier polygon of 2015 generated from the image analysis was used as the base map of glacier outlines. This base layer was overlaid on the Landsat images for 2010, 2000, and 1990. The glacier database for the respective year was then generated through a manual modification of the base layers. The results were further refined manually by back-dropping the respective Landsat images and then verified against available high-resolution images on Google Earth.

2.3 Glacier attributes

Attributes of the individual glaciers were generated using ArcGIS, including their estimated ice reserves. Attributes include the location, the GLIMS ID, elevation, slope, aspects, and morphological type of the glacier (Müller et al. 1997). The procedure followed and description of attributes are discussed in detail in Bajracharya and Shrestha (2011); Bajracharya et al (2014a); Bajracharya et. al. (2017); Maharjan et. al. (2017). Here, a very brief description of glacier attributes is provided (Table 2.1).

The location of individual glaciers was represented by the longitude and latitude of the centroid of the glacier polygon. The GLIMS ID for glaciers, developed by Global Land Ice Measurements from Space (GLIMS),

TABLE 2.1	FIELDS AND FORMATS OF GLACIER ATTRIBUTES			
S. No.	**Field name**	**Type**	**Format**	**Description**
1	Latitude	String	DMS	Latitude of the centroid of the glacier polygon
2	Longitude	String	DMS	Longitude of the centroid of the glacier polygon
3	GLIMS_ID	String	GXXXXXXEYYYYYN	Combination of longitude (X) and latitude (Y) of the centroid of the glacier polygon. G = glacier, E = East, and N = North
4	MBasin	String	Text	Name of the major river basin based on maps and the literature
5	Basin	String	Text	Name of the second-level river basin based on maps and the literature
6	SubBasin	String	Text	Name of the third-level river basin based on maps and the literature
7	Elv_min/ Elv_ mean/ Elv_max	Integer	Metres above sea level (masl)	The elevation for each glacier derived from the SRTM DEM. The mean elevation (Elv_mean) is calculated as the average value of all the pixels in the DEM governed by the glacier polygon. The minimum (Elv_min) and maximum (Elv_max) elevations represent the lowest point of a glacier's terminus and the highest point of a glacier's crown respectively
8	Slope_min/ Slope _mean/ Slope _max	Integer	Degrees	The slope of the glaciers was derived from slope data generated from the SRTM DEM. The mean slope (Slope_mean) values are the average values of all the pixels governed by glacier polygons. Similarly for the minimum (Slope_min) and maximum (Slope_max) values
9	Aspect	Integer	Degrees	The mean aspect was derived from the DEM as the average value of all cells covered by the glacier and transformed to the eight cardinal directions
10	Area	Double	km^2	A glacier's surface area, calculated using the UTM projection system
11	Thickness	Double	m	Calculated using the empirical relationship with the glacier's area
12	Ice reserve	Double	km^3	Product of the area and estimated thickness of the glacier
13	Year	Integer	Year	Representative year of glacier data
14	Image	Text	Landsat Image ID	ID of the Landsat images used for glacier mapping

combines the longitude and latitude of the glaciers' centroid (Raup et al. 2007; Raup and Khalsa 2010). The other parameters, such as elevation, slope, and aspect, were calculated automatically in the ArcGIS platform using SRTM DEM data. The surface area of the glaciers, measured in square kilometres (km^2), was calculated using the Universal Transverse Mercator (UTM) projection system (42N zone) for Afghanistan.

The ice reserves or glacier volume was calculated by multiplying the estimated mean ice thickness by the glacier area. The estimated mean thickness of a glacier is based on the empirical relationship between glacier area (F) and mean ice thickness (H), which is given below:

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

This empirical relationship between the area and mean ice thickness of a glacier was developed from the measurement of glacier ice thickness in the Tianshan Mountains in China in the northern Himalayas (LIGG/WECS/NEA 1988; Mool et al. 2001a, b; Shi et al. 2008). This relationship has been used by various organizations and researchers to estimate glacier volume in regions of the Hindu Kush Himalaya, including by the Lanzhou Institute of Glaciology and Geocryology (LIGG/WECS/NEA 1988); ICIMOD (Bajracharya et. al. 2014a; Bajracharya and Shrestha 2011; Mool et al. 2001a, b); the Indian Space Research Organization (Kulkarni et al. 2007, 2014; and Frey et al (2014).

Kunj glacier and glacial lake in Panjshir, Kabul basin, Afghanistan; August 2018.

2.4 Accuracy of glacier outlines

The accuracy of the glacier outlines depends, typically, on the resolution of the images used, the presence of seasonal snow and shadows, and the contrast between the glaciers and its surroundings (Bajracharya et al. 2014; DeBeer and Sharp 2007). The most accurate way to assess glacier outlines would be to use high-resolution images (Paul et al. 2013). However, such data was not available for our study region. Hence, freely available medium-resolution Landsat images with minimal or no snow and cloud cover were used for the delineation of glaciers. To minimise uncertainties, the OBIC-derived glacier image objects were refined by editing them manually with reference to the high-resolution images available on Google Earth.

The delineated glacier boundaries were affected by various types of obscurities, and the maximum offset of the boundary was assigned to each type of obscurity, which could not be greater than half of the image resolution (that is, ±15m in Landsat 7 ETM+ and Landsat 8 OLI). Hence, the uncertainties in glacier area were estimated by the variation of each glacier area from a glacier polygon (depending on the projection parameter), and area calculated using the pixel (which depends on the image resolution) covered by the glacier polygon. The pixel-based area is calculated as a product of the total number of pixels bounded by the glacier boundary and the image resolution.

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

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

Where a_i = Area of glacier from the glacier polygon and $\hat{a}_i$ = Area of glacier calculated by the pixel count.

The uncertainty of the glacier area ranged from 2% to 3% across glaciers. This extent of uncertainty is within the range of previous estimates, about 3% (Bajracharya et al. 2014b; Bolch et al. 2010; Frey et al. 2012; Paul et al. 2002).


A glacier-melt waterfall in the Baba mountain range.

The Baba mountain range: View of a glacier-deposited moraine with glaciers in the background.

SECTION 3

The status of glaciers in Afghanistan

The glaciers in Afghanistan are distributed only in its central and northeastern regions, where the Hindu Kush mountains attain heights of more than 5,000 masl. The present status of glaciers is based on Landsat 8 images for 2015. Altogether, 15 Landsat images for 2015 were used to prepare the status of glaciers in the country. Hence the glacier inventory attributes represent the status of glaciers in Afghanistan in 2015.

Of the five river basins in Afghanistan, only the Panj Amu and Kabul river basins contain glaciers. These basins are further subdivided into thirteen sub-basins, of which five sub-basins of the Panj Amu River basin and four sub-basins of the Kabul River basin contain glaciers. In terms of aerial extension, the largest is Panj Amu's Upper Panj sub-basin and the smallest is the Laghman sub-basin of the Kabul River basin. The Upper Panj sub-basin contains the largest number of glaciers and area under glacier cover, while the Ghorband sub-basin contains the smallest in terms of area.

The glaciers in Afghanistan extend from the latitudes 34°34'28" N to 38°20'44" N and longitudes 74°53'04" E to 67°37'52" E at an elevation range of 3,201–7,175 masl (Figure 3.1; Table 3.1). The highest concentration of glaciers is found from 36°26'38" N to 38°20'44" N and 70°38'52" E to 74°53'04" E in the Upper Panj sub-basin (the Wakhan Corridor). The glaciers at the lowest latitudes are in a small region of the Kabul River basin. The glaciers of the Upper Panj sub-basin are the most variable and rich in all glacier parameters.

3.1 Number of glaciers, area, and estimated ice reserves

All the perennial ice masses and debris-covered glaciers with areas larger than or equal to 0.02 km^2 were mapped for 2015, and each given a GLIMS ID. Altogether 3,891 glaciers were mapped. They cover an area of about 2,543 km^2 (0.4% of Afghanistan's land area) and are estimated to contain ice reserves of about 155 km^3.

FIGURE 3.1 DISTRIBUTION OF GLACIERS IN AFGHANISTAN

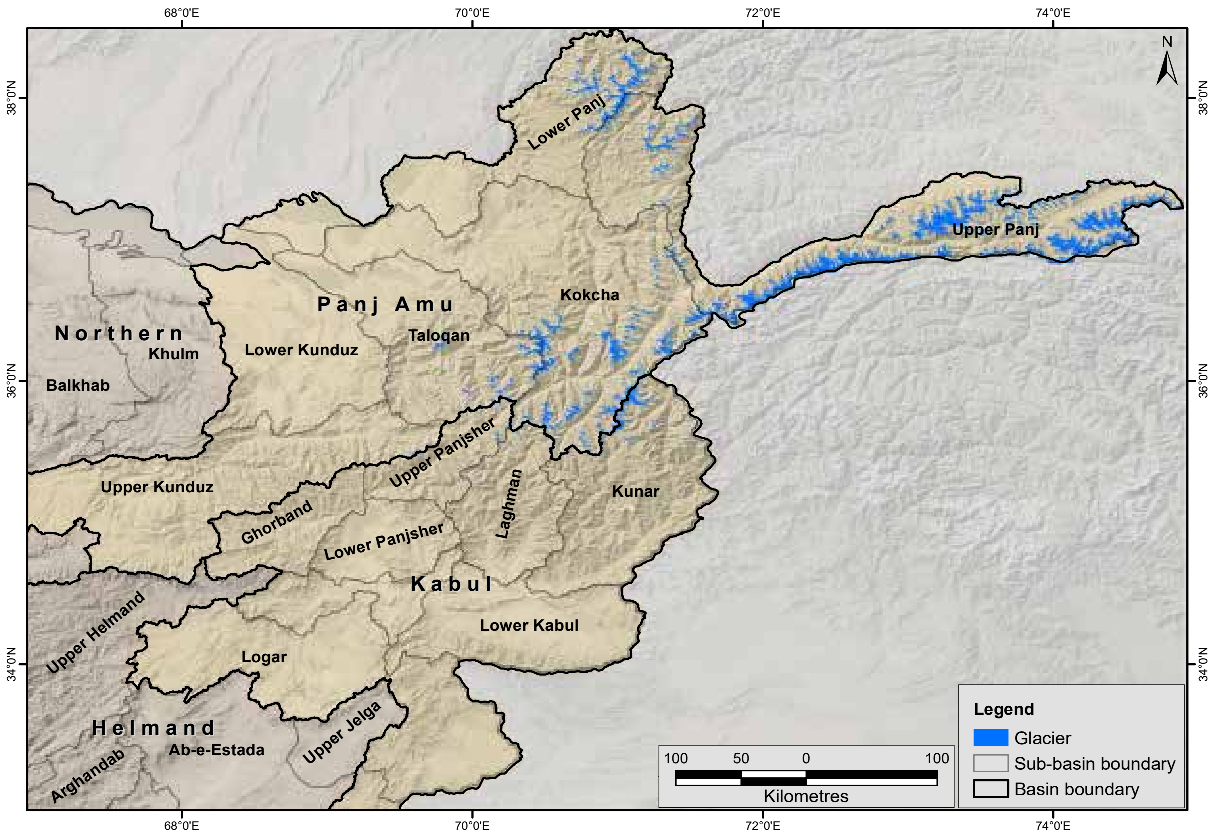


TABLE 3.1 BROAD OVERVIEW OF GLACIERS IN AFGHANISTAN

Parameter	Unit	Glacier details
Glaciated sub-basin area	km^2	104,044
Latitude	degrees	34°34'28" N to 38°20'44" N
Longitude	degrees	67°37'52" E to 74°53'04"E
Number of glaciers	unit	3,891
CI glacier area	km^2	2,364.06
DC glacier area	km^2	178.54
Total glacier area	km^2	2,542.60
Largest glacier	km^2	39.36
Total estimated ice reserves	km^3	155.146
Highest elevation	masl	7,175
Lowest elevation	masl	3,201
CI glacier max. elevation	masl	7,175
DC glacier max. elevation	masl	5,406
CI glacier min. elevation	masl	3,452
DC glacier min. elevation	masl	3,201
Mean CI glacier slope	degrees	27
Mean DC glacier slope	degrees	13
DC–CI area ratio	unit	0.076
Average glacier area	km^2	0.65

Almost 92% of the glaciers in Afghanistan, including its largest, are located in the Panj Amu River basin. The remaining 8% lie in the Kabul River basin. The Upper Panj sub-basin of the Panj Amu River basin contains the highest number of glaciers (1,897), followed by the Kokcha sub-basin, which contains 988 glaciers (Table 3.2; Figure 3.2). The Lower Panj sub-basin has 379 glaciers. All the other sub-basins contain fewer than 300 glaciers. The glaciers of the Panj Amu River basin cover a total area of 2,438 km^2, which is 96% of the glaciated area of Afghanistan.

The average size of the glaciers in the sub-basins of the Panj Amu River basin ranges from 0.21 km^2 to 0.87 km^2, with the average being 0.68 km^2. The average size of glaciers in the Kabul River basin is about half that, at 0.33 km^2. These differences are significant – the smaller a glacier's area, the greater the chances of it melting faster in the context of global warming. Yet, it is the larger glaciers that will likely lose a larger mass of ice and have greater impacts on downstream hydrology.

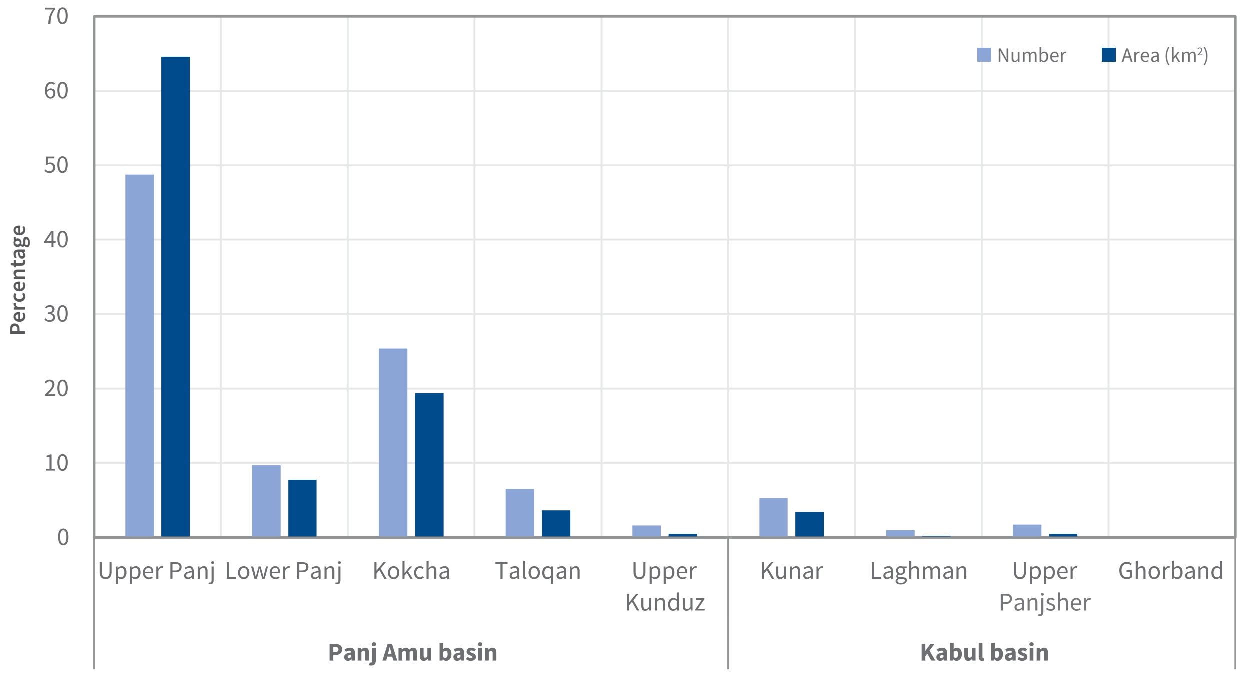
The smaller glaciers contain small volumes of ice reserves; hence the glaciers in the Kabul River basin contain merely 3% of the estimated ice reserves. Almost 97% is contained in the glaciers of the Panj

TABLE 3.2 **SUMMARY OF GLACIERS IN THE SUB-BASINS OF AFGHANISTAN, 2015**

Basin	Sub-basin Name	Sub-basin Area (km²)	Number	Glacier area (km²)	Largest glacier (km²)	Estimated ice reserves (km³)	Elevation (masl) Min	Elevation (masl) Max	Mean slope (deg)
Panj Amu	Upper Panj	17,196	1,897	1,642.25	39.36	114.205	3,201	7,175	26
	Lower Panj	11,611	378	197.09	4.94	8.917	3,524	5,182	22
	Kokcha	22,196	988	492.92	10.67	22.955	3,608	6,783	26
	Taloqan	10,888	253	92.85	5.77	3.917	3,668	5,746	27
	Upper Kunduz	16,524	62	12.97	1.33	0.355	3,783	5,050	24
	Total	**90,941**	**3,578**	**2,438.07**	**39.36**	**150.348**	**3,201***	**7,175***	**25**
Kabul	Kunar	11,009	206	86.74	9.38	4.270	3,924	6,147	25
	Laghman	6,224	38	5.63	1.24	0.145	4,246	5,216	29
	Upper Panjsher	4,486	68	12.09	2.40	0.382	3,912	5,254	26
	Ghorband	4,640	1	0.07	0.07	0.001	4,253	4,382	27
	Total	**72,646**	**313**	**104.53**	**9.38**	**4.798**	**3,912***	**6,147***	**27**
	Total		**3,891**	**2,542.60**	**39.36**	**155.146**	**3,201***	**7,175***	**26**

Note: * denotes the lowest and highest elevations in a basin or the country

FIGURE 3.2 **SHARE OF GLACIER NUMBER AND AREA IN EACH SUB-BASIN**



Amu River basin. The Upper Panj sub-basin contains the highest number, area, and estimated ice reserves of glaciers in Afghanistan.

3.2 Glacier area stratified by class

All the glaciers in Afghanistan greater than or equal to 0.02 km^2 were mapped for the present inventory. They were divided into five size classes: Class 1 (< 0.5 km^2); Class 2 (0.5–1 km^2); Class 3 (1–5 km^2); Class 4 (5–10 km^2); and Class 5 (≥10.0 km^2). The Class 1 glaciers are the highest in number (2,832) but their share of glacier area is only about 19% and estimated ice reserves about 7% (Table 3.3). The number of glaciers decreases as their area increases. The Class 3 glaciers are the third-highest in number (489) but their area (39%) and contribution to estimated ice reserves (36%) are the highest. Class 5 glaciers, which are larger than 10 km^2, are the smallest in number (24) but their share of glacier area and ice reserves is the second-highest. They have a total glacier area of 419.14 km^2 and ice reserves of 48.92 km^3 (Table 3.3).

The largest glacier in Afghanistan is G072584E36889N in the Upper Panj sub-basin. It is located at 36.889°N and 72.584°E, and extends from 6,294 masl to 3,201 masl in elevation. It is also the glacier that terminates at the lowest elevation. It has an area of 39.36 km^2 with estimated ice reserves of 5.858 km^3.

3.3 Clean-ice and debris-covered glaciers

Clean ice (CI) and debris-covered ice (DC) constitute the two main parts of a basin-type glacier, whether located in a mountain basin or a valley. Glaciers in mountain basins are mostly characterized by clean ice whereas valley glaciers tend to possess both components: clean ice at the upper levels and debris-covered ice at lower levels. Generally, clean-ice glaciers have steeper slopes than debris-covered glaciers.

Of the 3,891 glaciers in Afghanistan, 344 (9%) are debris-covered. Of a total glacier area of 2,543 km^2, clean-ice areas constitute 2,364.08 km^2 (almost 93% of the total glacier area), most of it (almost 90%) in the Panj Amu River basin. Only 7% of the total glacier area in Afghanistan is debris-covered. Debris-covered glaciers, both in number and area, are found to a greater degree in Panj Amu River basin (Figure 3.3).

The number and area of clean-ice glaciers are higher than debris-covered glaciers in all glacierized basins of Afghanistan. At least 81% of the glacier area in each sub-basin is constituted by clean-ice glaciers. The proportion of debris-covered glacier area is higher in the Upper Panj and Kokcha sub-basins than

FIGURE 3.3 CLEAN-ICE (CI) AND DEBRIS-COVERED (DC) GLACIERS IN AFGHANISTAN

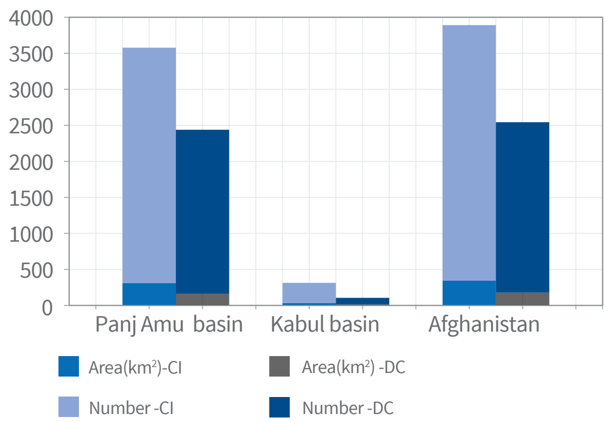


TABLE 3.3 NUMBER, AREA, AND ESTIMATED ICE RESERVES OF GLACIERS BY SIZE CLASS

Size class (km^2)	Glaciers		Glacier area		Estimated ice reserves		Mean area per glacier
	Number	%	km^2	%	km^3	%	km^2
Class 1 (< 0.5)	2,832	73	475.72	19	10.91	7	0.17
Class 2 (0.5–1.0)	502	13	352.76	14	13.03	8	0.70
Class 3 (1.0–5.0)	489	13	990.52	39	56.55	36	2.03
Class 4 (5.0–10.0)	44	1	304.46	12	25.74	17	6.92
Class 5 (≥10.01)	24	<1	419.14	16	48.92	32	17.46
Total	**3,891**	**100**	**2,542.60**	**100**	**155.15**	**100**	**0.65**

the others, though in terms of number, DC glaciers constitute about 5% and 13% in each sub-basin respectively. Debris-covered glaciers are almost 14% of the glaciers in the Kunduz sub-basin, but the debris-covered glacier area is only 1.8 km^2.

In three sub-basins of the Kabul river basin – Kunar, Laghman, and Upper Panjsher – 12%–19% of the glaciers are debris-covered, but the total DC glacier area ranges from 1 km^2 to 11 km^2. The overall debris-covered glacier area in Panj Amu River basin is about 164.68 km^2 (about 7% of the basin's total glacier area) whereas in the Kabul River basin it is merely 13.87 km^2, 13.3% of the total area. Though smaller in area, the percentage of debris-covered glaciers is higher in the Kabul River basin than in the Panj Amu River basin.

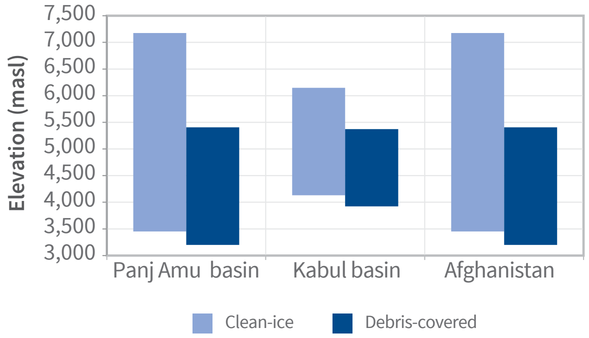
3.4 Glacier elevations

The elevations of the glacier snouts and crowns were derived from the SRTM DEM; hence, they might have uncertainties of ± 30 to 60m depending on the pixel resolution of the DEM. Afghanistan's highest point is 7,492 masl, at the peak of Nowshak Mountain; however, the highest crown elevation of its glaciers is 7,175 masl. Its lowest snout is at 3,201 masl. Both these elevations are from the Upper Panj sub-basin (Figure 3.4; Table 3.2).

Clean-ice glaciers are found at elevations of 3,452–7,175 masl and debris-covered glaciers at elevations of 3,201–5,406 masl. The lowest elevation of clean-ice glaciers ranges from 3,452 masl to 4,253 masl in each sub-basins.

Mountain glaciers occupy mountain slopes and do not extend down to the major river valleys; in contrast, valley glaciers are associated with the mountain slopes and also extend down the major river valleys. Hence there are high altitudinal differences among the valley glaciers in the Upper Panj sub-basin. The debris-covered glaciers in the Upper Panj, Kokcha, Taloqan, and Kunduz sub-basins of Panj Amu and Kunar sub-basin of the Kabul River basin generally extend to lower elevations than the clean-ice glaciers, indicating the presence of valley type of glaciers. The other sub-basins have debris-covered glaciers at elevations similar to the lowest elevation of the clean-ice glaciers, indicating that the clean-ice glaciers are mostly hanging glaciers (Figure 3.4).

FIGURE 3.4 **ELEVATION DISTRIBUTION OF CLEAN-ICE AND DEBRIS-COVERED GLACIERS IN RIVER BASINS OF AFGHANISTAN**



3.5 Area–elevation distribution

A comparison of the area–elevation distribution in each 100-metre elevation zone shows that the maximum glaciated area in the Panj Amu River basin (307.74 km^2; 12.6% of its total glaciated area) is at 5,000–5,100 masl, and at 4,800–4,900 masl (11.94 km^2; 11.5%) in the Kabul River basin (Figure 3.5). Although they have very different extents of glacierization, these basins have similar shapes as far as their area–elevation distributions are concerned. An important difference though is that the Kabul River basin lacks the high-elevation and low-elevation wings of the Panj Amu River basin's glacier distribution, a fact which is mainly attributable to the different distributions of elevations within these basins.

Table 3.4 shows the glacier area distribution of each basin in Afghanistan. The highest proportion in terms of area is observed between 5,000 and 5,500 masl, which is about 44% of the total area covered by glaciers in the country. The second highest is between 4,500 and 5,000 masl (34%). Less than 1% of the glaciated area is observed below 4,000 masl and above 6,500 masl in Afghanistan.

3.6 Aspects of glaciers

The orientation or aspect of a glacier is an important parameter both to understand glacier melting and for water resources modelling. The mean aspect, as derived from a DEM, allows one to consider the value of all individual cells covered by the glacier and to derive a mean value across all azimuths. The calculated values are transformed to the eight cardinal directions – N, NE, E, SE, S, SW, W, and NW. Each cardinal direction has a range of 45 degrees.

The glaciers in Afghanistan are mostly concentrated in the northeastern part of the country, in the Wakhan Corridor, an elongated valley along an ENE–WSW

FIGURE 3.5 GLACIER AREA DISTRIBUTION IN EACH 100-M ELEVATION ZONE IN THE TWO RIVER BASINS

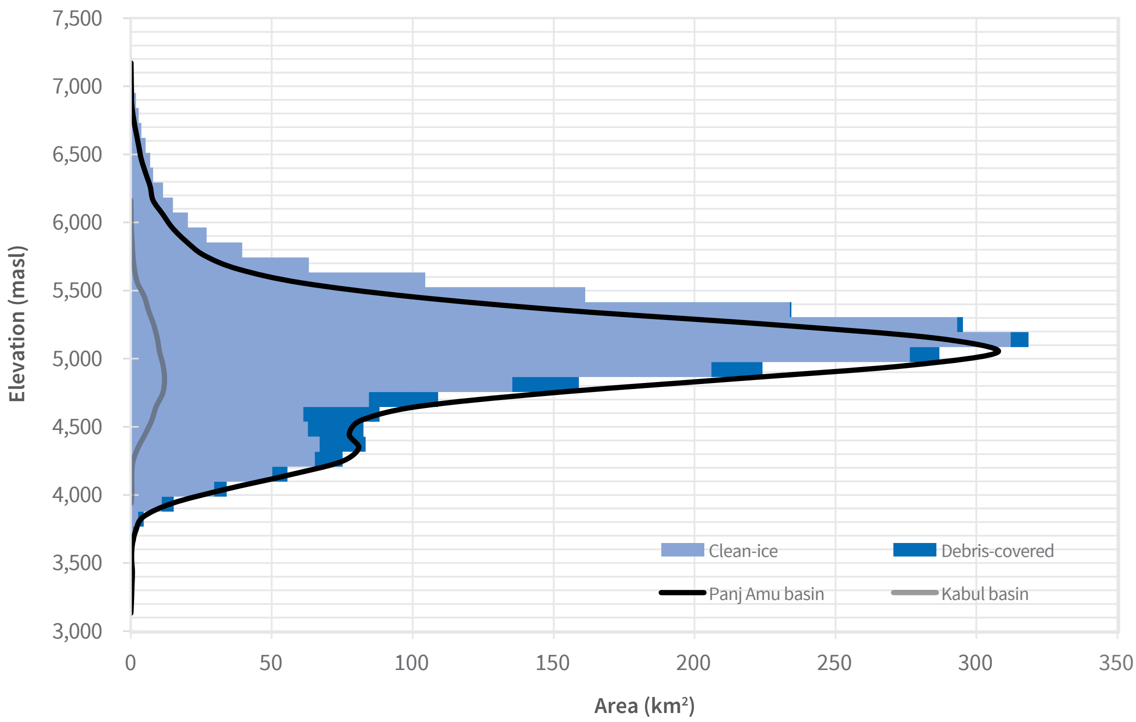
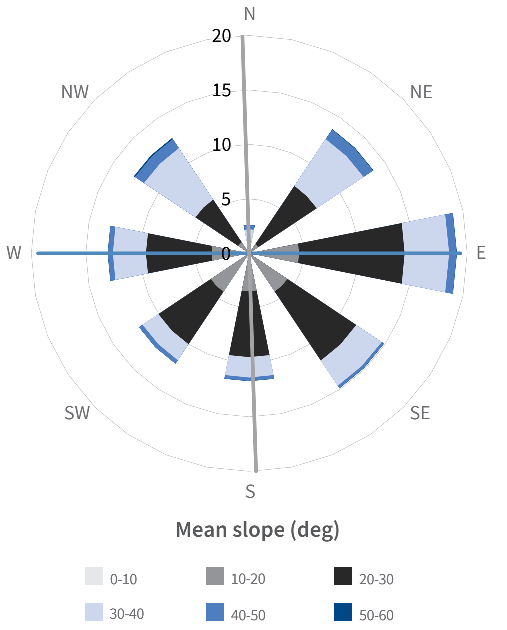


TABLE 3.4 GLACIER AREA DISTRIBUTION AT 500-M ELEVATION ZONES IN MAJOR RIVER BASINS OF AFGHANISTAN

Elevation ranges (masl)	Panj Amu		Kabul		Afghanistan	
	km²	%	km²	%	km²	%
3,000–3,500	1.18	0.05	0	0	1.18	0.05
3,500–4,000	21.91	0.90	0.15	0.14	22.06	0.87
4,000–4,500	321.69	13.19	8.98	8.59	330.67	13.01
4,500–5,000	819.23	33.60	51.39	49.16	870.62	34.24
5,000–5,500	1,073.44	44.03	38.95	37.26	1,112.39	43.75
5,500–6,000	159.55	6.54	4.99	4.77	164.54	6.47
6,000–6,500	34.97	1.43	0.07	0.07	35.04	1.38
6,500–7,000	5.94	0.24	0	0	5.94	0.23
7,000–7,500	0.16	0.01	0	0	0.16	0.01
Total	**2,438.07**	**100**	**104.53**	**100**	**2,542.60**	**100**

direction. Many other glaciers in other regions of the country are also similarly situated in tectonic valleys. This lends a strong influence on a glacier's aspect. Almost 20% of Afghanistan's glaciers, the highest percentage, have an easterly aspect; about 15% of them, the second-highest, have a south-easterly aspect. The north-easterly, southerly, south-westerly, westerly, and north-westerly aspects range from 11% to 14%. A small number of glaciers have a northerly aspect (Figure 3.6). This strikingly small number of glaciers with a northerly aspect and the high concentration of glaciers with an easterly aspect presumably relates to both the tectonic fabric of the landscape and the orography of precipitation.

FIGURE 3.6 ASPECT AND MEAN SLOPE DISTRIBUTION OF GLACIERS IN AFGHANISTAN



Note: Numbers within the concentric circles refer to percentages

3.7 Slope

The mean slope is derived for each glacier from the SRTM DEM with zone statistics. It is independent of the (uncertain) glacier length and refers to all individual cells of the DEM (Manley 2008). As the mean slope is a rough proxy for other parameters such as mean thickness (cf. Haeberli and Hoelzle 1995), it is recommended to include the DEM-derived mean slope value in the basic inventory. The average slope is calculated for CI and DC glaciers wherever both the length and elevation range are both available. The average slope of clean-ice glaciers in the various sub-basins range from 22° to 28° with their average slope being 27°. The average slope of debris-covered glaciers ranges from 10° to 14° in various sub-basins with an average slope of about 12°. At the steepest end of the scale, some of the glaciers have slopes in the range of 50°–60°.

This range of the mean slopes of CI and DC glaciers are fairly typical of the HKH. However, there are basin-to-basin variations in steepness; for example, the mean slope of debris-covered glaciers in the Talaqan sub-basin is higher than other sub-basins of Afghanistan. The Laghman sub-basin is the smallest in area, but the mean slope of its clean-ice glaciers is the highest and the mean slopes of its debris-covered glaciers is the lowest in Afghanistan.

Figure 3.7 shows the distribution of the number and area of the glaciers with respect to the mean slope of the glacier and the total area of the glaciers among the size classes 1 to 5. It indicates that the mean slope of most glaciers (95%) in Afghanistan are between 10° and 40°. The area distribution shows that the highest glacier area is mostly concentrated within the mean slope 10°–20°.

FIGURE 3.7 DISTRIBUTION OF THE NUMBER AND TOTAL AREA OF GLACIERS IN AFGHANISTAN BY SIZE CLASS AND MEAN SLOPE

Note: The numbers in the grid represent the number of glaciers and the colour codes denote the area distribution


Pik Yakh glacier, Panjshir valley

Hawz Chap glacier and Hawz e Sar Koh glacial lake on the eastern side of Shah Fuladi peak in the Baba mountain range.

SECTION 4

The status of glaciers in individual river basins

4.1 Panj Amu River basin

The glaciers in the Panj Amu River basin are distributed among five sub-basins – the Upper Panj, Lower Panj, Kokcha, Taloqan, and Kunduz. They are located between latitudes of 34°34'28" N and 38°20'44" N and longitudes of 67°37'52"E and 74°53'04"E. Seven tiles of Landsat cover the glaciated region of the basin. Altogether, 12 Landsat images were used to map the glaciers in the Panj Amu river basin. The distribution of glaciers in each sub-basin is shown in Figure 4.1.

The Panj Amu River basin covers almost 96% of the total glacier area in Afghanistan. The basin has 3,578 glaciers, of which the highest number is in the Upper Panj sub-basin (1,897), 988 in Kokcha, 378 in Lower Panj, 253 in Taloqan, and 62 in Kunduz. They have a total area of 2,438.07 km^2. The percentage of glaciers and the area distribution in each sub-basin is shown in Figure 4.2. The Upper Panj sub-basin has the highest percentage of glaciers (53%) and share of area (more than 67%), whereas the Kunduz sub-basin has barely 2% of the glaciers, covering less than 1% of the glacier area in the Panj Amu River basin.

Detailed information regarding clean-ice and debris-covered glaciers in each sub-basin is given in Table 4.1.

The size of glaciers in the basin range from 0.02 to 39.36 km^2. Both the smallest and the largest glaciers lie in the Upper Panj sub-basin. The distribution of the number, area, and estimated ice reserves of the glaciers in the sub-basins across area classes 1–5 is given in Figure 4.3 and Table 4.2. The greatest number of glaciers belong to Class 1 but constitute just 18% of the total glaciated area in the basin and contain

FIGURE 4.1 GLACIER DISTRIBUTION IN THE PANJ AMU RIVER BASIN

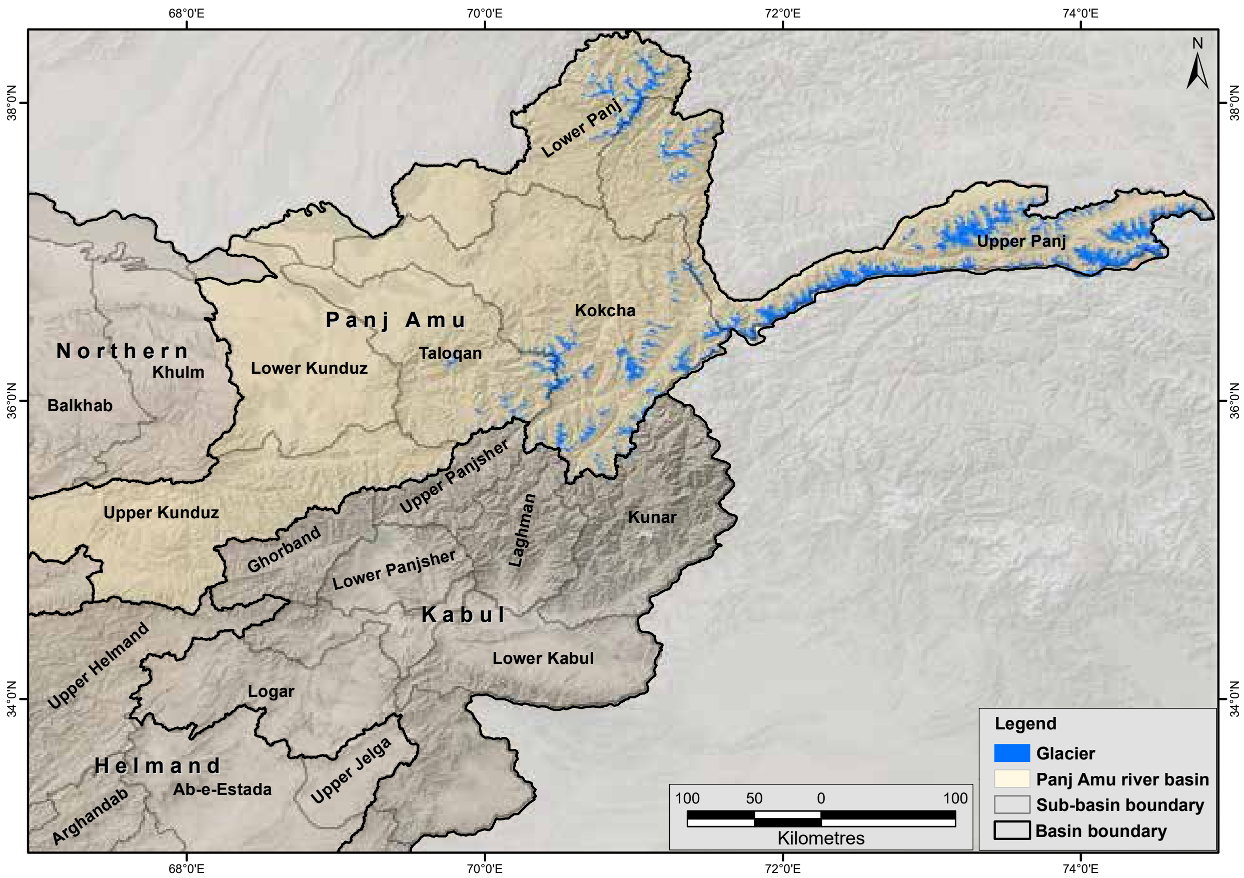


FIGURE 4.2 PERCENTAGE DISTRIBUTION OF GLACIERS IN SUB-BASINS OF THE PANJ AMU RIVER BASIN

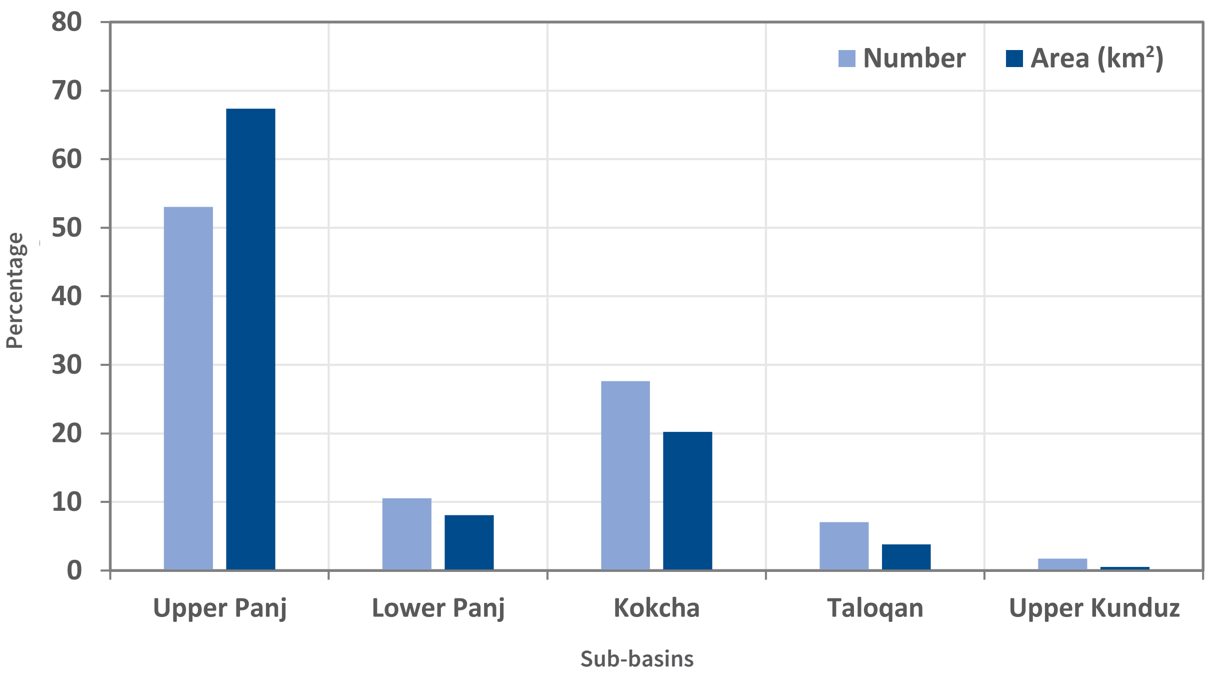


TABLE 4.1 **GLACIER AREA DISTRIBUTION AT 500-M ELEVATION ZONES IN MAJOR RIVER BASINS OF AFGHANISTAN**

Sub-basin	Number		Area (km²)			Largest glacier (km²)	Estimated ice reserves (km³)	Elevation (masl)				Mean slope (deg)	
								Min		Max			
	CI	DC	CI	DC	Total			CI	DC	CI	DC	CI	DC
Upper Panj	1,897	132	1,555.02	87.23	**1,642.25**	39.36	114.199	3,452*	3,201*	7,175*	5,298	26	11
Lower Panj	378	13	194.03	3.06	**197.09**	4.94	8.922	3,524	3,698	5,182	4,216	22	11
Kokcha	988	134	428.42	64.50	**492.92**	10.67	22.955	4,167	3,608	6,783	5,406*	27	12
Taloqan	253	25	84.76	8.09	**92.85**	5.77	3.917	3,995	3,668	5,746	4,986	28	15
Kunduz	62	7	11.17	1.80	**12.97**	1.33	0.355	3,877	3,783	5,050	4,602	25	13
Total	**3,578**	**311**	**2,273.40**	**164.67**	**2,438.07**	**39.36**	**150.348**	–	–	–	–	**26**	**12**

Note: * denotes the lowest or highest elevation across sub-basins

FIGURE 4.3 **DISTRIBUTION IN NUMBER AND AREA OF GLACIERS BY SIZE CLASS IN THE FIVE SUB-BASINS**

Note: The numbers in the grid represent the number of glaciers and the colour codes denote the area distribution

merely 7% of the estimated ice reserves. The number of glaciers in each category decreases as the area of the glaciers increases. Class 3 glaciers (which are 1–5 km²), though third-highest in number, extend over the largest area (39%) and contain the highest estimated ice reserves (36%). Class 5 glaciers (≥10 km²), though the smallest in number, have the third-largest share in terms of glacier area and the second-highest ice reserves.

The distribution in the number and area by size class in each of the five sub-basins is shown in Figure 4.3. The largest number of glaciers is in Class 1 of the Upper Panj sub-basin whereas the area covered is the highest in Class 3 of the same sub-basin. The Upper Panj has only 23 glaciers of Class 5, but they cover more than 25% of the glacier area in the sub-basin. The Kokcha sub-basin has one glacier of Class V,

TABLE 4.2 NUMBER, AREA, AND ESTIMATED ICE RESERVES OF GLACIERS BY SIZE IN THE PANJ AMU RIVER BASIN

Area classes (km²)	Glacier number		Glacier area		Estimated ice reserves		Mean area per glacier
	No. count	%	km²	%	km³	%	km²
Class 1 (< 0.5)	2,560	71.55	439.23	18.02	10.131	6.74	0.17
Class 2 (0.5–1)	484	13.53	339.86	13.94	12.546	8.34	0.70
Class 3 (1–5)	468	13.08	950.67	38.99	54.351	36.15	2.03
Class 4 (5–10)	42	1.17	289.17	11.86	24.396	16.23	6.89
Class 5 (≥10)	24	0.67	419.14	17.19	48.924	32.54	17.46
Total	**3,578**	**100**	**2,438.07**	**100**	**150.35**	**100**	**0.68**

which covers 2% of the glacier area. The other three sub-basins have no glacier of Class 5.

The average size of the glaciers in the sub-basins ranges from 0.16 to 17.8 km² (Figure 4.4). The average size of glaciers in each size class is comparatively higher in the Upper Panj sub-basin. The overall average size of the glaciers in the Upper Panj sub-basin is 0.87 km².

The glaciers in the Panj Amu River basin are distributed between 3,201 and 7,175 masl. The glaciers with both highest and lowest elevations lie in the Upper Panj sub-basin. The lowest elevation is of the largest glacier in the basin, G072584E36889N, and the glacier whose crown is at the highest elevation is from the Nowshak peak. Clean-ice glaciers extend from 3,452 to 7,175 masl and debris-covered glaciers from 3,201 to 5,406 masl (Figure 4.5). The lower extension of debris-covered glaciers indicates the presence of basin-type glaciers. The Upper Panj sub-basin consists of glaciers with large elevation ranges (3,201–7,175 masl) whereas glaciers in Kunduz have a lower elevation range, 3,783–5,050 masl.

The overall area distribution of debris-covered and clean-ice glaciers at different altitudes in the Panj Amu River basin is shown graphically in Figure 4.6. The area–elevation distribution, at elevation zones of 500 metres, of glaciers in specific sub-basins is summarised in Table 4.3. Almost 90% of glacier area in all the sub-basins lies at the elevation ranges

FIGURE 4.4 AVERAGE AREA OF GLACIERS IN EACH SUB-BASIN ACROSS SIZE CLASSES IN THE PANJ AMU RIVER BASIN

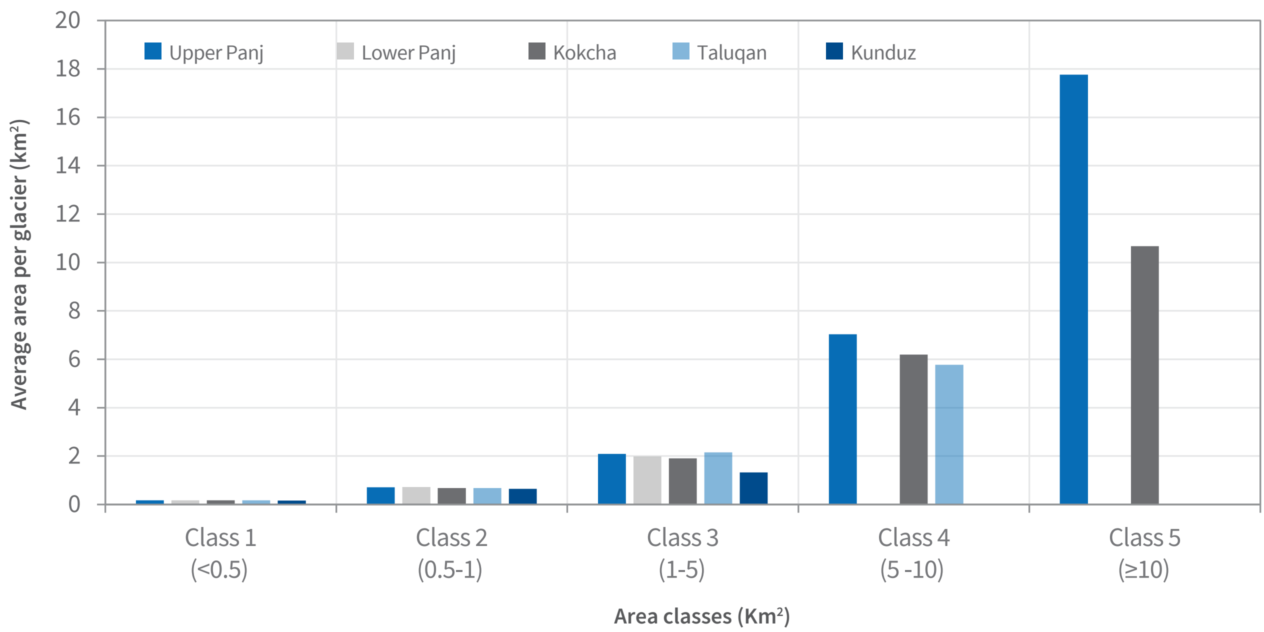


FIGURE 4.5 ELEVATION DISTRIBUTION OF CLEAN-ICE AND DEBRIS-COVERED GLACIERS IN SUB-BASINS OF THE PANJ AMU RIVER BASIN

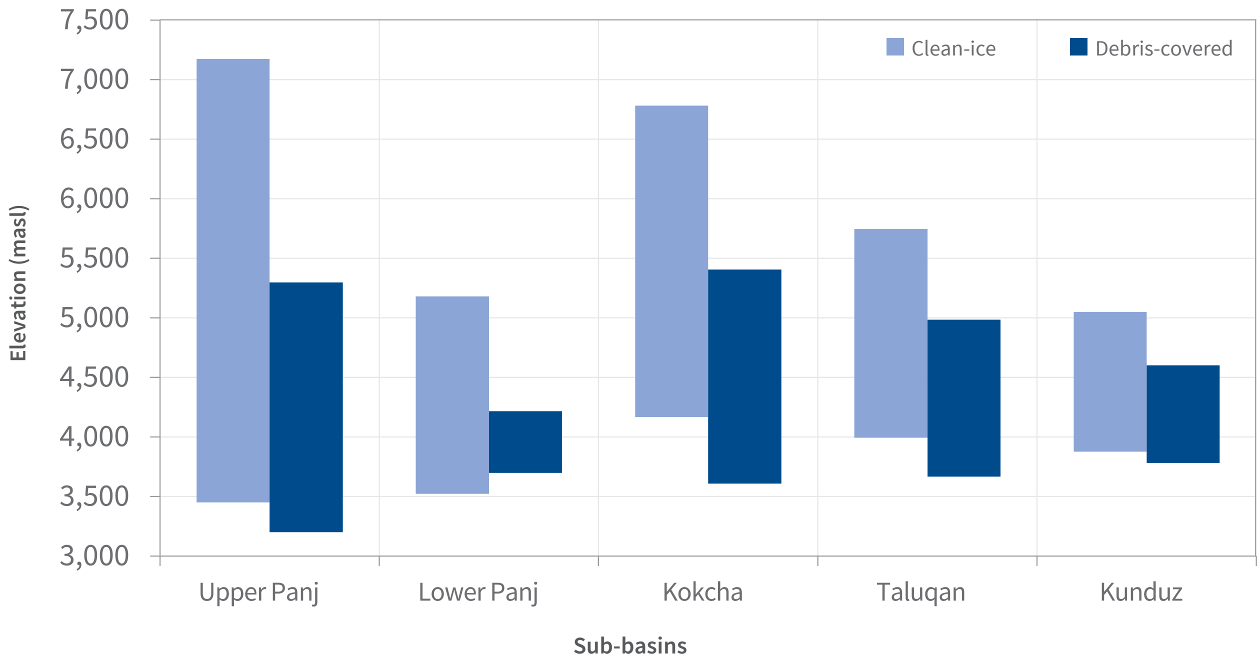


TABLE 4.3 GLACIER AREA DISTRIBUTION AT 500-M ELEVATION ZONES IN THE PANJ AMU RIVER BASIN AND ITS SUB-BASINS

Elevation range (masl)	Upper Panj		Lower Panj		Kokcha		Taloqan		Kunduz		Panj Amu	
	km²	%	km²	%	km²	%	km²	%	km²	%	km²	%
3,000–3,500	1.18	0.07	<0.01	<0.01	0	0	0	0	0	0	1.18	0.05
3,500–4,000	6.93	0.42	12.28	6.23	0.84	0.17	1.41	1.52	0.45	3.47	21.91	0.90
4,000–4,500	123.54	7.52	165.39	83.92	18.54	3.76	7.19	7.74	7.03	54.2	321.69	13.19
4,500–5,000	481.43	29.32	19.29	9.79	251.87	51.1	61.20	65.91	5.44	41.94	819.23	33.60
5,000–5,500	849.59	51.73	0.12	0	200.91	40.76	22.77	24.52	0.05	0.39	1,073.44	44.03
5,500–6,000	142.02	8.65	0	0	17.25	3.5	0.28	0.3	0	0	159.55	6.54
6,000–6,500	32.26	1.96	0	0	2.71	0.55	0	0	0	0	34.97	1.43
6,500–7,000	5.14	0.31	0	0	0.80	0.16	0	0	0	0	5.94	0.24
7,000-7,500	0.16	0.01	0	0	0.00	0.00	0	0	0	0	0.16	0.01
Total	**1,642.25**	**100**	**197.09**	**100**	**492.92**	**100**	**92.85**	**100**	**12.97**	**100**	**2,438.07**	**100**

between 4,000 and 5,500 masl. Almost 91% of glacier area in the Panj Amu River basin as a whole is at this elevation range. About 7% of the glacier area is in the 5,500–6,000 masl elevation zone and less than 1% is below 4,000 masl (Table 4.3). The greatest extent of glacier area in the Upper Panj sub-basin, almost 52%, is at 5,000–5,500 masl. In Kokcha and Taloqan sub-basins, this is between 4,500 and 5,000 masl and Lower Panj and Kunduz sub-basins have their highest concentration of glacier area at 4,000–4,500 masl.

Glaciers in the Panj Amu River basin are distributed well across all aspects, barring the north. The number, area, and estimated ice reserves of glaciers with their different aspects is given in Table 4.4. The percentage distribution of glaciers with their aspects and the

FIGURE 4.6 GLACIER AREA DISTRIBUTION IN EACH 100-M ELEVATION ZONE OF THE PANJ AMU RIVER BASIN

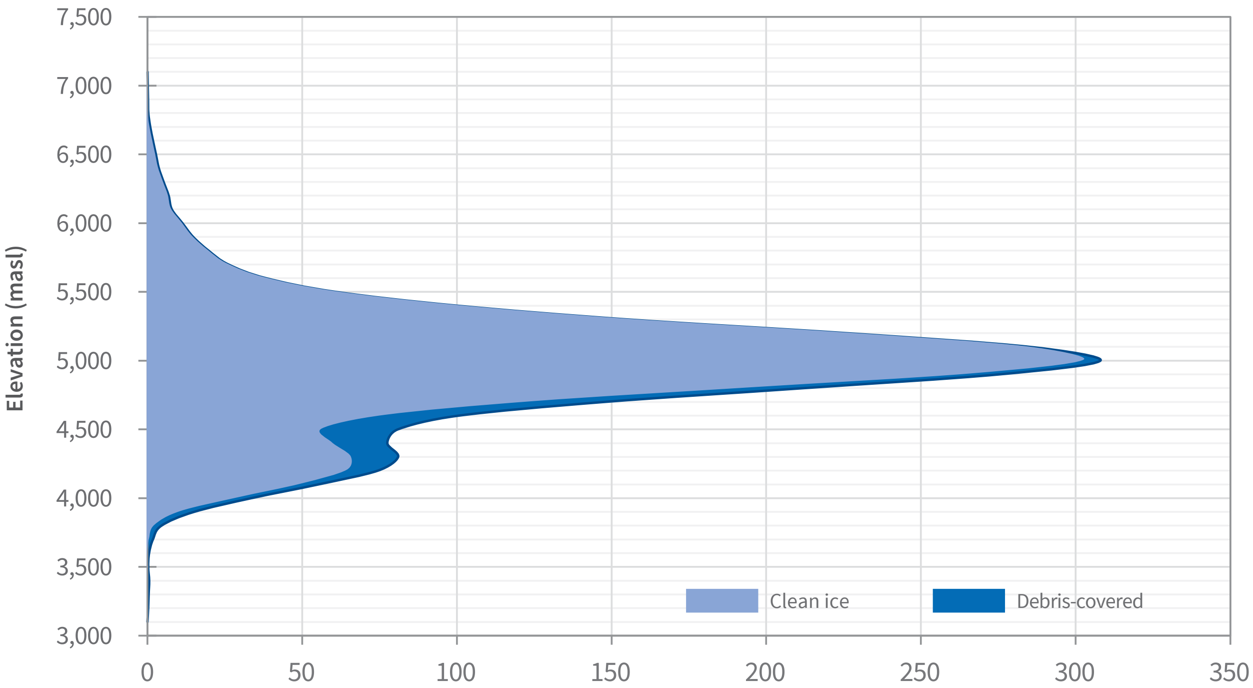


TABLE 4.4 GLACIER DISTRIBUTION IN EACH ASPECT OF THE PANJ AMU RIVER BASIN

Aspect	N	NE	E	SE	S	SW	W	NW	Total
Number	89	479	683	542	419	443	470	453	**3,578**
Area (km^2)	6.55	100.43	386.46	522.93	526.25	578.31	231.95	85.19	**2,438.07**
Estimated ice reserves (km^3)	0.096	2.818	18.757	34.826	41.317	40.352	9.980	2.202	**150.348**

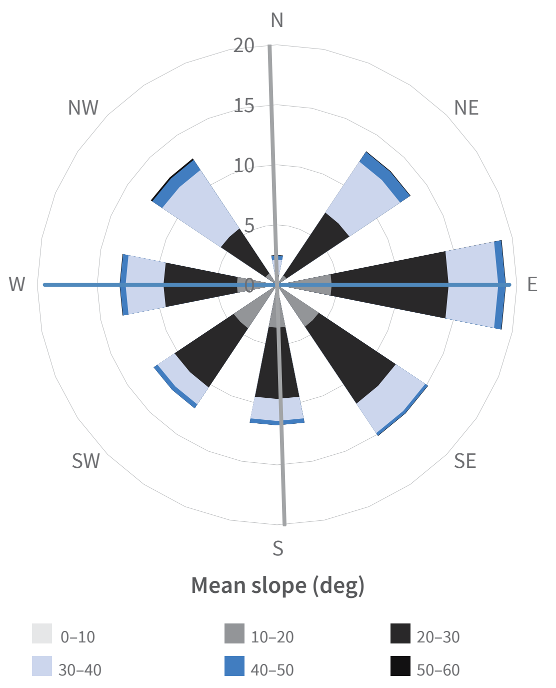
TABLE 4.5 GLACIER DISTRIBUTION IN EACH SLOPE CLASS OF THE PANJ AMU RIVER BASIN

Slope classes (deg)	0–10	10–20	20–30	30–40	40–50	50–60	Total
Number	5	793	1,678	932	159	11	**3,578**
Area (km^2)	0.57	1,229.63	980.30	209.08	17.53	0.96	**2,438.07**
Estimated ice reserves (km^3)	0.011	87.942	55.207	6.832	0.340	0.016	**150.348**

proportion of glaciers at different mean slopes classes are given in Figure 4.7. The glaciers in the Panj Amu River basin predominantly have an easterly (19%) and south-easterly aspect (15%). Between 11% and 14% have north-easterly, southerly, south-westerly, westerly, or north-westerly aspects. But glaciers with a south-easterly, southerly, and south-westerly aspects contribute the greatest area, more than 21% each of the total glacier area in the basin, with the southwest being the highest at about 24%. Only a very few glaciers (89) have a northerly aspect, with a total area of merely 6.55 km^2, indicating that they are very small.

Similarly, the glaciers in the basin have been categorised into six mean slope classes (Table 4.5). Almost half the glaciers in the basin are in the mean slope range 20°–30°. But little over half the total glacier area in the basin is in the range 10°–20°, indicating that a large part of the glaciers slope gently. The number and area distribution in each mean slope class with respect to area classes are given in Figure 4.8. It shows

FIGURE 4.7 **ASPECT AND MEAN SLOPE DISTRIBUTION OF GLACIERS IN THE PANJ AMU RIVER BASIN**



Note: Numbers within the concentric circles refer to percentages

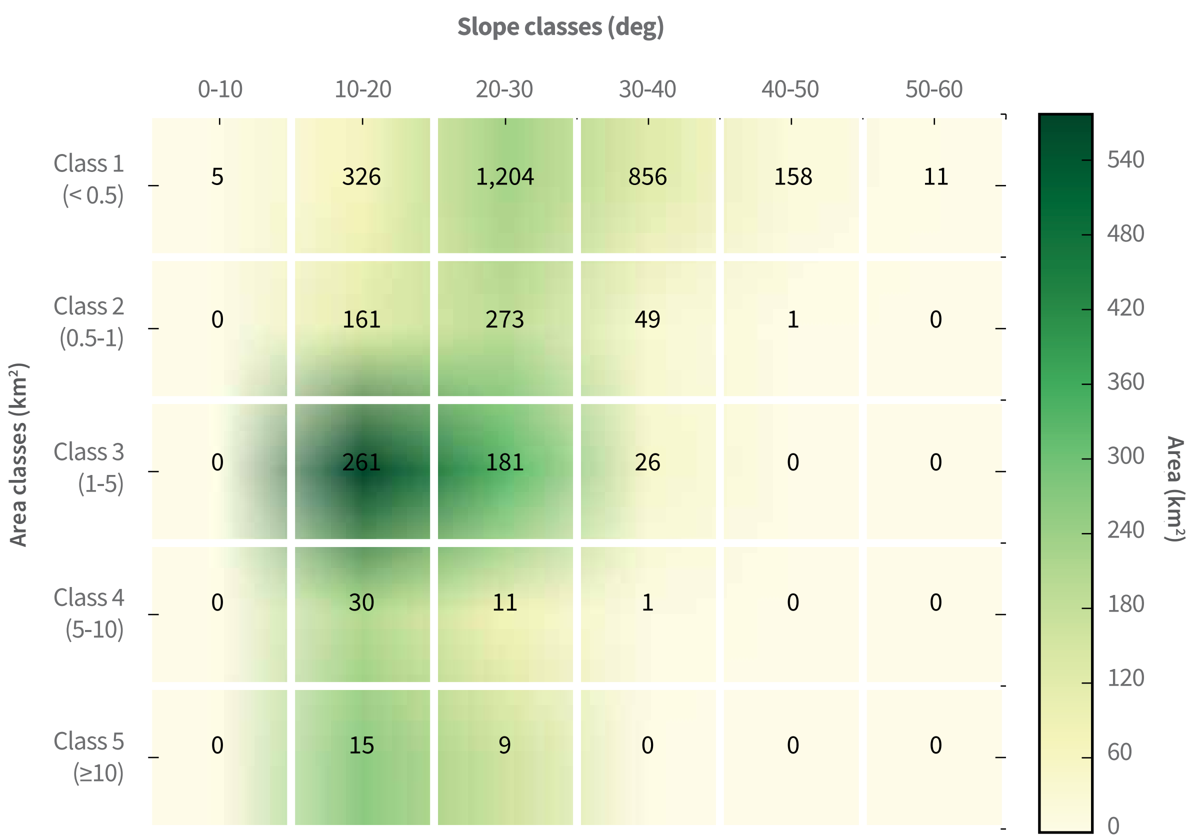
that the area is higher in the 10°–20° mean slope class whereas the number is higher in the 20°–30° slope class. In the 10°–20° slope class, the area is higher in Class 3 (1–5 km²) but the number of glaciers is higher in Class 1 (<0.5 km²). There is no glacier identified at slopes greater than 60° as the ice cannot remain on steep slopes.

4.2 Kabul River basin

The glaciers in the Kabul river basin are distributed in four sub-basins – Kunar, Laghman, Upper Panjsher, and Ghorband. The glaciers lie between the latitudes 36°01'25" N and 35°11'18" N and longitudes 71°32'57"E and 68°49'59"E. Five tiles of Landsat images cover the glaciated region of the basin. Altogether, 7 Landsat images were used to map the glaciers in this basin. The glacier distribution in each of the four sub-basins is shown in Figure 4.9.

Detailed information regarding clean-ice and debris-covered glaciers in each sub-basin is given in Table 4.6.

FIGURE 4.8 **DISTRIBUTION IN NUMBER AND AREA OF GLACIERS BY SIZE CLASS AND MEAN SLOPE IN THE PANJ AMU RIVER BASIN**



Note: The numbers in the grid represent the number of glaciers, and the colour code denotes the area distribution

FIGURE 4.9 **GLACIER DISTRIBUTION IN THE KABUL RIVER BASIN**

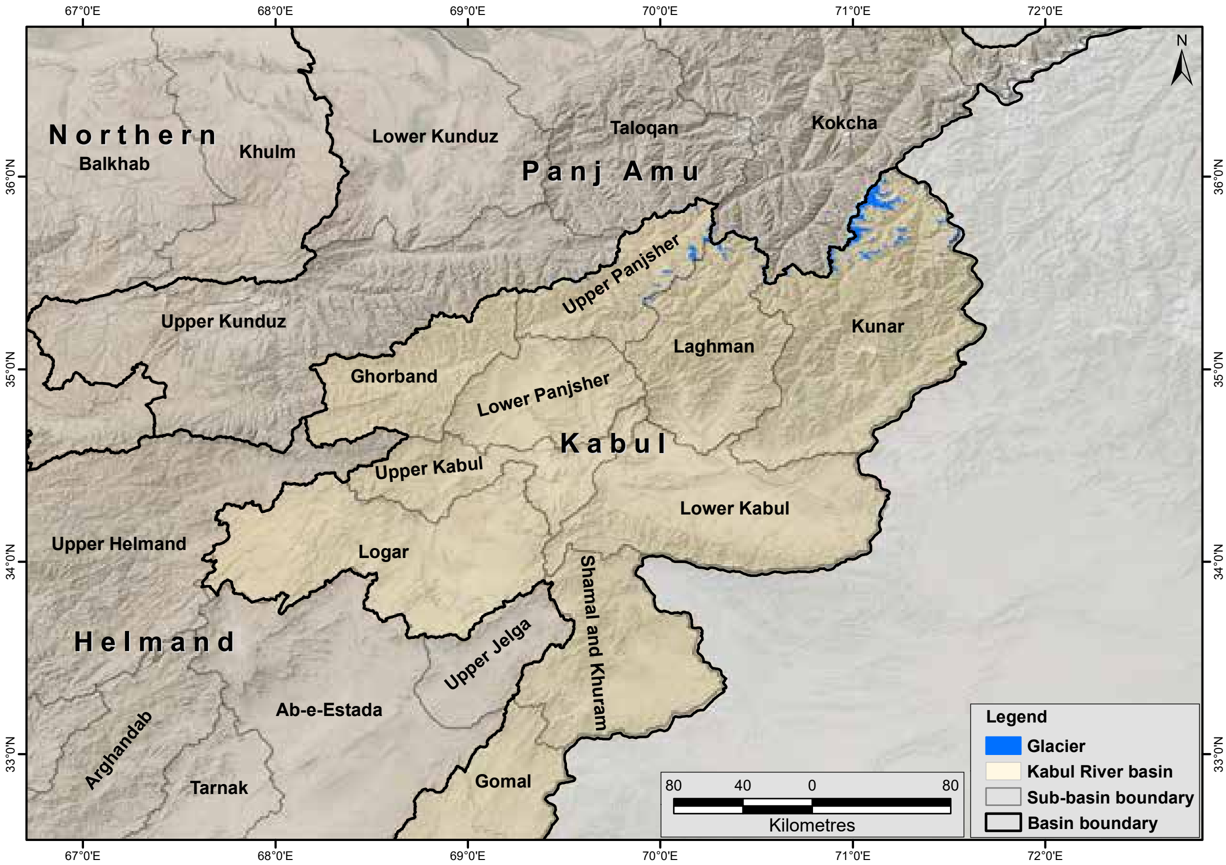
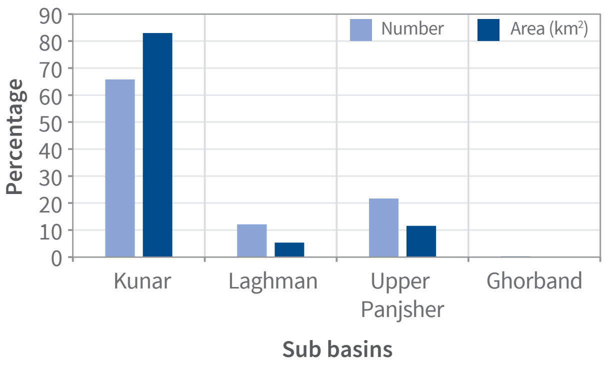


TABLE 4.6 **CLEAN-ICE AND DEBRIS-COVERED GLACIERS IN EACH SUB-BASIN OF THE KABUL RIVER BASIN**

Sub-basin Name	Number		Area (km²)			Largest glacier (km²)	Estimated ice reserves (km³)	Elevation (masl)				Mean slope (deg)	
								Min		Max			
	CI	DC	CI	DC	Total			CI	DC	CI	DC	CI	DC
Kunar	206	25	75.86	10.88	**86.74**	9.38	4.270	4,132	3,924*	6,147*	5,373*	25	14
Laghman	38	4	4.57	1.06	**5.63**	1.24	0.145	4,246	4,389	5,216	4,658	31	10
Upper Panjsher	68	4	10.18	1.91	**12.09**	2.40	0.382	3,912*	4,223	5,254	4,562	27	10
Ghorband	1	0	0.07	0	**0.07**	0.07	0.001	4,253	–	4,382	–	27	
Total	**313**	**33**	**90.68**	**13.87**	**104.53**	**9.38**	**4.798**	**–**	**–**	**–**	**–**	**28**	**11**

Note: * denotes the lowest or highest elevation across sub-basins

FIGURE 4.10 NUMBER AND AREA COVERED BY GLACIERS IN THE FOUR SUB-BASINS

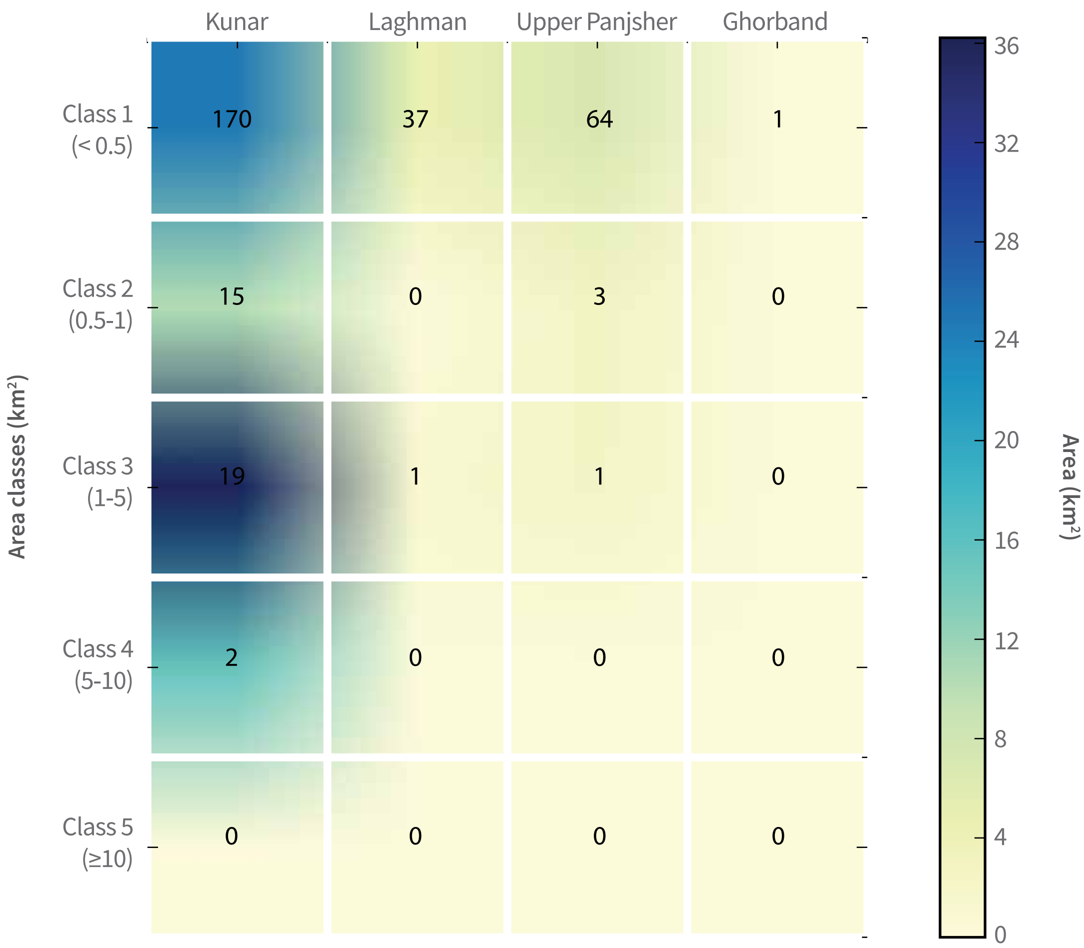


In all, 313 glaciers covering an area of 104.53 km^2 and estimated ice reserves of about 5 km^3 were mapped in the Kabul River basin. The basin contains only 8% of the glaciers in Afghanistan, which cover only 4% of the total glacier area. Among its four sub-basins, Kunar has the highest number of glaciers (206) covering almost 83% of the glacier area in the Kabul River basin (Figure 4.10). The second-highest concentration is in Upper Panjsher, which covers 11.6% of the glacier area in the basin. The Laghman sub-basin has 38 glaciers with a glacier area of 5.63 km^2. Ghorband has only one, small glacier.

The size of glaciers in the basin range from 0.02 km^2 to 9.38 km^2. Both the smallest and largest glacier lie in the Kunar sub-basin. They were categorised into five size classes. Their distribution in terms of number, area, and estimated ice reserves in each category is given in Figure 4.11 and Table 4.7.

The small glaciers in Class 1 are large in number, but make up just 35% of the total glacier area in the basin and 16% of its estimated ice reserves. Class 3 glaciers (1–5 km^2) are the second-highest in number, but the most in terms of area (almost 39%) and estimated ice reserves (46%). There is no glacier larger than 10 km^2 (Class 5). There are only two glaciers in Class 4 (5–10 km^2) but these two make up almost 15% of the total glacier area in the basin.

FIGURE 4.11 DISTRIBUTION IN NUMBER AND AREA OF GLACIERS BY SIZE CLASS IN THE FOUR SUB-BASINS



Note: The numbers in the grid represent the number of glaciers and the colour codes denote the area distribution

TABLE 4.7 **NUMBER, AREA, AND ESTIMATED ICE RESERVES OF GLACIERS IN EACH SIZE CLASS IN THE KABUL RIVER BASIN**

Area classes (km²)	Glacier number		Glacier area		Estimated ice reserves		Mean area per glacier
	No. count	%	km²	%	km³	%	km²
Class 1 (< 0.5)	272	86.90	36.48	34.90	0.778	16.21	0.13
Class 2 (0.5–1)	18	5.75	12.90	12.35	0.481	10.05	0.72
Class 3 (1–5)	21	6.71	39.86	38.13	2.199	45.82	1.90
Class 4 (5–10)	2	0.64	15.29	14.63	1.340	27.92	7.64
Total	**313**	**100**	**104.53**	**100**	**4.798**	**100**	**0.33**

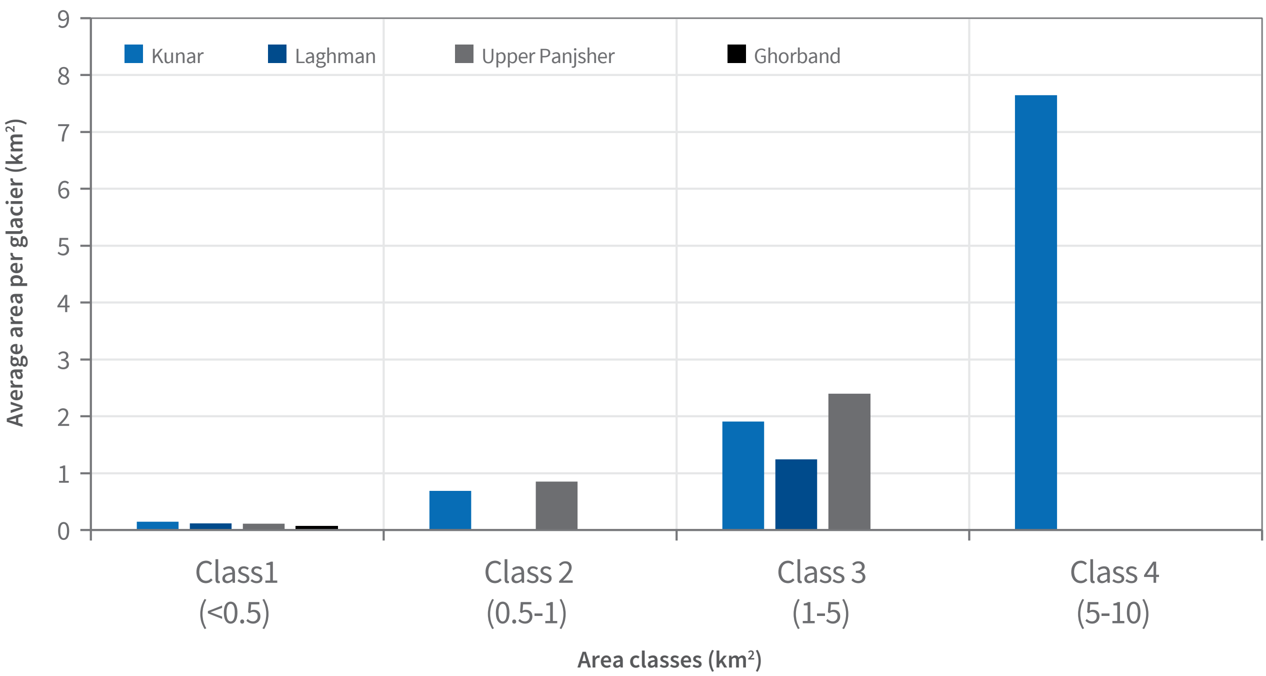
Figure 4.11 shows the distribution of the number and area of glaciers in each of the four sub-basins across size classes. Kunar sub-basin has the largest number of glaciers of Class 1 whereas Class 3 glaciers are the highest in terms of area. The other sub-basins have very few glaciers large than 0.5 km² (Class 1), one each between 1 and 5 km² in Laghman and Upper Panjsher sub-basins and three glaciers of 0.5–1 km² in the Upper Panjsher sub-basin.

The average size of the glaciers ranges from 0.11 to 7.6 km². Their average size in each size class is comparatively high in the Kunar sub-basin (Figure 4.12). The overall average size of glaciers in the Kabul River basin is 0.33 km².

The glaciers in the Kabul River basin are distributed between roughly 3,900 and 6,150 masl. The highest glacier is located in the Kunar sub-basin and the lowest glacier is a clean-ice glacier in the Upper Panjsher sub-basin. Clean-ice glaciers extend from 3,912 masl to 6,147 masl and debris-covered glaciers from 3,924 to 5,373 masl. The lowest extensions of debris-covered glaciers are in the Kunar sub-basin. This sub-basin also has the largest elevation range of clean-ice and debris-covered glaciers, from 3,924 to 6,147 masl. The Laghman sub-basin has a smaller elevation range, from 4,246 to 5,216 masl (Figure 4.13).

The area–elevation distribution of clean-ice and debris-covered glaciers in the Kabul River basin is

FIGURE 4.12 **AVERAGE SIZE OF THE GLACIERS IN EACH AREA SIZE CLASSES IN KABUL RIVER BASIN**



shown graphically in Figure 4.14. This is summarised for all glaciers at 500-m elevation zones for each sub-basin in Table 4.8. In all the sub-basins, the largest glacier area is at 4,500–5,000 masl. Almost half the glacier area in the Kabul River basin as a whole is at this elevation range. Both clean-ice and debris-covered glaciers also cover the largest area at this elevation range, more than 47% and 56% of the total glacier area in the basin, respectively. The second-largest spread of glacier area is at the elevation range 5,000–5,500 masl, more than 44% in the Kunar sub-basin and 37% in the Kabul River basin as a whole (Table 4.8).

The largest number of glaciers in the Kabul River basin have an easterly (59, 19%) or north-easterly aspect (55, 18%) (Table 4.9; Figure 4.15). Around 11%–14% have a south-easterly, southerly, westerly, or north-westerly aspect, whereas less than 10% of the glaciers have a south-westerly aspect. Barely 4% have a northerly aspect. But in terms of area, the south-easterly orientation has the largest share, 31% of the total glacier area in the basin. Glaciers having easterly and southerly aspects cover 22% and 20% of the basin's total area respectively. Glaciers with a northerly aspect cover less than 1% of the basin's area. The distribution of glaciers in each sub-basin also shows a similar pattern.

FIGURE 4.13 **ELEVATIONS OF CLEAN-ICE AND DEBRIS-COVERED GLACIERS IN THE FOUR SUB-BASINS OF THE KABUL RIVER BASIN**

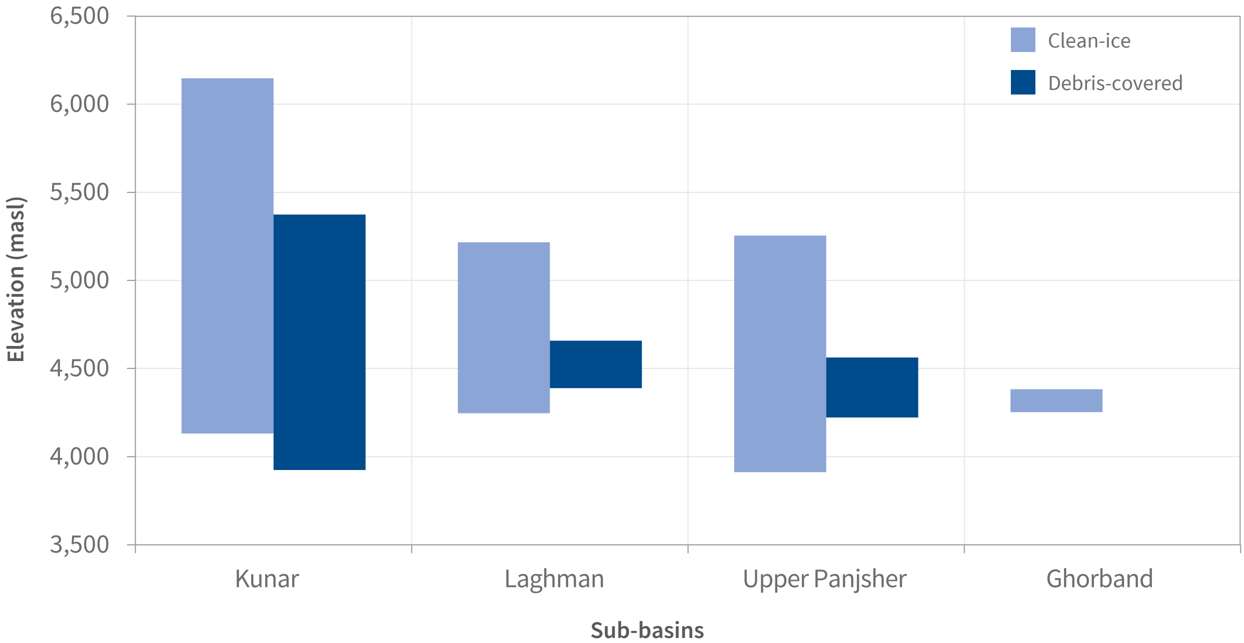


TABLE 4.8 **GLACIER AREA DISTRIBUTION AT 500-M ELEVATION ZONES IN THE FOUR SUB-BASINS AND THE KABUL RIVER BASIN**

Elevation range (masl)	Kunar		Laghman		Upper Panjsher		Ghorband		Kabul basin	
	km²	%	km²	%	km²	%	km²	%	km²	%
3,500–4,000	0.13	0.15	0	0	0.02	0.17	0	0	0.15	0.14
4,000–4,500	4.21	4.85	0.71	12.61	3.99	33.0	0.07	100	8.98	8.59
4,500–5,000	39.03	45.0	4.59	81.53	7.77	64.27	0	0	51.39	49.16
5,000–5,500	38.31	44.17	0.33	5.86	0.31	2.56	0	0	38.95	37.26
5,500–6,000	4.99	5.75	0	0	0	0	0	0	4.99	4.77
6,000–6,500	0.07	0.08	0	0	0	0	0	0	0.07	0.07
Total	**86.74**	**100**	**5.63**	**100**	**12.09**	**100**	**0.07**	**100**	**104.53**	**100**

FIGURE 4.14 DISTRIBUTION OF CLEAN-ICE AND DEBRIS-COVERED GLACIERS BY SIZE IN EACH 100-M ELEVATION ZONE OF THE KABUL RIVER BASIN

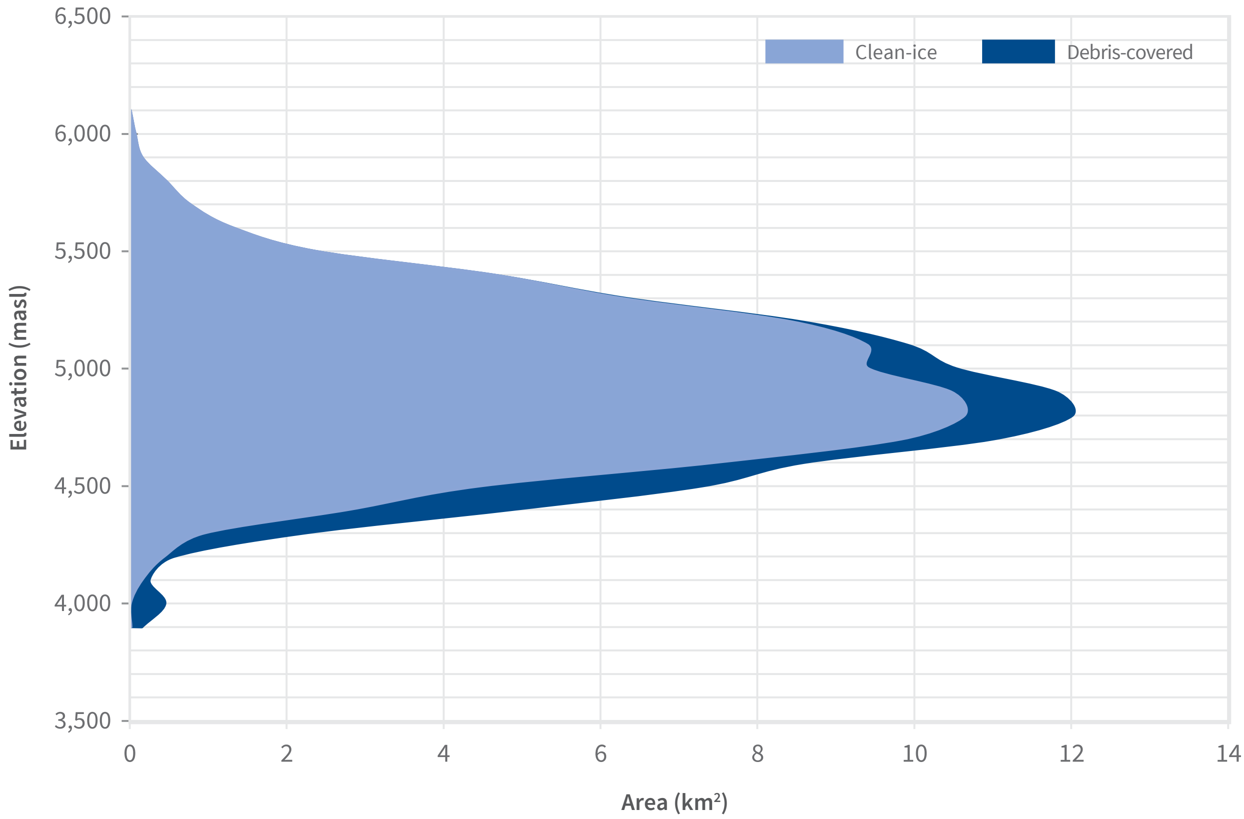


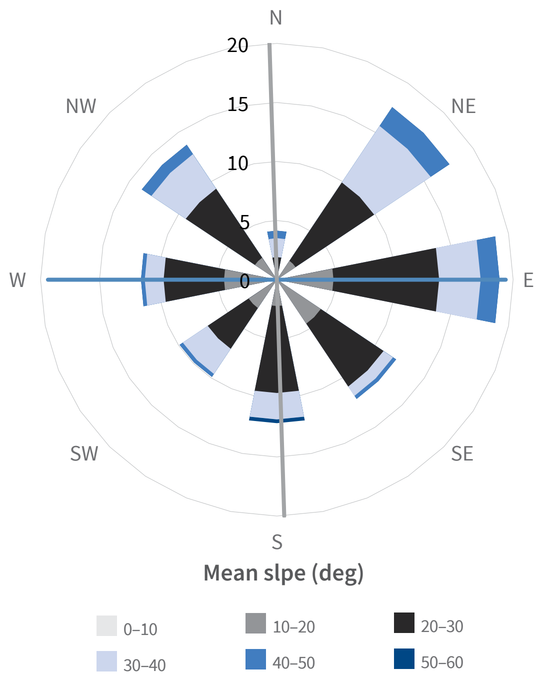
TABLE 4.9 DISTRIBUTION OF GLACIERS BY ASPECT IN THE KABUL RIVER BASIN

Aspect	N	NE	E	SE	S	SW	W	NW	Total
Number	13	55	59	38	38	31	36	43	**313**
Area (km²)	0.79	7.42	23.26	31.64	21.43	6.04	8.50	4.45	**104.53**
Estimated ice reserves (km³)	0.012	0.161	0.96	2.007	1.11	0.18	0.285	0.083	**4.798**

TABLE 4.10 DISTRIBUTION OF GLACIERS BY ASPECT IN THE KABUL RIVER BASIN

Slope classes (deg)	0–10	10–20	20–30	30–40	40–50	50–60	Total
Number	0	72	153	68	19	1	**313**
Area (km²)	0	52.30	42.47	8.49	1.24	0.03	**104.53**
Estimated ice reserves (km³)	0	2.97	1.631	0.179	0.017	<0.001	**4.798**

FIGURE 4.15 ASPECT AND MEAN SLOPE DISTRIBUTION OF GLACIERS IN THE KABUL RIVER BASIN

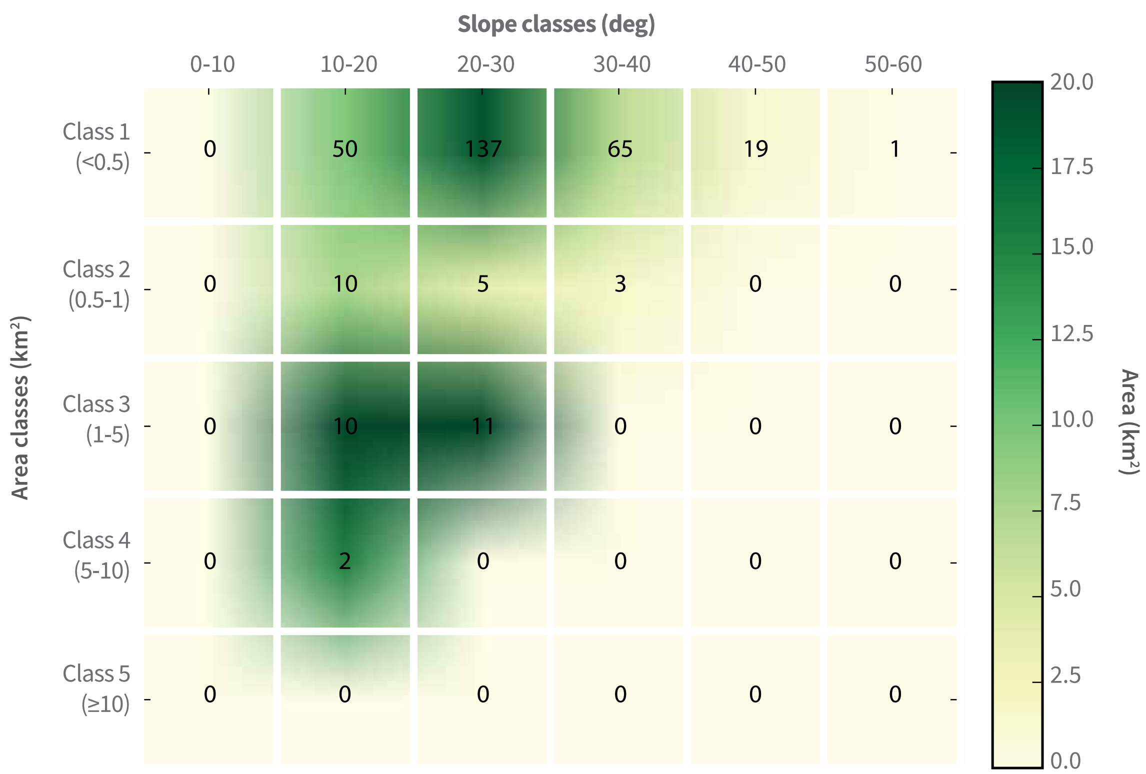


Note: Numbers within the concentric circles refer to percentages

The glaciers in the Kabul River basin have also been categorised into six mean slope classes (Table 4.10). Almost half the glaciers in the basin are in the mean slope range 20°–30°. But a comparatively higher share of the glaciers' surface area (50%) is in the gentle, mean slope range 10°–20°.

The area and slope distribution is shown graphically in Figure 4.16. It shows that larger glaciers exhibit a gentle slope. Almost 44% of the total number of glaciers are smaller than 0.5 km² belonging to the slope class 20°–30° and covering about 18% of the basin's total area. Class 3 glaciers (1–5 km²) with a 10°–20° slope comprise only 3% of the total number of glaciers in the basin, but almost 19% of its total area. There are only two glaciers of Class 4 and in the same slope category 10°–20° but they cover almost 15% of the total glacier area in the basin.

FIGURE 4.16 GLACIER DISTRIBUTION IN THE KABUL RIVER BASIN BY SLOPE CLASS



Note: The numbers in the grid represent the number of glaciers and the colour code denotes the area distribution

Transitional zone: Clean-ice and debris-covered sections of a glacier in the Noshaq valley, Badakhshan.

The shrinking and receding of glaciers will have an adverse impact on the long-term availability of freshwater downstream.

A glacier at the base of a hill slope in the Baba mountain range.

SECTION V

Decadal changes observed in glaciers in Afghanistan

Glaciers have been retreating rapidly over the past few decades in the HKH region (Bolch et al. 2008; Fujita et al. 2001; Kadota et al. 1997). Glaciers in Nepal, Bhutan, and some basins in the HKH elsewhere have retreated and shrunk by almost a quarter of their area in the thirty-year period from the 1980s to 2010 (Bajracharya et al. 2006, 2007, 2011, 2014a, 2014b, 2014c). Almost all glaciers in the HKH are retreating, barring the anomalous trends in some glaciers in the Karakoram (Hewitt 2005).

To analyse changes in glaciers in Afghanistan, a time series of the glacier inventory was prepared for 1990, 2000, 2010, and 2015. Landsat images were used to delineate glacier boundaries in the respective years with no cloud cover and least snow cover. Snow cover at the glaciers' margins made it difficult to delineate boundaries and created errors. However, the estimated levels of error are within an acceptable range, as described in the methodology section.

5.1 Number, area, and estimated ice reserves

The number, area, and estimated ice reserves of the glaciers over four time periods, and trends in them are given in Figure 5.1 and Table 5.1.

The number of glaciers decreased by 1.7% (68) over the 20-year period 1990–2010 and by 3.1% (123) over 1990–2015. The reduction in the number of glaciers (55) was higher in the five-year period 2010–2015 than in the entire previous decade (31).

However, an increase or decrease in the number of glaciers does not help us understand glacier health. It is changes in glacier area over a number of years that gives one a clearer picture about glacier advancement, retreat, or thinning. Overall, glaciers shrank by about 406.16 km^2 (13.8%) in Afghanistan in the 25-year period 1990-2015,

FIGURE 5.1 TRENDS IN THE NUMBER, AREA, AND ESTIMATED ICE RESERVES OF GLACIERS IN AFGHANISTAN, 1990–2015

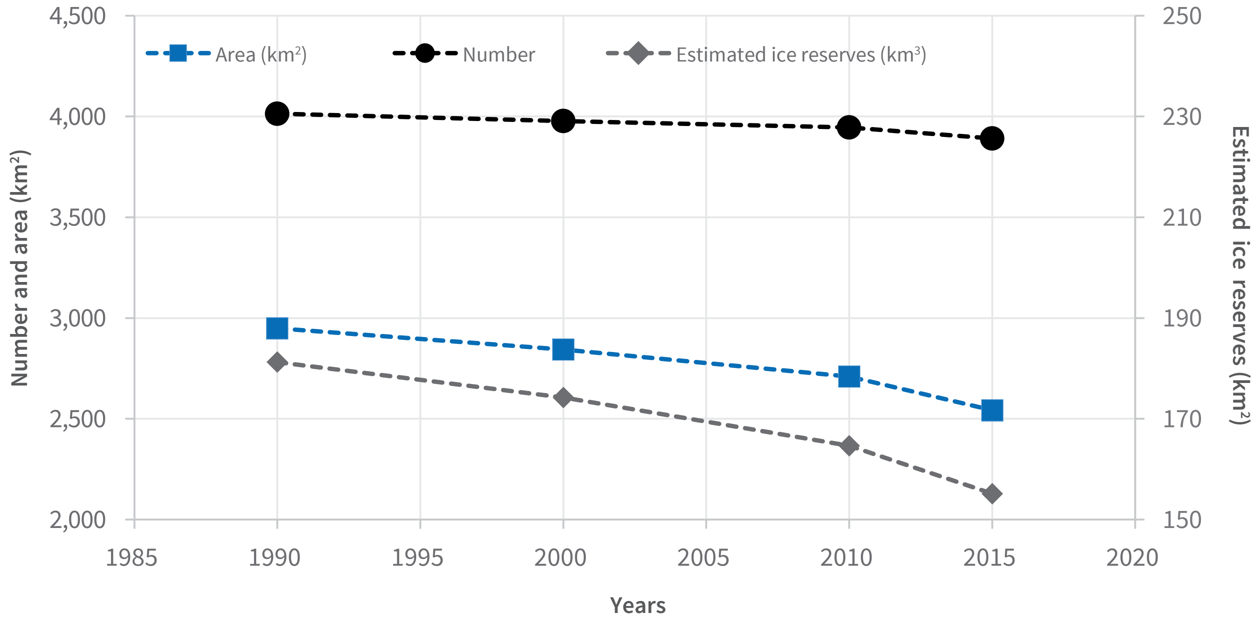


TABLE 5.1 CHANGES IN NUMBER, AREA, AND ESTIMATED ICE RESERVES OF GLACIERS IN AFGHANISTAN, 1990–2015

Glacier	Year				Percentage change			
	1990	2000	2010	2015	1990–2000	2000–2010	2010–2015	1990–2015
Number	4,014	3,977	3,946	3,891	-0.9	-0.8	-1.4	-3.1
Area (km²)	2,948.76	2,842.89	2,709.04	2,542.60	-3.6	-4.7	-6.1	-13.8
Estimated ice reserves (km³)	181.24	174.22	164.66	155.15	–3.9	–5.5	–5.8	–14.4

with the greatest loss in area during 2010–2015 (6.1%). The rate of loss was 3.6% during 1990–2000 and 4.7% during 2000–2010. This indicates an accelerating trend in loss of glacier area in recent decades.

In Table 5.2, these trends are disaggregated by sub-basin.

5.2 Glacier area classes

The number of glaciers decreased in all size classes in each decade since 1990 barring Class 1 (<0.5 km²), in which they have increased. However, the glacier area fell in all size classes in each of the decades.

The number of glaciers of Class 5 fell from 27 in 1990 to 24, with an even more drastic decrease in glacier area, from 476.46 km² in 1990 to 419.14 km² in 2015. The highest decline in terms of area has occurred among Class 3 glaciers in all decades, with a total loss of 155 km² over the 25-year period (Table 5.3). In percentage terms, the loss is the greatest among Class 4 glaciers, almost 21% over the 25 years (Figure 5.2). The loss in glacier area ranges from 2.5% to 21% over 1990–2010 and 10% to 21% from 1990 to 2015 in all classes.

FIGURE 5.2 PERCENTAGE CHANGE IN GLACIER NUMBER AND AREA IN EACH SIZE CLASS, 1990–2015

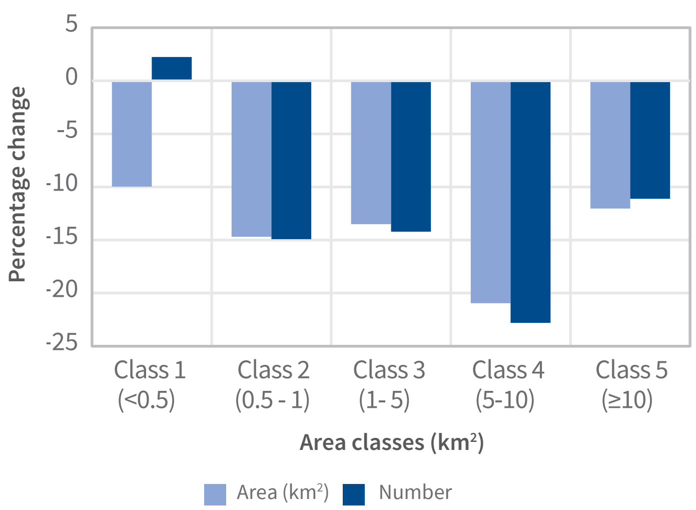


TABLE 5.2 NUMBER, AREA, AND ESTIMATED ICE RESERVES OF GLACIERS IN VARIOUS SUB-BASINS, 1990–2015

Major river basin	Sub-basin	Number				Area (km²)				Estimated ice reserves (km³)			
		1990	2000	2010	2015	1990	2000	2010	2015	1990	2000	2010	2015
Panj Amu	Upper Panj	1,889	1,892	1,901	1,897	1,858.95	1,803.05	1,706.45	1,642.25	130.57	126.33	118.81	114.21
	Lower Panj	415	398	387	378	250.59	225.56	206.30	197.09	11.63	10.37	9.38	8.92
	Kokcha	1,008	1,012	1,003	988	577.20	562.01	551.15	492.92	27.83	26.71	25.92	22.96
	Taloqan	258	255	254	253	112.10	109.68	106.75	92.85	4.81	4.65	4.51	3.92
	Kunduz	67	66	66	62	18.02	16.87	15.96	12.97	0.55	0.50	0.47	0.36
	Sub-total	**3,637**	**3,623**	**3,611**	**3,578**	**2,816.86**	**2,717.17**	**2,586.61**	**2,438.07**	**175.37**	**168.56**	**159.09**	**150.35**
Kabul	Kunar	231	219	208	206	102.97	100.33	97.45	86.74	5.02	4.91	4.82	4.27
	Laghman	52	50	50	38	8.74	7.96	7.94	5.63	0.24	0.21	0.21	0.15
	Upper Panj	93	84	76	68	20.10	17.33	16.98	12.09	0.61	0.54	0.54	0.38
	Ghorband	1	1	1	1	0.09	0.09	0.06	0.07	<0.001	<0.001	<0.001	<0.001
	Sub-total	**377**	**354**	**335**	**313**	**131.90**	**125.71**	**122.43**	**104.53**	**5.87**	**5.66**	**5.57**	**4.80**
	Total	**4,014**	**3,977**	**3,946**	**3,891**	**2,948.76**	**2,842.88**	**2,709.04**	**2,542.60**	**181.24**	**174.22**	**164.66**	**155.15**

TABLE 5.3 CHANGES IN NUMBER OF GLACIERS AND AREA ACROSS SIZE CLASSES, 1990–2015

Year/Class (km²)	Number					Area (km²)				
	Class1 (<0.5)	Class 2 (0.5–1)	Class 3 (1–5)	Class 4 (5–10)	Class 5 (≥10)	Class 1 (<0.5)	Class 2 (0.5–1)	Class 3 (1–5)	Class 4 (5–10)	Class 5 (≥10)
2015	2,832	502	489	44	24	475.72	352.76	990.52	304.46	419.14
2010	2,814	546	516	44	26	515.34	386.58	1,056.25	303.25	447.63
2000	2,772	574	551	54	26	514.10	401.64	1,100.40	366.81	459.93
1990	2,770	590	570	57	27	528.41	413.52	1,145.19	385.17	476.46
1990–2015	62	−88	−81	−13	−3	−52.69	−60.75	−154.67	−80.71	−57.32
Percentage change	2.2	−14.9	−14.2	−22.8	−11.1	−10.0	−14.7	−13.5	−21.0	−12.0

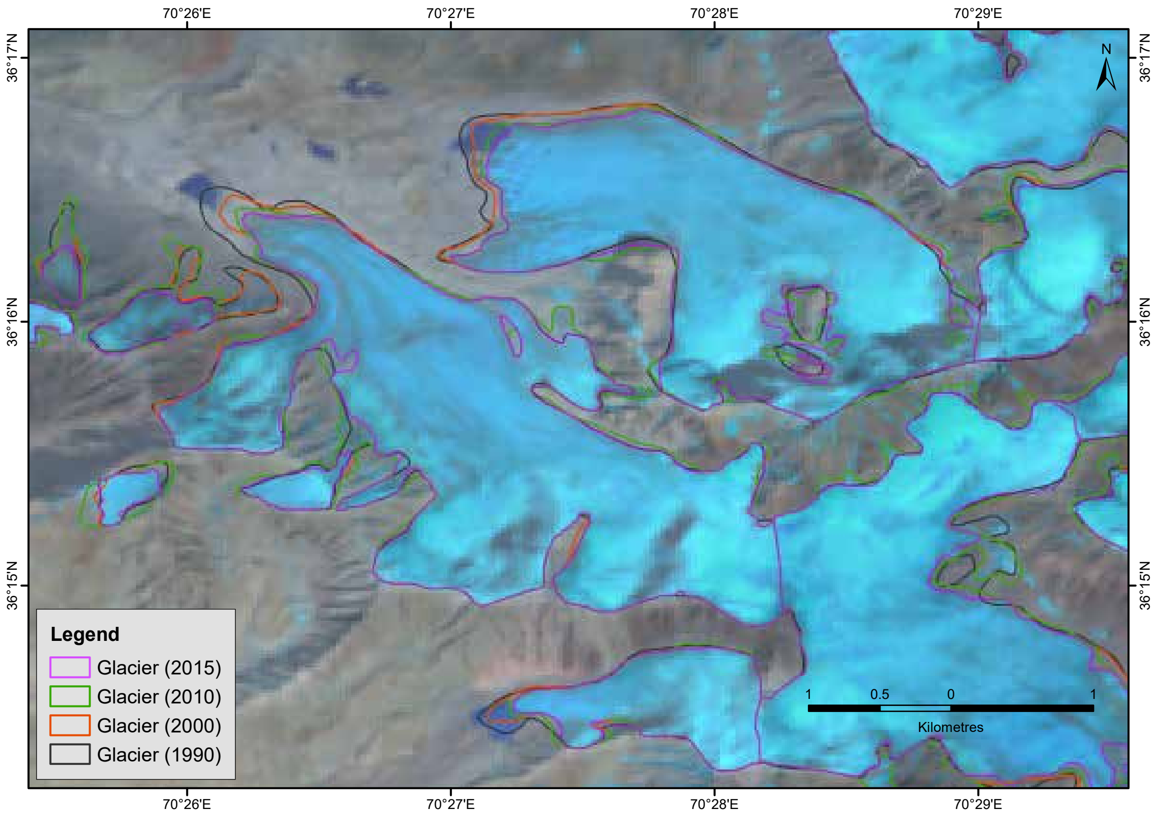
This indicates that the glaciers in Afghanistan are shrinking and retreating at an accelerating rate. Due to the shrinkage and fragmentation of larger glaciers, the number of large glaciers decreased and smaller, Class 1 glaciers increased in the years 1990–2000, 2000–2010, and 2010–2015.

Mean glacier area also decreased from 0.73 km² to 0.69 km² over 1990–2010, indicating that the glaciers are shrinking and retreating. The smaller a glacier's size, the faster its melt rate.

5.3 Glaciers in retreat

Glacier retreat is prominent in small glaciers at lower elevations, their snouts, and on steeper slopes (Figure 5.3). Elevation is one of the controlling factors in providing a healthy environment for glaciers in the HKH region. If the landform is of a valley type or has a gentle topography and at an elevation higher than 5,000 masl, it provides a conducive environment for a glacier. Afghanistan's highest point is 7,492 masl, but the highest elevation of its glaciers is 7,175 masl. The

FIGURE 5.3 GLACIAL RETREAT AND DEVELOPMENT OF GLACIAL LAKES IN THE TALOQAN SUB-BASIN, 1990–2015



slopes above 7,175 masl are very steep, and hence not conducive for glacier formation.

The lowest elevation of any glacier in Afghanistan was 3,114 masl in 1990. This has moved up to 3,164 masl in 2000, 3,182 masl in 2010, and 3,201 masl in 2015, or by 87 metres over the 25-year period. The glacier elevation shifted upward by 5 m per year from 1990 to 2000, 1.8 m per year from 2000 to 2010, and 1.9 m per year from 2010 to 2015. Glacier retreat depends on changes in average temperature, precipitation patterns, and other external factors, which need to be analysed to better understand why, and the rate at which glaciers are retreating.

5.4 Changes in glacier area at different elevations

In 1990, glaciers were observed at elevations of 3,114–7,175 masl. By 2015, this had changed to 3,201–7,175 masl. The area–elevation distribution of glaciers at 500-metre elevation ranges in each representative year are summarised in Table 5.4, and shown graphically using 100-metre slabs in Figure 5.4. Approximately 78% of Afghanistan's glacier area is to be between 4,500–5,500 masl in all decades with the greater share (more than 40%) between 5,000–5,500 masl (Table 5.4). Glacier area decreased in all bands in all decades, with the greatest loss between 4,500 and 5,500 masl (287.62 km^2 between 1990 and 2015). Proportionately though, the highest loss – almost half the original area – was observed in the 3,500–4,000 masl range.

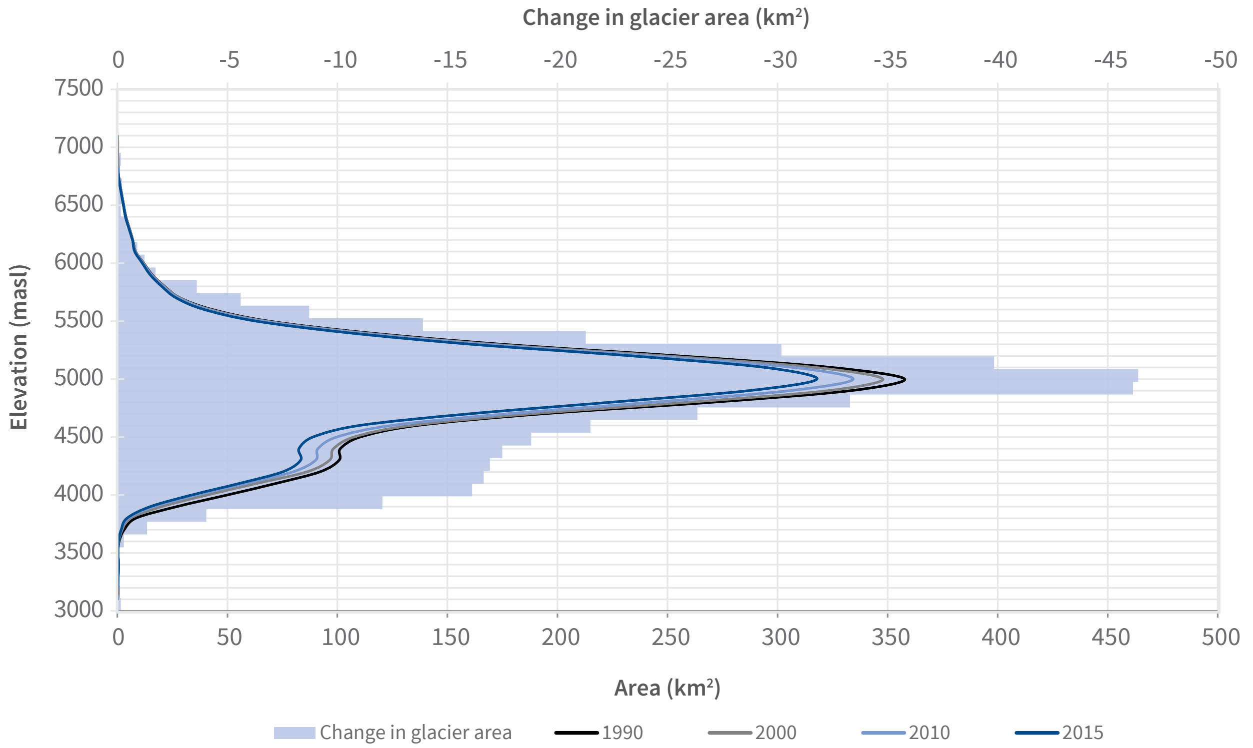
The glacier hypsography for the two-and-a-half decades shows the decrease in glacier area. The area below 3,700 masl is less than 1 km^2 at 100-m slabs. Glaciers have completely receded below 3,200 masl by 2015. The highest loss in glacier area is at 4,900–5,000 masl (Figure 5.4). The loss in glacier area below 4,100 masl is greater than 30% over 1990–2015. The extent of loss declined from 20% to 3% between 3,300 and 3,600 masl. The lesser rate of melting despite the lower altitude could be due to parts of the glaciers being debris-covered (Figure 5.5). Debris cover tends to insulate a glacier from the warmer air and hence reduces melting.

A larger loss of glacier area, more than 20 km^2 at each and every 100-m elevation zone, occurs between 4,500 masl and 5,300 masl. The loss of glacier area at these altitudes ranges from 7% to 20% in each 100-m elevation zone with a lower rate at higher elevations. There is a 5%–8% loss of glacier area at 5,300–6,000 masl. The rate of change in glacier area decreases at higher altitudes. However, the glacier area in the higher elevations above 6,700 masl are less than 1 km^2 in each 100-m zone.

TABLE 5.4 CHANGES IN GLACIER AREA IN AFGHANISTAN AT VARIED ELEVATIONS

Elevation range (masl)	Area (km²)				Rate of change (%)				Change in area per decade (%)
	1990	2000	2010	2015	1990–2000	2000–2010	2010–2015	1990–2015	
3,000–3,500	1.49	1.36	1.27	1.18	-8.7	-6.6	-7.1	-20.8	-8.3
3,500–4,000	39.85	29.41	24.49	22.06	-26.2	-16.7	-9.9	-44.6	-17.9
4,000–4,500	416.60	385.58	356.45	330.67	-7.4	-7.6	-7.2	-20.6	-8.3
4,500–5,000	1,043.99	1,012.00	950.79	870.62	-3.1	-6.0	-8.4	-16.6	-6.6
5,000–5,500	1,226.08	1,196.67	1,161.84	1,112.39	-2.4	-2.9	-4.3	-9.3	-3.7
5,500–6,000	177.61	175.14	172.05	164.54	-1.4	-1.8	-4.4	-7.4	-2.9
6,000–6,500	36.69	36.24	35.85	35.04	-1.2	-1.1	-2.3	-4.5	-1.8
6,500–7,000	6.29	6.32	6.14	5.94	0.5	-2.8	-3.3	-5.6	-2.2
7,000–7,500	0.16	0.16	0.16	0.16	0.0	0	0	0	0
Total	**2,948.76**	**2,842.88**	**2,709.04**	**2,542.60**	**–3.6**	**–4.7**	**–6.1**	**–13.8**	**–5.5**

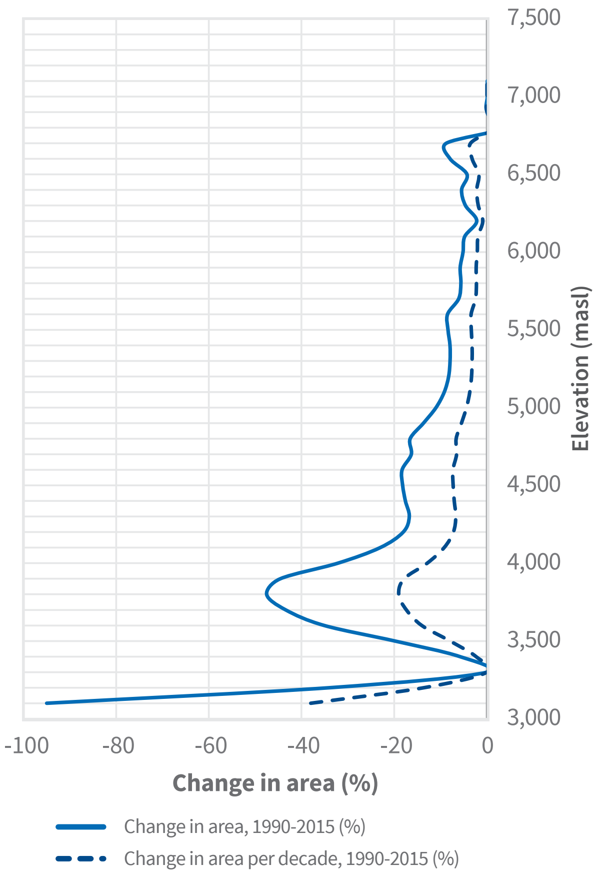
FIGURE 5.4 DISTRIBUTION AND CHANGES IN GLACIER AREA AT 100-M ELEVATION ZONES, 1990–2015



5.5 Slope

The glaciers are consistently distributed throughout the mountain slope range from 10° to 50° in all time periods from 1990 to 2015, but very few glaciers exist at slopes below 10° and above 50°. The largest number of glaciers occur within the mean slope class 20°–30° This slope class also contributes the highest concentration of glacier area in all time periods except for 2015 (Table 5.5), and plays a significant role in reservation of water volume. The number of glaciers is higher in the slope range 30°–40° than in 10°–20°, but glacier area is 4–5

FIGURE 5.5 **PERCENTAGE CHANGE IN GLACIER AREA, DECADAL AND FROM 1990 TO 2015, IN EACH 100-M ELEVATION ZONE**



times smaller in the former range. A similar pattern can be observed in slope ranges 10°–20° and 20°–30°; the slope class 20°–30° has more than double the number of glaciers but the area of both is almost the same in all time periods. This indicates that the glaciers with higher slope angles are mostly smaller in size and the slope 10°–30° is the topographic terrain most conducive to the accumulation of snow in the long run.

Overall, the number of glaciers has increased in most of the mean slope zones, barring the 20°–30° and 30°–40° slope classes. In these, they have decreased considerably over 1990–2015 (Figure 5.6). The greatest decrease in glacier area has occurred in the slope ranges 10°–20° and 20°–30° over 1990–2010. But in the slope range 10°–20°, the area and number have increased slightly during 2010–2015. The most significant loss in glacier area is from the slope range 20°–30° during all the time periods under study.

5.6 Aspects

The glaciers facing east, south-east, south, and south-west show a higher distribution in terms of both number and area. In total, the number of glaciers and the area they cover have decreased in the south, including the easterly and westerly aspects. The largest decrease in area has been in glaciers facing the south-east, followed by the southerly and south-westerly aspects. During 1990–2010, glaciers facing the south-east lost almost 15% of their area. This loss in area increased further from 1990 to 2015 (Figure 5.7).

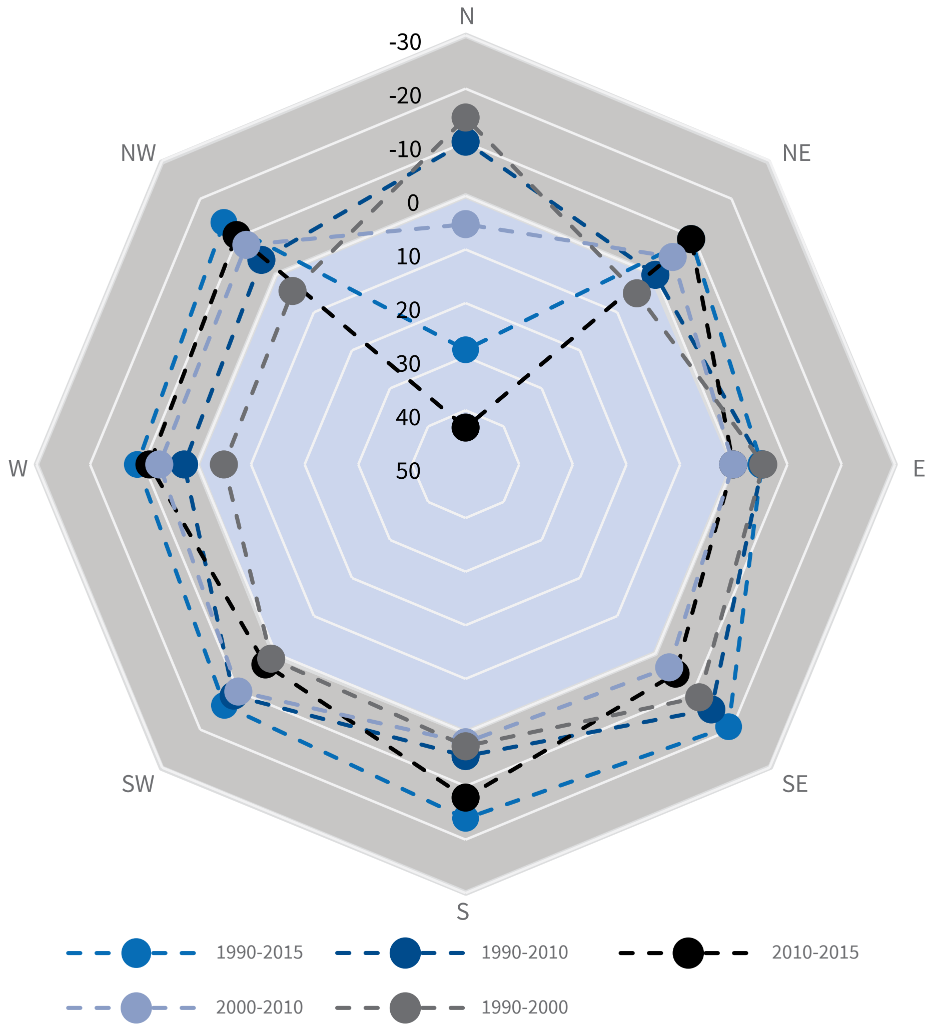
Very few glaciers are oriented to the north. Over 1990–2010, their area increased by 0.6 km^2 and their number by two, from 65 to 67. Glacier area has decreased in all cardinal directions, except the north. The increased area of glaciers facing north is significant, but their total area is quite small.

TABLE 5.5 **DISTRIBUTION OF NUMBER AND AREA COVERED BY GLACIERS IN EACH SLOPE CLASS, 1990–2015**

Glacier	Year	Mean slope (degrees)						Total
		0–10	10–20	20–30	30–40	40–50	50–60	
Number	1990	2	719	2,075	1,041	169	8	4,014
	2000	4	716	2,039	1,033	169	16	3,977
	2010	3	710	1,979	1,066	172	16	3,946
	2015	5	865	1,831	1,000	178	12	3,891
Area (km^2)	1990	0.20	1,314.72	1,343.20	268.40	21.54	0.70	2,948.76
	2000	0.27	1,271.13	1,282.34	265.62	22.18	1.34	2,842.88
	2010	0.25	1,209.00	1,211.80	265.48	21.05	1.46	2,709.04
	2015	0.57	1,281.95	1,022.78	217.56	18.77	0.99	2,542.60

FIGURE 5.6	CHANGES IN GLACIER NUMBER AND AREA IN EACH SLOPE CLASS, 1990–2015

FIGURE 5.7	PERCENTAGE CHANGE IN GLACIER AREA IN EACH ASPECT



Note: Numbers within the concentric circles refer to percentages

Glacier deposits in the Baba mountain range

A glacial lake in the Baba mountain range

Installing an automatic weather station on Pir Yakh glacier, Panjshir valley.

SECTION VI

Decadal changes in glaciers in individual river basins

6.1 Panj Amu River basin

The number of glaciers in the Panj Amu River basin, their area, and estimated ice reserves in four time periods (1990, 2000, 2010, and 2015) are summarised in Table 6.1 and the percentage change in them shown graphically in Figure 6.1. Their number has decreased by 1.6% over the 25-year period, around 0.3%–0.4% in each decade from 1990 to 2010, but higher (0.9%) in the five-year period 2010–2015. This is the case in all sub-basins. Overall, the number of glaciers has decreased by 0.6% per decade.

Similarly, the area covered by the glaciers has decreased from 2,816.86 km^2 in 1990 to 2,435.07 km^2 in 2015. The percentage decrease in area is also higher in recent decades. Overall, they have lost 13.4% of their area in 25 years, at the rate of 5.4% per decade.

Changes across size classes

The number and area of glaciers in classes 2–5 have decreased from 1990 to 2010, and also in 2015 (Figure 6.2). Their number has increased only among Class 1 glaciers, which indicates the glaciers in the basin are shrinking and retreating. Due to the shrinkage and fragmentation of larger glaciers, there has been a decrease in the number and area of large glaciers and an increase in the number of small glaciers. The area under even Class 1 glaciers has decreased, which indicates that glaciers in the basin are retreating across all size classes.

Figure 6.3 shows percentage changes in area within each size class over the 25-year period and per decade. The percentage loss in area is the highest (around 22%) in Class 4 over the 25-year period. Since

TABLE 6.1 **DECADAL CHANGES IN GLACIER NUMBER, AREA, AND ESTIMATED ICE RESERVES IN SUB-BASINS OF THE PANJ AMU RIVER BASIN**

Glacier	Basin	Year				Percentage change				
		1990	2000	2010	2015	1990–2000	2000–2010	2010–2015	1990–2015	Per decade
Number	Upper Panj	1,889	1,892	1,901	1,987	0.2	0.5	-0.2	0.4	0.2
	Lower Panj	415	398	387	378	–4.1	-2.8	-2.3	-8.9	–3.6
	Kokcha	1,008	1,012	1,003	988	0.4	-0.9	-1.5	-2.0	–0.8
	Taloqan	258	255	254	253	–1.2	-0.4	-0.4	–1.9	–0.8
	Kunduz	67	66	66	62	–1.5	0.0	-6.1	–7.5	–3.0
	Total	**3,637**	**3,623**	**3,611**	**3,578**	**-0.4**	**-0.3**	**–0.9**	**–1.6**	**–0.6**
Area (km^2)	Upper Panj	1,858.95	1,803.05	1,706.45	1,642.25	–3.0	-5.4	–3.8	–11.7	–4.7
	Lower Panj	250.59	225.56	206.30	197.09	–10.0	-8.5	–4.5	–21.3	–8.5
	Kokcha	577.20	562.01	551.15	492.92	-2.6	-1.9	–10.6	–14.6	-5.8
	Taloqan	112.10	109.68	106.75	92.85	–2.2	-2.7	–13.0	–17.2	-6.9
	Kunduz	18.02	16.87	15.96	12.97	–6.4	-5.4	–18.7	–28.0	-11.2
	Total	**2,816.86**	**2,717.17**	**2,586.61**	**2,438.07**	**–3.5**	**-4.8**	**–5.7**	**–13.4**	**-5.4**

FIGURE 6.1 **DECADAL CHANGES IN GLACIER AREA AND NUMBER IN THE PANJ AMU RIVER BASIN**

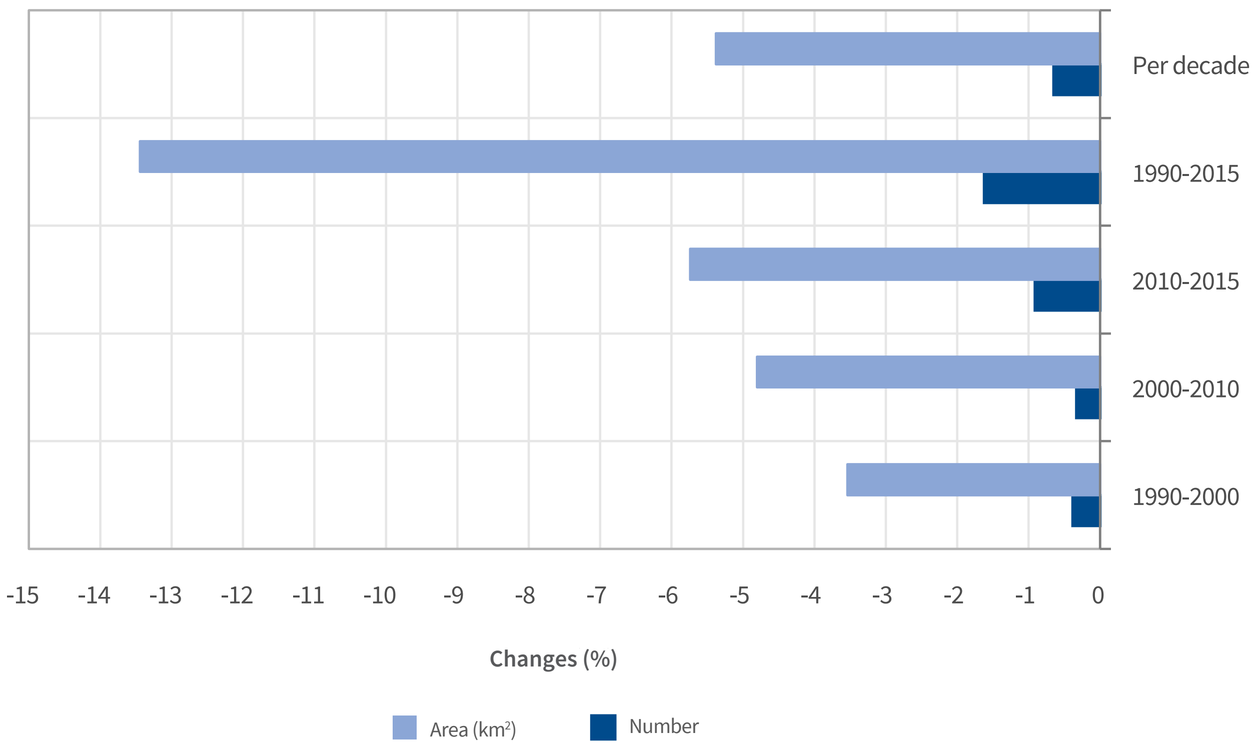


FIGURE 6.2 **CHANGES IN GLACIER NUMBER AND AREA, 1990–2015 IN EACH SIZE CLASS**

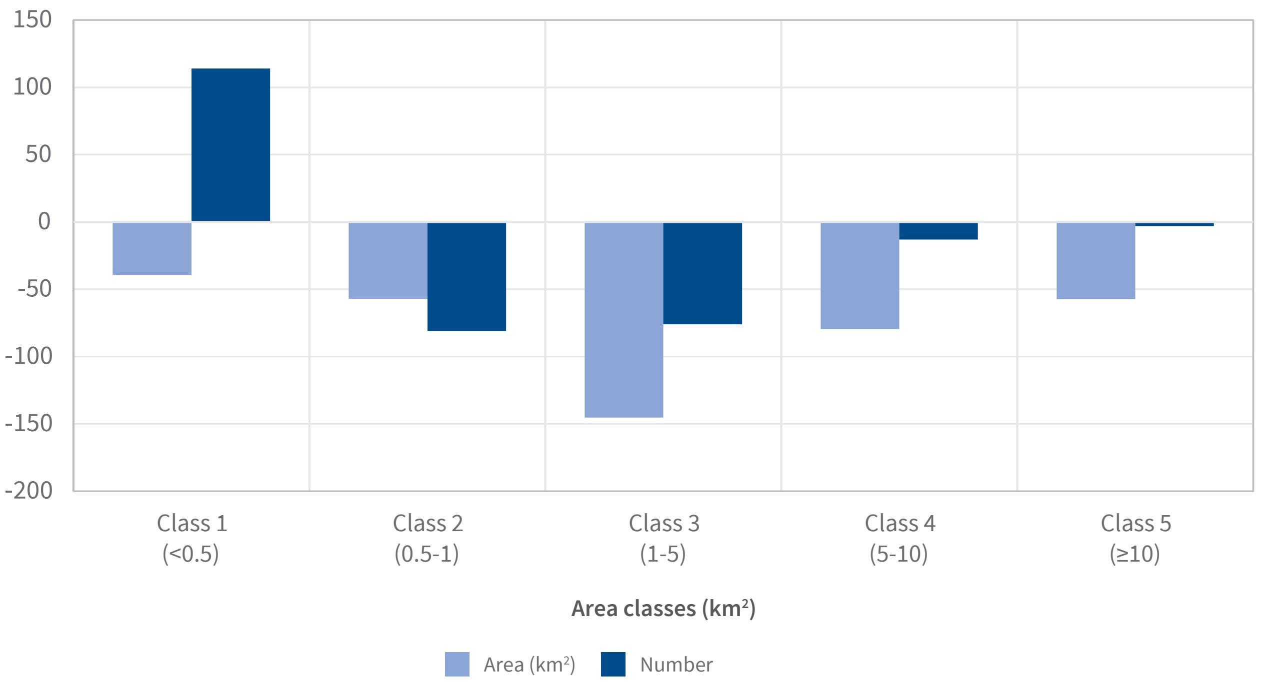
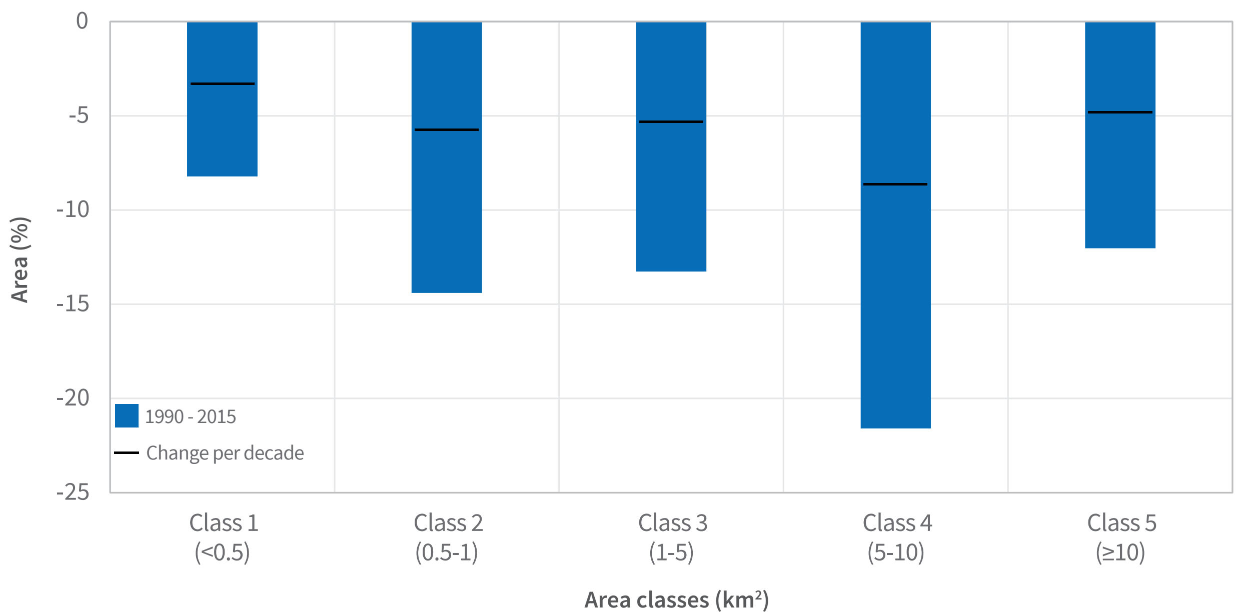


FIGURE 6.3 **PERCENTAGE CHANGES IN GLACIER AREA, 1990–2015 AND PER DECADE IN THE PANJ AMU RIVER BASIN**



the larger glaciers have shrunk and fragmented, the number of, and area under immediately lower size classes will increase. But the area of all classes decreased in the 25-year period. This indicates that the smaller glaciers are shrinking at an even higher rate.

The mean glacier area in the basin has also decreased, from 0.77 km^2 to 0.68 km^2 from 1990 to 2015, which indicates that the glaciers are shrinking.

Altitudinal changes

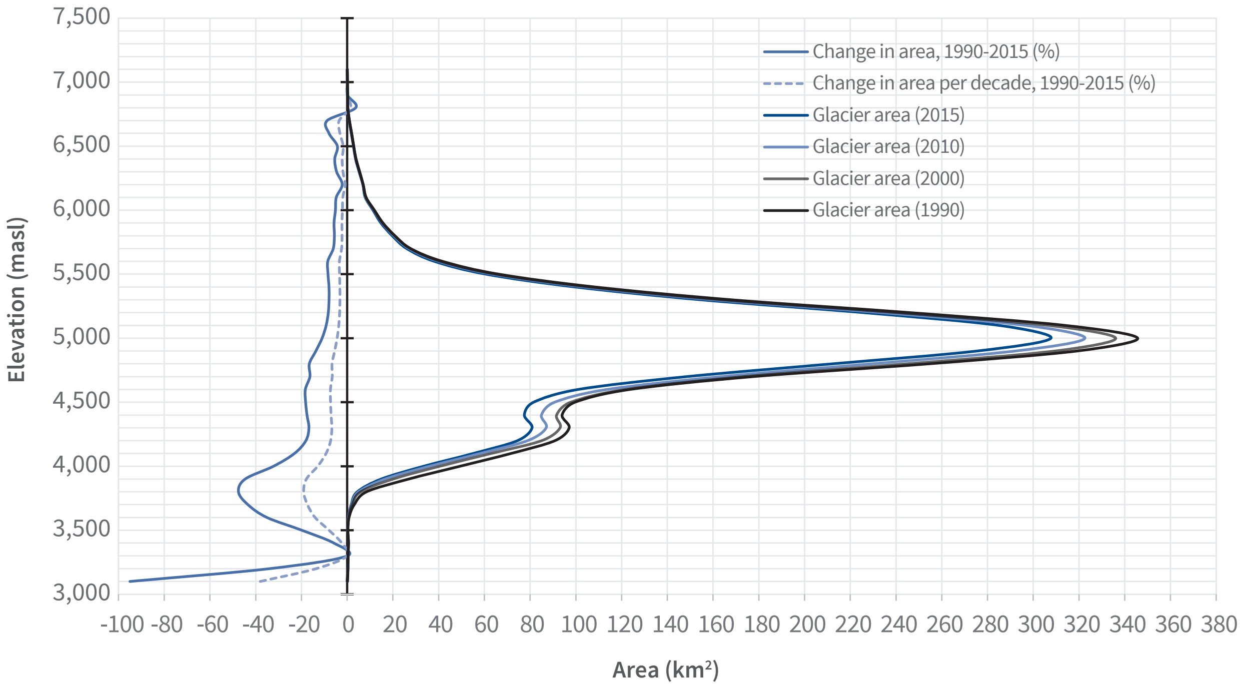
More than 97% of the glacier area is at 4,000–6,000 masl through the entire study period, with the largest area (more than 76%) between 4,500 and 5,500 masl (Table 6.2). Glacier area reduced at all elevation bands in all decades, with the greatest loss in area over the 25-year period totalling 264.39 km^2 between 4,500 and 5,500 masl, more than 70% of the total loss in area in the basin.

The glacier area below 3,600 masl is less than 1 km² at each 100-m bin. The highest loss in glacier area is at 4,900–5,000 masl. However, the percentage loss in area in each 100-m elevation band is the highest below 4,000 masl (Figure 6.4). The loss in area is the highest at 4,900–5,000 masl in all periods, and the greatest in recent years. The change in glacier area above 5,900 masl is not significant, less than 1 km², in all decades and over the 25-year period.

TABLE 6.2 DECADAL CHANGES IN GLACIER AREA IN EACH 500-M ELEVATION ZONE IN THE PANJ AMU RIVER BASIN

Elevation range (masl)	Area (km²)				Change in area (%)				Change in area per decade (%)
	1990	2000	2010	2015	1990–2000	2000–2010	2010–2015	1990–2015	
3,000–3,500	1.49	1.36	1.27	1.18	-8.7	-6.6	-7.1	-20.8	-8.3
3,500–4,000	39.63	29.23	24.33	21.91	-26.2	-16.8	-9.9	-44.7	-17.9
4,000–4,500	403.22	373.47	345.33	321.69	-7.4	-7.5	-6.8	-20.2	-8.1
4,500–5,000	974.61	947.80	889.53	819.23	-2.8	-6.1	-7.9	-15.9	-6.4
5,000–5,500	1,182.46	1,152.88	1,117.63	1,073.44	-2.5	-3.1	-4.0	-9.2	-3.7
5,500–6,000	172.41	169.79	166.45	159.55	-1.5	-2.0	-4.1	-7.5	-3.0
6,000–6,500	36.59	36.16	35.77	34.97	-1.2	-1.1	-2.2	-4.4	-1.8
6,500–7,000	6.29	6.32	6.14	5.94	0.5	-2.8	-3.3	-5.6	-2.2
6,500–7,000	0.16	0.16	0.16	0.16	0	0	0	0	0
Total	**2,816.86**	**2,717.17**	**2,586.61**	**2,438.07**	**–3.5**	**–4.8**	**–5.7**	**–13.4**	**–5.4**

FIGURE 6.4 DISTRIBUTION OF GLACIER AREA IN THE PANJ AMU RIVER BASIN IN EACH DECADE AND PERCENTAGE CHANGES FROM 1990 TO 2015 IN EACH 100-M ELEVATION ZONE



Slope

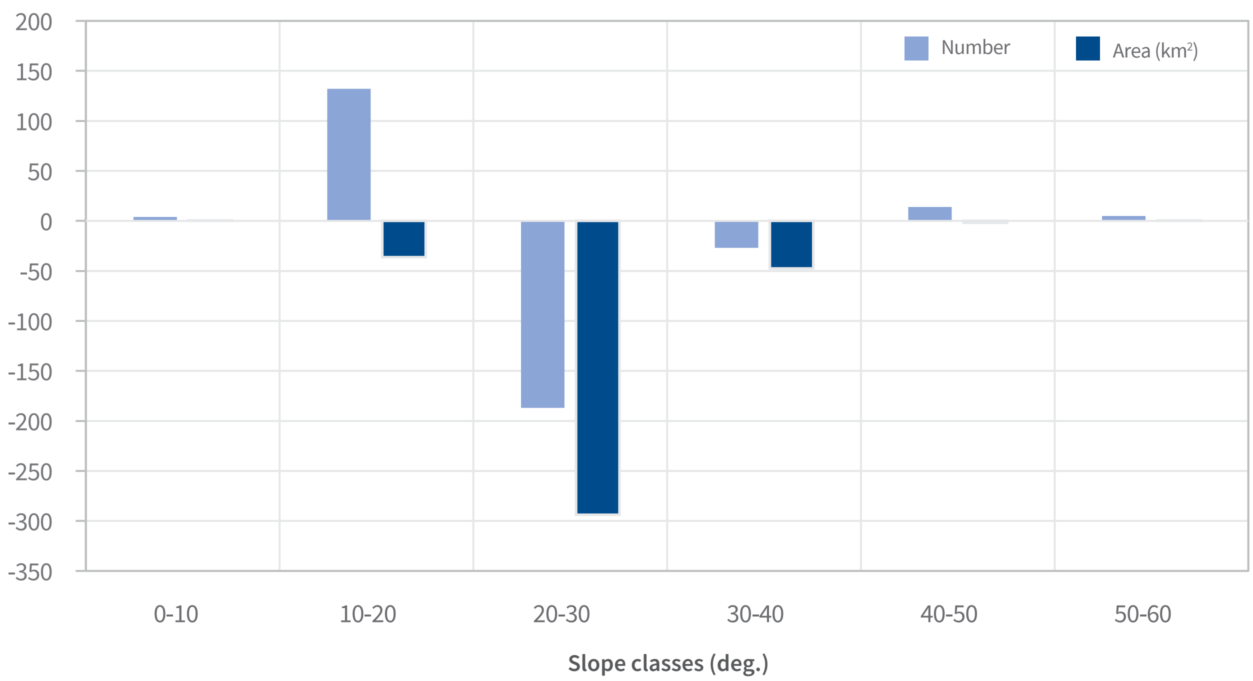
Most glaciers in the Panj Amu River basin lie between mean slope classes 10°–20°, 20°–30°, and 30°–40°. These slope classes also have the highest share of glacier area in all periods under study (Table 6.3).

The changes in glacier number and area in these slope classes show varied patterns. In the slope class 10°–20°, two glaciers were added during 1990–2000, fell by five during 2000–2010, and then increased significantly, by 135, during 2010–2015. The area under that slope class decreased by more than 8% over 1990–2010, and increased in the following five years with the increase in number. In the slope class 20°–30°, both the number and glacier area show a decreasing trend, with a higher rate in recent years. The number of the glaciers in the slope class 30°–40° decreased during 1990–2000 and then increased from 2000 to 2010. The area changes are very nominal, a decreased of 1.9 km^2 from 1990–2000 and a rise of about 1 km^2 from 2000 to 2010. Both number and area decrease significantly in 2010–2015. Over the 25-year period 1990–2015, the number of glaciers in the 10°–20° degrees slope range has increased, but their area has decreased. In the

TABLE 6.3 DISTRIBUTION OF GLACIER NUMBER AND AREA IN EACH SLOPE CLASS IN THE PANJ AMU RIVER BASIN, 1990–2015

Glacier	Year	Slope (degrees)						Total
		0–10	10–20	20–30	30–40	40–50	50–60	
Number	1990	1	661	1,865	959	145	6	**3,637**
	2000	3	663	1,850	953	142	12	**3,623**
	2010	3	658	1,798	992	147	13	**3,611**
	2015	5	793	1,678	932	159	11	**3,578**
Area (km^2)	1990	0.11	1,265.91	1,274.22	256.50	19.50	0.60	**2,816.86**
	2000	0.23	1,223.03	1,218.39	254.62	19.81	1.09	**2,717.17**
	2010	0.25	1,163.37	1,147.34	255.53	18.90	1.22	**2,586.61**
	2015	0.57	1,229.63	980.30	209.08	17.53	0.96	**2,438.07**

FIGURE 6.5 CHANGES IN GLACIER NUMBER AND AREA IN EACH SLOPE CLASS, 1990–2015



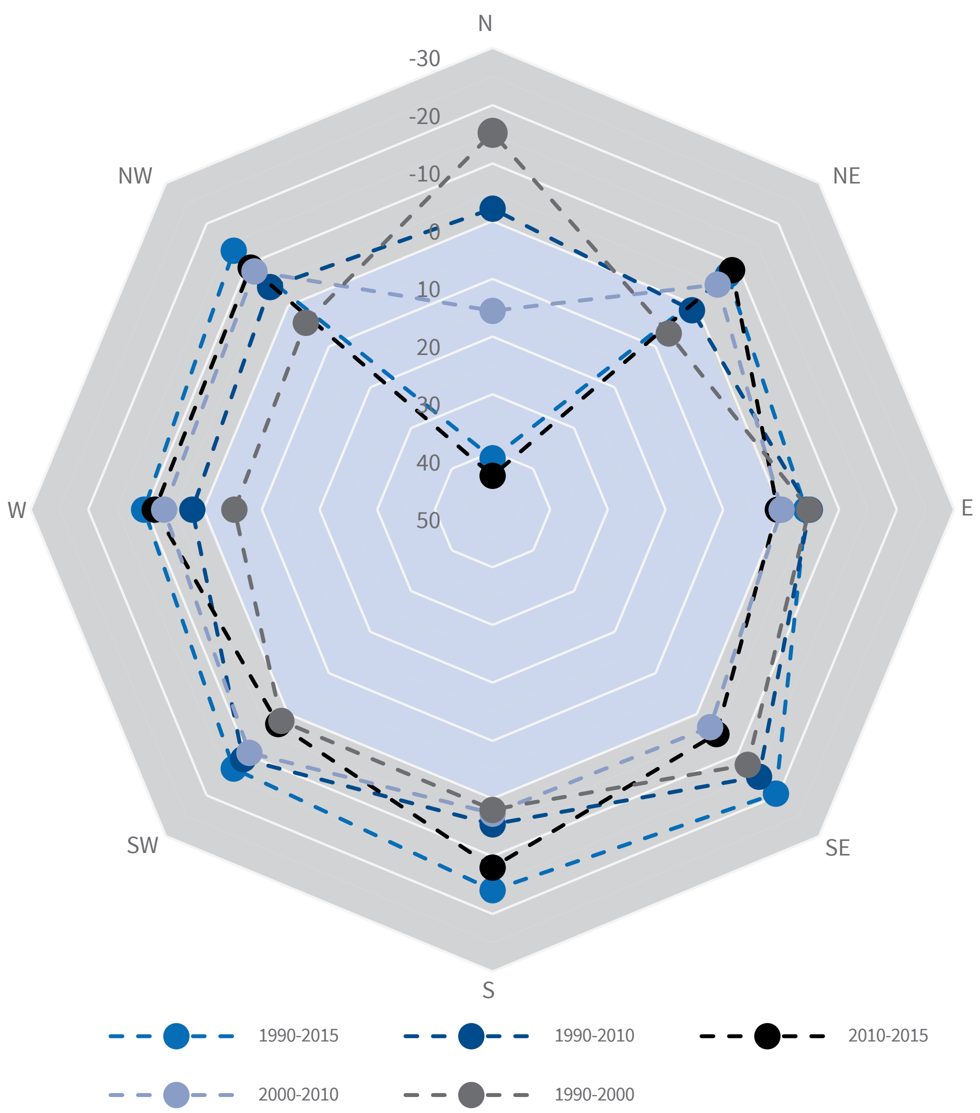
slope classes 20°–30° and 30°–40°, both their number and area has decreased significantly (Figure 6.5). This is an indication of the shrinking and fragmentation of glaciers in the higher slope classes.

The number of glaciers in the slope class 30°–40° is significantly higher than in the 10°–20° slope class during all time periods under study. However, the distribution of glacier area is just the reverse, which indicates that glaciers with higher slopes are, generally, smaller in size. This point about small average size of glaciers in the higher slope classes is verified by the distribution of glacier number and area in the slope classes 40°–50° and 50°–60°. Finally, the glacier number and area in the slope class 0°–10° is very nominal compared to other slope classes.

Aspects of the glaciers

The changes in glacier number and area are not consistent across all cardinal directions. In 1990–2000, there was a greater loss of area in glaciers facing the south-east; in 2000–2010, the loss was higher in glaciers facing the south-west (Figure 6.6). A similar pattern can be observed in their number as well. The eastern aspect has the highest number of glaciers during all the time periods under study, and where the decrease in number is the highest in 1990–2000, but it increases in 2000–2010, and in 2015. But their glacier area shows a decreasing trend, which indicates that the glaciers are shrinking and fragmenting.

FIGURE 6.6 **DECADAL CHANGE IN GLACIER AREA IN EACH ASPECT OF THE PANJ AMU RIVER BASIN**



Note: Numbers within the concentric circles refer to percentages

6.2 Kabul River basin

This subsection covers changes in glacier number and area and altitudinal changes in glaciers in the Kabul River basin. Changes pertaining to slope and aspects are not discussed as the changes in these in a time are not significant due to the glaciers in the basin are relatively small.

As is happening in the Panj Amu River basin, the number of, and area covered by glaciers in the Kabul River basin are decreasing as well. Their number has decreased from 377 in 1990 to 313 in 2015, at almost 7% per decade. Glacier area has also decreased, from 132 km^2 in 1990 to 104 km^2 in 2015. Hence, they have shrunk by almost 21% over the 25-year period, at a decadal rate of 8%. This overall rate of decrease in number and area is higher than in the Panj Amu River basin. Details of the number, area, and estimated ice reserves of the glaciers in the Kabul River basin in four time periods (1990, 2000, 2010, and 2015) are given in Table 6.4. The percentage change in their number and area is shown graphically in Figure 6.7.

Changes across size classes

The glacier number is the highest in Class 1 (<0.5 km^2) in all the time periods whereas their area is the highest among Class 3 glaciers (1–5 km^2) in most time periods. The basin has had no glaciers larger than 10 km^2 (Class 5) in the entire period under study.

The glacier number and area in all size classes decreased in the decades from 1990 to 2000, 2000 to 2010, and in 2015. There are two glaciers of Class 4 (5–10 km^2) through the time periods, but the area of these two glaciers decreased, from 16.36 km^2 in 1990 to 15.29 km^2 in 2015. The decrease in glacier number and area is higher in Class 2 over the entire period, with a 22% loss in area over 25 years. The loss in glacier area ranges from 6.5% to 27% from 1990 to 2015, and 2% to 19.5% from 1990 to 2010 across classes. The percentage change in area is higher among the smaller size classes, with an almost 27% shrinkage in area in Class 1 glaciers over the 25-year period (Figure 6.8; Table 6.5). Overall, Figure 6.8 indicates that the smaller glaciers shrink faster than larger glaciers in this basin.

TABLE 6.4 DECADAL CHANGES IN GLACIERS IN THE SUB-BASINS OF THE KABUL RIVER BASIN

Glacier	Sub-basin	Number				Change (%)				
		1990	2000	2010	2015	1990–2000	2000–2010	2010–2015	1990–2015	Per decade
Number	Kunar	231	219	208	206	-5.2	-5.0	-1.0	-10.8	-4.3
	Laghman	52	50	50	38	-3.8	0	-24.0	-26.9	-10.8
	Upper Panjsher	93	84	76	68	-9.7	-9.5	-10.5	-26.9	-10.8
	Ghorband	1	1	1	1	0	0	0	0	0
	Total	**377**	**354**	**335**	**313**	**-6.1**	**-5.4**	**-6.6**	**-17.0**	**-6.8**
Area (km^2)	Kunar	102.97	100.33	97.45	86.74	-2.6	-2.9	-11.0	-15.8	-6.3
	Laghman	8.74	7.96	7.94	5.63	-8.9	-0.3	-29.1	-35.6	-14.2
	Upper Panjsher	20.10	17.33	16.98	12.09	-13.8	-2.0	-28.8	-39.9	-15.9
	Ghorband	0.09	0.09	0.06	0.07	0	-33.3	-16.7	-22.2	-8.9
	Total	**131.90**	**125.72**	**122.43**	**104.53**	**–4.7**	**–2.6**	**–14.6**	**–20.8**	**–8.3**
Estimated ice reserves (km^3)	Kunar	5.02	4.91	4.82	4.27	-2.2	-1.7	-11.5	-14.9	-5.9
	Laghman	0.24	0.21	0.21	0.15	-10.2	-3.8	-28.6	-38.3	-15.3
	Upper Panjsher	0.61	0.54	0.54	0.38	-11.4	-0.7	-29.0	-37.6	-15.0
	Ghorband	<0.001	<0.001	<0.001	<0.001	0	0	0	0	0
	Total	**5.87**	**5.66**	**5.57**	**4.80**	**–3.5**	**–1.7**	**–13.8**	**–18.2**	**–7.3**

FIGURE 6.7 DECADAL CHANGES IN GLACIER AREA AND NUMBER IN THE KABUL RIVER BASIN

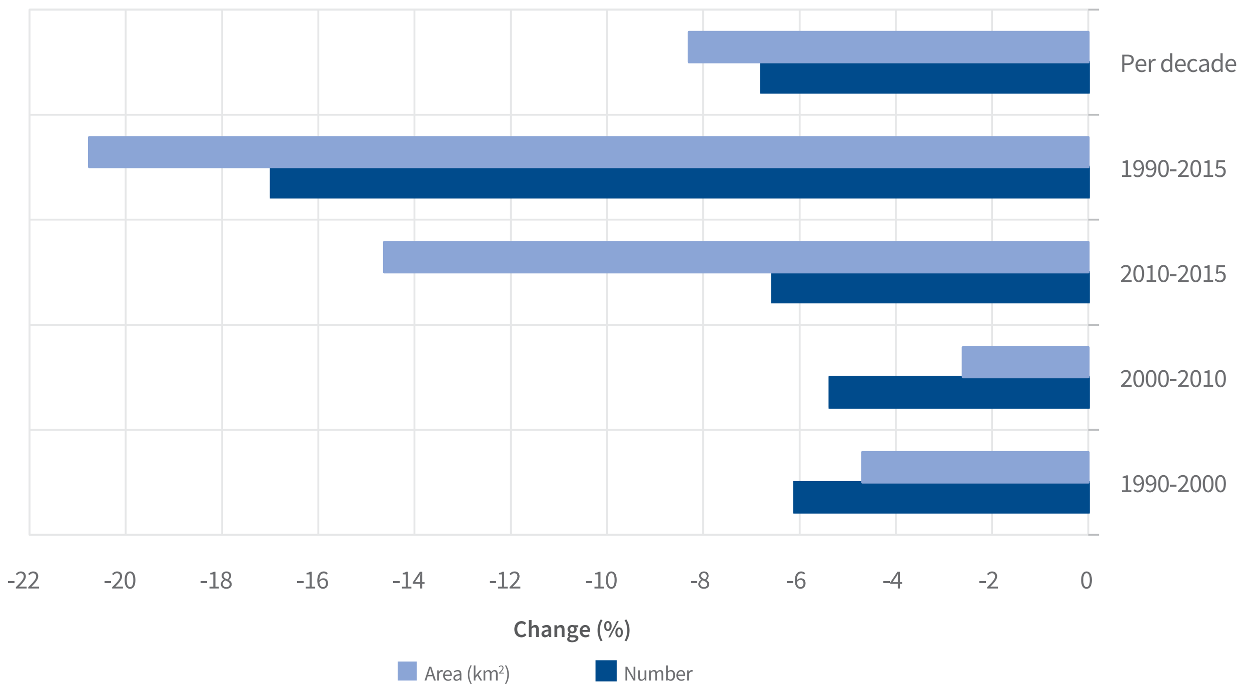
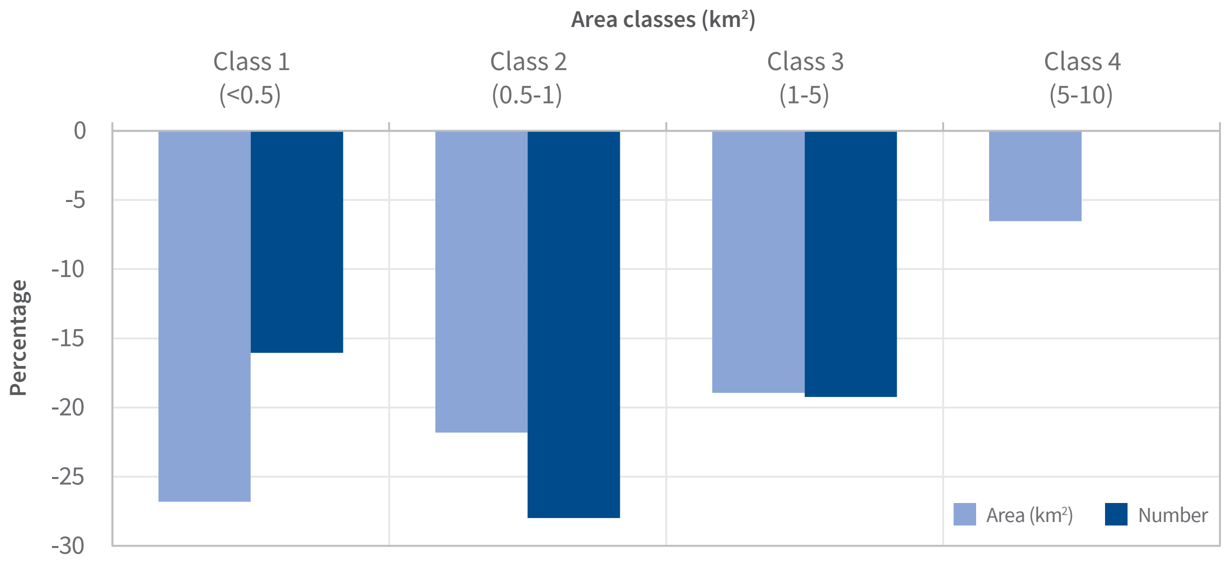


FIGURE 6.8 CHANGES IN GLACIER NUMBER AND AREA IN THE KABUL RIVER BASIN IN EACH SIZE CLASS, 1990–2015



Altitudinal changes

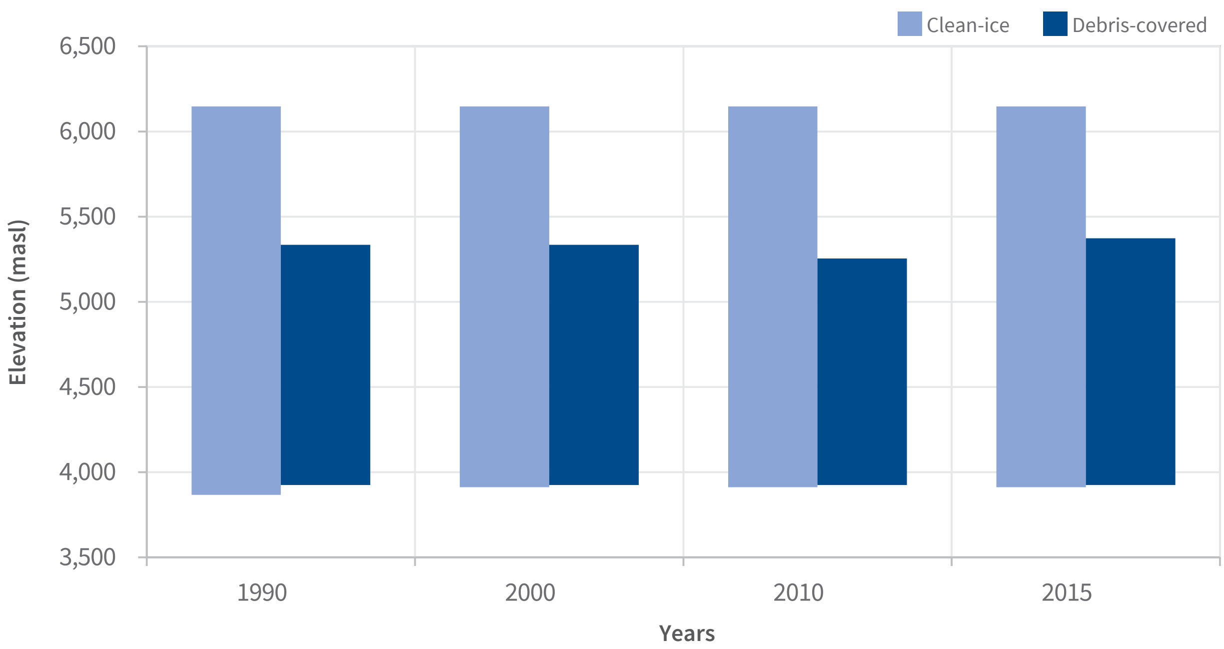
The highest and lowest elevations at which glaciers can be found in the Kabul River basin range from 3,867 to 6,147 masl. The lowest elevation has shifted upward by 45 m from 1990 to 2015, which represents a substantial change in glacier extent. This change at the snout of a glacier is very important and reflects glacial retreat and shrinking. This phenomenon is responsible for the formation and expansion of glacial lakes, which under certain conditions can cause GLOFs. The extent of clean-ice and debris-covered glaciers in the basin across four time periods is shown in Figure 6.9.

The glacier area vis-à-vis elevation distribution for decadal time periods from 1990 to 2010 indicates prominent variability in area, which is more pronounced below 5,200 masl. The area–elevation distribution curve for 1990 is highly deviated from

TABLE 6.5 DECADAL CHANGES IN GLACIER NUMBER AND AREA IN EACH SIZE CLASS IN THE KABUL RIVER BASIN

Glacier	Area classes (km²)	Year				Change (%)				
		1990	2000	2010	2015	1990–2000	2000–2010	2010–2015	1990–2015	Per decade
Number	Class 1 (<0.5)	324	301	288	272	-7.1	-4.3	-5.6	-16.0	-6.4
	Class 2 (0.5–1)	25	24	20	18	-4.0	-16.7	-10.0	-28.0	-11.2
	Class 3 (1–5)	26	27	25	21	3.8	-7.4	-16.0	-19.2	-7.7
	Class 4 (5–10)	2	2	2	2	0	0	0	0	0
	Total	**377**	**354**	**335**	**313**	**-6.1**	**-5.4**	**-6.6**	**-17.0**	**-6.8**
Area (km²)	Class 1 (< 0.5)	49.85	44.72	45.17	36.48	-10.3	1.0	-19.2	-26.8	-10.7
	Class 2 (0.5–1)	16.51	15.08	13.32	12.90	-8.6	-11.7	-3.1	-21.8	-8.7
	Class 3 (1–5)	49.18	49.91	47.95	39.86	1.5	-3.9	-16.9	-18.9	-7.6
	Class 4 (5–10)	16.36	16.00	16.00	15.29	-2.2	0	-4.4	-6.5	-2.6
	Total	**131.90**	**125.71**	**122.43**	**104.53**	**-4.7**	**-2.6**	**-14.6**	**-20.7**	**-8.3**

FIGURE 6.9 ELEVATION DISTRIBUTION OF CLEAN-ICE AND DEBRIS-COVERED GLACIERS IN THE KABUL RIVER BASIN, 1990–2015

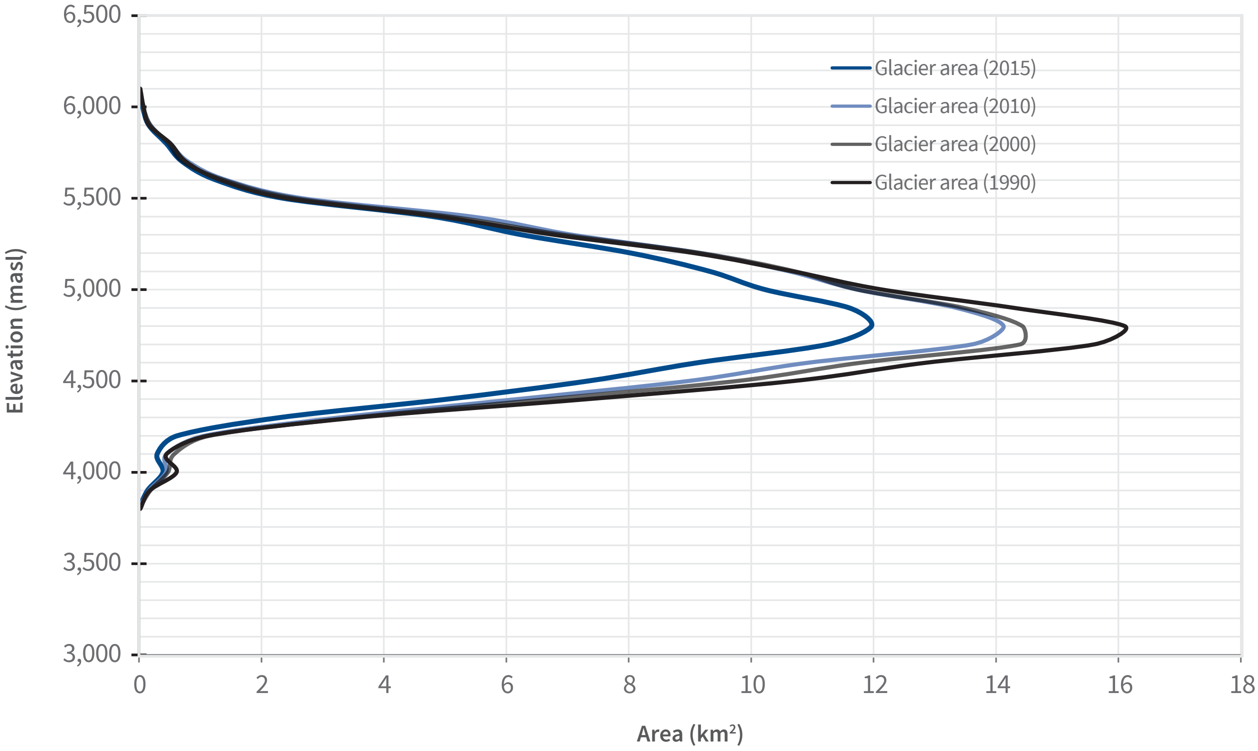


other time periods under study (Figure 6.10). Glacier area is the highest at the elevation ranges between 4,500 and 5,000 masl, with the maximum glacier area at around 4,800–4,900 masl. It is also noticeable that glacier extent above 5,400 masl has not changed much in each decadal period from 1990 on, and nor even in 2015. The glacier extent below 4,400 masl shows some reduction over 1990–2000, but limited change from 2000 to 2015. The highest loss of area over these 25 years, about 18 km² (or 26%), is at the elevation range 4,500–5,000 masl (Table 6.6). In percentage terms, the loss in glacier area is higher at lower elevations, which reflects the shifting of a glacier's terminus higher.

TABLE 6.6	DECADAL CHANGES IN GLACIER AREA AT EACH 500-M ELEVATION ZONE OF THE KABUL RIVER BASIN

Elevation range (masl)	Area (km²)				Change in area (%)				
	1990	2000	2010	2015	1990–2000	2000–2010	2010–2015	1990–2015	Per decade
3,500–4,000	0.21	0.18	0.16	0.15	-18.2	-11.1	-6.3	-31.8	-12.7
4,000–4,500	13.38	12.11	11.12	8.98	-9.5	-8.2	-19.2	-33.9	-13.2
4,500–5,000	69.39	64.20	61.26	51.39	-7.5	-4.6	-16.1	-25.9	-10.4
5,000–5,500	43.62	43.79	44.21	38.95	0.4	1.0	-11.9	-10.7	-4.3
5,500–6,000	5.20	5.35	5.60	4.99	2.9	4.7	-10.9	-4.0	-1.6
6,000–6,500	0.10	0.08	0.08	0.07	-20.0	0	-12.5	-30.0	-12.0
Total	**131.90**	**125.71**	**122.43**	**104.53**	**–4.7**	**–2.6**	**–14.6**	**–20.8**	**–8.3**

FIGURE 6.10 CHANGES IN GLACIER AREA AT EACH 100-M ELEVATION ZONE OF THE KABUL RIVER BASIN, 1990–2015



Kunj glacier and glacial lake in Panjshir, Kabul basin; June 2019

SECTION VII

Conclusions

This research report contains a detailed mapping of glaciers in Afghanistan for 1990, 2000, 2010, and 2015, and provides comprehensive information regarding the status of glaciers in those respective years and changes in them over time. This database of glaciers in Afghanistan is the first of its kind. The database on the latest status of glaciers in Afghanistan was prepared using the semi-automatic method. For greater accuracy while comparing decadal glacier data over the years, glaciers in decadal time periods (1990, 2000, and 2010) were mapped by overlaying glacier boundaries for 2015 against satellite images of these respective years, manually editing them where necessary, and cross-checking them with available higher-resolution images on Google Earth. Hence the glacier data for 1990, 2000, and 2010 can be taken as robust evidence of decadal changes in glaciers in Afghanistan.

The decadal data from these earlier years, seen along with the status of glaciers from the satellite images for 2015, clearly show that glaciers in Afghanistan are decreasing rapidly. Individual glaciers are shrinking, retreating, and fragmenting. As the glaciers serve as freshwater reserves, the shrinking and receding of glaciers will have an adverse impact on the long-term availability of freshwater downstream and integrated water resources management. The rapid melting of glaciers initially increases riverine water flows, but in the long term, there will be a reduction in riverine flows with the decrease in glacier mass. Furthermore, the increasing recession of glaciers can lead to the formation of new glacial lakes and the expansion of existing ones, which may lead to an increase in the risk or frequency of GLOFs.

There are 3,891 glaciers in Afghanistan, concentrated

A snow-covered orchard, Kahmard area, Afghanistan.

in two glacierized basins, the Panj Amu and Kabul river basins. The glaciers cover an area of 2,543 km^2 and contain 155.15 km^3 of estimated ice reserves. Their average area is 0.65 km^2 per glacier. Some major points based on the glacier data for 2015, and included in this report, are:

- The glaciers cover about 0.4% of Afghanistan's total land area, of which the Panj Amu River basin contributes about 96%.
- The glaciers are highly concentrated in the northeastern part of the country in the Wakhan Corridor.
- The largest glacier in Afghanistan is G072584E36889N, with an area of 39.36 km^2 and located in the Upper Panj sub-basin of the Panj Amu River basin.
- Clean-ice glaciers cover almost 93% of the total glacier area; the remaining 7% area has debris-covered glaciers.
- The glaciers are distributed at elevations of 3,201–7,175 masl. Clean-ice glaciers are to be found from 3,452 masl to 7,175 masl and debris-covered glaciers from 3,201 masl to 5,406 masl. The lowest and highest glaciers both lie in the Upper Panj sub-basin in the Wakhan Corridor.
- The maximum glaciated area in the Panj Amu River basin – 307.74 km^2, or 12.6% of the basin's glaciated area – occurs at 5,000–5,100 masl. In the Kabul River basin, it is 11.94 km^2, or 11.5% of the area, and occurs at the elevation range of 4,800–4,900 masl.
- Almost 20% of glaciers in the country have an easterly aspect. The second-highest share, about 15%, is of those with a south-easterly aspect. The proportion of glaciers with a north-easterly, southerly, south-easterly, westerly, and north-westerly aspect range from 11% to 14%. A small number of glaciers face the north.
- The average slope of clean-ice glaciers in the sub-basins range from 22° to 28°, with an average slope of 27°. Debris-covered glaciers in the sub-basins range from 10° to 14° with an average slope of about 12°.

Regarding changes over time, this report draws attention to the following significant trends. The overall glacier area in Afghanistan has decreased by 406.16 km^2 (13.8%) and the estimated ice reserves have diminished by 26 km^3 (14.4%) over the 25-year period 1990–2015. The number of glaciers has fallen by 68 (1.7%) over 1990–2010 and by 123 (3.1%) over the 25-year period 1990–2015. A similar pattern is observed in all the sub-basins, although with differences reflecting the differential elevation, type, and concentration of glaciers in each sub-basin. In general, the number of glaciers will increase either with the development of new glaciers or due to the fragmentation of larger glaciers, but here – as with other parts of the HKH region – their number has decreased due to the disappearance of small glaciers and also other small glaciers shrinking to sizes below the defined threshold.

The mean glacier area has decreased from 0.73 km^2 to 0.65 km^2 over 1990¬–2015. Small glaciers and low-altitude glaciers are more sensitive to rising temperatures and tend to melt faster; hence, glaciers at altitudes below 3,500 masl have retreated rapidly.

Moreover, glaciers at steep slopes and the frontal part of glaciers (associated with glacial lakes) are retreating at a faster rate.

Although some of the smaller glaciers that existed in 1990 had disappeared by 2010 and/or 2015, the number of the smallest class of glaciers has increased as a result of shrinkage and fragmentation of larger glaciers. The share of glacier area and estimated ice reserves of small glaciers is comparatively small, but as these glaciers tend to be more sensitive to climate change, they may play a more important role, proportionately, in the loss of ice reserves.

The separate information provided in this report regarding clean-ice and debris-covered glaciers will serve as an important parameter in climate change models. Clean-ice glaciers respond to a warming climate faster than debris-covered glaciers; the latter tend to respond slower because of the thermal insulation provided by the debris. As the glacier melts or thins, the debris carried by the glacier ice at the bottom and/or its side walls gets exposed on the glacier's surface. Additionally, due to the thinning of glaciers, lateral moraines can get destabilised and collapse onto the glacier surface, adding more debris on the surface of the glacier. These processes will increase the debris-covered area in glaciers in the region. The differentiated clean-ice and debris-covered glacier data shows that the clean-ice glacier area decreased by 9% from 1990 to 2010, and by 15% over 1990¬–2015, whereas the debris-covered area increased by 11% over 1990¬–2010 and by 15% over 1990–2015.

Ways forward

This study presents the database of the glaciers in Afghanistan from 1990 to 2015 using a uniform source, which will help to comprehend the behaviour of glaciers in the country in the years to come. This database provides the spatial distribution and changes in glaciers over this 25-year period with regular monitoring at least every five to ten years using the same method consistently. It presents data to better understand the trends in the changes taking place in these glaciers.

High-resolution images with 3D capability can be used for the precise monitoring of glaciers in some catchments. Further detailed investigations, such as geodetic glacier mass balance, fully distributed glacio-hydrological models, and establishing stations -, and glacier and snow melt modeling, can be deployed in some of the important and representative catchments to better understand (and manage) water resource availability, potential glacier-related hazards and risk reduction, and impacts on the glacial environment due to climate change. These data sets can be used to identify some representative glaciers for long-term, field-based monitoring of the cryosphere under conditions of climate change. Also needed are capacity-building activities, including training courses on both remote-sensing and field-based monitoring of glaciers and subsequent analysis, and scientific exchanges. They are important components for producing good-quality human resources as well as the data and information needed for the country to face new challenges pertaining to the cryosphere in the future.

A glacier at the base of a hill slope in the Baba mountain range.

SECTION 8

References

Aich, V., Akhundzadah, N., Knuerr, A., Khoshbeen, A., Hattermann, F., Paeth, H., Scanlon, A., ...Paton, E. (2017). Climate change in Afghanistan deduced from reanalysis and coordinated regional climate downscaling experiment (CORDEX)—South Asia simulations. *Climate*, 5, 38. doi:10.3390/cli5020038

Bajracharya, S. R., Maharjan, S. B., & Shrestha, F. (2011). Glaciers shrinking in Nepal Himalaya. In J. Blanco & H. Kheradmand (eds.), *Climate Change: Geophysical Foundations and Ecological Effects* (pp. 445–458). Rijeka: InTech.

Bajracharya, S. R., Maharjan, S. B., Shrestha, F., Bajracharya, O. R., & Baidya, S. (2014a). *Glacier status in Nepal and decadal change from 1980 to 2010 based on landsat data*. Kathmandu: ICIMOD.

Bajracharya, S. R., Maharjan, S. B., & Shrestha, F. (2014b). The status and decadal change of glaciers in Bhutan from 1980s to 2010 based on the satellite data. *Annals of Glaciology*, 55(66), 159–166. doi: 10.3189/2014AoG66A125

Bajracharya, S. R., Maharjan, S. B., & Shrestha, F. (2014c). Understanding dynamics of Himalayan glaciers: Scope and challenges of remote sensing. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Volume XL-8-1283, ISPRS Technical Commission VIII Symposium, 9–12 December, Hyderabad, India.

Bajracharya, S. R., Maharjan, S. B., & Shrestha, F. (2018). *Training manual on application of remote sensing and geographic information systems for mapping and monitoring of glaciers using eCognition software*. Kathmandu: ICIMOD.

Bajracharya, S. R., Mool, P. K., & Shrestha, B. R. (2006). *The impact of global warming on the glaciers of the Himalaya. In Proceedings of the International Symposium on Geodisasters, Infrastructure Management and Protection of World Heritage Sites*, 25–26 November 2006 (pp. 231–242). Kathmandu/Matsuyama: Nepal Engineering College, National

Society for Earthquake Technology Nepal, and Ehime University, Japan.

Bajracharya, S. R., Mool, P. K., & Shrestha, B. R. (2007). *Impact of climate change on Himalayan glaciers and glacial lakes: Case studies on GLOF and associated hazards in Nepal and Bhutan*. Kathmandu: ICIMOD.

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

Beekma, J., Condappa, D. D., & Forni, L. (2013). Investment Plan for the Panj-Amu Basin (Version 1), Afghanistan. Report submitted by Landell Mills Ltd at the request of the Ministry of Energy and Water, Islamic Government of Afghanistan. https://afghanwaters.net/wp-content/uploads/2017/10/2013-Amu-Investment-Plan.pdf

Bhambri, R., & Bolch, T. (2009). Glacier mapping: A review with special reference to the Indian Himalayas. *Progress in Physical Geography*, 33(5), 672–704.

Bishop, M.P., Shroder J.F., Ali, G., Bush, A.B.G, Haritashya, U.K., Roohi, R., Sarikaya, M.A, & Weihs, B.J. (2014). Remote Sensing of Glaciers in Afghanistan and Pakistan. In: Kargel J., Leonard G., Bishop M., Kääb A., Raup B. (eds) *Global Land Ice Measurements from Space*. Springer Praxis Books. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-540-79818-7_23

Bolch, T., Buchroithner, M. F., 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 Earth System Science*, 8(6), 1329–1340.

Bolch, T., Kulkarni A., Kääb A., Huggel C., Paul F., Cogley J. G., ...Stoffel, M. (2012). The state and fate of Himalayan glaciers. *Science*, 336, 310–314. DOI:10/1126/science.1215828

Bolch, T., Menounos, B., & Wheate, R. D. (2010). Landsat-based inventory of glaciers in western Canada, 1985–2005. *Remote Sensing of Environment*, 114(1), 127–137.

Braslau, D. (1972). The glaciers of Keshnikhan. In K. Gratzl (ed.), *Hindukusch: Österreichische Forschungsexpedition in den Wakhan 1970* (pp. 112–116). Graz: Akademische Druck-u. Verlagsanstalt.

Breckle, S. W., & Frey, W. (1976a). Die hochsten Berge im Zentralen Hindukusch [The highest mountains in the central Hindu Kush]. *Afghanistan Journal*, 3(3), 91–94.

Breckle, S. W., & Frey, W. (1976b). Beobachtungen zur heutigen Vergletscherung der Hauptkette des Zentralen Hindukusch [Observations of the present-day glacierization of the principal mountain ranges in the central Hindu Kush]. *Afghanistan Journal*, 3(3), 95–100.

Cruz, R. V., Harawawa, H., Lal, M., Wu, S., Anokhin, Y., Punsalmaa, B. ...Ninh, N. H. (2007). Asia. In M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, & C. E. Hanson (eds.), *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 469–506). Cambridge, UK: Cambridge University Press.

DeBeer, C. M., & Sharp, M. J. (2007). Recent changes in glacier area and volume within the southern Canadian Cordillera. *Annals of Glaciology*, 46, 215–221. doi:10.3189/172756407782871710

Dyurgerov, M. B., & Meier, M. F. (2004). Glaciers and the study of climate and sea-level change. In J. L. Bamber and A. J. Payne (eds.), *Mass Balance of the Cryosphere: Observations and Modelling of Contemporary and Future Changes* (pp. 579–621). Cambridge, U. K.: Cambridge University Press.

English, P. W. (1984). *World Regional Geography: A Question of Place*. New York: John Wiley & Sons.

FAO (2016). *The Islamic Republic of Afghanistan: Land Cover Atlas*. Food and Agricultural Organization of the United Nations. http://www.fao.org/geospatial/resources/detail/ar/c/1024570/

Favre R., & Kamal G. (2004). *Watershed Atlas of Afghanistan: 1st Edition – Working Document for Planners.* Kabul: AIMS, FAO and SDC.

Frey H., Machguth, H., Huss M., Huggel, C., Bajracharya, S., Bolch, T., ...Stoffel, M. (2014). Estimating the volume of glaciers in the Himalayan–Karakoram region using different methods. *The Cryosphere*, 8, 2313–2333. https://doi.org/10.5194/tc-8-2313-2014

Frey H., & Paul F. (2012). On the suitability of the SRTM DEM and ASTER GDEM for the compilation of topographic parameters in glacier inventories. *International Journal of Applied Earth Observation and Geoinformation*, 18, 480–490. https://doi.org/10.1016/j.jag.2011.09.020

Frey, H., Paul, F., & Strozzi, T. (2012). Compilation of a glacier inventory for the western Himalayas from satellite data: Methods, challenges and results. *Remote Sensing of Environment*, 124, 832–843. doi: 10.1016/j.rse.2012.06.020

Fujita, K., Kadota, T., Rana, B., Kayastha, R. B., & Ageta, Y. (2001). Shrinkage of glacier AX010 in Shorong region, Nepal Himalayas in the 1990s. *Bulletin of Glaciological Research*, 18, 51–54.

Gilbert, O., Jamieson, D., Lister, H., & Pendlington, A. (1969). Regime of an Afghan glacier. *Journal of Glaciology*, 8(52), 51–65.

Grotzbach, E. (1964). Munchner Hindukusch-Kundfahrt 1963. *Die Erde*, 95(4), 1–98.

Haritashya, U. K., Bishop, M. P., Shroder, J. F., Bush, A. B. G., & Bulley, H. N. N. (2009). Space-based assessment of glacier fluctuations in the Wakhan Pamir, Afghanistan. *Climatic Change*, 94, 5–18. DOI 10.1007/s10584-009-9555-9

Haeberli, W. (2004). Glacier and ice caps: Historical background and strategies of world-wide monitoring. In: J.L. Bamber and A.J. Payne (Eds.), *Mass Balance of the Cryosphere: Observations and Modelling of Contemporary and Future Changes*. Cambridge University Press, Cambridge, U.K., pp. 559–578.

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. *Ann. Glaciol.*, 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. https://doi.org/10.1659/0276-741(2005)025[0332:TKAGEA]2.0.CO;2

IPCC (2007). Parry, M. L., Canziani, O. F., Palutikof, J. P., van der Linden, P. J., & Hanson, C. E. (eds.). *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.

Kadota, T., Fujita, K., Seko, K., Kayastha, R. B., & Ageta, Y. (1997). Monitoring and prediction of shrinkage of a small glacier in the Nepal Himalaya. *Annals of Glaciology*, 24, 90–94.

King, M., & Sturtewagen, B. (2010). Making the most of Afghanistan's river basins: Opportunities for regional cooperation. New York: The EastWest Institute and Gerda Henkel Stiftung.

Kostka, R. (1974). Map Hoher Hindukusch Koh-e-Keshnikhan. In Hindukusch (edited by K. Gratzl): Akademische Druck- und Verlagsanstalt, Graz.

Kulkarni, A. V., Bahuguna, I. M., Rathore, B. P., Singh, S. K., Randhawa, S. S., Sood, R. K., & Dhar, S. (2007). Glacial retreat in Himalaya using Indian Remote Sensing satellite data. *Current Science*, 92, 1, 69-74.

Kulkarni, A., & Karyakarte, Y. (2014). Observed changes in Himalayan glaciers. *Current Science*, 106(2), 237-244. http://www.jstor.org/stable/24099804

LIGG/WECS/NEA. (1988). *Report on first expedition to glaciers and glacier lakes in the Pumqu (Arun) and Poiqu (Bhote-Sun Koshi) river basins, Xizang (Tibet), China: Sino-Nepalese joint investigation of glacial lake outburst floods in the Himalaya in 1987*. Lanzhou Institute of Glaciology and Geocryology, Academia Sinica, and Water and Energy Commission Secretariat of Nepal. Beijing: Science Press.

Maharjan, S. B., Shrestha, F., & Bajracharya, S. R. (2018). *Training manual on application of remote sensing and geographic information systems for mapping and monitoring of glaciers: Introduction to geographic information systems (GIS) and ArcGIS.* Kathmandu: ICIMOD.

Manley, W.F. (2008). Geospatial inventory and analysis of glaciers: a case study for the eastern Alaska Range. In Williams, R.S., Jr and J.G. Ferrigno, (eds). Satellite image atlas of glaciers of the world. Denver, CO, United States Geological Survey, K424–K439. (USGS Professional Paper 1386-K.)

Maurer, J. M., Schaefer, J. M., Rupper, S., & Corley, A. (2019). Acceleration of ice loss across the Himalayas over the past 40 years. *Science Advances*, 5, 6. DOI: 10.1126/sciadv.aav7266

Mool, P. K., Bajracharya, S. R., & Joshi, S. P. (2001a). *Inventory of glaciers, glacial lakes and glacial lake outburst floods, monitoring and early warning systems in the Hindu Kush Himalaya region*. Kathmandu: ICIMOD/UNEP.

Mool P. K., Wangda D., Bajracharya S. R., Kunzang K., Gurung D. R., & Joshi S. P. (2001b). *Inventory of glaciers, glacial lakes and glacial lake outburst floods monitoring* *and early warning systems in the Hindu Kush-Himalayan Region – Bhutan*. Kathmandu: ICIMOD.

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

NASA JPL. (2014). U.S. Releases Enhanced Shuttle Land Elevation Data. https://www.jpl.nasa.gov/news/news.php?release=2014-321

UNEP (2014). National Biodiversity. Strategy & Action Plan: Framework for Implementation 2014–2017. From National Environmental Protection Agency. http://hdl.handle.net/20.500.11822/7636

Palka, C. E. J. (2001). Afghanistan: *A Regional Geography*. West Point, N.Y.: West Point Department of Geography and Environment Engineering, United States Military Academy.

Paul F., & Andreassen L. M. (2009). A new glacier inventory for the Svartisen region, Norway, from Landsat ETM+ data: Challenges and change assessment. *Journal of Glaciology*, 55(192), 607–618. doi:10.3189/002214309789471003

Paul F., Barrand, N. E., Baumann, S., Berthier, E., Bolch, T., Casey, K., …Winsvold, S. (2013). On the accuracy of glacier outlines derived from remote-sensing data. *Annals of Glaciology,* 54(63). doi:10.3189/2013AoG63A296

Paul F., & Kaab A. (2005). Perspectives on the production of a glacier inventory from multispectral satellite data in Arctic Canada: Cumberland Peninsula, Baffin Island. *Annals of Glaciology*, 42, 59–66. doi:10.3189/172756405781813087

Paul F., Kaab A., Maisch M., Kellenberger T., & Haeberli W. (2002). The new remote-sensing-derived Swiss glacier inventory: I. Methods. *Annals of Glaciology*, 34, 355–361. doi: 10.3189/172756402781817941

Petersen G., Condappa D. D., & Forni, L. (2013). *Kabul Basin Investment Plan (Version 3)*. Report submitted by Landell Mills Ltd at the request of the Ministry of Energy and Water, Islamic Government of Afghanistan. https://afghanwaters.net/wp-content/uploads/2017/10/2013-KRB-Investment-Plan.pdf

Patzelt, G. (1978). Gletscherkundliche Untersuchungen im Grossen Pamir (Glacier research in the Greater Pamir). In: R.S. de Grancy and R. Kostka (Eds.), *Grosser Pamir, Akademische Druck Verlagsanstalt, Graz, Austria*, pp. 131–149 [in German].

Racoviteanu A. E., Pau l. F., Raup B., Khalsa S. J. S., & 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.

Raup B., & Khalsa S. J. S. (2010). *GLIMS analysis tutorial*. http://www.glims.org/MapsAndDocs/assets/GLIMS_Analysis_Tutorial_a4.pdf

Raup B., Racoviteanu A., Khalsa S. J. S., Helm C., Armstrong R., & Arnaud Y. (2007). The GLIMS geospatial glacier database: A new tool for studying glacier change. *Global and Planetary Change*, 56(1–2), 101–110. doi: 10.1016/j.gloplacha.2006.07.018

Rosenzweig, C., Casassa, G., Karoly, D. J., Imeson, A., Liu, C., Menzel, A. …Tryjanowski, P. (2007). Assessment of observed changes and responses in natural and managed systems. In M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, & C. E. Hanson (eds.), *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 79–131). Cambridge: Cambridge University Press.

Sakai A. (2019). Brief communication: Updated GAMDAM glacier inventory over high-mountain Asia. *The Cryosphere*, 13, 2043–2049. https://doi.org/10.5194/tc-13-2043-2019

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

Shroder, J. F. Jr. (1980). Special problems of glacial inventory in Afghanistan. *Hydrological Sciences–Bulletin*, 126, 142–147. World Glacier Inventory. Proceedings of the Reideralp Workshop, September 1978.

Shroder, J. F. Jr. (1989). Glacierized areas of Afghanistan. In W. Haeberli, H. Bosch, K. Scherler, G. Ostrem, & C. C. Wallen (eds.), *World Glacier Inventory, Status 1988*. pp C39–C40. Teufen, Switzerland: IAHS (ICSI)-UNEP-UNESCO.

Shroder, J. F. Jr., & Bishop, M. P. (2010a). Glaciers of Afghanistan. In R. S. Williams Jr. and J. G. Ferrigno (eds.), *Satellite Image Atlas of Glaciers of the World: Asia* (pp. F167–F199). USGS Professional Paper No. 1386-F3. Reston: U. S. Geological Survey.

Shroder, J. F. Jr., & Bishop, M. P. (2010b). Glaciers of Pakistan. In R. S. Williams Jr. and J.G. Ferrigno (eds.), *Satellite Image Atlas of Glaciers of the World: Asia* (pp. F201–F257). USGS Professional Paper No. 1386-F4. Reston: U. S. Geological Survey.

Wester, P., Mishra, A., Mukherji, A., & Shrestha, A. B. (eds.). (2019). *The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People*. Cham: Springer Nature Switzerland AG.

Yao, T. D., Thompson, L., Yang, W., Yu, W. S., Gao, Y., Guo, X. J. …Joswiak, D. (2012). Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings. *Nature Climate Change, 2(9), e663–e667.*

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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 Himalaya – 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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